THE SCIENCE BEHIND IMPACTS OF THE CLIMATE CRISIS

HEARING

BEFORE THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
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March 12, 2021

THE SCIENCE BEHIND IMPACTS OF THE CLIMATE CRISIS

FRIDAY, MARCH 12, 2021

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Committee met, pursuant to notice, at 11 o'clock a.m., via Webex, Hon. Eddie Bernice Johnson [Chairwoman of the Committee] presiding.

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
HEARING CHARTER

The Science Behind Impacts of the Climate Crisis

Friday, March 12, 2021
11:00 am ET
Cisco WebEx

PURPOSE

The purpose of this hearing is to discuss the importance of science in understanding the impacts of the climate crisis, as well as how climate change is already impacting the U.S. on regional and local scales, including the record-setting 2020 wildfire and Atlantic hurricane seasons and other recent climate disasters. This will include discussion of the disproportionate impacts of climate change on vulnerable communities. The Committee will consider new advancements in climate science and understanding, such as in observational and predictive capabilities and the ability to quantify climate impacts and assess societal risk. This hearing will also be an opportunity to discuss the importance of science in advancing adaptation and mitigation solutions.

WITNESSES

- **Dr. Michael Oppenheimer**, Albert G. Milbank Professor of Geosciences and International Affairs, Princeton University
- **Dr. Zeke Hausfather,** Director of Climate and Energy, The Breakthrough Institute
- **Dr. Noah Diffenbaugh**, Kara J Foundation Professor, Department of Earth System Science, Kimmelman Family Senior Fellow, Woods Institute for the Environment, Stanford University
- **Dr. Paula Bontempi**, Dean, Graduate School of Oceanography, Professor of Oceanography, University of Rhode Island

KEY QUESTIONS

- How is climate change already impacting the U.S. on regional and local scales, and how do current observations of climate change compare to previous predictions?
- What are the projected future impacts of climate change, and what will those look like if the world limits global warming to 1.5°C or 2°C?
- How have recent updates to climate science improved our understanding of the timing, intensity, and location of climate events?
- How has our understanding of attributing extreme events like the 2020 wildfire season or the 2020 Atlantic Hurricane season to climate change improved?
- What is the state of the ocean-climate nexus and resulting impacts on ocean processes from global warming?
- What has led to the improvement in our ability to quantify impacts and societal risk associated with climate change?
- As attention shifts to mitigation and adaptation solutions, how can science continue to be part of the solution to the climate crisis?

- What are the remaining climate research gaps and how can the Science Committee address them?

Background

The science is clear: modern climate change is primarily driven by human activities, largely the burning of fossil fuels. Atmospheric greenhouse gas concentrations are greater than 500 parts per million (ppm),[1] compared to pre-industrial levels of 280 ppm. Humanity has already exceeded global warming of ~1.0°C above pre-industrial conditions and is on track to warm at least an additional 1.5°C between 2030 and 2052 at the current emissions rate.[2]

On February 19, 2021, the U.S. officially rejoined the Paris Agreement, which commits to limiting global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels. The U.S. is expected to announce its carbon emission reduction target under the Agreement, called its "nationally determined contribution," as well as an economic plan to achieve the new target, around an April 22 climate summit hosted by President Biden.[3]

The 2020 economic downturn resulting from the COVID-19 pandemic only reduced global carbon emissions by about 5.8 percent.[4] While a record reduction, it was "not even a blip"[5] in terms of total carbon dioxide in the atmosphere and did not have a measurable effect on ocean warming. Global emissions are already back to being 2.1 percent higher than before the pandemic hit, suggesting the world is off track from meeting long-term climate goals.

2020 was a record-setting year for the climate, tying with 2016 as the hottest year on record.[6] The U.S. experienced a record 22 climate disasters that each caused at least $1 billion in damage, totaling $95 billion in damage and 261 deaths, even with NOAA counting all of the distinct wildfires in the West as a single event.[7] Ocean temperatures in 2020 reached their highest level in recorded history,[8] which supercharged extreme weather, including a record-setting Atlantic hurricane season with 30 named storms.[9]

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[1] In carbon dioxide (CO_2) equivalents. https://www.esrl.noaa.gov/gmd/aggi/aggi.html
[2] IPCC, 2018: Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels…* https://www.ipcc.ch/sr15/chapter/spm/
[3] https://www.whitehouse.gov/briefing-room/statements-releases/2021/01/27/fact-sheet-president-biden-takes-executive-actions-to-tackle-the-climate-crisis-at-home-and-abroad-create-jobs-and-restore-scientific-integrity-across-federal-government/
[4] https://www.iea.org/news/after-steep-drop-in-early-2020-global-carbon-dioxide-emissions-have-rebounded-strongly
[5] https://www.theguardian.com/environment/2020/sep/11/impact-of-covid-slowdown-on-co2-in-the-atmosphere-not-even-a-blip-australian-scientist-says
[6] https://www.nasa.gov/press-release/2020-tied-for-warmest-year-on-record-nasa-analysis-shows
[7] https://www.ncdc.noaa.gov/billions/
[8] Cheng, L. et al. 2021. "Upper Ocean Temperatures Hit Record High in 2020." *Advances in Atmospheric Sciences.* https://doi.org/10.1007/s00376-021-0447-x.
[9] https://www.noaa.gov/media-release/record-breaking-atlantic-hurricane-season-draws-to-end

The effects of climate change often have disproportionate impacts on historically marginalized communities. "Climate justice" is a term that acknowledges that climate change can have detrimental social, economic, public health, and other impacts on underprivileged populations. [10] Low-income communities; Black, Indigenous, and people of color; people with disabilities; older or very young people; and women can be more susceptible to risks posed by climate change impacts such as floods, storms, wildfires, extreme heat, poor air quality, and access to food and water. Multiple studies show that communities of color are often at greater risk from air pollution caused by the burning of fossil fuels.[11]

Role of the Ocean in the Climate System

There is growing recognition of the ocean-climate nexus, or the major role that the oceans play in the climate system and the fact that global terrestrial warming would be much worse without the oceans "taking the heat." The oceans have absorbed more than 90 percent of the heat trapped by carbon emissions, resulting in rising ocean temperatures.[12] Oceans reached the highest temperatures on record in 2020,[13] and are heating faster than any period in the last 2000 years.[14] Warmer oceans also disrupt rainfall patterns on land, leading to floods, droughts, and wildfires.[15] One of the Earth's major ocean current systems, the Atlantic Meridional Overturning Circulation, is slowing due to warming and is the weakest it has been in the last 1,000 years, threatening to disrupt weather and climate patterns across North America and Western Europe.[16]

Ocean warming has also led to increased deoxygenation (oxygen loss), species shifts, marine heatwaves, coral bleaching, increased storm intensity, and sea level rise.[17] The oceans have also absorbed a significant portion (approximately 30 percent) of the excess carbon emissions from the atmosphere, resulting in more acidic conditions.[18]

Regional and Local Climate Impacts in the U.S.

Climate change is no longer a far-off reality; it is impacting the globe and the U.S. on regional and local scales. According to numerous studies, climate change is causing more frequent and intense storms, heat waves, floods, wildfires, and other extreme events.[19] Climate change is increasing the frequency of extreme events, causing more extreme events to occur

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[10] https://yaleclimateconnections.org/2020/07/what-is-climate-justice
[11] Ibid.
[12] IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.
[13] Ibid.
[14] Gebbie, G. 2021. "Combining Modern and Palaeoceanographic Perspectives on Ocean Heat Uptake." *Annual Review of Marine Science*. DOI: https://doi.org/10.1146/annurev-marine-010419-010844
[15] Wang, B., et al. 2019. "Historical change of El Nino properties sheds light on future changes of extreme El Nino." *PNAS*. DOI: https://doi.org/10.1073/pnas.1911130116
[16] Caesar, L., et al. 2021. "Current Atlantic Meridional Overturning Circulation weakest in last millennium. *Nat. Geosci*. DOI: https://doi.org/10.1038/s41561-021-00699-z
[17] Ibid.
[18] Ibid.
[19] Wuebbles, D.J., et al. 2017: Executive summary. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. U.S. Global Change Research Program, Washington, DC, USA, pp. 12-34, DOI: 10.7930/J0DJ5CTG.

simultaneously or back-to-back.[20] The following subsections outline some of the major impacts of climate change across the U.S.

Drought and Wildfires
The U.S. had its most active wildfire year on record in 2020 due to very dry and warm conditions in the West. Wildfires burned a record 10.3 million acres in the U.S. last year, exceeding the 2000-2010 average by 51 percent.[21] Climate change plays a role in creating conditions for wildfires in the West. Global warming has increased the frequency of extreme wildfire weather in recent decades due to long-term warming, which has resulted in more dry, flammable vegetation, and decreasing autumn precipitation. [22] The number of autumn days with extreme fire weather have more than doubled in California since the early 1980s due to climate change.[23]

Hurricanes and Extreme Weather
2020 saw a record number of Atlantic hurricanes impacting the Southeastern U.S., as well as more storms that intensified rapidly like Hurricane Laura. Scientists have established the link between climate change and hurricane intensity, due to warmer oceans supercharging hurricanes.[24,25] Climate change is creating conditions that could worsen the impacts of hurricanes as well; however, it is less clear whether climate change could lead to an increase in the number of hurricanes.[26] Preparation for and recovery from increasingly intense hurricanes disproportionately affects communities of color and families living in poverty that face additional barriers from historic discriminatory policies.[27]

Climate change may also increase the likelihood of more frequent and intense derechos, or extreme wind events, as a result of increasing atmospheric instability, such as the devastating derecho that across the Midwest last August, damaging crops, homes, property, and causing massive power outages.[28]

Extreme Precipitation and Flooding
There has been an increase in the number of flooding and rainfall-related extreme events across North America in recent years, totaling billions of dollars in damage.[29] For example, last May, extreme precipitation-caused flooding breached two dams in Central Michigan, forcing thousands to flee and threatening a chemical plant and toxic waste cleanup site. Global warming

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[20] Zscheischler, J. et al. 2018. "Future Climate Risk from Compound Events." *Nature Climate Change*. DOI: 10.1038/s41558-018-0156-3
[21] https://www.noaa.gov/stories/record-number-of-billion-dollar-disasters-struck-us-in-2020
[22] Goss, M. et al. 2020. "Climate Change is Increasing the Likelihood of Extreme Autumn Wildfire Conditions Across California." Environmental Research Letters. DOI: https://doi.org/10.1088/1748-9326/ab83a7
[23] Ibid.
[24] https://www.noaa.gov/media-release/record-breaking-atlantic-hurricane-season-draws-to-end#:~:text=In%20total%2C%20the%202020%20season,of%20111%20mph%20or%20greater).
[25] Kossin, J.P., et al. 2020. "Global increase in major tropical cyclone exceedance probability over the past four decades." PNAS. DOI: https://doi.org/10.1073/pnas.1920849117
[26] https://www.c2es.org/content/hurricanes-and-climate-change/
[27] https://www.brookings.edu/blog/social-mobility-memos/2017/09/18/hurricanes-hit-the-poor-the-hardest/
[28] https://www.sciencenews.org/article/2020-extreme-weather-climate-change-hurricane-derecho-wildfire
[29] Kirchmeier-Young, M.C. and Zhang, X. 2020. "Human influence has intensified extreme precipitation in North America." *PNAS.* DOI: https://doi.org/10.1073/pnas.1921628117

is causing the intensity of extreme precipitation events to increase.[30] A recent study found that climate change contributed to approximately 36 percent of the rising costs of flooding damages due to intensifying precipitation.[31]

Sea Level Rise and Coastal Flooding

Sea levels have already risen by 6.5 inches on average across the U.S. since 1950, with nearly half of it occurring in the last 20 years.[32] The East Coast of the U.S. has seen higher rates of relative sea level rise,[33] leading to "nuisance," or high tide, flooding.[34] The Biloxi-Chitimacha-Choctaw tribe in Louisiana is already having to relocate to higher ground due to higher sea levels and has been called America's first "climate refugees."[35] While thermal expansion of warming seawater has contributed to some of the rise, the majority is due to recent accelerated rates of ice melt.[36] The rate of ice loss has significantly increased since the mid-1990s, with especially pronounced loss in the ice sheets in Antarctica and Greenland. A recent study shows that the ice sheets are following the worst-case climate warming scenarios laid out by the Intergovernmental Panel on Climate Change (IPCC) and that the half meter of sea level rise expected by 2100 could now occur with just an increase of 0.5°C.[37]

Extreme Heat

Last summer, much of the U.S. experienced a heat wave with temperatures 5°F to 20°F above average.[38] The U.S. has experienced record breaking heat every summer in recent years, with the past six years being the hottest six years on record. Climate change is increasing the intensity, duration, and frequency of extreme heat events in the U.S.[39,40,41] Seniors, people with disabilities, and people with chronic illnesses are most affected by heat waves. In addition, from 2004-2018, Indigenous communities had the highest rate of heat-related deaths and Black communities had the second highest.[42] The Committee heard from experts on the topic of extreme heat and environmental justice at a hearing last summer.[43]

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[30] Myhre, G., et al. 2019. "Frequency of extreme precipitation increases extensively with event rareness under global warming." *Scientific Reports.* DOI: https://doi.org/10.1038/s41598-019-52277-4

[31] Davenport, F.V., Burke, M, and Diffenbaugh, N.S. 2021. "Contribution of historical precipitation change to US flood damages." *PNAS.* DOI: https://doi.org/10.1073/pnas.2017524118

[32] https://sealevelrise.org/#:~:text=Although%20the%20sea%20level%20has,flooding%20across%20the%20United%20States.

[33] https://www.epa.gov/climate-indicators/climate-change-indicators-sea-level

[34] https://oceanservice.noaa.gov/facts/high-tide-flooding.html

[35] https://www.nytimes.com/2016/05/03/us/resettling-the-first-american-climate-refugees.html

[36] NCA4, Chapter 4: Sea Level Rise and Implications for Low-Lying Islands, Coasts, and Communities (2018)

[37] Grinsted, A. and Christensen, J.H. 2021. "The transient sensitivity of sea level rise." *Ocean Science.* DOI: https://doi.org/10.5194/os-17-181-2021

[38] https://www.climatesignals.org/events/continental-us-heat-wave-july-2020

[39] Paciorek, C.J., Stone, D.A, and Wehner, M.F. 2018. "Quantifying statistical uncertainty in the attribution of human influence on severe weather." *Weather and Climate Extremes.* DOI: https://doi.org/10.1016/j.wace.2018.01.002

[40] https://www.worldweatherattribution.org/u-s-heat-february-2017/

[41] Diffenbaugh, N.S., et al. 2017. "Quantifying the influence of global warming on unprecedented extreme climate events." *PNAS.* https://doi.org/10.1073/pnas.1618082114

[42] Vaidyanathan A, et al. 2020. "Heat-Related Deaths — United States, 2004–2018." *MMWR Morb Mortal Wkly Rep* 2020;69:729–734. DOI: http://dx.doi.org/10.15585/mmwr.mm6924a1

[43] https://science.house.gov/hearings/sweltering-in-place-covid-19-extreme-heat-and-environmental-justice

Recent Advancements in Climate Science

In recent years, several major consensus-based assessment reports led by the IPCC and U.S. Global Change Research Program (USGCRP) provided major scientific updates to our understanding of climate change, including the Fourth National Climate Assessment (2018)[44] and IPCC Fifth Assessment Report (2014),[45] as well as three IPCC Special Reports on Global Warming of 1.5℃ (2018), the Ocean and Cryosphere in a Changing Climate (2019),[46] and Climate Change and Lands (2019).[47] Since the release of these last major consensus climate change reports, additional peer-reviewed studies have been published that advance our understanding of climate change and suggest an even greater role for climate change in explaining observed extreme events.

One major area of scientific advancement has been in the ability of researchers to confidently link more extreme weather events directly to climate change, known as attribution science. New attribution science methods not only measure whether climate change played a role in the occurrence of an extreme event but can help explain how. Furthermore, research has incorporated econometric techniques to help quantify the economic impacts. For example, a 2020 study estimated that approximately $67 billion worth of damages caused by Hurricane Harvey in 2017 were attributable to human-influenced climate change.[48] More extreme events are being attributed almost entirely to climate change, such as a 2017 marine heat wave off Australia's coast and a 2018 dead heat wave in Japan.[49] Attribution science is also helping shape public understanding of climate change, and shaping policy and litigation dealing with climate change.

Other new research improves our understanding of future predictions and the question of how hot Earth is going to get. A landmark 2020 assessment by a team of 25 scientists significantly narrowed the bounds for how much Earth is going to warm with a doubling of greenhouse gas emissions, called "climate sensitivity."[50] For the past 40 years, climate scientists predicted that the atmosphere will warm between 1.5°C and 4.5°C, with a doubling of atmospheric carbon dioxide. The assessment found that "it now appears extremely unlikely that the climate sensitivity could be low enough to avoid substantial climate change (well in excess of 2℃ warming) under a high-emission future scenario," with warming now likely between 2.6℃ and 3.9℃.

While our understanding of the climate system is well established, the need to continue advancing our understanding of climate dynamics and impacts has not diminished. Continued improvements to climate observations and refinements to models, as well as interdisciplinary

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44 https://www.globalchange.gov/nca4
45 https://www.ipcc.ch/report/ar5/syr/
46 https://www.ipcc.ch/srocc/
47 https://www.ipcc.ch/srccl/
48 Frame, D.J., Wehner, M.F., Noy, I. *et al.* 2020. "The economic costs of Hurricane Harvey attributable to climate change." *Climatic Change*. DOI: https://doi.org/10.1007/s10584-020-02692-8
49 https://slate.com/technology/2019/12/attribution-science-field-explosion-2010s-climate-change.html
50 Sherwood, S.C., et al. 2020. "An assessment of Earth's climate sensitivity using multiple lines of evidence." Reviews of Geophysics. DOI: https://doi.org/10.1029/2019RG000678

research into societal and economic impacts, will help us better understand and predict future climate impacts and inform mitigation and adaptation solutions.

Upcoming Major Climate Reports

The IPCC's Sixth Assessment Report (AR6), Synthesis Report, and three Special Reports are currently under development, with the Synthesis Report due for release in June 2022.[51] Working Group (WG) I's contribution to the AR6 on the Physical Science Basis is expected in April 2021, WG III's AR6 contribution on Mitigation of Climate Change is expected in July 2021, and WG II's contribution on Impacts, Adaptation, and Vulnerability is expected in October 2021.

The USGCRP's Fifth National Climate Assessment is in the early stages of development and is anticipated to be delivered in 2023.[52]

[51] https://www.ipcc.ch/assessment-report/ar6/
[52] https://www.globalchange.gov/nca5

Chairwoman JOHNSON. Good morning. The hearing will come to order, and, without objection, the Chair is authorized to declare recess at any time, pursuant to *House Resolution 8*. Today the Committee meeting is virtual. I want to announce a couple of reminders to the Members about the conduct of the remote hearing. First, a Member should keep their video feed on as long as they are present in the hearing, and the Members are responsible for their own microphones. Please also keep your microphones muted until you are speaking. And finally, if Members have documents they wish to submit to the record, please e-mail them to the Committee Clerk, whose e-mail address was circulated just prior to the meeting.

Good morning, and welcome to the first climate change hearing of the Science, Space, and Technology Committee in the 117th Congress. I want to thank our esteemed panel for joining us today.

Our communities are already dealing with the very clear and present danger of climate change impacts. NOAA (National Oceanic and Atmospheric Administration) found that 2020 set a new record of 22 weather and climate disasters that each exceeded $1 billion in damages. The unprecedented year included the most active Atlantic hurricane season, multiple damaging severe wind events across the Midwest, and a record setting wildfire season in the West. In our own State of—my own State of Texas, we have seen the impacts of extreme weather over the past year.

As this Committee discussed last Congress, many of these devastating impacts fall hardest on our most vulnerable populations. We know that in many cases, climate change is making these weather and climate events more intense and more frequent. Our ability to predict extreme events, and our confidence in attributing some of them to climate change, has improved over the time. With that in—with that knowledge, we need to act to both mitigate and adapt to these impacts before it's too late.

Climate solutions are built on a foundation of robust, sustained, and long-term investment in climate science, observations, and modeling. In addition, we need to develop climate solutions that take into consideration multiple disciplines. Not only the physical and natural sciences, but the social sciences as well. Finally, we need to ensure that these disadvantaged communities that are hit first, worst, and hardest by the impact of the climate change are at the table when potential solutions are being developed and implemented. Addressing the climate crisis is a unique opportunity to help America back to work. Given the economic downturn our country has faced due to the COVID–19 pandemic, it is vital that Congress prioritize Federal investments that will provide well-paying and long-lasting jobs for Americans across the country.

Last Congress, the Committee had very success—great success in moving 15 bipartisan energy innovation bills in the *Energy Act of 2020* that were enacted into law. While this was a significant accomplishment, our work is not done, and I hope to build off this strong bipartisan work. This hearing is simply the first step in our Committee's efforts to address the climate crisis in the 117th Congress. I'm looking forward to working with our Subcommittee leadership, and Committee Members on both sides of the aisle, to develop and move strong, bipartisan, and impactful legislation to address the climate crisis and create actionable climate solutions. We have much to consider today, and I again want to thank our witnesses for participating in the hearing.

[The prepared statement of Chairwoman Johnson follows:]

Good morning and welcome to the first climate change hearing of the Science, Space, and Technology Committee in the 117th Congress. I want to thank our esteemed panel for joining us today.

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Addressing the climate crisis is a unique opportunity to help put America back to work. Given the economic downturn our country has faced due to the COVID-19 pandemic, it is vital that Congress prioritize federal investments that will provide well-paying and long-lasting jobs for Americans across the country.

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We have much to consider today, and I again want to thank our witnesses for participating in today's hearing.

I now yield to Ranking Member Lucas for his opening statement.

Chairwoman JOHNSON. And I now yield to Mr. Lucas for his statement.

Mr. LUCAS. Thank you, Chairwoman Johnson. As we kick off our first climate-focused hearing this year, I'd like to reflect quickly on the milestone energy legislation we passed last year. Together we were able to pass the first update to Federal energy policy in over a decade in the last Congress, and that is in no small part due to your leadership, and willingness to hold good faith negotiations with this side of the aisle. The *Energy Act of 2020* includes more than a dozen bills from our Committee, and focuses on competitive and innovative clean energy solutions driven by basic and early stage research. It's a prime example of the work this Committee is uniquely positioned to do to combat climate change and strengthen American energy.

The simple truth is this, America's clean energy future is driven by innovation, not by mandates. It's our job to support that innovation and invest in the basic research that will provide the springboard for new clean energy technologies. One of our witnesses today, Dr. Zeke Hausfather, points out that the U.S. is in a unique position right now to accelerate research, development, and deployment (RD&D) of low carbon technologies across all sectors of the American economy. Through targeted investment, and demonstration of Federal research, we can develop direct air carbon capture, small, modular nuclear reactors, and other technologies that will completely transform our energy production to a cleaner, more efficient industry, unrecognizable from a century ago. And we can do this without raising energy prices and hurting American consumers.

I worry that the cost of making immediate and drastic changes to our energy portfolio are being ignored by some of my friends. Imposing strict mandates is going to make it harder for our businesses to compete with China, whose greenhouse gas emissions continue to grow. But we have hard evidence that investing in innovation allows us to cut our emissions, while growing our economy. For instance, using discoveries at our National Labs to improve hydraulic fracturing technology has given us more access to clean natural gas. That, in turn, has played a large role in the 10 percent decline in U.S. greenhouse gas emissions between 2005 and 2018. And in that same period, our economy grew by 25 percent.

Higher costs also hurt American families, and rural households are especially vulnerable to energy price swings. We have to be mindful of the many communities whose economies depend on our current energy infrastructure. So I want to be very clear, abandoning our current energy infrastructure, you know, has a regional impact on climate change. Just like moving away from rising sea levels on the coast, entire families would be displaced if we move too quickly to prohibit fossil fuel use. Fossil fuels are not the enemy. They are the most reliable form of energy in the U.S., and will continue to be a large part of our energy portfolio. Our focus shouldn't be on eliminating fossil fuels, but on making their production and use cleaner and more efficient. We're already making headway. According to the International Energy Agency and the Breakthrough Institute, it's quite possible that global CO_2 emissions from fossil fuels peaked last year in 2019.

We know what we need to do from here, invest in the tools needed to reduce greenhouse gas emissions, like advanced nuclear, carbon capture, and greater energy storage capacity to make renewables more reliable. If we want to make real progress addressing climate change, we need to move forward with these bipartisan priorities. We've taken the first step with the *Energy Act*, and I look forward to working together on more practical clean energy solutions. Thank you, Madam Chair, and I yield back the balance of my time.

[The prepared statement of Mr. Lucas follows:]

Thank you, Chairwoman Johnson. As we kick off our first climate-focused hearing this year, I want to reflect quickly on the milestone energy legislation we passed last year. Together we were able to pass the first update to federal energy policy in over a decade last Congress, and that is in no small part due to your leadership and willingness to hold good faith negotiations with this side of the aisle.

The *Energy Act of 2020* includes more than a dozen bills from our Committee and focuses on competitive and innovative clean energy solutions driven by basic and early- stage research. It is a prime example of the work this Committee is uniquely positioned to do to combat climate change and strengthen American energy.

The simple truth is this: America's clean energy future will be driven by innovation-not by mandates. It's our job to support that innovation and invest in the basic research that will provide the springboard for new clean energy technologies.

One of our witnesses today, Dr. Zeke Hausfather points out that the U.S. is in a unique position right now to accelerate research, development, and deployment of low-carbon technologies across all sectors of the American economy.

Through targeted investment and demonstration of federal research, we can develop direct air carbon capture, small modular nuclear reactors, and other technologies that will completely transform our energy production to a cleaner, more efficient industry, unrecognizable from a century ago. And we can do this without raising energy prices and hurting American consumers.

I worry that the costs of making immediate and drastic changes to our energy portfolio are being ignored by some of my friends on the other side of the aisle. Imposing strict mandates is going to make it harder for our businesses to compete with China, whose greenhouse gas emissions continue to grow. But we have hard evidence that investing in innovation allows us to cut our emissions while growing our economy.

For instance, using discoveries at our National Labs to improve hydraulic fracturing technology has given us more access to clean natural gas. That in turn has played a large role in the 10% decline in U.S. greenhouse gas emissions between 2005 and 2018. In that same period, our economy grew by 25%.

Higher costs also hurt American families, and rural households are especially vulnerable to energy price swings. And we have to be mindful of the many communities whose economies depend on our current energy infrastructure.

So I want to be very clear: abandoning our current energy infrastructure is a regional impact of climate change. Just like moving away from rising sea level on the coast, entire families would be displaced if we move too quickly to prohibit fossil fuel use.

Fossil fuels are not the enemy. They are the most reliable form of energy in the U.S. and will continue to be a large part of our energy portfolio. Our focus shouldn't be on eliminating fossil fuels, but on making their production and use cleaner and more efficient. We're already making headway: according to the International Energy Agency and the Breakthrough Institute, it is quite possible that global CO_2 emissions from fossil fuels peaked last year in 2019.

We know what we need to do from here: invest in the tools needed to reduce greenhouse gas emissions, like advanced nuclear power, carbon capture, and greater energy storage capacity to make renewables more reliable. If we want to make real progress addressing climate change, we need to move forward on these bipartisan priorities.

We've taken the first step with the *Energy Act*, and I look forward to working together on more practical clean energy solutions. Thank you Madam Chair and I yield back the balance of my time.

Chairwoman JOHNSON. Thank you, Mr. Lucas. Now, if there are Members who wish to submit additional opening statements, your statements will be added to the record at this point. And now I'd like to introduce our witnesses.

Our first witness is Dr. Michael Oppenheimer. Dr. Oppenheimer is the Albert G. Milbank Professor of Geosciences and International Affairs at Princeton University, where he has served since 2002—2002. He also directs the Center for Policy Research on Energy and Environment at Princeton. His research focuses on projecting sea level rise, coastal flooding, and resulting risk to coastal communities, as well as adaptation and other responses to climate change, such as migration. He has been involved in the development of Intergovernmental Panel on Climate Change, IPCC, assessment research reports, since 1990, the IPCC special report on oceans and cryosphere in a changing climate, and the upcoming Sixth Assessment Report.

Our next witness is Dr. Zeke Hausfather. Dr. Hausfather is the Director of Climate and Energy at The Breakthrough Institute, an environmental think tank in Oakland, California. He is a climate scientist and energy systems analyst whose research currently focuses on observational temperature records, climate models, and mitigation technologies. He also serves as a research scientist at Berkeley Earth, and is a contributing author to the upcoming IPCC Sixth Assessment Report. He previously spent a decade as a data scientist in the clean technology sector, including co-founding the Efficiency 2.0, an energy efficiency software company.

Our third witness is Dr. Noah Diffenbaugh. Dr. Diffenbaugh is the Kara J. Foundation Professor in the School of Earth, Energy, and Environmental Sciences at Stanford University. He is also the Kimmelman Family Senior Fellow at Stanford's Woods Institute for the Environment. He researches the climate system, including how regional and local conditions, such as extreme weather, impact people and ecosystems. He is an elected fellow of the American Geophysical Union. He has been a lead author for a number of scientific assessments, including the IPCC Fifth Assessment Report, and the California Climate Safe Infrastructure Working Group.

Our final witness is Dr. Paula Bontempi. Dr. Bontempi is the Dean of the Graduate School of Oceanography at the University of Rhode Island, where she oversees academic research and outreach activities. Prior to this role, she was Acting Deputy Director of NASA's (National Aeronautics and Space Administration's) Earth Science Division within the Science Mission Directorate, where she provided leadership, strategic direction, and management of the agency's earth science portfolio. Overall she spent nearly 2 decades at NASA as a physical scientist and program manager in the biological oceanography. Her scientific interests include studying the Earth's systems, ocean sensors, and technology, and diversity, and equity initiatives in STEM (science, technology, engineering, and mathematics).

And now let me just say that our witnesses need to know that each of them have 5 minutes for the spoken testimony, and the written testimony will be included in the record for the hearing. When all of you have completed your spoken testimony, we will begin questions. Each Member will have 5 minutes to question the panel. So now we will start with Dr. Oppenheimer.

TESTIMONY OF DR. MICHAEL OPPENHEIMER, ALBERT G. MILBANK PROFESSOR OF GEOSCIENCES AND INTERNATIONAL AFFAIRS, PRINCETON UNIVERSITY

Dr. OPPENHEIMER. Thank you, Chairwoman Johnson. I'd also like to thank the Members of this Committee for inviting me to testify at today's hearing. The views expressed in this testimony are, of course, my own.

While a sharp global reduction of carbon dioxide and other greenhouse gases, with the aim of achieving net zero emissions by midcentury, is necessary, it will not be sufficient to protect people and places, unless accompanied by an aggressive program to adapt to unavoidable climate changes occurring now, and yet to occur in the near future. Even today the U.S. is falling short, particularly in protecting the most vulnerable segments of its population.

I'll focus first on sea level, which is rising due to warming, and also accelerating due to melting and disintegration of the edges of the Greenland and Antarctic ice sheets. The largest uncertainty in projecting sea level rise is how fast this process will eat into the ice that's further inland, and how much sea level rise is inevitable by 2100, even if the world meets the long-term objective of the Paris agreement. On the other hand, we have a pretty clear picture of sea level rise through the year 2050, when uncertainties are not large, providing a sound basis for coastal planning and implementation of defenses.

Sea level rise is already resulting in a radical shortening of the return time for what have in the past been rare events. Even on a pathway to a 2-degree Celsius warming of—global warming, that is about 3.6 degrees Fahrenheit, the Paris target, the historical once per century flood level at many U.S. locations is expected to recur every year, or more often, by 2050. The list of such locations includes Savannah, Jacksonville, Miami, Los Angeles, San Diego, and Honolulu, among others. Different areas will be affected to different extents. How to respond needs to be decided well before 2050, essentially right now, in many places, because building protection or implementing planned retreat to higher ground can take decades. Recent experience with a growing list of deadly climate disasters across the country, starting with Hurricane Katrina in 2005, and right up to the Texas cold snap of 2021, serves as a warning that we are not as effective at adapting at even today's level of risk as we should be.

Before delving into the causes of the U.S. adaptation gap, let me point out some encouraging experience. In the U.S. and worldwide, even as property damage has increased along the coasts, deaths in coastal storm surge since 1900, for instance that accompanying hurricanes, have decreased. While the reasons for this trend remain unclear, improved forecasting has, in all likelihood, made an important contribution. Now to the bad news. Recent events show that we are still leaving much too much undone before a big event strikes. For example, in 2012, Hurricane Sandy struck a metropolitan area, New York, where I live, that seemed to have grown complacent due to the lack of catastrophic coastal events in the preceding decades. For example, the subway system, the lifeblood of the city, was flooded and shut down for 3 to 4 days, and parts almost ruined, yet nine storms in the 60 years previous to that had almost flooded the subway system, and little or nothing had been done to protect it. And that's not just a city responsibility, it's the State also.

Our current ways of dealing with climate related risk create incentives for people in government, officials, to do precisely the wrong thing. A prime example is the imbalance between Federal funding available to assist States and local governments to plan and implement adaptation measures to avoid disaster, compared to the amount of money spent for cleanup after an extreme event. Even more distressing is the insufficient attention at all levels of government to the most vulnerable groups.

Extreme heat, the leading cause of climate related death in the U.S., provides a vivid example. Evidence from the period 1987 to 2005 suggests a decrease in heat related deaths for the overall population, but a constant death rate for people 65 years and older. Cities deal with this risk by establishing cooling centers. However, one recent study of Phoenix, New York, and Chicago showed that the locations of these centers bear no systematic relationship to the vulnerable populations that need them most, and distances from their neighborhoods to the cooling centers were often such as to make the centers effectively inaccessible to those aged, ill, or without motor vehicles. The current U.S. system for dealing with climate adaptation is highly fragmented across many dimensions. It must be reformed across the board to keep us from falling far behind as the climate warms, especially for those who are vulnerable due to age, illness, persistent discrimination, or economic status.

I'd like to thank the Committee once again for affording me this opportunity to testify.

[The prepared statement of Dr. Oppenheimer follows:]

Testimony of Dr. Michael Oppenheimer
Princeton University
at the

Committee on Science, Space, and Technology
US House of Representatives
March 12, 2021
On
Climate Change Science

Contents

Introduction

My name is Michael Oppenheimer. I am the Albert G. Milbank Professor of Geosciences and International Affairs at Princeton University and a member of the faculties of the Department of Geosciences, the School of Public and International Affairs, and the High Meadows Environmental Institute. I would like to thank Chairwoman Johnson and the members of this committee for inviting my testimony at this hearing. The views expressed in this testimony are my own. I am not speaking as an official representative of Princeton University. Let me first describe my professional background. A complete CV accompanies this testimony.

I received an S.B. from MIT and a PhD in chemical physics from the University of Chicago and served as a postdoctoral fellow and then Atomic and Molecular Astrophysicist at the Harvard Smithsonian Center for Astrophysics, researching interstellar gases and Earth's upper atmosphere. Subsequently, I served as Chief Scientist for the Environmental Defense Fund, a private, not-for-profit research and advocacy environmental organization (where I continue to serve as a paid advisor on scientific matters). In 2002, I became a professor at Princeton University where I direct the Center for Policy Research on Energy and the Environment. I have published over 200 articles in professional journals. Almost all of those published over the past 30 years cover aspects of climate change science and climate change policy. My current research focuses largely on projecting sea level rise and coastal flood levels in a warming world with special emphasis on the contribution of the Greenland and Antarctic ice sheets; the risk to coastal areas from sea level rise; and adaptation and other responses to climate change, sea level rise, and extreme climate events, such as human migration. I have served in various capacities as an author of assessments produced by the Intergovernmental Panel on Climate Change (IPCC) since its First Assessment Report in 1990, most recently as a Coordinating Lead Author of IPCC's Special Report on *Oceans and Cryosphere in a Climate Change* (SROCC), published 18 months ago. I shared responsibility for the chapter assessing sea level rise. I currently serve as a review editor on IPCC's Sixth Assessment Report for a chapter that synthesizes understanding of all risks associated with climate change. In 2018, along with six other experts in diverse fields, I published a book on scientific assessments, *Discerning Experts: The practices of scientific assessment for environmental policy*.

Purpose of This Testimony

The Committee invited me to discuss the state of our understanding of the effects of climate change on processes such as ice loss, sea level rise, coastal storms, and extreme heat; recent observations of accelerating rates of ice loss and sea level rise, and extreme heat events in the U.S., and how climate change is affecting the U.S. on regional and local scales. The Committee also asked for information on the relationship of climate change impacts to human migration, and the disproportionate impacts of climate change on vulnerable populations. In addition, I was asked to comment on the value of interdisciplinary research involving both the physical and social sciences in understanding climate risk, the importance of these fields of research to developing mitigation and adaptation solutions, and the importance of observations and modeling including research gaps or recommendations for additional investments in climate science that the Science Committee should address.

As background on the current state of the climate, some key findings of IPCC reports and research since their release are:

- In 2020, Earth was about 2°F (1.1°C) warmer than it was early in the industrial era.[1]
- IPCC's Fifth Assessment stated, "It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century",[2] i.e., the accumulation of greenhouse gases (such as carbon dioxide) in the atmosphere as a result of human activity (largely related to fossil fuel combustion to provide energy) is the primary cause of the observed global warming.

- Associated with this warming, pervasive changes have been detected in many features of Earth's climate system, including more frequent hot days and nights and fewer extremely cold ones, increases in the frequency, intensity, and amount of heavy precipitation events, greater intensity and duration of drought in some regions, increase in the intensity of North Atlantic hurricanes, and sea levels rising nearly worldwide.[3]
- Changes in heat, precipitation and sea level are attributed with medium or high confidence to the greenhouse gas buildup.[3]
- Characteristics of some extremely damaging events, like the intense precipitation from Hurricane Harvey, can now be attributed to the greenhouse gas buildup. In other words, it is no longer true that no single climate event can be connected quantitatively to the greenhouse gases – due to advances in computer modeling, many already have been.[4]
- All of these changes are projected with medium or high confidence to continue to build throughout this century. Those related to heat, precipitation, hurricanes, and sea level pertain to the US as well while the attribution of US drought changes is less clear.[5]
- Perhaps most important, global climate change cannot be halted unless emissions of the major greenhouse gases, particularly carbon dioxide, are eliminated. To keep warming from surpassing the Paris Agreement's long-term objective of maintaining the global average temperature well below 2°C with the aspiration of not exceeding a 1.5°C warming may require removing some carbon dioxide from the atmosphere by artificial means which are not yet economically viable.[6]

Sea Level Rise

According to IPCC's Special Report on *Oceans and Cryosphere in a Changing Climate (SROCC)*[7], global sea level is rising largely as a result of three processes that are adding water to the oceans and causing their volume to increase.

- Liquids generally expand when heated, and the same is true of ocean water as heat trapped by the greenhouse gases penetrates to great depths. As a result, the oceans are taking up greater and greater volume which translates into sea level rising. In addition, two other process are adding to the amount of water in the ocean and this also causes sea level rise:
- Mountain glaciers are in retreat nearly worldwide due to the warming and their meltwater generally winds up in the oceans.
- The major ice sheets have been losing ice faster and faster since about 1990. The Greenland ice sheet is melting at its lower elevations and the meltwater is running off into the ocean. In some locations, the ice is flowing faster down glacial fjords, breaking into icebergs at the coast, and in this way also adding more water to the ocean. Taken together, these two processes have caused a large increase in Greenland's contribution to global sea level rise. The Antarctic ice sheet is generally too cold to melt at its surface but, in several areas, warm waters beneath its floating shelves are causing melting from below, accelerating iceberg formation and causing a growing contribution to sea level rise (see Figure 2).
- As a result, the overall rate of sea level rise from 2006-2015 was about 2.5 times the rate during the 20th century (about 6 inches/century then; now about 14 inches/century). This may seem like a small amount but a rough rule of thumb applied to a typical East Coast beach estimates that each foot of vertical rise results in inland loss of about 100 feet due to erosion and permanent inundation, absent restoration. Taken together, losses from the ice sheets are now responsible for about 1/3 of the ongoing rise in sea level, and they are accelerating. *Sharpening our understanding of how fast the ice sheets will lose ice as the world warms further is a key to more precisely projecting sea level rise over this century.*

Sea level projection

The future behavior of the ice sheets presents the greatest uncertainty in projecting sea level rise. In a low emissions scenario that could meet the Paris target, global average sea level is expected to rise 7-13 inches by midcentury and 11-23 inches by 2100. In a high emissions scenario that could lead to global warming in excess of 9°F (5°C) above recent temperatures, sea level rise is expected to reach 9-16 inches by mid-century and 24-43 inches by year 2100 (Figure 1; all numbers compared to sea level around year 2000). [7]

However, sea level rise is not distributed uniformly around the world. Many local effects cause place-to-place variations of +/-30%. As it happens, the northeast US coast has already experienced sea level rise of 1.5-2.0 times the global average.

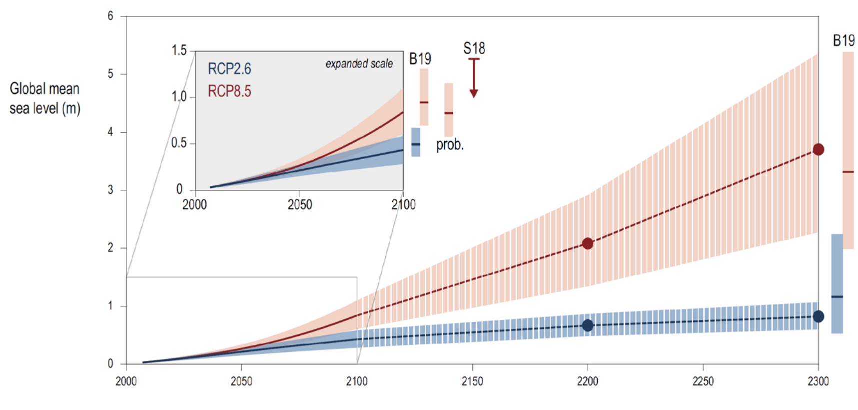

Figure 1. Projected global mean sea level rise for high (red) and low (blue) emissions scenarios. Large graph runs to year 2300, inset expands the period 2000-2100. Results are from mechanistic models that are based on equations describing the physics of ice. Solid lines are the median sea level rise for each case. The shaded blue or red areas above and below the median represent the 17—83% uncertainty range, combining both uncertainty in ice physics and uncertainty in climate and ocean sensitivity to

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warming. Vertical bars show results from other estimation methods (sensitivity studies, partially probabilistic approaches, and expert elicitation) that may capture low-probability outcomes better than the mechanistic approach. From SROCC (2019), figure 4.2[7]

Due to the possibility of various ice sheet instabilities developing in response to ocean and atmospheric warming (Figure 2), retreat of Antarctic ice may occur faster than our best current models suggest, particularly beyond 2100. The potentially unstable sectors of Antarctica contain ice equivalent to roughly 15 meters (50 feet) of sea level rise. About 25% of that total may already be on the brink of unstable retreat. There is disagreement among experts as to how fast unstable retreat would occur once it begins, with estimates ranging from about 200-900 years to completion. Accordingly, SROCC recommended that stakeholders, including policy makers, take the possibility of higher sea level rise into account when making judgments related to building long-lived coastal infrastructure, such as coastal defenses.

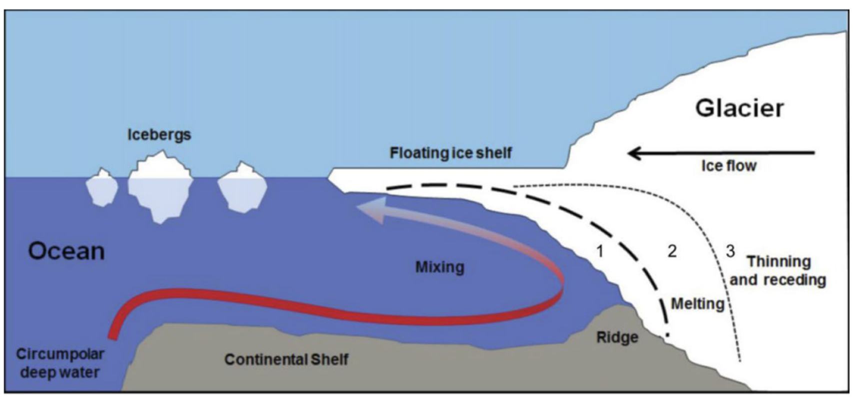

Figure 2: Warm water circulating under the floating ice shelf (red arrow) reaches the boundary, or grounding line, between ice resting on bedrock and the floating ice. Forward motion of the grounded ice there is obstructed by ridges in the bedrock but the warm water melts away some ice causing the ice just behind to lift off the ridge and accelerate into the ocean. This process can cause parts of the ice sheet to become unstable.[7] Figure from reference 8.

The flip side of this argument, indicated in figure 1, is that we have a pretty clear picture of sea level rise through 2050, when uncertainties are not large and provide a sound basis for coastal planning and implementation.

Consequences of sea level rise

Higher sea level sets a new baseline for the elevations along the coast and inland reached by water during high tides as well as the coastal storms like hurricanes and nor'easters that are accompanied by surge. That means that flood levels reached only rarely in recent times will become common as the sea rises. For example, at many US coastal locations, as well as worldwide, with about 2^0C global warming, the historical once-per-century water level is expected to occur ***every year*** or more often by 2050. The list of such locations includes Savannah, Jacksonville, Miami, Los Angeles, San Diego, and Honolulu. By 2100, New York and others will join this list.[7] Different cities will be affected to different extents – for some of these locations, particularly along the West Coast, the current hundred-year water level is a high tide rather than a storm so the corresponding flood level is lower than would be the case at, for instance, an East Coast city where the current hundred-year water level typically results from a hurricane. Nevertheless, substantial amounts of infrastructure have been built of the past century or two with the historical high-water level in mind, whether from a high tide or storm. Those sites will need to be reconsidered carefully, well before 2050, because building protection or implementing planned retreat to higher ground can take decades.

The effects of higher sea levels are already evident. The once-per-decade flood height in New York Harbor in 1940 now arrives once every five years. Sections of the old bulkhead that remains the only defense for some sections of lower Manhattan are only 5-6 feet tall,[9] about the same height as the current once-in-five-year event, leading to overtopping. Sunny-day or tidal flooding has become a regular event (several times

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per month) at many places along the coast where it was heretofore rare. Certain neighborhoods in Miami provide costly examples.

Adapting to the Risk

Recent experience with a growing list of deadly and costly climate disasters [Hurricane Katrina (2005), Hurricane Sandy (2012), Hurricane Harvey (2017), Hurricane Maria (2017), wildfires in California and elsewhere in several recent years, the Texas cold snap (2021) and several others] serves as a warning that we are not as effective at anticipating and adapting to *today's* level of risk as we should be. Yet, we are going to need to become much more effective, very quickly as climate change increases the likelihood of extreme heat, category 4 and 5 hurricanes, wildfire, and more frequent episodes of coastal high water.

We should learn from each case and start immediately to deal with the weak spots in our responses. Otherwise, the coming decades will bring ever more disastrous outcomes for more and more Americans. Before delving into causes, let me point out that there is some encouraging experience to learn from – *worldwide, deaths in coastal storm surge (e.g., accompanying hurricanes) have decreased since 1900.*[10] The same trend appears in US data but the uncertainty is larger due to the sparsity of events. While the reasons for this trend are unclear, improved forecasting has in all likelihood made an important contribution.

Now to the bad news: recent events show that we are still leaving much too much undone, or improperly done, before a big event strikes and it remains unclear how long the learning from any one event lasts. The levees that failed in Katrina in 2005 were the product of experience with Hurricane Betsy 40 years earlier. The current defenses are doubtless an improvement but are not designed to handle the higher surge that a category 5 storm may bring. Hurricane Sandy struck a metropolitan area (New York) that seemed to have grown complacent due to the lack of catastrophic coastal events in previous decades. Critical infrastructure (hospitals and an electric utility substation) were flooded, causing massive service disruptions and necessitating emergency evacuation of hospitalized patients and an enormous cost for repairs, on the order of a

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billion dollars in the case of one hospital. The subway system, the lifeblood of the City, was flooded and shut down for 3-4 days. Figure 3 shows that although Sandy was an unusual event with a return time of about 250 years, nine storms in the 60 previous years had *almost* flooded the system [11], yet little or nothing had been done to protect it.

Much of the damage could have been averted by measures taken only *after* Sandy struck: hardening low-lying subway entrances and ventilation systems, raising emergency generators and fuel to upper floors of hospitals where they had sat basements, forbidding construction of new hospitals in the flood zone. The same sort of hardening and rezoning is underway or has been completed for existing substations.

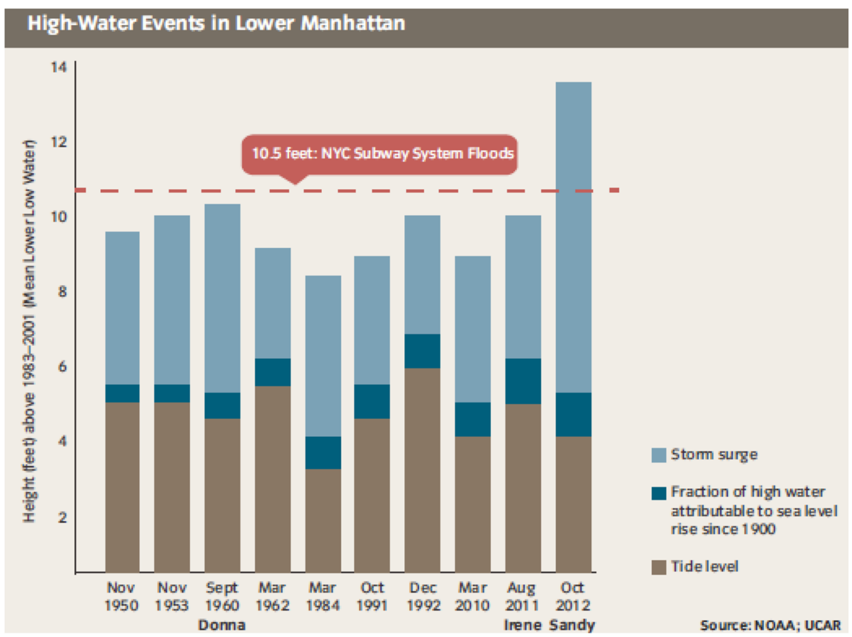

Figure 3: Nine highest flood levels at the southern tip of Manhattan (The Battery) preceding Hurricane

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Sandy (tenth bar on right). Flood level where seawater enters the subway system indicated by red dashed horizontal line. Fraction of high-water due to sea level rise, tide, and storm surge indicated.[11]

Ignoring even recent experience, and failing to adequately anticipate and adapt to extreme events was by no means unique to Hurricane Sandy, as Hurricane Katrina and the Texas cold snap vividly illustrate. The situation will grow more perilous as the probability of some extreme events continues to increase.

Lessons for other Climate Change Risks

Some systematic problems with the US approach to climate adaptation, like those plaguing the National Flood Insurance Program, are unique to governmental arrangements for coastal and inland flood preparation. Other such failings inhibit attempts to design effective climate adaptation across the board. While our understanding continues to evolve, the social science and psychology literature provides some explanations for the shortcomings discussed above.

- The general public's memory of even disastrous events is short. Along with the long implementation times for infrastructure projects like hard coastal protection, this reduces pressure on local officials to develop long term plans and initiate their implementation.

- Political rewards favor *ex post* cleanup to *ex ante* preparation because the public tends to see the latter in terms of its immediate cost to them while benefits may become obvious only years or decades into the future. This situation is exemplified and exacerbated by the relatively sparse federal funding for adaptation measures not tied to a specific disaster(s) compared to the vast sums spent *ex post* on clean up (e.g., under the Stafford Act). The result is a perverse incentive to local officials to continually defer adaptation actions.[12]

- Households sometimes take a single action to prepare in advance, like raising their houses above the level of a recent damaging flood, rather than a broad set of actions, e.g., purchasing insurance as well, just in case a yet higher flood event occurs. This "single-action bias" is especially troublesome when households assume that a government action is sufficient, like dune restoration, and take no further action to reduce the risk to lives and property.[13]

- States and localities often lack sufficient revenue to execute large scale adaptation projects without substantial federal assistance. In the case of coastal and inland flooding, resources dedicated to the US Army Corps of Engineers partially meet these local needs but it is doubtful whether appropriations and priority setting are aligned with the increasing risk from climate change. Other areas of risk, like wildfire on private land, lack any established federal adaptation funding, planning, or insurance role.

- As illustrated by the case of the failure of the New Orleans evacuation plan when Hurricane Katrina made landfall (see next section), characteristics of vulnerable groups are often not accounted for when designing either adaptation or emergency response. Questions over looming gentrification[14] have been raised about Miami's response to increasing tidal flooding and about some of the voluntary buyout programs implemented in the wake of Hurricane Sandy. Some of this reflects the realities of the real estate market but program design is also a concern.

My bottom line is that the current US system for dealing with climate adaptation is highly fragmented across many dimensions, is performing far from adequately to meet today's level of risk, and must be reformed across the board to keep from falling far, far behind as risk increases. Furthermore, as mentioned above and as we now show in the context of extreme heat, under some circumstances, adaptation planning aggravates rather than ameliorates the problems of vulnerable populations.

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Extreme Heat and Impacts on Vulnerable Populations

Some populations are more vulnerable than others to a range of climate impacts whether due to age, illness, persistent racial discrimination, or economic status. Any federal program to assure effective climate adaptation must address this inequality or it will fail a significant portion of the US population. I'll use the example of extreme heat to illustrate how this unequal distribution of vulnerabilities plays out in practice.

Extreme heat is the leading cause of climate-related death in the US. Heat is a contributory cause of about 700 deaths per year as indicated by death certificates. Heat also plays an indirect role as indicated by the much larger number of excess deaths attributed to high temperature, as many as 19,000 per year in one study.[15] Climate change will bring more frequent, more intense, and longer heat wave episodes. How we adapt will be critically important to avoiding a large increase in mortality, morbidity, and economic losses. Evidence between 1987-2005 suggests a decrease in heat-related deaths for the overall population but the constant death rate found for people 65 years and older is troubling.[16]

Adaptation to extreme heat is largely relegated to the household level and commonly includes air conditioning as well as behavior changes like shifts to less exertion and wearing lighter clothing. However, among the tens of millions living in the densest parts of urban areas where temperatures are generally several degrees above those of the surrounding countryside, are found many residents who cannot afford air conditioning. Many of them are among the aforementioned vulnerable groups as a consequence of race, income, health status, or age.

The frequent failure of governments to account for such differences in vulnerability was perhaps best illustrated during Hurricane Katrina – the New Orleans emergency evacuation plan was developed with the assumption that all residents had access to motor vehicles and could drive out of town. This assumption made no sense for a city whose residents were disproportionately of low income. Partially as a result, many people wound up in the Superdome or drowned. A similar lack of attention to vulnerable groups seems to characterize urban responses to heat emergencies.

Cities deal with this risk by establishing cooling centers. However, as shown by one recent study[17] of three US cities (Phoenix, New York, and Chicago), the locations of these centers bear no systematic relationship to the vulnerable populations that need them most and distances from their neighborhoods to cooling centers were often such as to make them effectively inaccessible to those aged, ill, or without access to a motor vehicle. Furthermore, days and hours of operation varied inexplicably from center to center.

Multidisciplinary Research to Address Climate Change

It should be apparent from the examples above that managing the climate change problem successfully requires a solid basis not just in the physical climate sciences (for which support certainly needs to be maintained and strengthened) but the social sciences, psychology, and climate economics, and for joint collaborations among these specialties. Such multidisciplinary research shouldn't mean experts burrowing ever deeper into their professional silos, then coming together periodically to share insights over lunch before returning to their silos. Rather, it means that specialists should assemble teams that are truly multidisciplinary and work together, sharing methods, and developing questions and answers in close collaboration. Universities were slow to realize what sort of arrangements for research and graduate education this requires but gradually, they are changing. None have solved the problem of how to do this optimally but many experiments are afoot, including on my own campus. The National Science Foundation has played a leadership role in supporting such efforts in the past but resources for the social sciences remain inadequate to fund multidisciplinary research. That would be my top priority for NSF and other agencies that consider it their mission to actually solve problems relevant to climate change that fall on real people.

Other priorities that are more specific to coastal defense, extreme heat, and other issues discussed in this testimony are too numerous to mention so here are my top 3 - my apologies for the many I have slighted. The first draws on traditional approaches but I place it there to underscore its importance.

- Continue and expand polar research programs including modeling of ice sheets and the ocean-ice sheet interaction, measurements and remote observations, because the fate of the ice sheets is a key unknown in projecting sea level rise.

- Expand research programs on voluntary migration, involuntary population displacement, and other forms of human mobility likely to be intensified by climate change. This requires a broadly multidisciplinary effort.

- Develop a comprehensive program to support research on adaptation to climate change including when, how, and why people make decisions about risk, what information these are based on, what actions result under which circumstances, and policies to encourage responses that are effective from both individual and collective perspectives.

Conclusion

Let us assume for the moment that the world, hopefully led by this country, attains the Paris Agreement's long-term objective. Even then, a large-scale, well-planned US adaptation effort, coordinated across the complex layers of government in our federal system, and adequately funded decade after decade, will be required to avoid calamity for many.

Absent such a program, the unavoidable warming that will occur, including what is already baked into the climate system, will cause more difficulties than much of the US population, not to mention the rest of humanity, can deal with.

On the other hand, if rapid, deep reductions in greenhouse gas emissions are not implemented, then we will eventually find ourselves in situations beyond our capacities to successfully adapt. Every few tenths of a degree of warming will bring more and more extreme heat, sea level rise, wildfire, decreases in access to water, and ecological destruction, accompanied by a panoply of social and political challenges.

Neither emissions reductions alone nor adaptation alone are sufficient. Only the combination of strong, persistent adaptation efforts coupled with transformation of our energy systems and modification of lifestyles sufficient to bring emissions sharply down to zero will solve the climate problem.

Only if both emissions reduction and adaptation are designed and implemented with our most vulnerable groups at the table rather than an afterthought, or as too often happens today, overlooked entirely, is the political consensus for this monumental task likely to gel. In this case, "vulnerable" includes not just those vulnerable groups I mentioned above in the context of adaptation, but also those who might come out at the losing end of the energy transformation needed to meet these challenges.

I'd like to thank the committee once again for affording me the opportunity to testify.

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Michael Oppenheimer is the Albert G. Milbank Professor of Geosciences and International Affairs at Princeton University. He is also the Director of the Center for Policy Research on Energy and the Environment at Princeton's School of Public and International Affairs. Oppenheimer is a long-time participant in the Intergovernmental Panel on Climate Change (IPCC), which won the Nobel Peace Prize in 2007. He served most recently as a coordinating lead author on IPCC's Special Report on Oceans, Cryosphere and Climate Change, published in September 2019, and now serves as a Review Editor of its Sixth Assessment Report. Oppenheimer is coeditor-in-chief of the journal *Climatic Change*. He is a science advisor to the Environmental Defense Fund and trustee of two other NGOs, Climate Central and the Climate Science Legal Defense Fund. He is a Heinz Award winner and a Fellow of the American Association for the Advancement of Science. His current research focuses on sea level rise, migration, and other impacts of climate change from the perspectives of science, adaptation, and risk.

Oppenheimer is the author of over 200 articles published in professional journals and is co-author (with Robert H. Boyle) of a 1990 book, *Dead Heat: The Race against the Greenhouse Effect*. He is also coauthor of the book *Discerning Experts: The Practices of Scientific Assessment for Environmental Policy*, published in 2019 by the University of Chicago Press. He has an SB degree from MIT in chemistry and a PhD from the University of Chicago in chemical physics. He joined the Princeton faculty in 2002 after more than two decades with the Environmental Defense Fund, where he served as chief scientist and manager of the Climate and Air Program. Earlier, he was an Atomic and Molecular Astrophysicist at the Harvard-Smithsonian Center for Astrophysics.

October 2020
https://scholar.princeton.edu/oppenheimer

Chairwoman JOHNSON. I was muted. Let me thank you very much, Dr. Oppenheimer, and call for Dr. Hausfather to do his testimony.

TESTIMONY OF DR. ZEKE HAUSFATHER, DIRECTOR OF CLIMATE AND ENERGY, THE BREAKTHROUGH INSTITUTE

Dr. HAUSFATHER. Thank you. Good morning, Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee. My name is Zeke Hausfather. I'm a climate scientist and Director of Climate and Energy at The Breakthrough Institute.

In many ways 2020 was the year in which both climate change and the accelerating energy transition became impossible to ignore. On the climate front, we saw 2020 tie with 2016 as the warmest year since records began, with global temperatures of around 1.3 degrees Centigrade, or 2.3 degrees Fahrenheit, above temperatures of the late 1800's. Land areas, where we all live, were nearly 2 degree Centigrade, or 3.6 degrees Fahrenheit, warmer. We saw devastating wildfires in California and Australia, extreme heat in Siberia, and the second lowest level of Arctic sea ice ever observed, among other climate extremes.

At the same time, the world has made substantial progress in moving away from the worst-case outcomes of climate change over the past decade. Rather than a 21st century dominated by coal the energy modelers foresaw, global coal use peaked in 2013, and is now in structural decline. We have succeeded in making clean energy cheap, with solar power and battery storage costs falling tenfold since 2009, and the world has produced more electricity from clean energy, solar, wind, hydro, and nuclear, than from coal over the past 2 years. And according to major oil companies, peak oil is soon upon us, not because we have run out of cheap oil to produce, but because demand is falling as consumers shift to electric vehicles (EVs).

Current policies adopted by countries today put us on track for around 3 degrees Centigrade of warming by the end of the century, compared to the late 1800's. Including pledges and targets, such as those in the Paris agreement, brings us down to 2.5 degrees Centigrade. We have seen a proliferation of longer term decarbonization commitments in recent years, with countries representing around half of global emissions, including China, pledging to reach net zero by 2050 or 2060. If these longer-term commitments are achieved, it would bring end of century warming down close to the global target of 2 degrees Centigrade.

Now, some caution is warranted here. Long term pledges should be discounted until reflected in short term policy commitments, and warming could well be notably higher or lower than these best estimates, given scientific uncertainties surrounding both the sensitivity of climate to our greenhouse gas emissions and likely changes in the ability of the land and oceans to absorb a portion of what we emit. CO_2 accumulates in the atmosphere over time, and until emissions reach net zero, the world will continue to warm. This is the brutal math of climate change, and it means that full decarbonization is not a matter of if, but when.

Cost declines in clean energy go a long way toward making deep decarbonization more achievable at a lower cost than appeared a decade ago. Low cost renewables can provide a sizable share of our energy needs in modern grid integration models. In the near term, however, America's cheap and abundant supplies of natural gas will play a key role in filling in the gaps as we buildup more wind and solar, and keep existing clean energy sources, like nuclear, online.

In the longer term, there's a growing recognition of both the need for complementary technologies, such as grid-scale storage and long distance transmission, as well as clean firm generation, like advanced nuclear, enhanced geothermal, and gas with carbon capture and storage, to ultimately wean the system off its dependence on natural gas. Studies have consistently shown that low carbon power grids with a sizable portion of clean, firm generation are a lower cost option than wind, solar, and hydro alone. CO_2 removal technologies will also play an important role to offset the long tail of hard to reduce emissions from sectors like aviation. The 2020's is the decade to invest in maturing a range of technologies that improve options for the long terms.

Debates around climate mitigation are often framed as a choice between the technologies we have today and future innovations. In reality, we need to do both, to deploy what is cost-effective today, and to invest in the range of solutions needed to tackle the hard to decarbonize parts of the economy. The recent omnibus bill takes an important step in this direction, authorizing billions of dollars for investments in clean energy, vital energy R&D (research and development), and grid modernization. It shows that there is real potential for bipartisan energy solutions that both reduce emissions and create jobs. If we want to ensure that the rest of the world follows the U.S. lead in reducing CO_2 emissions, there is no better step we can take than making clean energy technologies cheaper than fossil fuel alternatives. Making clean energy cheap can set the U.S. up to be a leader in developing and selling these technologies to the rest of the world, while building new industries, and creating jobs at home.

Climate change impacts pose a serious threat to our way of life, but are unlikely to lead to human extinction. However, existential risks are an unnecessarily high bar to take action. Nearly every other challenge we have dealt with in the past, poverty, war, hunger, disease, did not literally threaten the survival of our species. The impetus to mitigate climate change is less about enabling humanity to survive, and more about enabling it to thrive, and to leave our children a natural world that, while far from untouched, is at least largely intact. Thank you.

[The prepared statement of Dr. Hausfather follows:]

Written Testimony of

Zeke Hausfather

Director of Climate and Energy, The Breakthrough Institute

To the U.S. House of Representatives

Committee on Science, Space, and Technology

Hearing Entitled:

The Science Behind Impacts of the Climate Crisis

March 12th, 2021

Introduction

Good morning Chairwoman Johnson, Ranking Member Lucas, and members of the Committee. I am grateful for the opportunity to join you today and the opportunity to share my perspective on the science behind the impacts of climate change.

My name is Zeke Hausfather. I am the director of climate and energy at the Breakthrough Institute, an environmental think tank located in Oakland, California. I also serve as a research scientist with Berkeley Earth, and a contributor to Carbon Brief. I am a climate scientist whose research focuses on observational temperature records, climate models, and mitigation technologies. I am also a contributing author to the IPCC 6th Assessment Report. My testimony today will draw upon my work and that of my colleagues to present a view of our changing climate and its impacts, the future warming pathways the world may take, the accelerating global energy transition away from carbon-intensive fuels, and the technologies needed to decarbonize the US economy.

In many ways 2020 was the year in which both climate change and the accelerating energy transition became impossible to ignore. On the climate front we saw 2020 tie with 2016 as the warmest year since records began, with global temperatures around 1.3ºC (2.3ºF) above the temperatures of the late 1800s. Land areas – where we all live – were nearly 2ºC (3.6ºF) warmer. We saw devastating wildfires in California and Australia, extreme heat in Siberia, and the second lowest level of Arctic sea ice ever observed, among other climate extremes.

At the same time, the world has made substantial progress in moving away from the worst-case outcomes of climate change over the past decade. Rather than a 21st century dominated by coal that energy modelers foresaw, global coal use peaked in 2013 and is now in structural decline. We have succeeded in making clean energy cheap, with solar power and battery storage costs falling 10-fold since 2009. The world produced more electricity from clean energy – solar, wind, hydro, and nuclear – than from coal over the past two years. And according to major oil companies peak oil is upon us – not because we have run out of cheap oil to produce, but because demand is falling as consumers shift to electric vehicles.

Current policies adopted by countries put us on track for around 3ºC (or 5.4ºF) of warming by the end of the century, compared to the late 1800s. Including pledges and targets – such as those included in the Paris Agreement – brings this down to 2.5ºC (4.5ºF). We have seen a proliferation of longer-term decarbonization commitments in recent years, with countries representing around half of global emissions – including China – pledging to reach net-zero by 2050 or 2060. If these longer term commitments are achieved, it would bring end-of-century warming down close to 2ºC (3.6ºF).

Some caution is warranted here; long-term pledges should be discounted until reflected in short-term policy commitments. And warming could well be notably higher – or lower – than these best estimates, given scientific uncertainties surrounding both the sensitivity of climate to our greenhouse gas emissions and likely changes in the ability of the land and oceans to absorb a portion of what we emit. CO_2 accumulates in the atmosphere over time, and until emissions reach net-zero the world will continue to warm. This is the brutal math of climate change, and it means that the full decarbonization of our economy is not a matter of if but when.

Cost declines in clean energy go a long way toward making deep decarbonization more achievable at a lower cost than appeared possible a decade ago. Low-cost renewables can provide a sizable share of our energy needs in modern grid-integration models. In the near term, however, America's cheap and abundant supplies of natural gas will play a key role in filling in the gaps as we build out more wind and solar and keep existing clean energy sources like nuclear online.

In the longer term, there is a growing recognition of the need for both complementary technologies – such as grid-scale storage and long-distance transmission – as well as clean firm generation like advanced nuclear, enhanced geothermal, and gas with carbon capture and storage to wean the system off natural gas. Studies have consistently shown that low-carbon power grids with a sizable portion of clean firm generation are a lower cost option than wind, solar, and hydro alone.

Debates around climate mitigation are often framed as a choice between the technologies we have today and future innovations. In reality we need to do both; to deploy what is cost-effective today, and to invest in the range of solutions needed to tackle the hard-to-decarbonize parts of the economy. The recent omnibus bill takes an important step in this direction, authorizing billions of dollars for investments in clean energy, vital energy R&D, and grid modernization. It shows that there is real potential for bipartisan energy solutions that both reduce emissions and create jobs.

If we want to ensure that the rest of the world follows the US lead in reducing CO_2 emissions, there is no better step that we can take than making clean energy technologies cheaper than fossil fuel alternatives. Making clean energy cheap can set the US up to be a leader in developing and selling these technologies to the rest of the world while building new industries and creating jobs at home.

This testimony is divided into three parts. The first focuses on our changing climate, looking at the exceptional conditions of 2020, the uncertainties in future climate change and recent advances in our understanding of climate sensitivity, what we do and do not know about climate impacts, and the reason why emissions need to be reduced to net zero emissions to avoid continued warming.

The second part focuses on the accelerating energy transition, examining the declining fortunes of coal and the rise of cheap clean energy, the implications for future emissions pathways, the reasons why worst-case emissions outcomes are increasingly unlikely, and why the 1.5ºC global climate target is likely out of reach at the same time that pathways to well-below 2ºC are becoming more plausible.

The third part explores how have some – but not all – of the technologies we need to cost-effectively decarbonize different parts of the economy, examines the results from three newly-published US decarbonization models, and looks toward the challenge of stranded fossil fuel assets in a post peak-oil future.

Our changing climate

The state of the climate in 2020

2020 was a remarkable year for the Earth's climate. It saw surface temperatures tying for the warmest year since records began in the mid-1850s, a fact all the more remarkable because the latter half of 2020 saw some natural cooling effect from a modest La Niña event in the tropical Pacific. It was the warmest year on record for ocean heat content – which in many ways serves as a our best indicator of the Earth's changing temperature as upwards of 90 percent of net heat trapped by greenhouse gases in the atmosphere accumulates in the oceans. It was the warmest or second warmest in the Earth's troposphere – the lower part of the atmosphere – depending on the dataset examined. Arctic sea ice experienced its second lowest summer minimum, with record lows in sea ice extent and volume in the Arctic for much of the period between July and November. Sea level and atmospheric greenhouse gas concentrations continued to rise, while the world's glaciers continued to shrink and decline.[1]

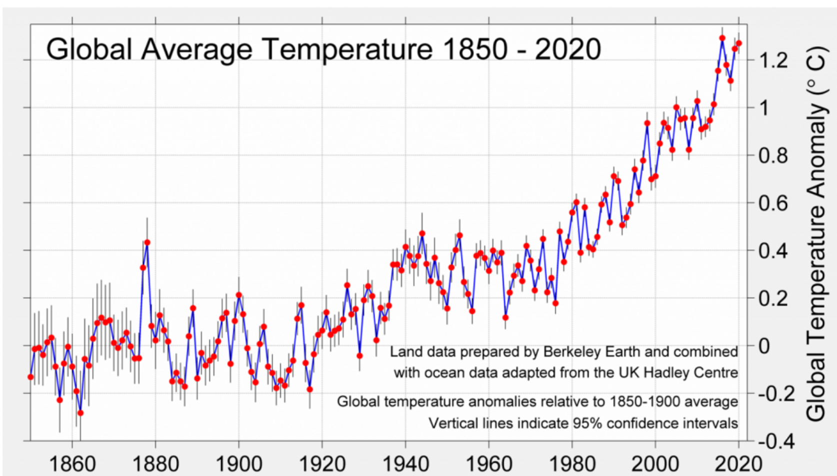

Figure 1: Annual global mean surface temperature anomalies between 1850 and 2020 from Berkeley Earth, along with 95% confidence intervals.[2]

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[1] For more details on 2020 climate see: Hausfather, Z. 2021. State of the climate: 2020 ties as warmest year on record. *Carbon Brief*. Available: https://www.carbonbrief.org/state-of-the-climate-2020-ties-as-warmest-year-on-record

[2] Rohde, R., and Hausfather, Z. 2020. The Berkeley Earth Land/Ocean Temperature Record. *Earth System Science Data*. Available: https://essd.copernicus.org/articles/12/3469/2020/

Global surface temperatures in 2020 were between 1.2ºC and 1.4ºC (2.2ºF and 2.5ºF) above the 1880-1900 average depending on the dataset used.[3] The earth has been warming at a rate of nearly 0.2ºC (0.4ºF) per decade since the 1970s.

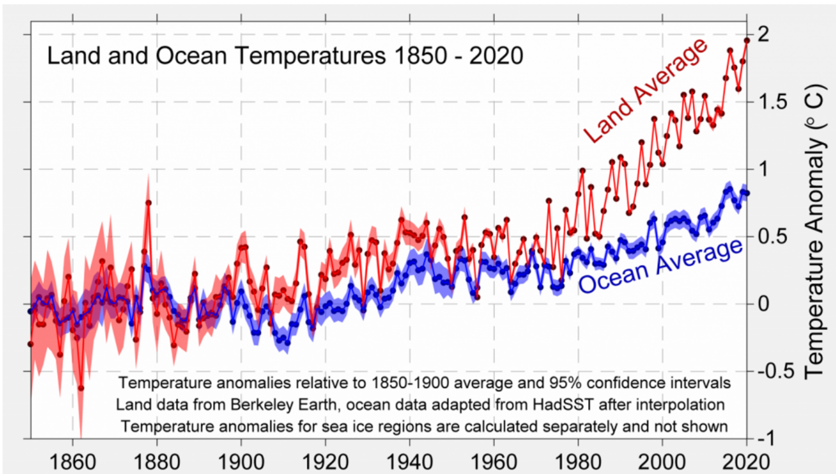

Figure 2: Annual mean surface temperature anomalies for land (red) and ocean (blue) regions between 1850 and 2020 from Berkeley Earth, along with 95% measurement confidence intervals.

Two thirds of the Earth's surface is covered by oceans, where temperatures are increasing at a slower rate than land regions. While the globe as a whole was around 1.3ºC warmer than late 19th Century levels in the Berkeley Earth dataset in 2020, we find that land temperatures are already nearly 2ºC (3.6ºF) above preindustrial levels, compared to only 0.8ºC (1.4ºF) over the oceans. Some regions of the land are warming faster still; high latitude areas above 60N – which includes nearly all of Alaska and Northern Canada – have warmed by 3ºC (5.4ºF).

[3] The 1880-1900 period is used for this calculation to maximize the number of global surface temperature datasets that can be compared. Note that the "preindustrial" baseline period is itself inconsistently defined. Some global surface temperature datasets begin in 1850, and tend to use an 1850-1900 baseline, while others start in 1880 and use an 1880-1900 or 1880-1899 baseline.

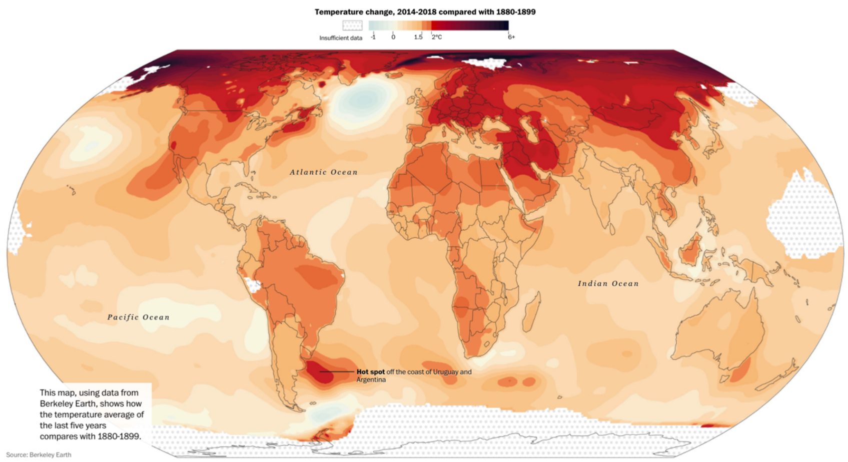

Figure 3: Global surface temperature changes between the 1880-1899 period and the 2014-2018 period in the Berkeley Earth dataset. Figure from the Washington Post; white areas represent regions where 1880-1899 temperature estimates are unavailable.[4]

A simple continuation of the warming trend over the past few decades suggests that the world will pass 1.5ºC above preindustrial levels in the mid 2030s and 2ºC in the early 2060s. This is also consistent with the results that the latest generation of global climate models find in scenarios where our emissions of CO_2 and other greenhouse gases remain close to current levels through 2050.[5,6]

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[4] Washington Post. 2019. 2°C: Beyond the Limit: Dangerous new hot zones are spreading around the world. Available: https://www.washingtonpost.com/graphics/2019/national/climate-environment/climate-change-world/

[5] E.g. in the RCP4.5 scenario for the prior generation of climate models (CMIP5) and the SSP2-4.5 scenario in the latest generation (CMIP6). For details see: Hausfather, Z. 2020. Analysis: When might the world exceed 1.5ºC and 2ºC of global warming? *Carbon Brief*.

[6] For more details on climate/earth system models see: McSweeney, R. and Hausfather, Z. 2018. Q&A: How do climate models work? Carbon Brief. Available: https://www.carbonbrief.org/qa-how-do-climate-models-work

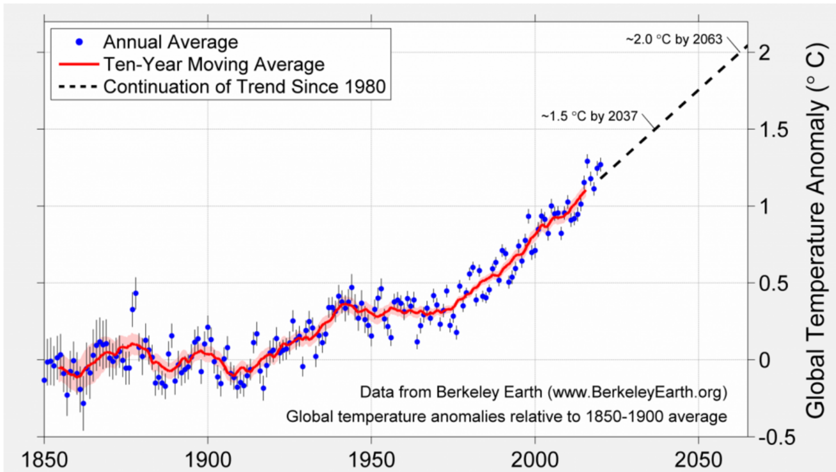

Figure 4: Annual global mean surface temperature anomalies between 1850 and 2020 from Berkeley Earth and a linear projection of future warming through 2065 if the warming trend since 1980 continues.

Uncertainties in future climate change

When projecting future climate change we have to deal with three different – and important – sources of uncertainty.

The first of these is the one that is in our control – our emissions of CO_2 and other greenhouse gases.[7] The IPCC 5th Assessment Report examined four different future concentration scenarios – called Representative Concentration Pathways (RCPs) – that are driven by different emission trajectories:

- RCP2.6 – would require sharp near-term reductions in CO_2 emissions and ultimately result in around 1.7ºC (3.1F) global mean surface temperature warming by 2100 relative to preindustrial.[8]
- RCP4.5 – has global CO_2 emissions remaining roughly flat though 2050 before declining to around half of current levels by 2100, and would result in around 2.5ºC (4.5F) warming by 2100.

[7] While human emissions of CO2 is the major factor driving recent warming, our emissions of black carbon, halocarbons, sulphur dioxide, nitrous oxide, methane, nitrogen oxide, and albedo changes from land use also contribute to our changing climate (and to total “radiative forcing”).
[8] Note that the number associated with each RCP – 2.6, 4.5, 6.0, and 8.5 – refers to the change in well-mixed greenhouse gas radiative forcing in watts per square meter of the Earth’s surface by 2100.

- RCP6.0 – has emissions staying relatively flat, ending only around 25 percent above current levels by 2100 with warming of around 3ºC (5.4F).
- RCP8.5 – has rapid growth of future emissions, with global emissions around 2.5 times greater than current levels by 2100 and warming of around 4.6ºC (8.3F).

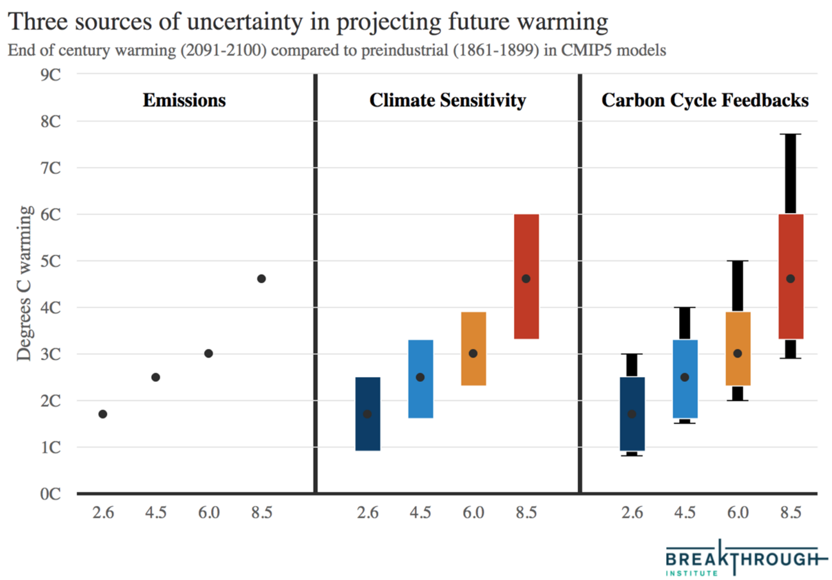

Figure 5: Projected end-of-century (2091-2100) warming relative to 1861-1899 across the four RCP scenarios (2.6, 4.5, 6.0, and 8.5) based on the climate models (CMIP5) featured in the IPCC Fifth Assessment Report. The first panel shows the multimodal mean warming for each RCP scenario; the second panel shows the range of warming across all the individual models in each RCP driven by differences in model sensitivity; the third panel shows the estimated range of warming for each RCP when carbon cycle feedback uncertainties are also included.

Unfortunately future emissions alone provide a fairly limited picture of the amount of warming the world may actually experience. This is due to the other two sources of uncertainty: climate sensitivity and carbon cycle feedbacks. Climate sensitivity refers to the amount of warming the world will experience as CO_2 in the atmosphere increases; it is typically expressed using a simple metric of how much the world will warm over the long-term if atmospheric concentrations of CO_2 are doubled.

Climate sensitivity has long been a “holy grail” of sorts for the climate science community, but has been difficult to narrow down. Back in 1979 Dr. Jules Charney led a National Academy of Sciences report that suggested if atmospheric concentrations of CO_2 were to double (e.g. from their preindustrial value of 280 parts per million to 560 parts per million), the world would likely warm by somewhere between 1.5ºC and 4.5ºC (2.7F to 8.1F). The most recent IPCC assessment report (AR5), published 34 years after Charney's report, gave the same "likely" range of 1.5ºC to 4.5ºC warming per doubling of CO_2.[9]

Thankfully some meaningful progress has been made on the question of climate sensitivity in the past few years. A recent assessment of climate sensitivity undertaken under the auspices of the World Climate Research Programme – where I was a coauthor – provided the first comprehensive case for narrowing the range of climate sensitivity based on multiple lines of evidence.[10] We suggest that climate sensitivity is likely to be between 2.6ºC and 4.1ºC per doubling CO_2; we also find that it now appears extremely unlikely that the climate sensitivity could be below 2C. While we were unable to fully rule out that the sensitivity could be above 4.5C, we find that it is not likely.

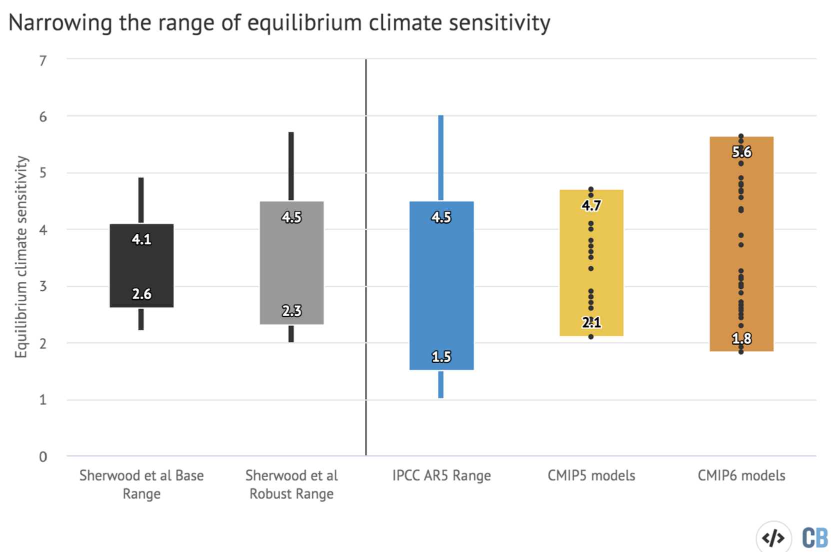

Figure 6: Equilibrium climate sensitivity estimates (degrees C warming per doubling of atmospheric CO_2 concentrations in Sherwood et al 2020 compared to the IPCC AR5 range and the climate sensitivity of all the old CMIP5 models and new CMIP6 models. Thick bars represent the "likely" (66%) range, while narrow bars represent the "very likely" (90%) range. Sherwood et

[9] Note that "likely" here refers to a 66th percentile range; e.g. there is a roughly 33% chance that sensitivity could either be above or below this range.
[10] Sherwood, S.C., et al. 2020. An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Reviews of Geophysics*. Available: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019RG000678

al ranges are shown for both the base case when all lines of evidence are included, and the robust case where any one line of evidence is excluded. Figure via Carbon Brief.[11]

This suggests that some of the latest generation of climate models – CMIP6[12] – that have very high climate sensitivity may not provide realistic long-term global surface temperature projections, a conclusion supported by numerous other recent studies showing that most of these very high (5C+) sensitivity models have relatively poor hindcast performance when compared with observed global mean surface temperature change over the past decade or the Earth's more distant past.[13,14,15,16,17,18,19]

Carbon cycle feedbacks represent the third major source of uncertainty when projecting future warming. Today, around half of the CO_2 emitted by humans remains in the atmosphere, with the remainder absorbed by the oceans and land. However, as the Earth warms this is expected to change. For example, warming reduces the amount of CO_2 absorbed by surface ocean waters and the amount of carbon sequestered in soils. It can also accelerate tree death and the risk of wildfires. Thawing permafrost may release additional carbon into the atmosphere. Overall, the carbon cycle is expected to weaken as a result of climate change, leading to more emissions remaining in the atmosphere and less being absorbed by the land and oceans. All of these processes introduce uncertainty when translating future CO_2 emissions into changes in atmospheric CO_2 concentrations.

Future warming scenarios developed by the climate modelling community do consider carbon-cycle feedbacks, but often use single estimates of the feedback strength from previous studies and do not include any of the uncertainties in carbon-cycle feedbacks. The reason scenarios leave out carbon-cycle feedback uncertainties is that about half of the climate modelling groups do not currently include the biogeochemical cycles needed to model carbon-cycle feedback changes. Including uncertainties in future carbon cycle feedbacks results

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[11] For more details see Forster, P., et al. 2020. Why low-end 'climate sensitivity' can now be ruled out. *Carbon Brief*. Available: https://www.carbonbrief.org/guest-post-why-low-end-climate-sensitivity-can-now-be-ruled-out

[12] For more on the new generation of climate models, see: Hausfather, Z. 2019. CMIP6: the next generation of climate models explained. *Carbon Brief*. Available: https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained

[13] Nijsse, F.J.M.M., et al., 2020. Emergent constraints on transient climate response (TCR) and equilibrium climate sensitivity (ECS) from historical warming in CMIP5 and CMIP6 models. *Earth System Dynamics*. Available: https://esd.copernicus.org/articles/11/737/2020/

[14] Zhu, J. et al. 2020. High climate sensitivity in CMIP6 model not supported by paleoclimate. *Nature Climate Change*. Available: https://www.nature.com/articles/s41558-020-0764-6

[15] Tokarska, K.B., et al. 2020. Past warming trend constrains future warming in CMIP6 models. *Sci. Adv.*

[16] Flynn, C.M., and Mauritsen, T. 2020. On the climate sensitivity and historical warming evolution in recent coupled model ensembles. *Atmospheric Chemistry and Physics*.

[17] Brunner, L., et al. 2020. Reduced global warming from CMIP6 projections when weighting models by performance and independence. *Earth System Dynamics*.

[18] Ribes, A., et al. 2021. Making climate projections conditional on historical observations. *Sci. Adv.*

[19] Zhu, J. et al. 2021. Assessment of Equilibrium Climate Sensitivity of the Community Earth System Model Version 2 Through Simulation of the Last Glacial Maximum.

in as much as 13 percent less warming or 25 percent more warming than estimates based on climate sensitivity alone.[20]

What we do and do not know about climate impacts

Continued climate change is expected to result in substantial negative impacts to both human and natural systems. The degree of impact will in large part be determined by our future emissions. One important finding from climate models is that the climate as a whole is not particularly prone to tipping points, at least within the range of emissions we would reasonably expect to occur this century. Climate models show that warming is proportional to our cumulative emissions, but there is no discernable point at which we end up getting “runaway” climate change. Despite the popular portrayal by some in the media, global climate targets like well-below 2ºC do not represent a “point of no return” where “climate change, intensified by various feedback loops, spins completely out of control”.[21]

Rather, targets like well-below 2ºC are themselves largely political constructs informed by the climate impacts literature.[22] We know that impacts on both human and natural systems increase sharply as the climate warms, at 2ºC is a point at which impacts across a number of human and natural systems are likely to have become severe enough that they are best avoided if possible. However, climate change is ultimately a matter of degrees rather than thresholds; the world does not suddenly experience runaway global warming if a particular threshold is passed, but the magnitude of impacts continues to accelerate as the world warms.

That is not to say that tipping points in the climate system are not concerning. There are clear thresholds associated with natural systems, and a world of increasing future emissions is one in which most coral reef ecosystems cease to exist, parts of the Amazon rainforest may permanently shift into a savannah-type ecosystem, ocean circulation may significantly slow, greenhouse gas releases from Arctic permafrost will accelerate, summer Arctic sea ice may cease to exist, and the world will lock-in multiple meters of sea level rise from melting ice sheets over the next millennium. These are all serious impacts, but at the same time there is relatively limited evidence that they could result in substantial additional warming compared to what is already projected in modern climate models.

At the same time, we should also be humbled by what we do not know about the Earth’s climate. Models are necessarily imperfect representations of reality, and large and not-fully-explained changes to the climate in the distant past should make us cautious. The

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[20] For details see Hausfather, Z., and Betts, R. 2020. Analysis: How ‘carbon-cycle feedbacks’ could make global warming worse. *Carbon Brief*.

[21] See Chrobak, U. 2019. Can we still prevent an apocalypse? What Jonathan Franzen gets wrong about climate change. *Popular Science*. Available: https://www.popsci.com/climate-change-new-yorker-franzen-corrections/

[22] Victor, D., and Kennel, C. 2015. Climate policy: Ditch the 2°C warming goal. *Nature*. Available: https://www.nature.com/news/climate-policy-ditch-the-2-c-warming-goal-1.16018

more we push the Earth out of the climate that it has experienced over the past few million years, the larger the chance that we encounter “unknown unknowns”.[23]

Beyond concerns over climate tipping points, there are many impacts that are clearly detectable and attributable to the climate changes we have already experienced. Extreme heat events are becoming more common as the Earth warms, with many more all-time heat records being set than cold records across the world. A warming world increases the amount of water vapor in the atmosphere, resulting in more extreme precipitation events. Higher temperatures result in lower soil moisture and contribute to exacerbating drought conditions. Melting ice sheets and glaciers combined with the thermal expansion of water drive higher sea levels, contributing to higher and more damaging storm surges when storms hit coastal areas. Higher ocean temperatures contribute to the formation of more intense hurricanes and tropical cyclones. Sea ice loss and melting permafrost result in dramatic changes in the Arctic. Dryer vegetation due to high temperatures enables the rapid spread of devastating wildfires.[24]

However, despite the increases in extreme events due to climate change, the risk of death from extreme events worldwide has declined dramatically – by around two orders of magnitude – over the past century. This is because our adaptive capacity has increased, through the use of technology to construct more resilient structures, better storm forecasts, cooler interior environments, more thorough communications and stronger institutions to provide disaster relief.[25] Back in the 1970s major cyclones hitting Bangladesh would result in hundreds of thousands of deaths; today storms of a similar magnitude result in only hundreds.[26] Human adaptive capacity is an important factor to account for in determining climate change impacts, and a more equitable, prosperous world is likely one where climate impacts are much less severe, all things being equal. This does not mean that climate change impacts on human systems are not real or severe; a world without climate change but with the same level of adaptive capacity would be one with notably smaller impacts. It is also possible that impacts of climate change will outpace our ability to adapt to them.[27]

One of the particularly pernicious aspects of climate change is that those least responsible tend to be most vulnerable; its poorer countries with vanishingly small per-capita CO_2 emissions that

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[23] Schmidt, G.A. 2006. Runaway tipping points of no return. *RealClimate*. Available: http://www.realclimate.org/index.php/archives/2006/07/runaway-tipping-points-of-no-return/comment-page-2/

[24] For a comprehensive summary of climate change attribution studies across different types of extreme events, see: Pidcock, R., and McSweeney, R., 2021. Mapped: How climate change affects extreme weather around the world. Available: https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world

[25] Formetta, G., and Feyen, L. 2019. Empirical evidence of declining global vulnerability to climate-related hazards. *Global Environmental Change*. Available: https://www.sciencedirect.com/science/article/pii/S0959378019300378

[26] Haque, U., et al. 2012. Reduced death rates from cyclones in Bangladesh: what more needs to be done? *Bulletin of the World Health Organization*. Available: https://www.who.int/bulletin/volumes/90/2/11-088302/en/

[27] Mehrabi, Z., et al. Can we sustain success in reducing deaths to extreme weather in a hotter world?. *World Development Perspectives*. Available: https://www.sciencedirect.com/science/article/abs/pii/S2452292918301449

are the most severely affected by increases in extreme events because they lack the adaptive capacity that we in the US take for granted. There need not be a tradeoff between climate mitigation and development, but we should work to ensure that decarbonization policies support rather than inhibit poorer countries and disadvantaged communities from pursuing prosperity.

While human systems are often quite adaptable on short timescales, the same is not true for the natural environment. The timeframe over which plants and animal species evolve to respond to changes in their environment is orders of magnitude slower than the rate of changes we are seeing to many environments today. A high warming future could consign many of the world's species to extinction. It is quite possible to imagine a humanity that adapts to – but does not thrive in – a high-warming future amid the ruin of natural ecosystems. Even here other human activities make an important difference in the capacity of natural ecosystems to respond to climate change. Deforestation, air quality, water pollution and other environmentally damaging activities make the natural world more vulnerable to disruptions from climate change. Addressing them can help make nature more resilient.

Climate change impacts pose a serious threat to our way of life, but are unlikely to lead to human extinction. However, existential risks are an unnecessarily high bar to take action; nearly every other challenge we have dealt with in the past – poverty, war, hunger, disease, conventional environmental pollution, etc. – did not literally threaten the survival of our species. The impetus to mitigate climate change is less about enabling humanity to survive and more about enabling it to thrive, and to leave our children a natural world that, while far from untouched, is at least largely intact.

The need for net-zero emissions

Our best estimate is that approximately all of the observed global mean surface temperature warming since the 1950s is due to human emissions of CO_2 and other greenhouse gases. Natural climate "forcings" such as changing solar output, variations in the Earth's orbit, and volcanic activity would have likely led to a slight cooling over the past 70 years in the absence of human influences on the climate.[28]

CO_2 increases are the primary driver of recent warming, and have the same effect on the climate no matter where in the world it is emitted. CO_2 accumulates in the Earth's atmosphere, and the amount of warming that the Earth has and will experience is approximately proportional to our total cumulative emissions.[29] This means that the total cumulative emissions since the

[28] This is the finding of both the IPCC 5th Assessment Report and the recent US Fourth National Climate Assessment. For more details and an independent assessment of the different drivers of warming since 1850 see Hausfather, Z. 2017. Analysis: Why scientists think 100% of global warming is due to humans. *Carbon Brief*. Available: https://www.carbonbrief.org/analysis-why-scientists-think-100-of-global-warming-is-due-to-humans

[29] For a good review of the cumulative emissions-temperature relationship see: Matthews, H.D., et al. 2018. Focus on cumulative emissions, global carbon budgets and the implications for climate mitigation targets. *Environmental Research Letters*. Available: https://iopscience.iop.org/article/10.1088/1748-9326/aa98c9/meta

industrial revolution are driving current global temperatures rather than the emissions of any given year. The long atmospheric lifetime of CO_2 perturbations means that emissions would need to be cut fairly dramatically – by around 80 percent or so – for atmospheric CO_2 concentrations to stabilize.

However, stable atmospheric CO_2 concentrations do not necessarily result in stable global temperatures. The Earth is currently out of equilibrium; that is, more heat is being trapped by greenhouse gases in the Earth system than is being reradiated back to space. The oceans are slowly absorbing this extra heat, and will continue to slowly heat up even if CO_2 levels begin to fall. It turns out – rather conveniently – that if emissions of CO_2 are brought all the way down to net-zero, the cooling from falling atmospheric concentrations of CO_2 is nearly perfectly balanced out by warming "in the pipeline" as the oceans continue towards equilibrium, and global temperatures remain relatively flat.[30]

This has a number of important implications. First, it means that even if we get emissions all the way down to net-zero, global temperatures will not fall for many centuries to come. To actually reduce global temperatures we need net-negative emissions – sucking more CO_2 out of the atmosphere than is going in. To put it another way, if we ever wanted to bring the Earth back to the temperatures of the 1970s, we would have to actively remove an amount of CO_2 from the atmosphere roughly equal to all of our emissions since the 1970s. Second, it means that we have significant influence over future warming through the control of our emissions; there is likely not a large amount of additional warming that is inevitable, and we can effectively stop the world from warming any further by reaching net-zero emissions. But as long as emissions remain above net-zero, the world will continue to warm.

[30] MacDougall, A.H., et al. 2020. Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2. *Biogeosciences*. Available: https://bg.copernicus.org/articles/17/2987/2020/

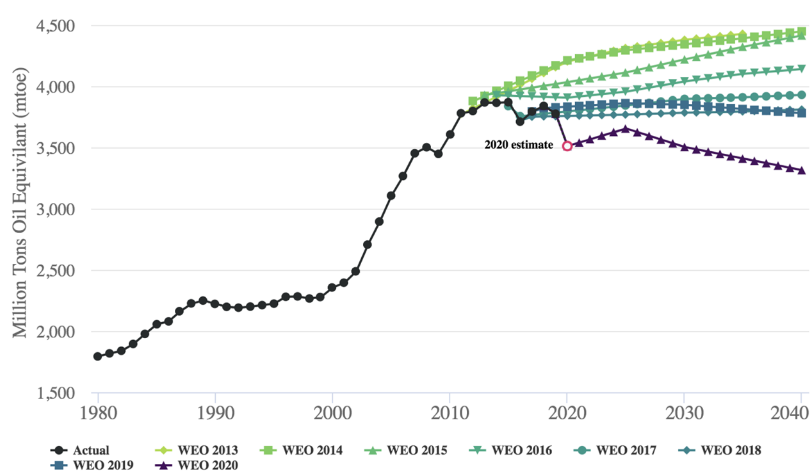
The accelerating energy transition

Moving toward a clean energy future

A decade ago global CO_2 emissions were rising rapidly. Global use of coal – the most CO_2-intensive fossil fuel per unit of energy – had nearly doubled between 2000 and 2010, driven in large part by a massive expansion in China, where a new coal plant opened every few days.[31] A continuation of this dramatic expansion of coal seemed like a plausible path the world could take, and many global energy system models saw a 21st century dominated by coal in the absence of much stronger climate policies enacted by countries.

A decade later, we live in a very different world. Rather than continuing to grow, global coal use likely peaked in 2013 and has been declining since. Global coal use is in "structural decline" for the foreseeable future according to the International Energy Agency's recent 2020 World Energy Outlook (WEO). Actual coal use has nearly always turned out to be lower than forecasts, as shown in Figure 7, below.

Global Coal Use – Actual and WEO Forecasts from 2013-2020



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[31] Evans, S., and Pearce, R., 2020. Mapped: The world's coal power plants. *Carbon Brief*. Available: https://www.carbonbrief.org/mapped-worlds-coal-power-plants

Figure 7: Global coal use (black line, in million tons oil equivalent) compared with IEA World Energy Outlook forecasts for each year between 2013 and 2020.

Declines in coal use for electricity have been even more rapid; the world now produces more of its electricity from clean energy sources – wind, solar, hydro, and nuclear – than from coal.[32]

The trajectory of coal in the US is even more dramatic; despite continued projections of a coal renaissance by the Department of Energy's Energy Information Agency (EIA) – which has long been a key resource to the climate and energy community – coal use for electricity generation has fallen to less than half its 2007 peak even before the COVID-19 pandemic created a host of new challenges for the industry.[33] Both renewables and nuclear each produced more electricity than coal in the US in 2020. The speed of the energy transition in the US power sector – driven by a combination of cheap natural gas and renewables – shows how quickly things can change when clean(er) energy sources become the more cost-effective option.

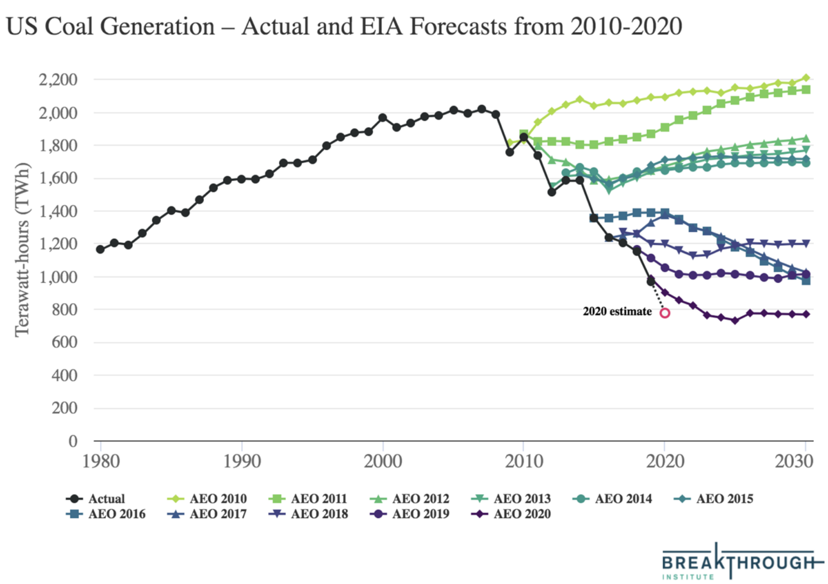

Figure 8: US coal generation (black line, in terawatt-hours) compared with EIA Annual Energy Outlook (AEO) forecasts for each year between 2010 and 2020.

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[32] IEA World Energy Outlook 2020. Available: https://www.iea.org/reports/world-energy-outlook-2020
[33] EIA 2020. U.S. Energy-Related Carbon Dioxide Emissions, 2019. Available: https://www.eia.gov/environment/emissions/carbon/

It is also remarkable that coal's decline in the US not only continued but accelerated during the Trump administration, despite the rollback of a number of regulations that could have increased the cost of coal generation. This is a testament to the power of making clean energy cheap, as it produces a transition that is somewhat resilient to policy choices.[34]

Cheap renewables (and – in the US – cheap natural gas) have contributed to both an acceleration of coal retirements and a significant decline in coal capacity factors worldwide. For example, in the US coal plants only ran 40 percent of the time on average in 2020, compared to 67 percent a decade ago.[35] Similarly, the capacity factor of Chinese coal generation has declined from 60 percent in 2011 to 49 percent today, though overcapacity in the sector played a larger role there.[36]

The decline in power sector emissions in the US has been one of the larger – but by no means the only – drivers of reduction in overall US CO_2 emissions.[37] US emissions from fossil fuels were down by 24 percent below 2005 levels in 2020, down from 14 percent below 2005 levels in 2019. While emissions are expected to recover as the economy rebounds, the EIA expects emissions to remain well below 2019 levels at least through 2022, as shown in Figure 9. Given the historically pessimistic nature of EIA CO_2 emissions forecasts, it is quite possible that US CO_2 emissions will be even lower over the next few years.

[34] Hausfather, Z., and Anderson, L. 2019. Trump's War on Coal. *Breakthrough Institute*. Available: https://thebreakthrough.org/issues/energy/trumps-war-on-coal

[35] EIA Electric Power Monthly. 2021. Table 6.07.A. Available: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_a

[36] Myllyvirta, L., et al. 2020. Analysis: Will China build hundreds of new coal plants in the 2020s? *Carbon Brief*. Available: https://www.carbonbrief.org/analysis-will-china-build-hundreds-of-new-coal-plants-in-the-2020s

[37] For more details on the different drivers of US CO_2 reductions, see Hausfather, Z. 2017. Analysis: Why US carbon emissions have fallen 14% since 2005. *Carbon Brief*. Available: https://www.carbonbrief.org/analysis-why-us-carbon-emissions-have-fallen-14-since-2005

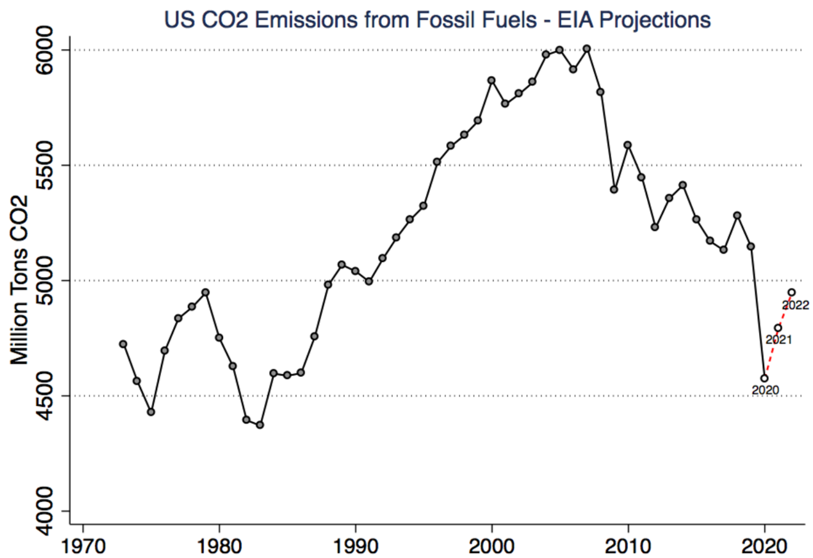

Figure 9: US CO_2 emissions from fossil fuels (in million tons) from 1973-2020, along with 2021 and 2022 projections from the EIA Short Term Energy Outlook (STEO).[38]

The decline of coal use and the rise of clean energy – both in the US and globally – has been driven by a combination of technology and policy. The two are strongly interrelated, as policy has played a role in driving down technology costs both through investing heavily in early research, development, and deployment (RD&D) and driving economies of scale through tax incentives and other subsidies.[39] Solar photovoltaics (PV), wind, and batteries have seen the most dramatic cost declines in recent years. Back in 2009 solar PV cost approximately $350 per megawatt-hour (MWh); since then it has fallen by a factor of 10x, down to $35 per MWh. Electricity generated by wind turbines has fallen from around $140 per MWh to around $40 per MWh.[40] At the same time, battery costs – which are important both to enable higher levels of variable renewable energy use and make electric vehicles more cost-effective – have fallen from $1200 per kilowatt-hour (kWh) to $137, a decline of nearly a factor of 10x.[41]

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[38] EIA Short Term Energy Outlook. February 2021. Available: https://www.eia.gov/outlooks/steo/
[39] Jenkins, J., et al., 2010. Where Good Technologies Come From. *The Breakthrough Institute*. Available: https://thebreakthrough.org/articles/american-innovation
[40] Lazard 2020. Levelized Cost of Energy and Levelized Cost of Storage – 2020. Available: https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/
[41] BloombergNEF 2020 Battery Price Survey.

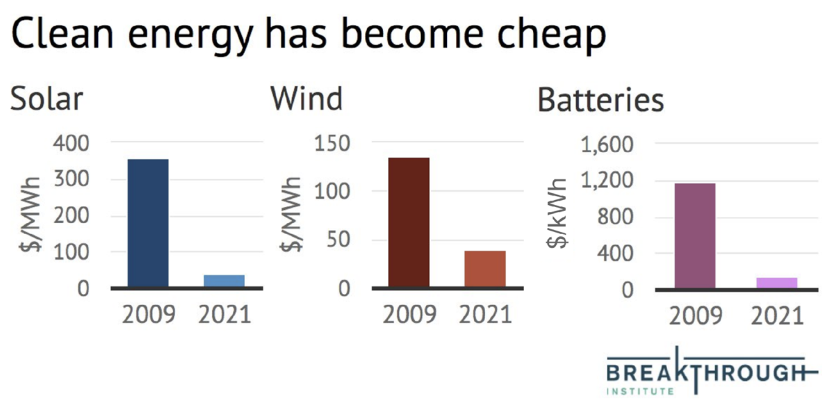

Figure 10: Levelized cost of energy from solar photovoltaics, onshore wind, and lithium ion batteries in 2009 and 2021. Data from Lazard and BloombergNEF.

Non-hydro renewables – primarily wind and solar PV – now produce 10.4 percent of the world's electricity, up from 3.5 percent in 2010 and 1.4 percent in 2000. In 2019, non-hydro renewables accounted for 48 percent of new electricity generation globally, with natural gas accounting for 31 percent, new nuclear accounting for 14 percent, and hydro accounting for 7 percent (both coal and oil generation declined globally in 2019).[42]

Cheap renewables by themselves are not a panacea for decarbonization; as discussed below, clean firm electricity generation like nuclear and additional technological innovation in hard-to-decarbonize sectors like industrial processes, long-distance transportation, and agriculture are needed to cost-effectively fully decarbonize the economy.[43] But cheap renewables coupled with electrification can get us a good part of the way there, and will likely be the largest driver of global decarbonization for at least the next decades or two.[44]

In many ways, technology enables policy. While decarbonizing the US economy seemed like a very costly endeavor a decade ago, falling prices of renewables, electric vehicles, and other technologies makes it appear far less costly today. Cost-effective pathways to decarbonization

[42] BP Statistical Review of World Energy 2020. Available: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
[43] Electricity generation in grid decarbonization models can broadly be divided into fuel-saving resources like wind and solar that have near-zero operational costs and displace other higher-cost resources when available, fast-burst balancing resources such as batteries and demand response, and clean firm generation such as nuclear, hydro, gas with carbon capture, and geothermal that can be counted on to meet demand when needed in all seasons and over long durations. For details see: Sepulveda, N.A., et al. 2018. The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. Joule. Available: https://www.sciencedirect.com/science/article/pii/S2542435118303866
[44] Larson, E., et al., 2021. Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Princeton University. Available: https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/

are driving a slew of new net-zero commitments by countries worldwide. Making clean energy cheap also has important spillover effects; the fact that renewables are the cheapest form of new electricity at the margin in many parts of the world is helping drive large-scale development in middle-income countries like India and China that will account for the bulk of 21st century increases in CO_2 emissions. If we want to ensure that the rest of the world follows the US in reducing CO_2 emissions, there is no better step that we can take than making clean energy cheaper than fossil fuel alternatives. Making clean energy cheap can set the US up to be a leader in developing and selling clean energy technologies to the rest of the world while building new industries at home.

Implications for future emissions pathways

A decade ago the world seemed to be on track for a best estimate of around 4ºC (7F) global mean surface temperature warming by the year 2100, compared to preindustrial levels.[45] To put this in perspective, the peak of the last ice age – which was a drastically different planet than we have today – was only around 6ºC (11F) cooler than preindustrial temperatures.[46]

Today there is cause for some cautious optimism regarding our climate future. We have bent down the curve of future emissions, and seem on track for warming closer to 3ºC (5.4F) in a current policy world and 2.5ºC (4.5F) if additional near-term pledges and targets by counties – such as those included in the Paris Agreement – are met.[47] We are no longer in a "business as usual" world, and the combination of technology and policy has made outcomes where global emissions double or triple by the end of the century far less likely.

[45] Note that RCP8.5-type outcomes with ~5ºC warming were always intended to be the upper end of possible emissions outcomes, and reflected roughly the 90th percentile of no policy baseline emissions scenarios in the literature. The median no policy baseline estimates are generally closer to 4ºC (e.g. the new SSP3-7.0 scenario). For more details see: Hausfather, Z. 2019. Explainer: The high-emissions 'RCP8.5' global warming scenario. *Carbon Brief*. Available: https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario

[46] Tierney, J.E., et al. 2020. Glacial cooling and climate sensitivity revisited. *Nature*. Available: https://www.nature.com/articles/s41586-020-2617-x

[47] Current policies are reasonably in-line with a RCP6.0 outcome, while near-term pledges and targets are in-line with a RCP4.5 outcome. For more see: Hausfather, Z., and Ritchie, J. 2019. A 3C World Is Now "Business as Usual". *The Breakthrough Institute*. Available: https://www.nature.com/articles/d41586-020-00177-3

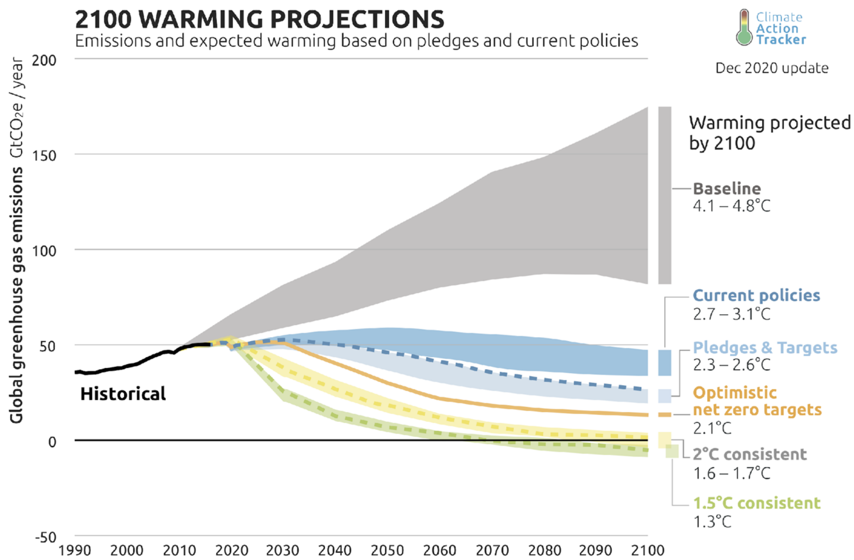

Figure 11: Mean expected global surface temperature warming across various future emissions scenarios. Note that the warming ranges here only reflect emissions uncertainties, and do not include climate sensitivity or carbon cycle feedback uncertainties. Figure from Climate Action Tracker.[48]

There is even a reasonable chance that global emissions may have already peaked in 2019, as the rate of decarbonization was already on track to overtake the rate of global economic growth by the mid-2020s.[49] Even if 2019 did not represent peak emissions, it is clear that global emissions are on a path to plateau this decade.[50] China is likely on track to peak emissions in the next five years, and has pledged to reach net-zero by 2060.[51] In fact, in recent years there has been an explosion of new net-zero pledges, which taken all together would put the world at a best estimate of 2.1ºC (3.8F) above preindustrial levels by 2100.

Today countries representing 43 percent of global emissions have now pledged to reach net-zero by 2050 or 2060, with countries representing another 11 percent of global emissions

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[48] Climate Action Tracker 2020. 2100 Warming Projections. Available: https://climateactiontracker.org/global/temperatures/
[49] Hausfather, Z. 2020. CO2 Emissions from Fossil Fuels May Have Peaked in 2019. Available: https://thebreakthrough.org/issues/energy/peak-co2-emissions-2019
[50] IEA World Energy Outlook 2020.
[51] BBC, March 4th 2021. Climate change: Will China take a 'great leap' to a greener economy? Available: https://www.bbc.com/news/science-environment-56271465

actively discussing implementing targets.[52] This includes the European Union, United Kingdom, China, Brazil, Japan, South Korea, Canada, South Africa, Argentina and Mexico, as well as the Biden Administration's net-zero target. This is also notably up from the number of countries that had similar commitments at this point in 2019.[53] It is still unclear how seriously these 2050/2060 net-zero targets should be taken, as long-term targets are easy to put on paper but may prove much harder to achieve. The extent to which long-term commitments are reflected in nearer-term policy goals will prove an early test.

These long-term commitments are a promising development, and if countries prove serious in achieving them it will lead to substantial new investment in technology for sectors of the economy that are difficult to decarbonize today, with large global spillover effects. While the Paris Agreement goal of limiting warming to well-below 2ºC remains challenging, the fact that current commitments in aggregate get us close to that point makes much more plausible than it appeared even a few years ago.

Worst-case emissions outcomes increasingly unlikely

The falling price of clean energy and enactment of climate policies have moved the world away from worst-case outcomes where coal dominates the 21st century energy mix. At the same time, however, a sizable part of the climate impacts literature still tends to focus on the high-end RCP8.5 emissions scenario, where global coal use increases 500 percent by 2100 and global emissions nearly triple. In a piece we published in the journal *Nature* last year, Glen Peters of Norwary's CICERO and I argued that researchers should focus on modeling the world as it is today, rather than a counterfactual where all of the progress made over the last decade is erased.[54] It can be useful to examine worst case outcomes, and current policies represent neither a ceiling nor a floor on future emissions outcomes; however, we need to be sure not to conflate what is a worst case outcome with what is "business as usual" today.

[52] Bloomberg New Energy Finance 2021 Executive Factbook. Available: https://about.bnef.com/blog/bloombergnef-2021-executive-factbook/
[53] UNEP. 2020. Emissions Gap Report 2020. Available: https://www.unep.org/emissions-gap-report-2020
[54] Hausfather, Z., and Peters, G. 2020. Emissions – the 'business as usual' story is misleading. Nature. Available: https://www.nature.com/articles/d41586-020-00177-3

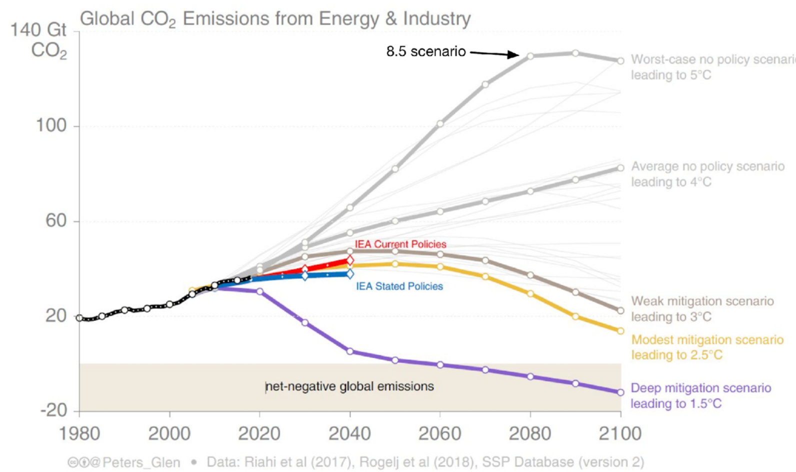

Figure 12: Comparison of emission scenarios featured in the upcoming IPCC 6th Assessment Report to near term current policy and stated policy (e.g. near-term pledges and targets) projections from the IEA 2019 World Energy Outlook. Adapted from Hausfather and Peters 2020.

As the world makes progress on tackling climate change we will necessarily exclude higher-end no-policy emissions outcomes. This is a good thing, but at the same time we need to be cognizant that there are still severe climate impacts to human and natural systems in a 3ºC world, even if they are not as potentially catastrophic as in a 4ºC or 5ºC one. The impetus to limit warming to well-below 2ºC does not depend on a high warming counterfactual, and even current commitments by countries fall short of what would be needed to avoid 2ºC+ warming by 2100.[55]

While the world has moved away from high-end future emissions scenarios, we cannot be as confident in ruling out high levels of future warming. We need to avoid being too deterministic about temperature outcomes based on emissions scenarios; as discussed earlier, there are additional large uncertainties from climate sensitivity and carbon cycle feedbacks. This means that while current policies and pledges and targets put us on track for a best estimate of 3ºC and 2.5ºC warming, respectively, we cannot rule out warming of up to 5ºC and 4ºC, respectively, if both climate sensitivity and carbon cycle feedbacks end up at the highest end of our estimates. The small chance of extremely severe warming outcomes serves as a strong incentive to pursue aggressive emissions mitigation.

[55] For more details on how current commitments compare with 1.5ºC and 2ºC pathways, see: Hausfather, Z. 2020. UNEP: Net-zero pledges provide an ‘opening’ to close growing emissions ‘gap’. *Carbon Brief*. Available: https://www.carbonbrief.org/unep-net-zero-pledges-provide-an-opening-to-close-growing-emissions-gap

The world also does not end in 2100, even if most of our climate and energy system models stop there. As long as emissions remain above net-zero, the world will continue to warm. If emissions remain at current levels, RCP8.5-type outcomes could occur in the 22nd century, though not in the 21st. Regardless of what level of warming we feel is achievable in the 21st century, we still need to plan to ultimately bring emissions down to net-zero.

The 1.5ºC target is likely out of reach – but not the 2ºC one

Every year that global emissions remain close to current levels narrows the range of possible futures, making both high-end warming outcomes and low-end warming outcomes less likely. While technological development and climate policy has moved the world away from RCP8.5-type trajectories, delays in reducing global emissions have also put the 1.5ºC aspirational goal of the Paris Agreement increasingly out of reach.

Global surface temperatures in 2020 were between 1.2ºC and 1.4ºC above preindustrial levels, depending on the dataset used. While the 1.5ºC target is defined based on long-term average warming rather than any individual year (which are subject to short-term natural variability from El Niño events, for example), we still have a very small amount of additional warming allowable before the 1.5ºC target is reached.

The relationship between cumulative emissions and warming allows the creation of simplified "carbon budgets" that can inform us about the remaining allowable emissions under different climate targets. While the topic of carbon budgets is not without its controversies and uncertainties, budgets can be a useful tool.[56,57] Figure 13, below, shows a set of simplified emissions pathways for various proposed warming targets, in the absence of net-negative emissions (e.g. below-zero global emissions). It includes scenarios where the best estimate of future warming is either 1.5ºC or 2ºC (e.g. with a 50 percent chance), as well as scenarios that have a two-thirds (66 percent) chance of avoiding 1.5ºC or 2ºC warming based on uncertainties in climate sensitivity.

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[56] Peters, G. 2018. Beyond carbon budgets. *Nature Geosciences*. Available: https://www.nature.com/articles/s41561-018-0142-4
[57] Geden, O. 2018. Politically informed advice for climate action. *Nature Geosciences*. Available: https://www.nature.com/articles/s41561-018-0143-3

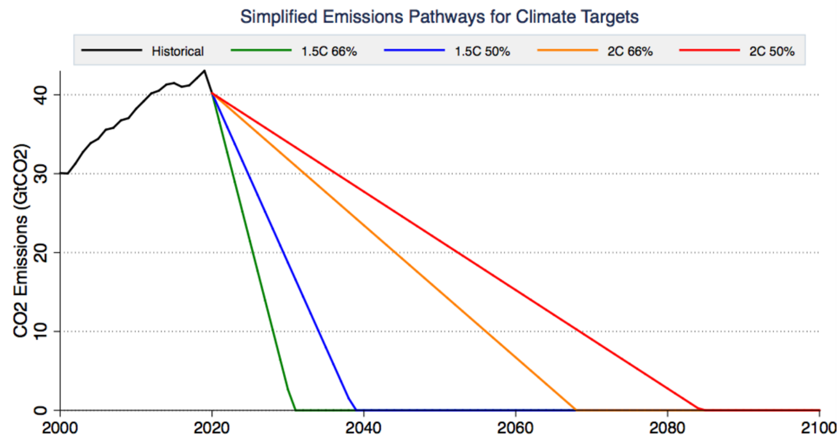

Figure 13. Simplified global emissions pathways associated with a 66% and 50% chance of limiting warming to 1.5ºC or 2ºC above preindustrial levels in the absence of net-negative global emissions. Historical emissions from the Global Carbon Project; cumulative carbon budgets for each scenario from the 2020 CONSTRAIN report.[58]

To limit warming to 1.5ºC would require getting all global emissions to zero by the year 2031 (for a 66 percent chance of avoiding 1.5ºC) or by 2039 (for a 50 percent chance). While it might be possible – in theory – for rich countries to get their emissions all the way down to zero in the next 10 to 20 years, this would come at a huge cost as large amounts of existing infrastructure (cars, furnaces in homes, industry, power plants, etc.) would have to be prematurely retired. It is unclear if we will have viable zero-carbon alternatives for aviation, industrial heat, and agriculture in that short a timeframe. It seems implausible that low and middle-income countries – whose near-term priorities are focused on poverty alleviation – would be willing to make the magnitude of sacrifices needed for such rapid near-term mitigation. The current commitments by countries to reach net-zero emissions by 2050 or 2060 are inconsistent with the 1.5ºC carbon budget.

In order to find possible pathways to 1.5ºC, energy system models trade more gradual near-term reductions in emissions for large-scale net-negative emissions later in the century. These scenarios have a more gradual target – say, net zero in the 2050s – coupled with planetary scale engineering late in the century to remove tens of gigatons of CO_2 from the atmosphere every year. To give a sense of the staggering scale of assumed negative emissions, some of these models devote an amount of land equal to the entire United States (including

[58]CONSTRAIN 2020. Zero in on a new generation of climate models, COVID-19, and the Paris Agreement. Available:
https://constrain-eu.org/wp-content/uploads/2020/12/Constrain-Report-2020-Final.pdf

Alaska and Hawaii) to bioenergy with carbon capture and storage – growing energy crops to absorb CO_2 from the atmosphere, turning them into useful energy, and capturing the CO_2 for underground storage.[59]

This is not to suggest that large-scale negative emissions technologies are not something we should pursue, just that planning to remove greater and greater amounts of CO_2 in the future with largely-unproven technology should not be used to justify temperature targets that would otherwise be much less plausible to achieve.

A world where temperatures are kept well-below 2ºC in line with Paris Agreement targets – e.g. where there is a 66 percent chance of avoiding more than 2ºC warming relative to preindustrial temperatures – without the use of net-negative emissions requires that global emissions reach zero in the late 2060s. This outcome is broadly consistent with the long term net-zero goals that have been adopted by countries. If global temperatures are limited to 2ºC with a 50 percent chance – rather than well-below 2ºC – the required global emissions pathway is more permissive, requiring the net-zero be reached by the mid-2080s in the absence of net-negative emissions.

While the 1.5ºC target has slipped out of reach as global emissions have failed to fall in the aftermath of the Paris Agreement – at least in the absence of remarkable breakthroughs in our ability to remove CO_2 from the atmosphere later in the century – a well-below 2ºC outcome seems a lot more plausible today than even a few years ago. The price declines in clean energy and the willingness of countries to commit to net-zero emissions targets are putting a world of only 2ºC warming within reach. However, actually achieving global net zero emissions in the next 50 to 60 years will require significant advances in technology as well as greater political will by countries than has been in evidence to date.

[59] For details on carbon budgets and the amount of negative emissions used in models, see Hausfather, Z., 2018. Analysis: Why the IPCC 1.5C report expanded the carbon budget. *Carbon Brief*. Available: https://www.carbonbrief.org/analysis-why-the-ipcc-1-5c-report-expanded-the-carbon-budget

A broad range of solutions

Some – but not all – of the technologies we need

There is a widespread view by some in the environmental community that we have all the technology we need to solve climate change today, and that all we lack is the political will to deploy it at the scale needed. It is true that many technologies that will play a key role in decarbonization – including variable renewable energy sources like wind and solar, as well as electric vehicles – are increasingly cost-competitive with fossil fuels.

At the same time, there is a real need for additional innovation, both in terms of clean firm generation and complementary technologies that will allow us to cost-effectively fully decarbonize the power sector,[60] and for parts of the economy like industrial heat, agriculture, and long-distance transportation where cost-effective alternatives to fossil fuels are not readily available.[61] Advocates of renewables or nuclear often treat them like a silver bullet to climate change, whereas in reality we need an all-of-the-above approach to decarbonization, recognizing that the most effective approaches will differ based on geographic location, resource availability, and may change over time as the costs of new technologies decrease.

Currently around a quarter of US greenhouse gas emissions comes from the power sector, a quarter comes from transportation, a quarter from industry, and the remaining quarter is split between commercial and residential building and agriculture.[62] We are making significant progress in the first two of these sectors – representing roughly half our emissions. As discussed earlier, coal use in the US has fallen in half over the past decade, replaced by lower-emission natural gas and renewable sources. In the transportation sector many automakers are putting massive investments behind electric light vehicles, and planning to phase out the sale of internal combustion engine light vehicles over the next two decades. While it may be a bit of a bubble, the fact that Tesla had a valuation equal to all the oil supermajors combined is a sign of what the market sees as the future of transportation.

Even in these sectors where solutions are cost-effective today, challenges remain. One consistent finding from the energy modeling community is that the lowest cost decarbonization pathways include a sizable amount of clean firm generation in addition to variable renewables. Variable renewables are predictably unreliable; their primary role today is as fuel-saving technologies that enable expensive-to-run gas and coal plants to curtail generation when the sun is shining and wind is plentiful. Energy system planners have to keep sufficient dispatchable

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[60] Sepulveda, N.A., et al. 2018. The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. *Joule*. Available: https://www.sciencedirect.com/science/article/pii/S2542435118303866

[61] Davis, S.J., et al. 2018. Net-zero emissions energy systems. *Science*. Available: https://science.sciencemag.org/content/360/6396/eaas9793

[62] US EPA. 2021. Sources of Greenhouse Gas Emissions. Available: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

resources in reserve for when variable renewable generation declines, and need to plan for the rare combination of extreme demand and low renewable resource availability, as we saw recently in Texas when extreme cold conditions coincided with low-wind conditions and low seasonal solar output (though in that case large amounts of firm capacity from natural gas, coal, and nuclear went offline unexpectedly).

Renewable generation varies both short-term and seasonally. Solar generation has a predictable daily and annual cycle, while wind conditions can vary both within and across days. There are also large differences in seasonal generation, with solar producing only half as much electricity in the winter than in the summer in areas like California. The variable nature of renewables makes them subject to a phenomenon called value deflation. Because they cannot be turned on and off when needed (e.g. are not dispatchable), it is quite possible to have more renewables than the grid can effectively use during periods of low demand and high generation. High mid-day generation from solar already causes electricity prices to drop closer to zero (or even go negative) in California in the Spring and Fall months; Texas similarly sees increasingly common negative electricity prices from high wind generation.

This value deflation means that the value of a renewable resource tends to decrease the more is installed on the grid, particularly at higher levels of installation; we already see this in California, where solar represents around 20 percent of total state-wide electricity generation, and is about 35 percent less valuable today compared to other sources of electricity than it was in 2014.[63] Value deflation to-date has been largely countered by continued decline in solar PV module costs, though if cost declines will win the race against value deflation over the longer term remains an open question.[64]

While value deflation – and day-to-day variability – can be mitigated in part by investments in complementary technologies like energy storage, long distance transmission, and demand response, seasonal variations in renewable generation represent a larger challenge to high variable renewable electricity systems. Seasonal energy storage is currently extremely costly, given the need to have batteries or other storage technologies sitting idle for much of the year until needed during winter periods when renewable generation is lower. Here clean firm generation can play a critical role; technologies like advanced nuclear, gas with carbon capture and storage, and next-generation geothermal are all able to reliably provide firm, dispatchable generation but are largely not cost-competitive today.

Currently the US has an energy technology that is widely deployed and provides a good complement to variable renewable energy: natural gas. Gas turbines tend to have low capital costs and high operational costs; they are well suited to reduce generation when large amounts of renewable energy is available and electricity costs are low, and ramp up generation when renewable generation is lower and electricity costs are high. However, we need to be cognizant

[63] Based on a soon-to-be-published analysis of the differences between solar and non-solar hourly energy prices in CAISO between 2014 and 2020. Data available here: http://oasis.caiso.com/mrioasis/logon.do
[64] Sivaram, V., & Kann, S. (2016). Solar power needs a more ambitious cost target. Nature Energy, 1(4), 16036. https://doi.org/10.1038/nenergy.2016.36

that high renewable systems will put more pressure on thermal generators; ramping up only when needed creates a higher likelihood of failure than near-constant operation, and we need to have redundancies in place to avoid blackouts when some thermal generators fail.

Natural gas is also still a significant source of emissions, albeit one that is only about half the CO_2 per unit of electricity generated than coal – and is still better than coal even when fugitive methane emissions are taken into account.[65] But “better than coal” is a distinctly low bar when it comes to fully decarbonizing the power sector; while gas will likely serve as a key element to enable accelerated variable renewable energy deployment over the next two decades, new technological advances are needed to fully replace its role in a decarbonized power system.

Nuclear currently provides around 20 percent of US electricity generation. These existing power plants are fully paid off, and represent relatively low cost firm clean generation. Unfortunately, a combination of cheap natural gas and the absence of subsidies to reflect the benefits of their low-carbon generation has put a sizable portion of the US nuclear fleet at risk of premature retirement. Around 38 TWh of nuclear generation has already been retired in recent years, with another 90 TWh scheduled to retire. An additional 135 TWh of nuclear is at risk of premature retirement, primarily due to competition from cheap natural gas.[66] To put these numbers in perspective, the amount of nuclear scheduled to retire is roughly equal to all the US solar power generated in 2018. The amount either scheduled to retire or at risk of retirement is equal to two thirds of current US wind generation. Decarbonizing the US power sector will be difficult enough without losing a sizable portion of our existing clean energy generation, and one of our only sources of clean firm generation.

In the transportation sector it seems increasingly clear that electric vehicles will be the dominant future technology for both light and medium-duty vehicles. There are still challenges, however, in electrifying heavy duty freight, and relatively few options for electrifying long-distance shipping or aviation. It is likely that some combination of electrification, biofuels, synfuels from captured carbon, and hydrogen will ultimately replace fossil fuels for these applications, but substantial additional RD&D efforts are needed before these technologies can be deployed at scale.

In the industrial sector, a sizable portion of energy use comes in the form of heat. Industrial heat is used in making concrete, steel, glass, ammonia, and many other products.[67] While electric heating is increasingly cost-effective for buildings, reaching temperatures in excess of thousands of degrees Fahrenheit using electricity is prohibitively costly. Options for industrial heat decarbonization include direct combustion of natural gas with carbon capture, use of hydrogen produced from natural gas with carbon capture of from clean energy sources such as

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[65] Hausfather, Z. 2015. Bounding the climate viability of natural gas as a bridge fuel to displace coal. *Energy Policy*. Available: https://www.sciencedirect.com/science/article/abs/pii/S0301421515300239
[66] Hausfather, Z. 2018. Mapped: The US nuclear power plants ‘at risk’ of shutting down. *Carbon Brief*. Available: https://www.carbonbrief.org/mapped-the-us-nuclear-power-plants-at-risk-of-shutting-down
[67] Friedman, J., et al. 2019. Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today. Available: https://www.energypolicy.columbia.edu/research/report/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today

nuclear or renewables, biomass, or high-temperature small and modular nuclear reactors. Again, significant additional technological advancements are required to bring down the costs of these technologies to make them cost-competitive with current fossil fuel usage for industrial heat.

In the residential and commercial sectors, most of the non-electricity usage comes in the form of space and water heating (gas ranges and ovens are a relatively minor end-use). Heat pumps can serve as a cost-effective way to electricity building heating, though there are still some challenges to cost-effectively using heat pumps in cold climates, and additional RD&D efforts are working toward improving the technology at the same time that further deployment is driving down costs.

Agriculture will be one of the most challenging sectors to fully decarbonize. While ammonia production for fertilizers without emissions is possible, it requires both high temperatures and a ready source of hydrogen. Current production is largely from natural gas, though other sources of hydrogen can also be used. Emissions from ruminants (e.g. methane from cows) will be a particularly difficult source to decarbonize. While plant-based meat alternatives are gaining market share and numerous companies are working on cell-based meat alternatives (e.g. lab-grown steaks), the technologies are still fairly early-stage. Much of the environmental impact of agriculture is associated with land use; when forested areas are turned into fields a lot of CO_2 is released. Intensive agriculture – producing more food on less land – can be an important tool to reduce impacts and free up areas for reforestation.[68]

We will likely also need at least some carbon removal technology – such as afforestation/reforestation, direct air capture or bioenergy with carbon capture and storage – to remove excess CO_2 from the atmosphere. There may well be some hard-to-decarbonize sectors, such as aviation, where it will prove more cost-effective to offset emissions through capturing CO_2, at least in the near-to-medium term. CO_2 removal is not a replacement for emissions reductions writ large, but could play a role in some cases if costs can be reduced to lower levels than are possible are present.

The next decade will be critical to reach the US's decarbonization goals, both to accelerate the deployment of existing clean energy technologies and heavily invest in RD&D for maturing and improving a range of technologies that will be needed longer-term — such as advanced nuclear, gas with carbon capture and storage, enhanced geothermal, blue/green hydrogen, and direct air capture.

Private sector forces and innovation have gone a long way toward making deep decarbonization plausible. But the private sector cannot achieve this alone. Government energy RD&D spending has historically played a critical role in bringing energy technologies to the market, from solar panels to hydraulic fracturing to the diamond drill bits now enabling enhanced geothermal

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[68] Nordhaus, T. 2018. No Sustainability Without Intensification. *The Breakthrough Institute*. Available: https://thebreakthrough.org/issues/food/no-sustainability-without-intensification

power.[69] Well-designed government policies are needed to accelerate smart deployment of wind and solar energy, drive zero-carbon technology innovation, and ensure the needed cuts in emissions.

In December, Congress passed a sweeping bipartisan spending package that authorizes billions of dollars for investments in clean energy, vital energy R&D, grid modernization, energy efficiency, and phasing down superwarming hydrofluorocarbons.[70] This represents perhaps the single most impactful congressional bill to-date that accelerates the energy transition and mitigates greenhouse gas emissions. It shows the potential for "quiet climate policy" – bipartisan energy solutions that both reduce emissions and create jobs.

In the current legislative session there are opportunities for cooperation on further energy innovation funding, grid modernization and interconnection, EV charging infrastructure, and agricultural innovation, as we propose in a newly released report: Saying the Quiet Part Out Loud: Quiet Climate Policy in a Post-Covid World.[71] Longer-term, it may make sense to phase out federal subsidies for mature clean energy technologies such as wind and solar in exchange for a technology-neutral mitigation policy like a clean electricity standard.[72]

Statements that "we have the technology we need and just need to build it" get it half right — we do need to build clean energy much more quickly than we are today. But we will need continued innovation and investment in supporting technologies like long-distance transmission and storage in addition to this multi-decade buildout of existing clean energy technologies. Clean energy policy is not zero-sum. Keeping this in mind as the US designs energy policy and debates the merits of various decarbonization options will help ensure we pursue more cost-effective and socially-acceptable pathways going forward.

What we can learn from decarbonization scenarios

The future of the energy system is difficult to foresee perfectly, and history is a graveyard of failed energy model predictions. All models are wrong, as the saying goes, but some are useful. A slew of new net-zero studies have been published in recent months, including Princeton's Net Zero America (NZA) project,[73] the Vibrant Clean Energy Zero By Fifty scenario,[74] and by a team

[69] Jenkins, J., et al., 2010. Where Good Technologies Come From. The Breakthrough Institute. Available: https://thebreakthrough.org/articles/american-innovation
[70] Larson, J., et al. 2020. Climate Progress in the Year-End Stimulus. *Rhodium Group*. https://rhg.com/research/climate-progress-in-the-year-end-stimulus/
[71] Blaustein-Rejto, D., et al. 2021. Saying the Quiet Part Out Loud: Quiet Climate Policy in a Post-Covid World. *The Breakthrough Institute*. Available: https://thebreakthrough.org/articles/press-release-qcp
[72] Trembath, A., et al. 2020. Reforming Federal Policy to Support Innovation and Clean Energy in the U.S. Power Sector. *The Breakthrough Institute*. Available: https://thebreakthrough.org/articles/renewables-grid-memo
[73] Larson, E., et al., 2021. Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Princeton University. Available: https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/
[74] Vibrant Clean Energy. 2021. Insights from Modeling the Decarbonization of the United States Economy by 2050. Initial results; available: https://vibrantcleanenergy.com/wp-content/uploads/2021/01/VCE-UCSD-01272021.pdf

of researchers led by Jim Williams at USF.[75] All three of these take a deep-dive into how the US could reach net-zero emissions by 2050, down to the level of where each new generating facility might be located, where new transmission lines would be built, and how electricity generation sources can meet hourly grid demand in different regions of the country.

Figure 14, below, shows the current 2020 US electricity generation mix, as well as the projected generation mix in 2030, 2040, and 2050 across each of the three models.

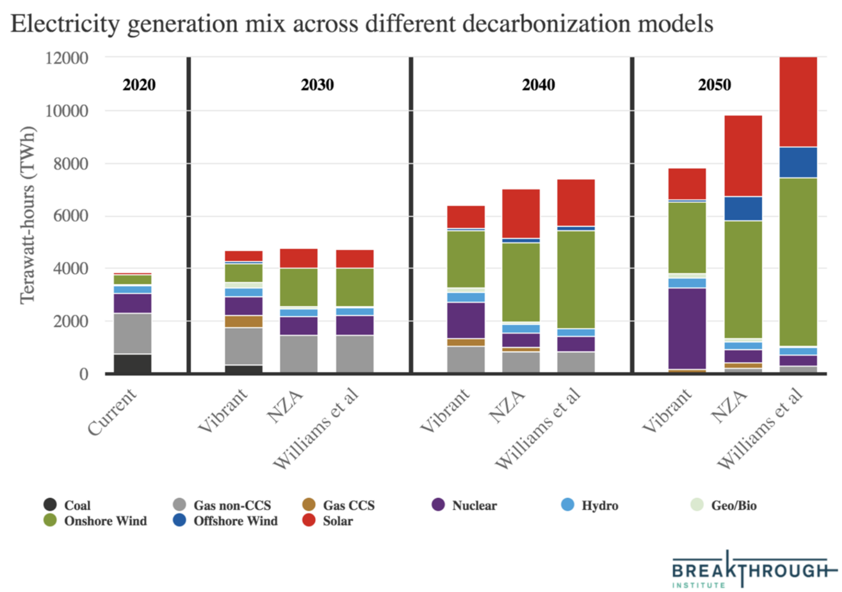


Figure 14. Annual US electricity generation (in TWh) in the initial year of each decade. 2020 values from the February 2021 EIA Short Term Energy Outlook. 2030, 2040, and 2050 values from the respective Vibrant, NZA, and Williams et al. scenarios examined. Note that CCS in the legend refers to carbon capture.

While the models differ in important ways, they all paint a broadly similar picture:

- Overall energy use increases to double or triple currently levels as other sectors of the economy such as transportation and building heating electrify.
- Wind and solar expand rapidly in the next three decades, accounting for between 51% and 91% of US electricity generation in 2050 across the three models.
- US coal use falls off a cliff, reaching zero by 2030 or 2035.

[75] Williams, J.H., et al. 2021. Carbon-Neutral Pathways for the United States. AGU Advances. Available: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284

- Natural gas use stays rather flat — or even increases modestly — between 2020 and 2030, as it serves a key role in filling in the gaps in variable renewable generation. Gas capacity actually increases in two of the three decarbonization models through 2050, though capacity factors — how often the gas plants are run — fall rapidly, and gas increasingly becomes a blend of hydrogen and methane closer to 2050.
- Existing nuclear reactors are kept online as long as possible, and in one of the three models is eventually replaced by advanced nuclear in the form of small and modular reactors and larger molten salt reactors. In the Vibrant model nuclear provides more electricity generation than any other energy source by 2050.
- All three scenarios also feature large-scale expansion of transmission, energy storage, and demand management to help support higher levels of intermittent generation. They demonstrate that the supporting technologies around renewable energy are in many ways just as important as the renewable energy itself.
- Carbon capture and CO_2 removal technologies all play a big role in these models' scenarios – albeit in different ways.

The difference between the trajectories of coal and gas in these decarbonization models is particularly notable. Figure 15, below, shows both coal use (solid lines) and the natural gas (dashed lines; excluding CCS) over time across the three models.

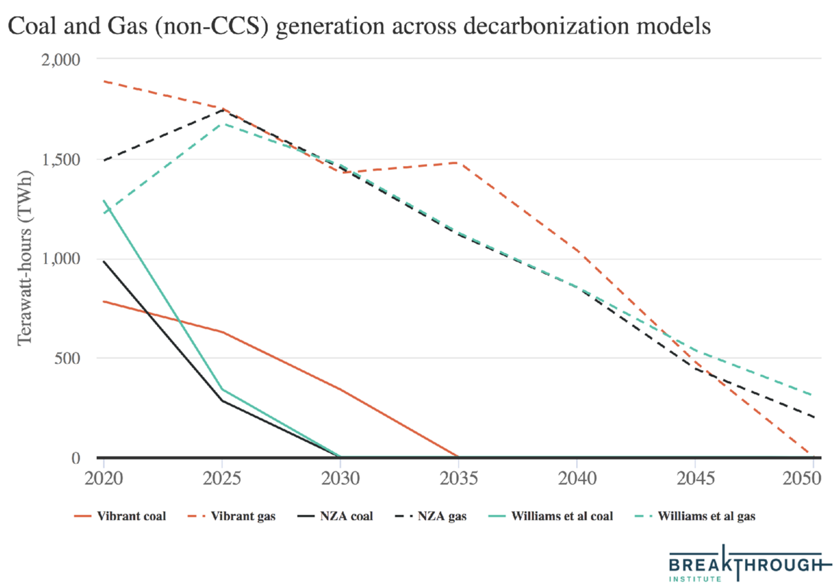


Figure 15. Annual US electricity generation (in TWh) by year from coal and natural gas (excluding carbon capture) in the Vibrant, NZA, and Williams et al. scenarios examined. Note that none of the scenarios include any meaningful coal use with carbon capture.

US coal generation falls dramatically from current levels, reaching zero between 2030 and 2035. Natural gas generation, by contrast, stays close to today's levels through 2030 and remains around 50% below current levels by 2040. It is only by 2050 that gas without carbon capture is mostly gone in the models. Modest amounts of gas with carbon capture is also used in two of the three models (Vibrant and NZA).

High natural gas capacity plays an important role in all three models to fill in the gaps in variable renewable generation as more wind and solar energy are installed on the grid. In the longer term, transmission expansion, storage, and development of alternative clean firm generation sources result in falling capacity factors, as gas increasingly operates as a peaking resource, reserved for either periods of exceptional demand or long periods of abnormally low variable renewable generation.

Current technologies can get us a long way toward power sector decarbonization, but if we ever want to fully decarbonize — and move away from our reliance on natural gas — we need technologies such as grid-scale storage, advanced nuclear, gas with CCS, or hydrogen that are not mature today. We need to both accelerate the deployment of current cost-effective clean energy resources and invest considerably more in future technologies that will simultaneously lower system costs and enable deep decarbonization. As the NZA report argues, "the 2020s is the decade to invest in maturing and improving a range of technologies that improve options for the long term."

These decarbonization models give us a sense of what may be needed. We should not fixate too much on the specific generation mixes in any particular scenario, but we should take heed of where the models agree: on the importance of near-term renewables deployment, the medium-term role of gas capacity to fill in the gaps, and the importance of clean firm generation and complementary technologies to wean the power system off its dependence on natural gas in the longer term.

Stranded assets in a post peak-oil future

A rapid transition is occurring in the world's automotive industry. Electric vehicles are rapidly approaching cost-parity with conventional internal combustion engine vehicles. Major automakers are committing to invest many tens of billions in electric vehicle manufacturing over the next decade, and General Motors recently announced that it will phase out all internal combustion vehicles after 2035.[76] This is not only a US phenomenon, with electric vehicle sales

[76] Boudette, N.E., and Davenport, C. 2021. G.M. Will Sell Only Zero-Emission Vehicles by 2035. *New York Times*. January 21st. Available: https://www.nytimes.com/2021/01/28/business/gm-zero-emission-vehicles.html

accelerating rapidly in both Europe and China. Due in large part to this trend – but also other broader market forces – many groups including BP, Equinor, Rystad, and Bernstein Energy project that global oil production has either already peaked or will peak in the next decade.[77] While fears of peak oil in the past inaccurately worried about running out of low-cost production, we are now faced with a very different – and more plausible – scenario: peak oil driven by declining global demand.

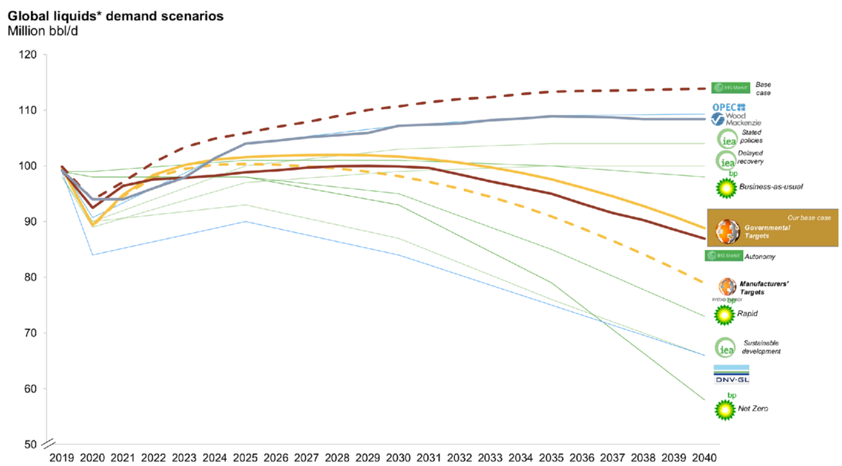


Figure 16: Projections of global oil demand between 2020 and 2040. From a Rystad Energy analysis undertaken for The Breakthrough Institute.

Even in the absence of strong additional climate policy, it is unlikely that US oil producing regions will be able to develop all of their resources. The US has substantially higher oil production costs than the Middle East, which would be favored in a demand constrained world. In a scenario where automakers meet their stated EV targets, a Rystad Energy analysis undertaken for The Breakthrough Institute finds that 32% of total US oil resources would be uneconomic to produce. Some parts of the US with higher oil production costs will be even harder hit; in Colorado and California about half of resources would be uneconomic to produce, while in North Dakota, Alaska, and Oklahoma it would be roughly a third of resources.

[77] Reuters. 2020. Pandemic brings forward predictions for peak oil demand. November 27th. Available: https://www.reuters.com/article/us-oil-demand-factbox/factbox-pandemic-brings-forward-predictions-for-peak-oil-demand-idUSKBN2870NY

Figure 17: Portion of oil resources that could be cost-effectively developed in a scenario with limited new climate policy but where stated auto manufacturer EV targets are met. From a Rystad Energy analysis undertaken for The Breakthrough Institute.

Many regions whose economies depend on oil production today may be left behind in a world of rapidly expanding electric vehicle sales, regardless of any congressional action to tackle climate change. It is important that these regions plan ahead to a world of lower future oil demand. Diversifying local economies is a smart hedge given real uncertainties around the extent to which oil demand is coming back – and how robustly. Coal country can serve as a cautionary tale here; the fact that coal use has fallen by more than 50 percent in just a decade shows just how fast things can change when driven by technological progress.

Dr. Zeke Hausfather

Dr. Zeke Hausfather is the Director of Climate and Energy at the Breakthrough Institute, an environmental think tank located in Oakland, California. He also serves as a research scientist at Berkeley Earth and a contributor to Carbon Brief, and is a contributing author to the upcoming Intergovernmental Panel on Climate Change 6th Assessment Report. He received his PhD from the Energy and Resources Group at the University of California, Berkeley. He previously spent 10 years working as a data scientist and entrepreneur, serving as the lead data scientist at Essess, the chief scientist of C3.ai, and the cofounder and chief scientist of Efficiency 2.0. His research focuses on observational temperature records, climate models, and mitigation technologies.

Chairwoman JOHNSON Thank you very much. We'll now hear from Dr. Diffenbaugh.

TESTIMONY OF DR. NOAH S. DIFFENBAUGH, KARA J. FOUNDATION PROFESSOR, DEPARTMENT OF EARTH SYSTEM SCIENCE, KIMMELMAN FAMILY SENIOR FELLOW, WOODS INSTITUTE FOR THE ENVIRONMENT, STANFORD UNIVERSITY

Dr. DIFFENBAUGH. Thank you, Chairwoman Johnson, and Ranking Member Lucas, for the invitation. My name is Noah Diffenbaugh. I'm a professor and senior fellow at Stanford University, but I'm appearing in my personal capacity. I'll focus on the topics noted in your invitation.

A brief summary is that global warming is causing extreme events to increase, including unprecedented events, we are not adapted to these changes, meaning that global warming is already impacting people and ecosystems, the greater the global warming in the future, the more these risks will intensify, achieving the Paris agreement goals will reduce intensification of these risks, however, even if those goals are achieved, there will still be more climate change than has already occurred, meaning that adaptation will be necessary to avoid further impact. And, finally, research is needed to develop and deploy the scale of mitigation and adaptation solutions that are necessary to curb the intensification of these risks.

Disasters are ultimately the function of the difference between the magnitude of the hazard and the level of preparation. The rising risk of extremes, including heat, rainfall, flooding, drought, wildfire conditions is causing the climate envelope around which so many of our systems have been designed, built, and operated to be exceeded with increasing regularity, from our disaster management systems, to our electrical grids, to our water and transportation infrastructure. This past year, while the western U.S. was in the midst of its most severe wildfire season in recorded history, the Atlantic had a record-breaking hurricane season. In both cases there are multiple lines of evidence linking historical global warming to elevated risk of extreme conditions, including increased probability of extreme wildfire weather, and of extreme precipitation and storm surge flood from landfalling storms. And these are just two of the most recent examples.

In the absence of adaptation, we can expect more big disasters to happen in more places more often, with poor and marginalized communities experiencing the greatest vulnerability. And this is already costing us. My research group recently documented that historical changes in precipitation account for approximately 1/3 of the cumulative flood damages in the U.S. in the past 3 decades. Similar methods suggest that historical warming has cost the U.S. economy approximately $5 trillion in aggregate growth within the past 2 decades. These economic impacts are likely to accelerate at higher levels of warming, with the poorest counties being harmed around twice as much as the richest counties.

Fortunately, there are options. Extreme climate conditions will intensify less at 1–1/2 or 2 degrees C than at 3 or 4 degrees C.

These lower levels of warming are also very likely to reduce the level of impact on the economy, on our food and water systems, and on human and ecosystem health. There is thus substantial benefit to achieving the Paris agreement goals. In addition, many of the mechanisms that we have for reducing emissions can also increase resilience to climate stresses, by providing critical energy resources to communities whose well-being has been hampered by energy poverty or pollution, and by increasing the resilience of the energy system overall. We can also increase resilience by investing in marginalized communities, which we know are both more vulnerable and more exposed to climate stresses. And, carefully considering how and where we build, and how we preserve and manage ecosystems as we meet the growing need for fair and equitable housing and livelihood is important for managing a range of climate risks, including wildfires in the West, hurricanes in the Southeast, and floods in the Midwest.

In your invitation letter you asked me to identify recommendations for additional investments in climate science. Given what I've described, successfully managing the risks of climate change will require acceleration of both mitigation and adaptation. We have sufficient understanding to begin that acceleration. And, given the scale of solutions that are necessary, additional research is also needed. A cohesive research agenda that integrates mitigation and adaptation in support of a climate resilient nation would include the following themes. Improved observational and modeling capacity for predicting extreme events across scale, R&D for the technologies and deployment necessary to transition to a secure, reliable, equitable, net zero emissions energy system, improved understanding of the climate impact of overshooting the Paris agreement goals, R&D for development, implementation, and deployment of adaptation approaches across a variety of geographic, climatic, and socioeconomic contexts, new methodologies and division support for updating our infrastructure and disaster risk management to accommodate the growing likelihood that multiple unprecedented events occur simultaneously, and improved understanding of how to generate synergies between mitigation, adaptation, and other policy priorities, like economic growth, job creation, environmental conservation, and economic, racial, and environmental justice.

I applaud the Committee for working on these critical issues, and I look forward to your questions.

[The prepared statement of Dr. Diffenbaugh follows:]

Written Testimony of Dr. Noah S. Diffenbaugh

Hearing on "The Science Behind Impacts of the Climate Crisis"
March 12, 2021

Congress of the United States
House of Representatives
Committee on Science, Space, and Technology

Thank you Chairwoman Johnson, Ranking Member Lucas, and the members of the Committee for the invitation to testify.

My name is Noah S. Diffenbaugh. I am the Kara J Foundation Professor in the School of Earth, Energy and Environmental Sciences at Stanford University, and the Kimmelman Family Senior Fellow at Stanford's Woods Institute for the Environment. I am testifying before the committee in my personal capacity, not on behalf of Stanford University.

I study Earth's climate, including how changes in regional and local conditions – such as extreme weather events – affect people and ecosystems. I received my Ph.D. degree from the University of California–Santa Cruz in 2003. I am an elected Fellow of the American Geophysical Union (AGU), the largest scientific society of Earth and space sciences in the world. For more than a decade, I have served as an Editor of peer-review journals published by the AGU, including a four-year term as Editor-in-Chief of *Geophysical Research Letters*, one of the leading peer-review journals publishing climate science research. I have been a lead author for a number of scientific assessments, including the IPCC Fifth Assessment Report and the California Climate-Safe Infrastructure Working Group.

The subject of this hearing of the Committee on Science, Space, and Technology is "The Science Behind Impacts of the Climate Crisis". I will focus my remarks on the topics noted in your invitation letter, including recent improvements in our understanding of how climate change is contributing to increased risk from extreme events such as wildfire, drought, and severe storms; the disproportionate impacts on vulnerable communities; the importance of quantifying climate impacts and risk for achieving Paris Agreement targets; and the implications for mitigation and adaptation solutions.

The brief summary is that:

(i) Extreme events are increasing in frequency and severity, including those that are unprecedented in our historical experience;

(ii) We are not adapted to these changes, meaning that global warming is already impacting people and ecosystems in the United States and around the world, including through financial costs, loss of life and destruction of habitat, with disproportionate impacts on poor and marginalized communities;

(iii) The greater the global warming that occurs in the future, the more these risks will intensify, including non-linear intensification of many impacts;

(iv) As a result, achieving the Paris Agreement global warming goals will reduce the impacts that we experience, including reducing the financial costs of further climate change;

(v) However, even if the Paris Agreement global warming goals are achieved, there will still be more climate change than has already occurred, and hence adaptation will be necessary to avoid further impacts; and

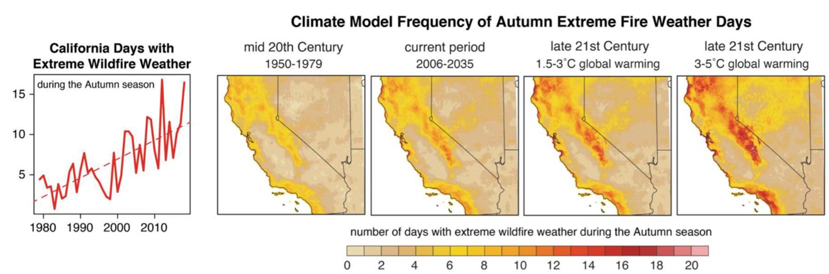
(vi) Research is needed to successfully develop and deploy the mitigation and adaptation solutions that are necessary to curb the intensification of climate extremes and the associated impacts on people and ecosystems.

We now have ample evidence that global warming has increased the risk of many kinds of climate and weather extremes (e.g., [*NAS*, 2016]), including extreme heat, heavy rainfall, storm-surge flooding, severe drought, and extreme wildfire conditions. And by increasing the frequency of extremes in multiple locations, climate change is increasing the odds that multiple extremes happen simultaneously, which is increasing the odds that our infrastructure and disaster management systems are stretched past their limit.

The last year has brought these accelerating risks into stark relief. While it has felt like an unrelenting string of bad luck, this is the world that global warming has created: a world in which more extreme conditions happen simultaneously, both on top of each other in a given location, and at the same time in different parts of the country and the world. And when an additional, unrelated disruption occurs – like a global respiratory pandemic – it is now much more likely to coincide with extreme climate conditions, ratcheting up the stress on our disaster response systems.

This is exactly what happened in California this summer: a dry winter was followed by a very warm spring that caused rapid snowmelt, which was followed by a record summer heat wave, leading to record- or near-record fuel loads. The heat wave was unusually humid, which led to a very unusual lightning siege, which caused hundreds of wildfires. Having so many fires burning in such flammable conditions simultaneously stretched the firefighting resources beyond their limit, resulting in more than 1 million acres burned in less than two weeks, and more than 4 million acres burned for the season, including five of the six largest wildfires in California's recorded history.

There are now multiple lines of evidence that global warming has increased wildfire

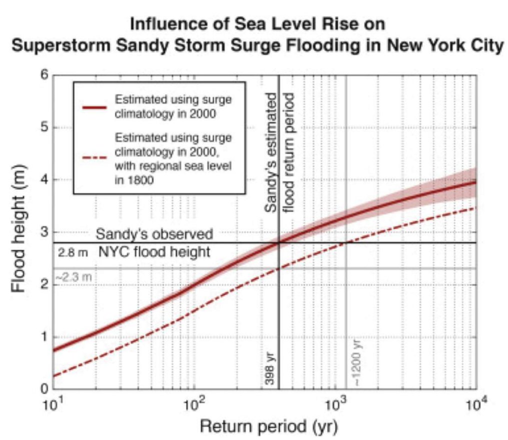


Adapted from Goss et al. (2020)

risk in California and the American West. Previous work has shown that the annual area burned has increased approximately 10-fold in the West over the past 4 decades [*Duffy et al.*, 2019], and that rising temperatures have increased fuel loads, contributing around half of the increase in area burned [*Abatzoglou and Williams*, 2016]. This effect has also been prominent in California [*Williams et al.*, 2019]. In addition, this summer my colleagues and I published a paper showing that the frequency of extreme wildfire weather has more than doubled in California during the autumn season [*Goss et al.*, 2020]. Critically, we find that global warming is increasing the risk that periods of extreme wildfire weather overlap across far-flung regions of the state.

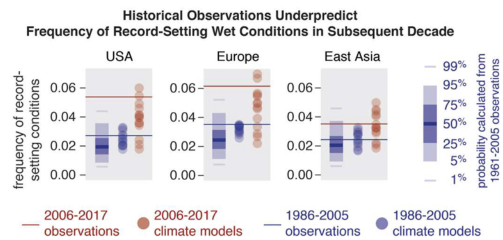
Given limited resources, many of our disaster response systems are designed to pre-stage resources in areas that are likely to experience disasters, meaning that those systems become stressed – sometimes beyond the breaking point – when multiple events occur simultaneously. And because the increasing co-occurrence of extreme events is a global phenomenon, it is creating novel challenges for our globalized economy, including our globalized risk management systems. This was made starkly clear in late 2019, when autumn wildfires in California overlapped with spring fires in Australia, stressing the limited aircraft and other resources that normally move between the hemispheres during the seasonal transition. In addition, that same combination of warm and dry conditions that increases wildfire risk has other impacts, including on our food system. Several studies, including from my research group, have shown that "bread basket" regions that are responsible for the majority of the world's grain production are now much more likely to experience adverse growing conditions in the same year, compared with just a few decades ago [*Sarhadi et al.*, 2018].

Recent hurricane seasons have put similar stresses on our disaster preparation and response systems. In 2017, Hurricane Harvey's record rainfall produced one of the most expensive disasters in U.S. history. In addition, with multiple hurricanes striking the U.S. and Caribbean, there were too many landfalls for ships to transport supplies to all affected areas fast enough. The 2020 Atlantic hurricane season was even more active, with more named storms than any previous year in recorded history, and some areas – including Louisiana and Guatemala – experiencing multiple landfalls in rapid succession.



Swain et al. (2020) [adapted from Lin et al., 2016]

While there is still uncertainty about exactly how global warming influences the number of hurricanes, we know that the warming of the ocean increases the energy available for storms (e.g., [*Emanuel*, 2005; *Trenberth et al.*, 2018]). We also know that the warming of the atmosphere has increased the likelihood that hurricanes produce extreme precipitation, like occurred during Hurricane Harvey (e.g. [*Emanuel*, 2017; *Trenberth et al.*, 2018]) and Hurricane Florence in 2018 [*Reed et al.*, 2020]. And we know that the sea level rise that has already occurred has increased the risk of extreme storm surge flooding, like what occurred in New York City during Superstorm Sandy in 2012 [*Lin et al.*, 2016], and this season along the Gulf Coast when storms rapidly intensified before making landfall.



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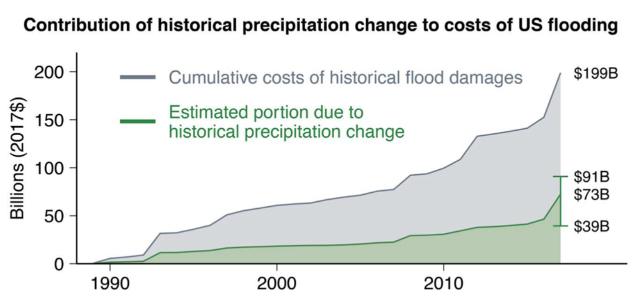
Disasters are ultimately a function of the difference between the magnitude of the hazard and the level of preparation [*IPCC*, 2012]. We have now crossed the threshold where the climate envelope for which so many of our systems have been designed, built and operated is exceeded with increasing frequency [*Diffenbaugh*, 2020] – from our disaster management systems, to our electrical grids, to our water and transportation infrastructure. Crossing that threshold means that we're now living in a world where our status quo risk management systems are inadequate. And as a consequence, in the absence of adaptation, we can expect more big disasters to happen in more places more often, with poor and marginalized communities experiencing the greatest vulnerability.

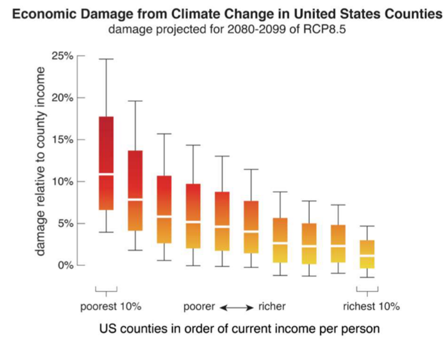
Recent research shows that this is already costing us financially. In January, my research group published a paper documenting that historical changes in precipitation – particularly intensification of the extreme wet events – account for approximately one third of the cumulative flood damages in the U.S. over the past three decades [*Davenport et al.*, 2021]. Using similar research methods to analyze the impact of temperature variations on aggregate economic activity, colleagues have estimated that historical warming has cost the U.S. economy approximately 5 trillion dollars within the past two decades [*Burke and Tanutama*, 2019]. These economic impacts are likely to accelerate in the U.S. at higher levels of global warming, with the poorest counties being harmed



Adapted from Davenport et al. (2021)

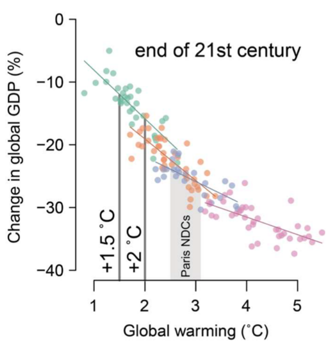
around twice as much as the richest counties, exacerbating existing economic inequality [*Hsiang et al.*, 2017; *Duffy et al.*, 2019].

These impacts on economic inequality are not confined to the United States. For example, my collaborator and I have documented that country-level economic inequality is approximately 25% greater today than in a counterfactual world in which historical global warming had not occurred [*Diffenbaugh and Burke*, 2019]. The strongest contributor has been the accumulated effects of diminished GDP growth in countries that are already warm, including our neighbors in Central and South America.



Duffy et al. (2019) [adapted from Hsiang et al., 2017]

Fortunately, there are options. Over the long-term, achieving the Paris Agreement goal of holding global warming below 2˚C will substantially curb the intensification of these impacts. For example, we have evidence that the frequency of extreme conditions such as extreme heat, extreme precipitation, extreme storm surge flooding and extreme wildfire weather will increase less at 1.5 or 2˚C than at 3 or 4˚C (e.g., [*IPCC*, 2014; *Diffenbaugh et al.*, 2018; *Sarhadi et al.*, 2018; *Allen et al.*, 2019; *Goss et al.*, 2020; *Davenport et al.*, 2021]). Likewise, in addition to substantially reducing the level of global economic damages [*Burke et al.*, 2018], the Paris Agreement goals are also very likely to reduce the magnitude of economic damage in the poorest countries [*Burke et al.*, 2018], and in the poorest U.S. counties (e.g., as in [*Burke and Tanutama*, 2019; *Duffy et al.*, 2019]).



Adapted from Burke et al. (2018)

Therefore, in terms of reducing the risks of high-impact climate change, there is substantial benefit to achieving the Paris Agreement goals. Further, in addition to curbing the severity of climate change, many of the mechanisms that we have for reducing emissions can also increase resilience to climate stresses by providing critical energy resources to communities whose development and well-being have been hampered by energy poverty and/or pollution, and by increasing the resilience of the energy system overall. We also have opportunities to increase resilience by investing in marginalized communities, which we know are both more vulnerable and more exposed to climate extremes. And carefully considering how and where we build – and how we preserve and manage ecosystems – as we provide for growing needs for fair and equitable housing and livelihoods is important for managing a range of climate risks, including wildfires in the West, hurricanes in the Southeast, and floods in the Midwest. And, in addition to all of these "win-win" opportunities, avoiding frequent, widespread, devastating disasters will require re-designing our infrastructure and disaster risk management around the growing likelihood that multiple unprecedented events occur simultaneously – locally, regionally and around the world.

How can we do this? In your invitation letter, you asked me to "Please include any research gaps or recommendations of additional investments in climate science that the Committee should address." Given the unprecedented climate events that we are already facing, and the high confidence that further warming will lead to further intensification of those unprecedented conditions, the reality is that successfully managing the risks of climate change – including both the unequal impacts across society and the costs born by all Americans – will require acceleration of both mitigation and adaptation actions. We have sufficient understanding to begin that acceleration.

In addition, in order to achieve the level of mitigation that is necessary to stabilize the climate system and the level of adaptation that is necessary to respond to the further climate change that will occur, additional research is needed. In particular, a cohesive research agenda that integrates mitigation and adaptation in support of a climate-resilient nation would include the following six themes:

(i) improved observational and modeling capacity for predicting extreme events across weekly, seasonal and decadal timescales;

(ii) R&D for both the technologies and large-scale deployment necessary to transition to a secure, reliable, equitable net-zero-emissions energy system;

(iii) improved understanding of the climate impacts of "overshooting" the Paris Agreement goals, as well as the options for – and risks of – negative emissions technologies;

(iv) R&D for development, implementation and deployment of adaptation approaches across a variety of geographic, climatic and socioeconomic contexts;

(v) information, methodologies and decision support for updating the design guidelines and operational practices for our local, state and national infrastructure to be resilient in the current and future climate; and

(vi) improved understanding of how to generate synergies between mitigation, adaptation and other policy priorities such as economic growth, job creation, environmental conservation, and economic, racial and environmental justice.

In addition, the pandemic has revealed many limitations in our real-time observing systems, including critical Earth system elements such as real-time measurements of greenhouse gas emissions and the vertical structure of air pollutants in the atmosphere, as well as real-time measurements of human elements that are critical for the Earth system, such as real-time measurements of economic activity and its consequences [*Diffenbaugh et al.*, 2020].

As recent events have made painfully clear, climate change is already impacting us. Decades of objective, thorough, systematic research show that we can expect those impacts to intensify as long as global warming continues. Addressing this challenge will require both mitigation and adaptation, including the research necessary to make each of those possible.

I applaud the Committee for working on these critical issues, and thank you for the opportunity to provide this testimony. I look forward to discussing any questions that you may have.

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Brief Narrative Biography, Noah S. Diffenbaugh

Dr. Noah S. Diffenbaugh is the Kara J Foundation Professor in the School of Earth, Energy and Environmental Sciences at Stanford University and Kimmelman Family Senior Fellow at Stanford's Woods Institute for the Environment. His research interests are centered on the dynamics and impacts of climate variability and change, including the role of humans as a coupled component of the climate system. Much of his work has focused on the role of fine-scale processes in shaping the phenomena that influence natural natural and human systems, including the processes by which climate change could impact extreme weather, water resources, agriculture, and human health.

Dr. Diffenbaugh is currently an Editor of the peer-review journal *Earth's Future*. He previously served as an Editor of the peer-review journal *Geophysical Research Letters*, including a four-year term as Editor-in-Chief from 2015-2018. He has served as a Lead Author for Working Group II of the Intergovernmental Panel on Climate Change (IPCC), as a panelist for the "What We Know" Report of the American Association for the Advancement of Science, and as a member of the Climate Safe Infrastructure Working Group for the State of California and the National Academy of Sciences Ad Hoc Committee on Effects of Provisions in the Internal Revenue Code on Greenhouse Gas Emissions. Dr. Diffenbaugh is an elected Fellow of the American Geophysical Union (AGU). He is a recipient of the James R. Holton Award and William Kaula Award from the AGU, a CAREER award from the National Science Foundation, and a Terman Fellowship from Stanford University. He has also been recognized a Kavli Fellow by the U.S. National Academy of Sciences, and as a Google Science Communication Fellow. Before coming to Stanford, Dr. Diffenbaugh was a member of the faculty of Purdue University, where he was a University Faculty Scholar and served as Interim Director of the Purdue Climate Change Research Center (PCCRC).

Chairwoman JOHNSON. Thank you very much. We'll now hear from Dr. Bontempi.

TESTIMONY OF DR. PAULA S. BONTEMPI, DEAN, GRADUATE SCHOOL OF OCEANOGRAPHY, PROFESSOR OF OCEANOGRAPHY, UNIVERSITY OF RHODE ISLAND

Dr. BONTEMPI. Chairwoman Johnson, Ranking Member Lucas, Members of the Committee, thank you for the opportunity to discuss the state of the science regarding Earth's climate crisis. Today I will highlight the role of the oceans in Earth's climate.

I deliver this testimony from Narragansett, Rhode Island, the traditional land of the Narragansett tribal nation. I deliver this testimony to the U.S. Government, centered in Washington, D.C., the homeland of the Nacotchtank, or Anacostan, people. I honor their histories, and ancestors, and perseverance in our communities today, as our communities were built on indigenous land. We acknowledge the indigenous people, and honor their stewardship of the land, sea, and resources that they hold sacred. The Fourth National Climate Assessment, Volume 2, highlights the disproportionate impact of climate change on indigenous communities. This threat is highlighted in IPCC's Special Report on Oceans and Cryosphere in 2019, and is especially relevant to our discussion today, as social and environmental justice must be central to our climate strategies and solutions.

For the last 7 years Earth's global average temperature has been the warmest on record. This warming is dramatically changing the physical characteristics of the ocean, and altering its ecosystems in unprecedented ways. These impacts are felt today, and will continue for decades, and their duration will extend even longer if action is not taken to rapidly reduce greenhouse gas emissions. I will point out that a lot of the long-term trends that we see in climate would not be possible without Earth-observing satellites today.

The ocean exchanges large quantities of heat, water, and carbon dioxide with the atmosphere, absorbing approximately 1/3 of annual carbon dioxide emissions. The ocean also moves excess heat, like a conveyor belt, from the tropics to the poles. Near the poles, cold, salty, and dense water sinks from the surface, and carries carbon dioxide and heat into the interior ocean, where it may be stored for hundreds to thousands of years. Understanding ocean dynamics is therefore central to understanding Earth's climate crisis. The ocean conveyor belt is directed impacted by climate change, and if any or all of its major currents diminish in the future, both heat and carbon dioxide could accumulate in the atmosphere at an accelerated rate.

The 2019 IPCC report presented the extreme damage being done to the world's glaciers, permafrost, and oceans by climate change. Dramatic changes are projected to continue under every emissions scenario, but outcomes under a business as usual approach are particularly grim. However, if global emissions are capped in the near term, and reduced sharply by mid-century, and if aggressive approaches are taken to support resilience in marine ecosystems in coastal communities, we may yet avoid the worst impacts. Ocean chemistry is impacted by carbon dioxide uptake from the atmosphere, and since the beginning of the Industrial Revolution this uptake has increased the acidity of the surface ocean waters by 30 percent.

In tropical oceans, warming and acidification have increased coral bleaching, mortality events, and reef decline worldwide over the last 2 decades. A 2019 IPCC report identifies additional changes in ecosystem distributions and migration patterns. On average, marine species have moved poleward at rates of up to 50 kilometers per decade since the 1950's, and sometimes more. Climate change impacts on ocean physical and chemical properties cause additional wide-ranging ecosystem responses, including frequent harmful algal blooms (HABs), altered ocean plant growth, reduction of fish stocks, many of which are either fully exploited or overexploited already. The diverse climate change effects threaten foundations of marine food webs, pulling—putting whole ecosystems, and those who rely on them for food and jobs, at risk. Substantial and sustained reductions in global greenhouse gas emissions will significantly reduce projected risks and—to ocean ecosystems and communities that rely on them. We need investments in research and management.

Here I would like to recognize and applaud Congressman Grijalva and Congresswoman Bonamici for their introduction earlier this year of the ocean-based *Climate Solutions Act*, which includes many needed steps for adapting to and mitigating climate change impacts. Recent Federal investments connecting research to management are groundbreaking, including the U.S. and National Science Foundation's contribution to an international global profiling robotic network measuring key ocean properties essential for understanding ocean carbon cycle and ecosystem health. Coupling these observations with new Earth-viewing satellite data, such as NASA's Plankton Aerosol Cloud and Ocean Ecosystem mission, and potentially groundbreaking technologies, like ocean-profiling LIDARs (light detection and rangings), will provide researchers and managers unprecedented local and global-scale observations of our living marine resources. I applaud these investments, but they're an appetizer. Modeling is also particularly important for climate change research and impact adaptation and mitigation studies.

We must facilitate and capitalize on investments in science, technology, engineering, computing, architecture, and education. These investments are strategic, tactical, and sustain our blue economy, and all of my points point to one pivotal need. To understand climate change and its impacts on the Earth, we need sustained investments in global observing networks and high-performance computing, integrated with—excuse me, science communication, public engagement, and education programs. We need a well-trained, interdisciplinary, climate literate workforce, including natural and social science, as well as policy experts, engineers, and educators.

As we look ahead, we must allow our science questions to evolve as our needs change. We must begin to meaningfully invest in adaptive science, and support adaptive and sustainable management and marine resources, and we must never forget that climate change as a crisis is no longer a threat of the future, but a reality occurring already today. Thank you for the opportunity to discuss these topics. I look forward to questions.

[The prepared statement of Dr. Bontempi follows:]

Written Testimony of
Dr. Paula S. Bontempi
Dean, Graduate School of Oceanography
The University of Rhode Island

Hearing on "The Science Behind Impacts of the Climate Crisis"

before the

Committee on Science, Space, and Technology
U.S. House of Representatives

Chairwoman Johnson, Ranking Member Lucas, Members of the Committee, thank you for the opportunity to discuss the state of the science regarding Earth's climate crisis. Today I will highlight the ocean's role in Earth's climate, and the major impacts that climate variability and change have on our oceans and coasts from local to global scales. I will also highlight needed investments and opportunities for the U.S. in marine research and technology.

I deliver this testimony from Narragansett, Rhode Island, the traditional land of the Narragansett Tribal Nation. I deliver this testimony to the U.S. Government centered in Washington, D.C., the homeland of the Nacotchtank, or Anacostan, people. I honor their histories and ancestors, as well as their perseverance in our communities today, as our country was built on Indigenous land. We acknowledge the Indigenous people and honor their history and stewardship of the land, sea, and resources that they hold sacred.

The Fourth National Climate Assessment Volume II on Impacts, Risks, and Adaptation (USGCRP, 2018) in the United States highlights the disproportionate impacts of climate change on Indigenous and other frontline and fenceline communities. This threat is highlighted in the IPCC special report on Oceans and Cryosphere (IPCC, 2019), and is especially relevant to our discussion today, as social and environmental justice must be central to our climate strategies and solutions.

For the last seven years, Earth's global average surface temperature has been the warmest on record (NASA, 2021). In addition to its severe terrestrial impacts, this warming is dramatically changing the physical characteristics of the ocean and altering its ecosystems in unprecedented ways (IPCC, 2019, medium to high confidence). The impacts are felt today and will continue for decades, and their duration will extend even longer if action is not taken to rapidly reduce greenhouse gas emissions. Among the most obvious direct impacts of climate change are melting ice sheets and increased ocean heat content (IPCC, 2019, medium to high confidence), which together have caused global sea level to rise by nearly 10 centimeters since 1993 (very high confidence), a rate nearly double that of last century. Ice sheets contain the greatest amount of freshwater on Earth and their loss contributes to both the freshening of the surface ocean in polar regions and to rising sea level. The 2019 IPCC report on oceans and cryosphere (IPCC, 2019) predicts global sea level to rise by one third to one meter by the end of this century, subjecting U.S. coastal zones to inundation, flooding, and erosion and threatens our homes, our infrastructure, and our well-being. There are large regional variations in relative sea level rise, with some areas of the U.S. experiencing much faster local sea level rise due to compounding drivers such as subsidence and tectonics (USGCRP, 2018). The impacts to coastal communities are likely to be dire - 13 million people in the U.S. could be forced to relocate by 2100, moving to cities and increasing pressure on infrastructure (Robinson et al, 2020). The very existence of low lying island nations and cultures is being challenged. Polar sea ice has also melted at an accelerating rate as well with estimates of 28 trillion tons of ice lost since the mid-1990s (Slater et al., 2021). The decline in extent and thickness of sea ice over the last several decades has resulted in younger Arctic sea ice that is easier to melt with less surface area to reflect sunlight (very high confidence), leading to a rise in ocean temperatures. It is essential to note is that most of these global findings would be unconfirmed without the contribution of sustained observations and analyses of Earth observing satellite data.

The ocean significantly influences Earth's weather and climate. The ocean exchanges large quantities of heat, water, and carbon dioxide with the atmosphere, absorbing approximately one-third of annual carbon dioxide emissions. The ocean moves excess heat, like a conveyor belt, from the tropics to the poles over hundreds to thousands of years. Near the poles, cold, salty, and dense water sinks from the surface and carries carbon dioxide and heat into the interior ocean where it may be stored for hundreds to thousands of years. Understanding ocean dynamics is therefore central to understanding Earth's climate crisis. The ocean conveyor belt is directly impacted by climate change and if any or all of its major currents diminish in the future, both heat and carbon dioxide could accumulate in the atmosphere at an accelerated rate. Changes in the distribution of heat within the belt occur over tens to hundreds of years. Excess heat is absorbed by the ocean thermocline, the transition zone between warmer surface and colder deep waters. Energy or heat in the thermocline fuels ocean storms. The conveyor belt is complemented by vigorous surface currents driven by atmospheric winds. Surface ocean variations may be linked to short-term climate changes, while long-term changes in the deep ocean may take longer to detect.

The portion of this global conveyor belt in the Atlantic Ocean is known as the Atlantic Meridional Overturning Circulation, or AMOC. In recent weeks, newly published research suggests that the warming atmosphere is impacting the AMOC, specifically the powerful Gulf Stream in the North Atlantic (Caesar et al., 2021). The Gulf Stream moderates temperatures in economically important human and marine habitats along the east coast of North America, Western Europe, and northwestern Africa, among others. The consequences of such a change in the Gulf Stream remain a subject of very important research, and these findings are potentially weighty. We know the system will slowdown, and we have yet to definitively measure this slowdown due to our relatively short observational records and large amplitude short-term climate signals. At the opposite end of the Earth, the Southern Ocean functions as a sink for excess heat and carbon dioxide, but observations over the last several decades indicate that the water is warming, freshening, and decreasing in oxygen (Sallée, 2018). Continued warming and declines in sea ice will lead to a decrease in carbon drawdown (Brown et al., 2019) in the Southern Hemisphere.

The 2019 IPCC report presented the extreme damage being done to the world's glaciers, permafrost, and oceans by climate change. For example, there has been a temperature rise and increase in frequency of marine heatwaves (Oliver et al., 2018; IPCC, 2019) that can devastate marine life, including mammals and seabirds. The report also contains recommendations on needed steps to mitigate and adapt to these impacts. Dramatic changes are projected to continue under every emissions scenario, but outcomes under a business as usual approach are especially grim. However, if global emissions are capped in the near term and reduced sharply by mid-century, and if aggressive approaches are taken to support resilience in marine ecosystems and coastal communities, we may yet avoid the worst impacts.

Ocean chemistry is impacted by carbon dioxide uptake from the atmosphere and, since the beginning of the Industrial Revolution, this uptake has increased the acidity of surface ocean waters by about 30%. In tropical oceans, warming and acidification have increased coral bleaching, mortality events, and reef decline worldwide over the last two decades. Even if global warming remains below two degrees Celsius, existing coral reefs will decline and the remaining shallow coral reef communities will differ in species composition and diversity from present reefs, decreasing ecosystem services. The 2019 IPCC report identifies additional changes in ecosystem distributions and migration patterns. On average, marine species have moved poleward at rates of up to 50 kilometers per decade since the 1950s, sometimes more. A recent study showed that the annual migration of several important fish stocks in Narragansett Bay in my home state of Rhode Island have been altered by warming temperatures in ways that will impact both fishers and managers (Langan, 2021). This same pattern is being repeated in stocks along both coasts of the continental U.S. and Alaska. Importantly, these changes are not simply a response to fish following a given temperature gradient but are also reflective of deeper ecosystem shifts in spawning behavior and predator-prey interactions. Geographic shifts in species distributions may soon raise jurisdictional challenges – even potential conflict – as stocks move across borders and become accessible to new fishers while others lose access. Long-term research on these ecosystems is a key to understanding how marine species distributions are changing, and how to manage commercially and recreationally important species under such quickly changing conditions.

Climate change impacts on ocean physical and chemical properties cause additional wide-ranging ecosystem responses, including frequent harmful algal blooms, altered ocean plant growth, and reduction of fish stocks, many of which are either fully exploited or overexploited already. These problems will be exacerbated by an overall decline in ocean productivity with some regions such as the tropics potentially seeing a 50% decline in available fish stocks under worst case scenarios. We have already seen a nearly 10% decline in some fish stocks in response to Earth's warming (IPCC, 2019). Coupled to the fact that over 90 percent of the world's fish stocks are either fully exploited or overexploited already, the additional stress from warming is inhibiting the ability of overexploited stocks to recover and increases the likelihood of overfishing. While aquaculture is proposed as a part of the solution to declining fish stocks, these facilities are not immune to climate change effects, and will have to be incorporated in to climate adaptation plans. These diverse climate change effects threaten foundations of marine food webs, putting whole ecosystems – and those who rely on them for food and jobs – at risk.

Physical and ecological impacts of climate change go well beyond the ocean surface. The deep sea plays a critical role in global climate regulation through the aforementioned uptake and storage of heat and carbon dioxide. However, global warming exacerbates acidification and open ocean deoxygenation, or the decline in oxygen due climate-driven changes in ocean circulation, solubility, and biological productivity. This leads to decreased biodiversity and distributions of deep-sea fauna, impacting ecosystem services. As the home environment for deep-sea species, including deep-sea fish, corals and sponges within the North Atlantic shifts, recent research projects a decrease of 28%–100% in suitable habitat for cold-water corals and a shift in suitable habitat for deep-sea fishes of 2.0°–9.9° towards higher latitudes (Morato et al, 2020).

In polar ecosystems, rapid changes in Arctic food webs pose a challenge for adaptation. The rapid loss of sea ice exposes previously ice covered regions to solar radiation, even through melt ponds, changing the timing and nature of regional ecosystem cycles. The warming also causes challenges for large marine mammals and fish stocks that have adapted to a polar environment. The general trend of poleward migration of species is especially pronounced in the Arctic with whole ocean ecosystems shifting poleward at a rate six times greater than terrestrial species (Lenoir, 2020).

Two major anthropogenic forces, climate change and whaling, have altered trophic dynamics of marine krill predators in the Southern Ocean (McMahon, 2019). Pioneering molecular isotope techniques have been used to reconstruct carbon flow and trophic dynamics of Antarctic penguins. One species is able to capitalize on dramatic environmental shifts in prey, while another species' dietary specialization has made the population vulnerable to recent declines in krill availability associated with sea ice decline. This work provides historical context to recent shifts in ecosystem dynamics in one of the fastest changing regions of the world, and provides valuable scientific support in the context of the growing Southern Ocean krill fishery.

Impacts of climate change on Earth's ocean have a cost, but provide an opportunity to invest in our future. The Fifth National Climate Assessment, under the U.S. Global Change Research Program, will analyze impacts of global change in the United States in a balanced and policy-neutral way, identify climate knowns and unknowns, and ideas for investment in to our future. Some may balk at the cost of the sustained investment needed to understand and protect our home planet and its limited resources from the pressures of anthropogenic climate change. I offer this example to reflect on those long term potential returns on our research investments. Hurricane-prone landfall areas of the U.S., including the Atlantic and Gulf Coasts, face above-average climate risks. Hurricane Katrina impacted 93,000 square miles of the Gulf Coast with a storm surge that crested at 27ft, or over eight meters, at a staggering cost of $125 Billion U.S. (NOAA, 2020). A 2014 (Cooke et al.) paper estimated that a tripling of the then current global climate research budget from $5 billion to $15 billion U.S. per year is needed for at least 30 years to monitor Earth's climate, a cost that includes the infrastructure plus advances in climate monitoring, process studies, and advanced climate modeling. An updated analysis in 2018 (Weatherhead et al, 2018) pointed to the additional $10B per year global cost of such a system in net present value is ~$200–$250 billion U.S. When compared to a $10–$20 trillion U.S. value of information of such a system, the return on investment varies from 40 - 100 to 1, or roughly $50 return for every $1 invested. Even if total uncertainties in the economic analysis were off by a factor of five above or below such estimates, the return on investment would still be worthy of proceeding. Not acting would be costly; an advanced climate observing system takes years to develop and implement. On a global scale, the IPCC report estimates that climate-induced declines in ocean health will cost the global economy $428 billion per year by 2050 and $1.98 trillion per year by 2100. The U.S. needs to invest in research infrastructure, from ground networks to field and laboratory studies, to provide data that enable us to manage future scenarios. When coupled with proactive planning and steps to adapt to more frequent, widespread, and severe climate change driven events, we can conserve economically important coastal ecosystems and decrease direct losses and cascading impacts. While one could view such a scenario with a pessimistic lens, these situations have historically generated opportunity for innovation and U.S. leadership in engineering, science, and technology, while also protecting our homeland.

Substantial and sustained reductions in global greenhouse gas emissions will significantly reduce projected risks to ocean ecosystems and communities that rely on them. We need investments in research *and* management. Here, I would like to recognize and applaud Congressman Grijalva for his introduction earlier this year of the Ocean Based Climate Solutions Act, which includes many needed steps for adapting to and mitigating the climate change impacts. A separate report released by the High Level Ocean Panel For A Sustainable Ocean Economy (Hoegh-Guldberg et al., 2019), identifies opportunities for ocean management as both a source of adaptation and mitigation. The Panel calls for increased investments in: 1) ocean-based sources of renewable energy; 2) that we work toward "net zero" emissions in ocean transportation; 3) restoration and protection of coastal and marine habitats to both increase their resilience and carbon storage; 4) expand sustainable approaches to aquaculture and fisheries as part of a dietary shift away from greenhouse gas emissions-heavy protein sources; and 5) increase research into carbon storage in the sea bed. This would result in a sustainable blue economy, 12 million new jobs by 2030, and billions of dollars in energy and sustainable seafood benefits by 2050.

Strategic investments at federal agencies must bridge ocean exploration to economics, facilitate diverse institutional collaborations, and engage the U.S. population and allow them to play a role in climate solutions. We must better connect science with states, local, and tribal governments, and a range of community stakeholders. We need to better define the boundaries to commercial partnerships for long-term scientific analyses, modeling, and technology - balancing fiduciary responsibilities with government support of industries to provide a short term deliverable for profit. This must be inherently federal responsibilities and investments – and each domestic or international partner must contribute resources toward a common goal. The U.S. government must allow federal agencies to pursue their missions and new ideas through investments in America's future without unfunded mandates or mandatory pathways to solutions grounded in the best science available, and provide funds for new and innovative investments for these agencies to connect basic research with applied research that supports management, decision and policy makers.

Recent federal investments connecting research to management are groundbreaking, including the U.S. and National Science Foundation's contribution to an international global profiling robotic network measuring key ocean properties essential for understanding ocean carbon cycles and ecosystem health. Coupling these observations with new Earth viewing satellite data, such as NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission and, potentially, an ocean-profiling satellite lidar system, will provide researchers and managers unprecedented local and global scale observations of our living ocean and marine resources. I applaud these investments, but they are an appetizer.

Supporting a more sophisticated understanding of the ocean's role in the climate system, and the impact of climate change on ecosystems and coastal communities, will require the U.S. to develop a comprehensive observing strategy and a plan for continuity of Earth science observations and data records. Without this coordinated information, scientists and managers may not know the impacts of climate variability and change until it is too late to undo the damage or effectively adapt. The Graduate School of Oceanography at the University of Rhode Island hosts the longest running time series of on Earth for ocean plankton, tiny animals that provide food for fisheries (Time Series, 2021). The National Science Foundation recently extended this ocean sampling from the Narragansett Bay estuary all the way to the continental shelf edge, crossing one of the most productive and economically significant fisheries in the US. This commitment and investment in sustained observations puts the state of Rhode Island, and all scientific and management partners, in a position to better understand how climate influences local and commercially important marine resources.

Modeling is particularly important for climate change research and impact, adaptation, and mitigation studies. Modeling elements of interdisciplinary research programs must be considered from early planning stages forward. Success stories, such as NASA's Carbon Monitoring System, connect scientists and managers to test real solutions to climate change. Modeling barriers include scientific knowledge and the provision of open source, affordable, robust, and meaningful high-resolution products for user and stakeholder communities. Here, an avenue for advancement may be increased partnering with private entities and enterprise-level cloud-based computing, while simultaneously recognizing issues of repeatability, sustainability, public access, and security that are associated with all climate data records.

We must facilitate and capitalize on investments in science, technology, engineering, computing, architecture, and education. These investments are strategic, tactical, and sustain our blue economy.

All of my comments point to a pivotal need: to understand climate change and its impacts on the Earth, we need sustained investments in global observing networks and high performance computing, integrated with science communication, public engagement, and education programs. We need a well-trained, interdisciplinary, climate-literate workforce, including natural and social science as well as policy experts, engineers, and educators. We must engage our next generation of scientists, particularly marginalized and low-wealth groups disproportionately affected by climate change, and facilitate opportunities, education, and innovations to diversify science and engineering if we are to effectively tackle all of the consequences of the climate crisis. All of these investments directly impact our standing in the world, our ability to lead 21st century global economy, and our role in advancing Earth system climate science that yields innovative solutions connecting exploration, discovery, and research with social science, management, and policy.

As we look ahead, we must allow our science questions to evolve as our needs change, we must begin to meaningfully invest in adaptive science to support adaptive and sustainable management of marine resources, and we must never forget that the climate change crisis is no longer a threat of the future but a reality already impacting us today.

Thank you for the opportunity to discuss these Earth and ocean system issues and to present ideas for future research and adaptive science. I would be pleased to respond to questions.

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An alumna of the URI Graduate School of Oceanography (Ph.D. '01) and a biological oceanographer for more than 25 years, Dr. Paula Bontempi became Dean of GSO in September 2020. As Dean, Bontempi has executive responsibility for the graduate school and its Narragansett Bay Campus, providing leadership and oversight for its academic, research and public engagement activities. Her scientific interests include studying the Earth as a system, the connection of ocean exploration to economics, ocean sensors and technology, mentorship, and justice, equity, diversity, and inclusion (JEDI) initiatives in science, technology, engineering and mathematics (STEM).

Previous to her current position, Bontempi served as acting deputy director at NASA's Earth Science Division, Science Mission Directorate of NASA Headquarters in Washington, D.C. She provided leadership, strategic direction, and overall management for the agency's entire Earth science portfolio, from technology development, applied science, and research to mission implementation and operation.

In addition to allocating resources and leading a division of approximately 75 scientists, engineers, and administrative professionals, Bontempi was charged with developing policies and priorities for numerous programs. She also coordinated with the scientific and applications communities throughout NASA, federal advisory committees, and other entities, including the National Academy of Sciences, Engineering, and Medicine, U.S. Global Change Research Program, and international partnerships. She also taught Earth science in NASA's astronaut training class.

Prior to her appointment as acting deputy director, Bontempi spent more than 16 years as the physical scientist and program manager for ocean biology and biogeochemistry at NASA Headquarters. She also served as the lead for NASA's carbon cycle and ecosystems focus area and for the agency's carbon cycle science research. This included leading the coordination of relevant research and program collaborations with all U.S. and international partners, and serving as NASA program scientist with oversight responsibility for instrument and mission science integrity on a number of Earth observing satellite..

Before joining NASA, Bontempi was an assistant professor of oceanography in the University of Southern Mississippi's Department of Marine Sciences. She holds a Master of Science degree in Oceanography from Texas A&M University, and a Bachelor of Science degree from Boston College. She grew up in Upper Saddle River, New Jersey.

Chairwoman JOHNSON. Thank you very much. That completes our outstanding witnesses, and at this point we will begin our first round of questions. I will recognize myself for 5 minutes, and then Mr. Lucas, and after that the Clerk will call on the persons for their questions—from the queue.

Extreme heat is the deadliest climate related event in the U.S., and cities are the most vulnerable, although I must say that within the last month, in my hometown of Dallas, which is known for its heat, would argue at this point whether or not it is heat that brings forth most of the temperatures that are out of line with what we consider normal. Dr. Oppenheimer, you discussed in your testimony how climate change will cause more frequent, more intense, and longer heat waves. You also note how populations are more vulnerable to heat than others based on race, income, health status, or age. How are these vulnerable communities being disproportionately impacted by extreme heat, and what are the consequences of failing to design policies that recognize and address these impacts?

Dr. OPPENHEIMER. Thank you, Congresswoman. People, as I pointed out, die in higher numbers in extreme heat than any other climate-related event in the United States, and, you know, if you look at the way extreme heat is handled in much of the country, because it's kind of something that people think they're used to, there isn't really a very effective system for adapting to it. But what happens instead is that it goes on the back burner, and people are expected to have air conditioning. Well, a lot of people can't afford air conditioning. In central cities you get situations where people are too poor to have air conditioning, they live in apartments which are—don't have very good ventilation, in many cases afraid to open the windows for security reasons. So, again, it's the disadvantaged that extreme heat hits particularly hard.

In addition, the statistics don't capture very well people who die due to the indirect effects of extreme heat, for instance, the interaction of heat with air pollution. Again, people who tend to live in underserved areas, central cities, areas where people who are poorer or suffer various forms of discrimination, are disproportionately represented, but that's a problem. It's a problem for the society as a whole, it's a problem for those particular populations.

Chairwoman JOHNSON. Thank you very much. Now, we consider a climate literate workforce, and I'd like to have some comment on what do we mean by that? Dr. Bontempi, in your testimony you describe that one critical, and often overlooked, component of science-based solutions is the need for a climate literate workforce that is trained in the natural and social sciences, as well as policy. The U.S. produces some of the best climate science in the world to inform climate adaptation and mitigation strategies, but we need a climate literate workforce to turn these goals into reality. How do we provide that right interdisciplinary and multi-disciplinary training to build that workforce that is prepared to tackle these complex challenges?

Dr. BONTEMPI. Thank you, Congresswoman, for the question. It's a good one. So what we have to do on the whole is start blending interdisciplinary and multi-disciplinary science and research into our teaching curricula. We have to acknowledge the needs and desires of our growing workforce. We have to provide mentorship, and we have to provide pathways and investment into research that facilitates the training of students, and we have to start early. We have a global population of young people that are unbelievably connected to each other, to their environment, and to their role in the Earth system, and the climate as a whole.

We actually also need to focus on historically marginalized or excluded groups, and we have to create a safe environment for them to join the workforce. We have to provide a support network, we have to provide mentorship, and it's not enough to just recruit people. We have to focus on retention, advancement, and placement, and we have to shepherd all students through these pieces. So people are very focused on this, they're very interested in this.

When I look at the campus that I'm a dean on, the Narragansett Bay Campus at the University of Rhode Island, I have seen a real shift in working desires of the students to not go just the tenure track faculty positions, but into positions where they can actually have an immediate impact on the world. Blended into this is also our capability to science—communicate our science. Science communication, and inclusive science communication, cannot be an afterthought in the research that we pursue, or the education that we pursue. It has to be blended in from the start. And I think if we start to follow these pathways we'll have a lot more success not only in creating a climate literate workforce that thinks of the Earth system, and not just their backyard, and also have the reach globally.

Chairwoman JOHNSON. Thank you very much. Mr. Clerk, what is my time like?

The CLERK. I believe it's expired, Ms. Johnson.

Chairwoman JOHNSON. Thank you very much. I now recognize Mr. Lucas.

Mr. LUCAS. Thank you, Madam Chair. I'd like to turn to Dr. Hausfather. In a recent report published by The Breakthrough Institute, which you co-authored, you refer to climate policy as quiet, if it swims with the tide of existing sociopolitical institutions and economic growth, if it uses technology and infrastructure as its main lever, and if it disrupts, rather than exploits, political partisanships. That's the kind of policy I've always aimed to achieve because it's what I refer to as the carrot, not the stick approach. To you, what comes to mind as examples both of non-quiet policy proposals and some examples of quiet policy proposals? Doctor?

Dr. HAUSFATHER. Thank you for your question, Congressman. So I think it's important to emphasize that what we call quiet climate policy is not necessarily an alternative or statement of opposition to setting broader goals, such as nationally determined contributions in the Paris agreement. Rather, it's a recognition that, to meet those goals, we need real bipartisan climate solutions. So quiet climate policy seeks to make substantial forward progress recognizing the realities of divided government. It seeks to create durable policy that will not change with every new administration, and I think the recent energy bill is a great example of quiet climate policy in action.

When we think of quiet climate policy, there's really three pillars. First, it involves a recognition of the importance of government investment in research, development, and deployment. Most of the technologies that are reducing emissions today were enabled by decades of sustained RD&D efforts made by Federal and State governments. We need additional advances in both clean, firm generation in the power sector, and advances for hard to decarbonize parts of the economy like long-distance freight, aviation, industrial heat, and agriculture. A focus on RD&D also includes demonstration and early stage deployment. The Forge Program for geothermal is a great example here, as is the *Nuclear Energy Leadership Act* to enable the deployment of first of a kind advanced reactor designs.

Second, investments in infrastructure are needed to support the energy transition. While we can endlessly debate about the right amount of renewables on the grid, what is clear is that, given their impressive and continuing cost declines, we will have more in the future than we have today. That will involve modernizing our electricity grid, including investing in high voltage, long-distance transmission and interconnections, as well as grid fuel storage.

And finally, while there's a need for broader mitigation policies, we should try to do so in a technologically neutral way. While picking winners is fine for early stage technologies, it is more problematic for mature technologies whose deployment is primarily being driven by market forces. We should also recognize that technology enables policy. It is a lot easier to nudge a system further in a direction than it is already heading than to try to turn it around, and the advent of cheap energy—or cheap clean energy has dramatically reduced the expected costs of mitigation.

We should be a bit humbled by the rate of change enabled by making clean energy cheap. We have exceeded both Waxman-Markey goal of 17 percent reductions in emissions by 2020, even including COVID impacts, and the clean power plant goal of 32 percent reduction in the power sector emissions by 2030, despite neither being enacted. This is not to say that there's not a need for policy, but rather to highlight the importance of both technology and policy in solving the problem.

Mr. LUCAS. You know, Doctor, it's been my experience a lot of times, when I was in State legislature or in Congress, sometimes we get in kind of an echo chamber effect, and that happens both at the State capitals and the U.S. Capitol. Would you agree that the public wants to see responsible action on energy—climate change?

Dr. HAUSFATHER. I think there is a desire for action on climate change, and in a way that, you know, supports the building of American prosperity in the long term. I think that we have shown in the past decade that taking strong action on climate change need not require large scale sacrifices by the American people, and that, through smart policy, we can both build our economy and reduce our emissions at the same time.

Mr. LUCAS. Doctor, you used shale gas unlocked by the fracking revolution as an example of sustained, technology specific research developed demonstration deployment efforts by the Federal Government, and it took less than a decade for research at DOE's (Department of Energy's) National Labs to lead to the U.S. becoming the world's leading natural gas producer. For something like advanced nuclear reactors, geothermal energy, direct air capture research areas, which are well underway at the National Labs today, should we have expectations similar to shale gas potential results that, for that matter, does the *Energy Act of 2020* speed the timeline up significantly for these things?

Dr. HAUSFATHER. So we can't know what future investments will sort of catch lightning in a bottle in the way that horizontal drilling and hydraulic fracturing did, and we shouldn't put all of our hopes in any single future technology, be it carbon capture and storage, advanced nuclear, hydrogen, direct air capture, or any others. Rather, we should try to be pretty equimenical in our investments, and for a wide range of future decarbonization technologies, you know, recognizing that the market will ultimately drive the deployment of what proves to be cost-effective.

In the case of sort of the fracking revolution, it's important to emphasize that it wasn't just Federal R&D. There were tax credits, demonstration products—projects funded by a FERC (Federal Energy Regulatory Commission) approved surcharge on—pipelines, and other measures that really drove it forward. Investments that led to the fracking revolution took place over decades at every stage of the RD&D pipeline. So I think it is a good example of the type of Federal investments in basic R&D that can have dramatic effects on the energy system, as are prior investments in solar photovoltaics and battery storage. And I think, you know, more of these are needed for the harder to decarbonize sectors of the economy and for sort of clean firm generation sources that will provide an important part of our future electricity mix.

Mr. LUCAS. Thank you, Doctor, and I yield back, Madam Chair.

Chairwoman JOHNSON. Thank you very much, Mr. Lucas. I will now call on the Clerk, and he will start to ask Members to use their 5 minutes of questioning.

The CLERK. Thank you, Madam Chair. Ms. Bonamici is next.

Ms. BONAMICI. Thank you so much. Thank you, Chairwoman Johnson, and Ranking Member Lucas, and really thank you to all of our witnesses for this productive conversation. In Northwest Oregon the climate crisis isn't a distant threat, it's our reality, and the testimony from our witnesses today demonstrate this, I think, in many ways. We hear obscene raging wildfires creating hazardous air quality, increased flooding, sea level rise jeopardizes our coastal communities, and ocean acidification. And we know that the climate crisis is a national emergency, and we know we need to implement bold policies to solve it. Last year I joined my colleagues on the Select Committee on the Climate Crisis, and we released a comprehensive science-based road map to reach net zero emissions no later than mid-century, net negative thereafter, and I look forward to working with my colleagues on this Committee to advance the recommendations and legislation in the Climate Action Plan.

We know that carbon dioxide from human-caused greenhouse gas emissions is causing our ocean and estuaries to become more acidic. Ocean acidification makes it more difficult for marine organisms to build their shells, but now we also know that it's causing some finned fish, including endangered salmon, which are a fundamental part of the identity and culture of our Northwest tribes, is causing them to lose the sense of smell that they need to survive and reproduce. Last week I introduced my bipartisan *COAST Research Act*, which is a comprehensive bill to expand scientific research and monitoring of ocean and coastal acidification, and help coastal communities adapt.

So I'm going to direct my questions to Dr. Bontempi. First, thank you, Dr. Bontempi, for your acknowledgement of the *Ocean-Based Climate Solutions Act*. I want to start by asking, how can we apply our current understanding of ocean acidification to implement even stronger adaptation and resilient strategies?

Dr. BONTEMPI. Yes, we definitely need to apply the information we have to strategies for the future. And, as I said, I acknowledge the way you've phrased it, blending research and management approaches and solutions. Right now I'd say the hardest thing that—one of the greatest challenges for scientists is actually collecting enough information so they understand different aspects of what's happening. I'd go so far as to say off the Oregon coast, and even in the State of Oregon, you know, you—the last decade you have new seasons to look at, right? Hypoxia seasons, ocean acidification seasons. The reason that scientists are able to understand what's happening is because we have long-term time series. So I would recommend, you know, continued investment in observations of our ocean at the surface, down deep, on multiple scales at the local, regional, and global scale to understand what's happening in the ocean physically, chemically, biologically so you can understand how to manage your local marine resources.

I think the other piece is thinking about things like the modeling capability. Do we have all the pieces in place to actually model our marine ecosystems? This is a cutting edge area, right? We're very good at putting things in in sort of a black box, but we don't know all the processes that happen in the ocean related to ocean acidification and the impacts on marine ecosystems, and you pointed——

Ms. BONAMICI. [inaudible] but I really want to get another question in.

Dr. BONTEMPI. I'm sorry. Go ahead.

Ms. BONAMICI. I wish we had more than 5 minutes. So I was glad that you mentioned the high level panel for sustainable ocean economy in your testimony. So in 2019, in a report the panel found that the protection and restoration of coastal blue carbon ecosystems could prevent approximately one gigaton of carbon dioxide from entering the atmosphere by 2050, so I'm going to soon reintroduce my *Blue Carbon For Our Planet Act* to map, protect, and restore blue carbon ecosystems. So as the United States—as we establish our next nationally determined contribution under the Paris Climate Agreement, can you please expand on how and why a better assessment of the sequestration potential of blue carbon ecosystems would be useful?

Dr. BONTEMPI. Sure. Blue carbon will be an important part of our planning strategy for carbon, you know, cycling in the future. I think anything in the coastal zone where land meets water, wetlands, seagrasses, things like that, have the ability to capture carbon and actually utilize it and recycle it, and that will be very important. One of the things that's very alarming is that with all of the sea level change, sea level rise, coastal inundation, and things that come with it, these areas are being highly impacted by climate variability and change. And so we're going to have to also take steps to conserve these areas, to support them and enable marine and coastal resilience.

Ms. BONAMICI. Right, and that restoration work is great for the coastal communities as well. So I—my time is just about to expire. Again, thank you to all our witnesses, and I yield back the balance of my time.

The CLERK. Mr. Posey is next.

Mr. POSEY. Thank you, Chairwoman Johnson and Ranking Member Lucas, for holding this hearing. It is important to discuss the importance of climate change research, and the push toward lower carbon energy. We all support moving to lower carbon energy, and we've made a lot of progress already, but it would be wrong to ignore the impact on the people we're elected to serve. I'm particularly interested in hearing from the panel what they would say to senior citizens in Florida living on Social Security about doubling or tripling their electric bill because of the higher costs associated with lower carbon energy.

The administration announced a plan to eliminate carbon emissions from the electric sector by 2035 by pushing wind, solar, nuclear, and other lower carbon energy resources. This previous date was 2050. Florida uses mostly natural gas for electric generation, and, according to the Florida Municipal Power Agency, the cost to convert natural gas to renewable energies by 2035 could increase Florida's electric bills by 200 to 300 percent on an annual basis. The current monthly residential electric bill in Florida is $123. That's about 8 percent of the average Social Security recipient's monthly income. By doubling or tripling their electric bill would end up taking 18 to 25 percent of their annual income. I'm concerned about moving the goalposts from 2050 to 2035. How do any of you think we could best explain the increase to senior citizens, who we all represent, when, according to the Social Security Administration, they earned an average of just $1,452 per month as of December of 2019? Anyone can answer that.

Dr. OPPENHEIMER. Let me take a shot at—let me answer it a little more generically. I think there are a lot of people who will gain, and some people that will lose, if we do a rapid energy transition. That's in the nature of change. But what shouldn't happen is that these groups—and that includes, for instance, the coal mining communities, be allowed to fall through the bottom of whatever safety net we have in this country. And so I, you know, would fully endorse an approach that—in fact, I'll say I doubt a solution to this problem is possible unless we afford the appropriate protection to people who might be hurt, and we've done so in the past. During the energy crisis of the 1970s, the U.S. provided support for payment of electric bills of low-income families. It's been done.

Dr. HAUSFATHER. To echo Dr. Oppenheimer, you know, I think that we can certainly move forward in an energy transition in a way that does not increase people's bills. Now, whether or not we get all the way down to zero in the electricity sector by 2035, or, say, 80 to 90 percent of the way there I think is still a bit of an open question. Renewable energy is very cheap at the margins today, but once you get closer to 100 percent decarbonization of the system driven by renewables, you start getting much higher costs associated with the complementary technologies, like battery storage and whatnot. And so, you know, a world where we get 80, 85, even 90 percent of the way there by 2035, while still having a fair amount of natural gas backup to fill in the gaps between intermittent generation, is a much lower cost system than one where we get all the way to 100 percent.

Now, by 2050, the longer term decarbonization target, we will hopefully have more mature alternative technologies to fill in those gaps in a cost-effective way. And so I think we can definitely, you know, both decarbonize, while hopefully reducing, or if not reducing, at least keeping costs similar to they are today for most customers. And I think it's just important that we make sure we do that the right way. And there's been a number of recent U.S. decarbonization models that I refer to in my written testimony that are very instructive there, including by folks like Dr. Chris Klack and Dr. Jesse Jenkins, who's testifying before you guys next week.

Mr. POSEY. Now——

Dr. DIFFENBAUGH. Yeah, I would add——

Mr. POSEY. Just following up on that, I think Ranking Member Lucas makes a good point about investing in more technology development. Now, how can we use those new technologies to produce a cleaner energy economy that doesn't create more expenses for those that can't afford it?

Dr. DIFFENBAUGH. Yeah, I would add in this discussion, including the statement you just made, it is critical that the distributional impact of policies are quantified and considered, and that's both for policy actions that your Committee is considering, as well as for the impact of the climate changes that are happening, and that cost-benefit analysis is, you know, requires both sides of the equation. And I'll just amplify that, you know, we have clear evidence that global warming is already costing Americans billions of dollars a year. We know from the contribution to net climate and water disasters that that's already cumulatively billions of dollars a year, and then in—and impacts on economic growth, you know, those economic impacts are even greater. And I'll go back to the Chairwoman's question——

Mr. POSEY. My time has expired, and I have to yield back. Thank you, Madam Chairwoman.

The CLERK. Ms. Sherrill is next.

Ms. SHERRILL. Thank you, and thank you to our Chair and Ranking Member for calling such an important discussion, and our panelists as well. You know, Dr. Oppenheimer, in 2012 Hurricane Sandy ravaged New Jersey. It was the most devastating, costly storm in New Jersey history, and it turned the lives of thousands of families upside down. With a greater understanding of climate events our State may have been better prepared to handle the adverse impacts of the storm. We also see people in Texas making decisions about resiliency that would be better made with an understanding of the adverse impacts of climate change. So how have recent updates to climate science improved our understanding of the timing, intensity, and location of climate events?

Dr. OPPENHEIMER. Well, as far as location is concerned, one of the big challenges is always predicting something at a scale that's really meaningful to people in enough detail. And it—the big changes in the climate computer models that do the forecasting is the increase in resolution of those models, so it's become gradually more and more possible to make statements about climate change that are true of not just a continent, or a hemisphere, or even a region like the Northeast, but be more—but that are more specific. So the support that's gone into climate modeling has been absolutely crucial in helping communities, like the ones on the Jersey Coast that was so devastated, plan—look to the future, plan, and implement those plans for protection in the future.

It's also true that we're never going to be perfect at prediction, and to some extent over the next decade or two, for some impacts, we're going to have to rely on generalities because specific predictions will remain beyond the capabilities of the models.

Ms. SHERRILL. Thank you. And then I—I'd love to turn to Dr. Diffenbaugh on—about harmful algal blooms. They now occur more severely, and more often, and in more bodies of water due to the impacts of climate change, and they're a serious environmental and economic threat to New Jersey, and States across the country. Lake Hopatcong, in my district, is the largest freshwater lake in New Jersey, and it was closed for most of the summer in 2019 due to HAB outbreaks, impacting residents, businesses, and the economy of Northwest Jersey. So what has led to the improvements in our ability to quantify impacts and societal risks associated with climate change, and how can we ensure that these efforts continue?

Dr. DIFFENBAUGH. Well, I—you know, the risks from climate change result from the intersection of the physical hazards, whether they're storm surge, heat, drought, et cetera, as well as the intersection of those physical hazards with exposure and vulnerability. And certainly, you know, there are a number of scientific studies on harmful algal blooms, for example, showing that intersection in the Great Lakes, for example, and other regions. So certainly the human dimension is critical, and as we heard earlier, in terms of research for understanding these intersections of the physical climate hazards with the exposure and vulnerability of people and ecosystems, we clearly need improved research in—at the nexus of physical sciences, social and behavioral sciences, in order to understand, you know, what the—what solutions would be necessary to prepare for, and, in the case of the algal blooms that you're mentioning, you know, reduce or prevent those events.

Ms. SHERRILL. As you can imagine, we look at huge costs associated with different climate events, and the impact they have, and the aftermath, and so as we're looking forward, as we're forward-looking in trying to make decisions on where this—where to most efficiently spend money for infrastructure resilience, for example, I'm wondering what more Congress can do to help our communities make these costly decisions, and make them better? For example, if it's going to be a once in a 100-year storm, maybe make different decisions than if it's going to be a once every 5-year storm type situation. So I'm just going to open it up in my last few seconds to the panel, if you have any ideas on how Congress could better support decisionmaking like that?

Dr. OPPENHEIMER. Yeah——

Dr. DIFFENBAUGH. Well, we need——

Dr. OPPENHEIMER. Go ahead, Noah. Go ahead.

Dr. DIFFENBAUGH. Well, I think we now have clear evidence that the methods that have been used historically of using the historical envelope of climate extremes are not applicable to the present climate that we're in, and so I think research into how to improve the combination of climate forecasts, and climate observations, and statistical analysis to improve those hazard calculations will be critical for, you know, the design and operation of infrastructure going forward. I——

Ms. SHERRILL. [inaudible] so much. I'm afraid my time's expired. Thank you so much.

The CLERK. Mr. Weber is next. Mr. Weber, you're muted. Mr. Weber's having technical issues. Why don't we go to Mr. Babin next?

Mr. BABIN. Thank you. Thank you, Madam Chairwoman, and Ranking Member Lucas. Thank you to our witnesses for being here today, and Houston is home to a cutting edge state-of-the-art technology that is revolutionizing how we produce our energy. I'm proud to represent Houston, and many of these companies, and will continue to advocate for a stronger and more secure energy industry here in the United States.

When we have a debate over carbon emissions and greenhouse gas——

Mr. WEBER. OK, can you all hear me?

Mr. BABIN. Can you all hear me? I think I'm—am I——

Mr. WEBER. Can you hear me now?

Mr. BABIN. Madam Chair, can you hear me?

STAFF. Yes, we can hear you, Mr. Babin. Mr. Weber, we moved along to Mr. Babin due to your technical issues, and then we will circle back to you as the next Republican. Please continue, Mr. Babin.

Mr. BABIN. Pardon me? Pardon me?

The CLERK. You're recognized to continue, Mr. Babin.

Mr. BABIN. OK, especially when regulations become so burdensome here that our companies are forced to outsource production to these countries with very few regulations. We have to remember that these are countries willing to do anything to get ahead of the United States.

So, Dr. Hausfather, I'd like to ask you, China's commitment to reach net zero emissions by 2060 was heralded as a potential gamechanger, but it lacks the detail to make me really believe that it will happen. It doesn't show how China plans to decarbonize by 2060, or peak their emissions by 2030, which leaves many critics rightly being skeptical. Additionally, it also doesn't disclose a—question is how do we hold these other countries accountable, especially those like China, when they don't play by the same rules that we do? Dr. Hausfather?

Dr. HAUSFATHER. Thank you, Congressman Babin. So I think it is very important that we ensure that we hold countries to the commitments they've made, and in the case of China, you know, it's still early, and there are some very mixed signals coming out of the new 5 year plan in terms of how, you know, seriously they're going to reflect these long term commitments in short term policy. Now, I suspect China's emissions will probably peak sooner rather than later, but the magnitude of the decline that they promised is a very different story.

And so, you know, I think there's a few things that are important to consider here. One is, you know, the potential to consider things like carbon border adjustments in a carbon constrained future, where we actually can punish countries, and products coming from countries, that are laggards in this space. Another area of focus should be on, you know, making it so we, in America, are innovating and creating cheap technologies that countries like China, and India, for that matter, can purchase themselves. Because, again, if they have options that are cheaper than burning coal for electricity generation, and do not reduce—or do not produce the, you know, staggering levels of pollution that are huge problems in those countries, they will transition to those.

And so, as I mentioned in my testimony, I think the real key to getting middle income countries, like China and India, that will be the biggest drivers of emissions this century, to follow the lead of the U.S. in reducing our emissions is to make clean energy cheap, is to give them compelling alternatives to using coal, to using oil, in a way that does not get in the way of their economic growth. And I think that is an achievable——

Mr. BABIN. OK.

Dr. HAUSFATHER [continuing]. Goal, and it's something we've seen an immense amount of progress on.

Mr. BABIN. All right. Thank you very much. And expounding upon that same point, China's overall CO_2 emissions in 2020 increased by .8 percent from 2019 levels, and that was in the middle of a pandemic. This originated in a pandemic which originated in China, where many other nations saw——

Chairwoman JOHNSON. I think we lost him.

The CLERK. Yes, ma'am, Mr. Babin's connection appears to have frozen. We're also investigating possible network issues on House campus.

Dr. DIFFENBAUGH. I'll just add on this topic that, as Dr. Hausfather said, you know, the U.S. can be a source of innovation for enabling leapfrogging to lower carbon energy sources. I'll also note that global warming is proportional to the total cumulative emissions. The U.S. is around a quarter of the historical cumulative emissions, and, you know, as has been published in *The Economist* and elsewhere, you know, China, India, Indonesia are actually decarbonizing faster in terms of their per capita GDP (gross domestic product) than the U.S. and Western Europe have. So those countries are actually on a more rapid decarbonization pathway relative to their economic growth.

Dr. OPPENHEIMER. Yeah, and I'd chip in also that the comment that Zeke made about border tax adjustments, while they're a heavy instrument, may well be the only way to see that any of these things are enforced on an equal playing field, and that countries that make commitments, and then take advantage of them in international trade, are prevented, actually, from doing so because countries have the right to protect themselves by taking compensatory action if they themselves have an honest and strong carbon reduction program.

The CLERK. Thank you. Mr. Bowman is next.

Mr. BOWMAN. Thank you so much, Madam Chair, and Ranking Member Lucas, for this important hearing that we're having today.

Dr. Bontempi, you alluded to this before, but I want to go back to the comments you made about education, and sort of re-imagining and redesigning our education system to make sure our students are prepared, our children are prepared, for the climate realities that we all are dealing with. Can you speak to what that might look like in the K–12 school setting, or even focus on the K–8 school setting? What might that look like as we prepare our kids for this new reality?

Dr. BONTEMPI. Thank you for asking about the education in the K–12 and K–8 systems. I will say I have never been a teacher in that realm, but I was a student, and one of—and I have fourth grader, and what I can say really speaks to him is experiential learning, actually bringing—using tools that will bring what the Earth is like to him. We have these incredible visualization capabilities, we have these students who are so conscious of the environment around them, and so when we have that sort of hands-on teaching, when we actually put tools—the same tools we use for modeling and visualization in the hands of second, third, and fourth graders, they really learn, and they really take to it. They are electronic literate, media literate, and we just have to make them climate literate. The tools are there.

Mr. BOWMAN. Awesome. Thank you so much. Dr. Oppenheimer, can you speak to why investment in technology is not enough to reach our goals, and why we also need strong regulations?

Dr. OPPENHEIMER. Yeah, sure. And I want to say I—there—it's not clear that there's any big disagreement between Dr. Hausfather and myself on this, but I do want to emphasize one point, which is that supporting technology alone doesn't necessarily get the right results. It can move you in all sorts of directions. To assure that the Federal support for technology, whether it's tax incentives or, you know, direct subsidies, or some other approach, are pointed in the right direction, the combination of regulation with such technology incentives are a very effective way to produce the outcome, or at least an outcome in the direction that you want to go.

And I'll point to DOE's longstanding program to increase the energy efficiency of appliances, which goes back to the *Energy Security Act of 1980*, I believe, which combines the development of regulation with a program of R&D support, and has resulted in monumental gains on appliance efficiency, which has really significantly reduced the U.S. contribution to greenhouse gases over a very long term period.

The CLERK. You're muted, Mr. Bowman.

Mr. BOWMAN. Thank you very much. Sorry about that. Dr. Diffenbaugh, your research group has estimated a cost of—cost to the economy from global warming of $5 trillion over 2 decades. Are you able to speak to the loss of life caused by these impacts historically? Are there any projections on your team—that your team has made about the possible loss of life in poor and marginalized communities as warming continues to rise?

Dr. DIFFENBAUGH. Yeah, thank you. And I should note that the—that estimate of the accumulated economic impact on the—from the

U.S. economy of annual—eroding of annual GDP growth is from my colleague Marshall Burke at Stanford. There are a number of pathways by which extreme events impact human health, mortality, as well as economic and ecosystem—the economy and ecosystems. Just with respect to heat, we have clear evidence that heat affects GDP growth, labor productivity, agricultural yields and insured crop losses, food security, migration, mental health, interpersonal and intergroup violence, cognitive performance, wildfire risks, air quality, and a suite of ecosystem impacts, including both on biodiversity and on, you know, biodiversity that is valued for ecotourism.

So there are a number of pathways just by which rising heat exerts those impacts. We also have evidence of, you know, in terms of your question, on mortality, both via the direct impact of heat on human health and via the mental health impacts, and this is also research from my colleague Marshall Burke and his collaborators, that mental health, including suicide risk, is elevated by extreme heat.

Mr. BOWMAN. Thank you. I yield back the balance of my time.

The CLERK. We'll try Mr. Weber now.

Mr. WEBER. Can you hear me now?

The CLERK. We can.

Mr. WEBER. Very good. Even a blind hog finds an acorn occasionally. Listen, it's great to be here. I will note that the gentlelady from New Jersey said earlier Hurricane Sandy hitting in 2012, that she made the comment she sees Texas, I think I'm quoting her, "making decisions without understanding climate change." I would say to my friend from New Jersey that Texas is such a large State that we have just about every kind of climate there is, and I see our great Chairwoman nodding. We have deep freezes in North Texas, and I know that her and her son Kirk probably experienced that here about a month or so back. We have dust storms, we have floods, we have heat waves, we have hurricanes, like she mentioned New Jersey getting a random hurricane, for lack of a better term. We have ice storms in Texas. We've had wildfires in Texas, even earthquakes in Texas, and we have high winds in Texas. And, by the way, for the record, Texas is the No. 1 wind energy producing State in the country, and No. 5 in solar panels.

So I think we've made decisions pretty well based on the fact that we have all kinds of weather, and have had for a long time, so I don't think we should discount the fact that what happened recently was a once in a lifetime storm—winter storm in Texas. I'm 67 years old, never seen anything like it. But anyway, I want to go to Mr. Hausfather. In his exchange with Congressman Lucas, one of the comments he made was while picking winners in early research is OK, but I think he said something to the effect that in latter times the market should drive it. Is that pretty accurate, Mr. Hausfather?

Dr. HAUSFATHER. It is. For mature energy technologies, it makes a lot more sense to use what we call technologically neutral means if we want to create incentives for them. Things like carbon prices, clean electricity standards, clean energy subsidies that are not tied to any particular technology, and so that way we can, you know, give some reward to these technologies for being low carbon, because that is a benefit that is not reflected in the market today, but at the same time not, you know, put our finger on the scale too much in favor of one technology or another.

Mr. WEBER. Right, and we would agree, you know, I think most of us would agree. And just a quick breakdown of the Texas grid, since I went there. It's 108,000 megawatts of generating capacity. 48 percent of it is natural gas, 13 percent coal, about 1/2 a percent nuclear, almost 29 percent wind, and almost 1 percent solar. And, of course, we saw in that historic event that the wind generation severely hampered because the blades iced up. Of course, obviously, at night we don't get a lot of solar energy, and so nuclear would seem to be about one of the best possibilities for the cleanest energy. What say you, Mr. Hausfather?

Dr. HAUSFATHER. So I think nuclear is a really important technology. It's 20 percent of our clean generation today, it's our single biggest source of clean generation nationwide, and we should really make sure that we don't lose that, because a lot of our nuclear reactors today are at risk of shutting down, in large part because they can't compete with natural gas on the market. And some of that is the fact that the clean energy benefits of nuclear are not being reflected.

But beyond that, you know, as I mentioned in my testimony, there is a real need for a solid amount of clean, firm generation if we want to fully decarbonize our economy, and nuclear is one of the key technologies to get there. Now, the challenge we have today is that building new current generation nuclear reactors has proven really expensive. They've been over time, over budget, and, you know, as Americans, we've just gotten bad at building big things, and so we need to figure out how to do that again, how to build these projects on time, on budget so we don't lose out to China, who is really doubling down on sort of conventional nuclear reactors. At the same time, you know—go ahead.

Mr. WEBER. OK. Well, thank you for that, and lest I sound—you know, we're good at building big fences around the Capitol. Did I say that out loud? But anyway, I do want to say that you also said—I would think—you were hearing a clarion call for the Federal Government to get involved in producing energy, it sounds like, or paying for energy, for there's a lot of communities who the people suffer when it's hot, they suffer when it's cold, but I just want to make this point. In my opinion, it would be more appropriate that the local communities—yes, Texas, believe it or not, can make decisions for itself that does take into account all kinds of weather patterns. And I would say that it's more appropriate to let cities and States decide what action, if any, they want to make in those endeavors, and for us to be involved in the research. And with that I will yield back Madam Chair. Thank you.

The CLERK. Mr. McNerney is next.

Mr. MCNERNEY. Well, I thank the Chairwoman for this hearing, and I thank the witnesses. Your testimony is stark, it's somewhat alarming. Clearly we need to take action.

Dr. Oppenheimer, thank you for your testimony. I thank all the witnesses, really. You noted that achieving the Paris Climate Agreement goal of limiting to 2 degrees Centigrade will not only require halting greenhouse gas emissions, but will also require removing carbon dioxide from the atmosphere. Carbon removal can take many forms, including forest and ocean-based sequestration, better soil management, which I'm thrilled about in my district, direct air capture, and storage. What is the state of the science on carbon removal, and what will it take to make these technologies viable?

Dr. OPPENHEIMER. Well, first of all, thank you for the question, Congressman. I'd like to say first that it's not clear how much what are called negative emissions we will need, that is carbon removal, because we don't know really what the business as usual baseline emissions are going to be. But let's assume we're going to need some if we're to get close, or actually comply with the Paris well below two degrees Celsius target. The technology that's been talked about recently is, as you mentioned, direct air capture. It's one in which we kind of know all the pieces, but we don't have it put together yet as an integrated system at a price that's commercially acceptable.

So the National Academy came out with a report I think 2 years ago asking for a substantial Federal commitment to R&D on direct air capture, and I think that's a wise investment, among many, that should be made on ways to avoid having too much carbon in the atmosphere. Of course, it goes without saying that we ought to get our act better together on using natural ecosystems as carbon reservoirs, and that means, first and foremost, finding ways to assist the global move toward ending deforestation.

Mr. MCNERNEY. Thank you. Well, even if we eliminate carbon and other greenhouse gas emissions, the climate's going to continue to warm for years, or even decades, because of the greenhouse gases already in the atmosphere. I worry that we're going to go—blow past the 2 degrees Celsius increase, given both the political roadblocks to measures such as a carbon fee here in the United States, and given the technology that we have available. We clearly need to develop—we clearly need to reduce carbon emissions and achieve zero—net zero emissions, we need to implement carbon removal technology as soon as possible, but we also need to do the science necessary to understand if taking direct steps to cool the atmosphere, such as cloud brightening, and injecting sunlight reflecting particles into the stratosphere, are those viable strategies? What's the risk? Dr. Oppenheimer, given the complexity of the climate system, and the risks associated with further human interference in it, how do you think the U.S. should approach the field of climate intervention?

Dr. OPPENHEIMER. I personally feel that we should approach it with great caution, that we're not at a point where we understand the climate impacts at the regional and local level that would occur as a result of geoengineering. We know that such methods can be used to offset the global warming, but people don't live in the globe, they live in places, and how it will affect particular places has substantial uncertainty. But we ought to support research. I think it's important to do computer-based modeling of what a geoengineered world would look like. You know, I don't think we should be out there blasting things—into the atmosphere to see the effect now. It's way too premature for that.

And I'll so say there's another component to this, which is how will countries react? This is something that could be done, in theory, by one country. Can we reach agreement on how that's to be done? If we become kind of familiar or friendly to the technology, we unleash a lot of possibilities, which could lead to global conflict between countries in the long term. We ought to be very cautious.

Mr. MCNERNEY. Sure. Dr. Diffenbaugh, would you like to answer the same question?

Dr. DIFFENBAUGH. Yeah. Well, I like what Professor Oppenheimer just said about the research on potential for single actor geoengineering and potential conflict. This is an area where, you know, there are—there is scholarly inquiry, and we certainly need more of that, and we need that to be enhanced in order to fully understand the dimensions. It's certainly asymmetric with the collective action problem of greenhouse gas emissions and global warming. You know, the greenhouse gas emissions affect the global climate system through the aggregate effects of emissions everywhere. There's no single actor that can singlehandedly stop global warming from happening. That is very asymmetric with the geoengineering that was described, where there is potential for single actor, frankly, disruption, and I mean disruption in a very technical sense, in terms of climate patterns regionally.

Mr. MCNERNEY. Thank you. I yield back.

The CLERK. Mr. Sessions is next. Mr. Sessions? Mr. Sessions is recognized.

Ms. SESSIONS. Thank you very much. I really want to commend Chairwoman Johnson and our Ranking Member Lucas for this meeting. I think that the most important thing that I have heard today comes from our witnesses who have talked about necessarily throwing out the occurrences of things that have happened maybe on a once in every 100 year basis, and going to things that are reoccurring, working together and finding things that, on a bipartisan way, we can agree with that then last through administration after administration, but that become meaningful, and agreements between reasonable people who are trying to make progress. One of these may be the tax credits that come from wind usage.

There may be many other things that I think that would fit, but I think that the balance of this hearing should be off finding common ground, and I think, after listening to our guests this morning who gave testimony, that is the most important part of what I've learned, so that we don't start and stop, and move one direction and then back, but rather make meaningful money, policy, the needs of the Nation to be consistent, and it is what I have enjoyed hearing from this important viewpoint of why we have to make progress, and how measurable it can be if we work together in a balanced way.

With that said, I am from Texas. I recognize we're going to have hearings that are going to be on Texas. What happened in Texas was one of those activities that perhaps Noah or Paula may have been in reference to that it was something that happened, and it might happen again, and we ought to understand how we ought to prepare for it, but that the system that was designed, is designed on a regular basis to support each other, and in this case Mother Nature made sure all 254 counties in Texas had virtually the same outcome, meaning effect, and so it diminished our ability to effectively help each other. And it's this kind of thing that we do need to study, and Michael, I think you addressed part of this, study of facts and data can draw you to a conclusion.

Michael, when I was at the old Bell Labs in New Jersey, four or 500 years ago, we tried to learn about how often things occurred, and what that impact is, and I find your balance, and the balance that you bring with Noah also to this, and Paula, really helps us focus on making a difference in a bipartisan way, meaningful to where we move with each other on a consistent basis over years, and set a national strategy that is not based upon outliers, but based on regularly occurring things. And this is one of the things that's a takeaway for me, Michael, for living in New Jersey—a Texan living in New Jersey, but around a lot of people who tried to be artful about making a difference.

I'm now down to my last 23 seconds, but the last part is I'd like to thank our Chairwoman, Eddie Bernice Johnson, for bringing together not just the discussion, but also bringing along Frank Lucas in a way to where we can make a difference together. My time is now at 1 second. I yield back my time, and I thank our witnesses.

The CLERK. Mr. Tonko is recognized.

Mr. TONKO. Thank you, and, Madam Chair, thank you for this hearing. By working to address the climate crisis we have the opportunity, I believe, to usher in a new era of economic growth, job creation, and prosperity for all Americans. And it's clear that there is a great deal of potential for the United States to be a leader in developing climate adaptation and mitigation strategies and solutions, particularly through innovative research and emerging technologies.

So, Dr. Diffenbaugh, aside from the obvious economic benefits of being a lead developer of cutting edge technology, what else does the United States stand to lose if we do not focus on developing these technologies?

Dr. DIFFENBAUGH. Well, we're experiencing the impact of the global warming that's already happened literally day after day, month after month, year after year here in the United States. And I mentioned in my opening remarks, you know, the recent research from my group about flooding costs in the U.S., and when we look back at, you know, the—month by month what damages, you know, financial cost of flooding over the last 3 decades, you know, we find that not only have the, you know, the most extreme precipitation events are responsible for a large fraction of the flooding, but that precipitation has been changing in many parts of the country. In particular the intense precipitation events have been increasing the most, and what that means is that around a third of the flooding costs from, you know, over the last 3 decades are, you know, being contributed by those changes in precipitation. Those changes in precipitation are exactly what was predicted, you know, literally decades ago. It is exactly what we have high confidence will continue to intensify.

So as with this one example I've described in detail, and so many other examples of extreme events that are already impacting us here in the United States, and around the world, the more global warming we have, the greater the impact, the more it will cost.

Achieving lower levels of global warming, like what's in the Paris agreement, will reduce the trajectory of those costs, and will still leave us with further change. And so, as I said in my opening remarks, we need both mitigation and adaptation. We have enough knowledge to get started on accelerating both of those, and the transition—the gap for both of those is large, and so we need research in how to achieve both of those in concert, and in concert with other policy priorities.

Mr. TONKO. And I want to thank you for that. And, again, Dr. Diffenbaugh, what are the impacts of not developing a robust climate response program in the U.S. that includes scientific research alongside the development and deployment of technology?

Dr. DIFFENBAUGH. Well, there certainly are financial costs, and, you know, various estimates, including from my colleague Marshall Burke and I, you know, are in the trillions of—in terms of damages at higher levels of warming relative to the Paris agreement, and that's just in the U.S., so we're facing potentially trillions of dollars in, you know, eroded economic growth. And just as important, you know, we're facing an increasing intensification of the kinds of once in a lifetime events that we're experiencing more and more frequently. It's not just that we're now more aware of everything happening everywhere all the time, it's actually true that these unprecedented events are increasing in frequency.

And I would say that the biggest transition in both our thinking and our research that's needed for curbing these events, for not being caught off guard and incurring these huge costs is an acknowledgement that we're now in a climate, and we will continue to be even in a more intense version of a climate where unprecedented events are happening overlapping, overlapping in one place one after another, and overlapping in different parts of the country at the same time. And so what used to be this never happened in my lifetime is already becoming frequent, and at two degrees of global warming it will become normal, and at four degrees of global warming it will become, you know, in some places, you know, every year warmer than the historical coldest year that we know in our lifetime.

Mr. TONKO. OK. Well, with that I thank you, and I yield back, Madam Chair.

The CLERK. Mr. Garcia is recognized.

Mr. GARCIA. Thank you. Thank you very much, and thank you to all the witnesses, and Madam Chair, for this very great hearing.

We are in the midst of a crisis, and I applaud our collective use of the word crisis. I think when there's lives endangered, and our national security is being threatened, that's an appropriate word. And I think we should apply that same concept, and have the courage to apply that to what's happening at our southern border, but that's another Committee hearing. I think during any crisis the key is to make the right decisions. There's critical decisionmaking processes that we're going through right now. There's multiple paths to success, there's multiple paths to failure. Some of the failures can be catastrophic. Some of the successes can be more beneficial than others, and I think we're at that point in our Nation's history where the next 5 to 10 years will determine our trajectory, and the long term longevity of our Nation, as a result of how we deal with this.

I come from California, where we have a lot of wildfires. I'm right in the middle of wildfire season and country, right? We see it all the time. One of the failures that we're recognizing here locally is that our local politicians, counties, at the State level especially, and even some of our Federal representatives are not recognizing the physics of the fire triangle, and they're instead blaming climate change for the fires. Therefore, they're not investing in things like deforestation, forest management to remove the fuels from the fire triangle, or to, for instance, invest in more large aerial tankers to actually remove the heat and BTUs from the fires once they start. And attributing it to climate change rather than addressing the physics locally has actually cost us more money, and more lives, and infrastructure than we probably should've realized. That's one example of making poor decisions in response to a crisis, and I think we can do better in that regard.

My question, I think, is for Mr. Oppenheimer. One of the commitments as part of the Paris Climate Accords is a contribution of I believe $100 billion from I believe the language is from rich countries to poor countries. How are the other nations, call it 195, or the subset thereof that's responsible for this distribution of wealth program, performing relative to those commitments? I believe our Nation is on the hook for roughly $3 billion. What are the other nations doing, and what is the status of that $100 billion target?

Dr. OPPENHEIMER. So the $100 billion target has to be understood. It was not supposed to come out of public funds, but was—public funds was supposed to leverage private investment in projects like developing renewable energy in countries that need a little assistance to get there for—or to stimulate adaptation in countries that have barely any emissions, but who are affected by the climate change that's brought about by the emissions of China, the U.S., Europe, Japan, et cetera. So it's not like it was supposed to be a government—a big government slug of money.

That being said—and I—there has been one assessment, you'll have to allow me to get you the reference later, which showed that actually the governments were, after a very slow start, beginning to hold up their end of the commitments. I can't tell you how much the U.S. versus China, or India—well, India probably isn't a donor in this case—the European countries gave. I'd have to look that up. But after myself being very skeptical, because these are the kinds of commitments that are rarely actually abided by, they're rhetoric, the countries actually have stepped forward more than I would've expected, more than many expected, and it's that leverage on private funding that had made the program work better.

Mr. GARCIA. OK. So I guess if we're not really tracking, or necessarily thinking too much about the financial commitments of the accord, how are we doing from an actual performance relative to reductions of CO_2 as an organization within an agreement, besides the United States?

Dr. OPPENHEIMER. So the latest suggests that the commitments that were made, the nationally determined contribution at Paris, and in some cases shortly thereafter, are not being fully implemented. That doesn't mean that nothing's being done, it means that countries have, in some cases, put other things ahead of climate change. It's shortsighted, but that's happened. Or, in some cases, that the political consensus hasn't been as solid as it would need to be, like in the United States. But you can't—so you can't declare Paris at this point either a failure or a success.

Mr. GARCIA. Understood. Thank you, Dr. Oppenheimer. If I can reclaim, I think the cost estimates of us remaining in the Paris Climate Accords are $3 trillion to our U.S. GDP, and will ultimately cost us 6.5 million jobs. I think this is one of these decisions we do need to look more closely at. There may be other alternatives to get to success that are actually more beneficial to the climate and our economy. Thank you. I yield back.

The CLERK. Mr. Beyer is next.

Mr. BEYER. Thank you, John, very much, and Madam Chair, and Ranking Member Lucas, thank you very much for pulling this together. This is the existential crisis before us, and with respect to the tradeoffs, we traditionally underestimate our existential threats. All the psychology research shows that, and that's what we have done for far too long.

Dr. Hausfather, you've mentioned how, even if we get emissions all the way down to net zero, global temperatures aren't going to fall for many centuries to come. We're going to actually reduce global temperatures, we need net negative emissions, sucking more CO_2 out of the atmosphere than is going in. We've been looking at a number of these different net negative technologies, but can you talk about direct air capture and the scale of their deployment?

Dr. HAUSFATHER. Sure. So direct air capture is one of the most promising negative emission technologies on the table, in part because it has the ability to capture a large amount of carbon using a fairly small amount of land area. The other that we look at, like Dow Energy with carbon capture and storage, have a huge land footprint, and involve huge tradeoffs with land that would otherwise be used to provide agriculture, which can lead to additional deforestation if it pushes that into other areas.

But direct air capture is essentially using chemical compounds to bind with carbon in air that's pumped through a large device, and produce a solid sort of calcium carbonate type output that then can be easily buried and sequestered underground. The challenge with direct air capture is it is very energy intensive. It requires a lot of energy to run these machines. We would need many hundreds, if not thousands of them, to make a big dent into global emissions. And because they're very high capital cost, you really want to have a high operating capacity factor for these devices. And so a world where, say, we have lots of extra solar during the day, using that extra solar to run direct air capture is great, but it doesn't make much economic sense, unless you can run these devices close to 24/7.

And so there's been a lot of discussion around, you know, potentially tying them to new advanced nuclear reactors, or, you know, ensuring that the larger grid is decarbonized by the time we deploy these at scale. Because we don't want to be using energy that releases CO_2 to capture CO_2 from the air, otherwise, you know, we're not really making much of a benefit at all.

Mr. BEYER. OK, thank you. My hometown's Alexandria, Virginia, and we suffer nuisance flooding. And, of course, I'm in Virginia, with Norfolk and Virginia Beach, which seem to be underwater half the year. And the coastal resilience is such—so incredibly important. We have the *National Ocean and Coastal Security Improvement Act* just to try to prepare this. But, Dr. Oppenheimer, can you touch on how we need to proactively take higher sea level rise into account, and why it's so much more important to be proactive than reactive on this?

Dr. OPPENHEIMER. Well, just to get to nuisance or sunny day flooding, that's become a real nuisance around the country. It was a very rare occurrence where people actually lived, where infrastructure existed, if you look at the data from 50, 60 years ago. And it's gradually increased, and that's largely because of sea level rise. And so communities, you know, parts of the city I live in, New York, parts of Miami, parts of other places are starting to see this gradual problem go from 1 or 2 days a year to 30, 40, or 50 days a year. And that—and you can't defend against that instantaneously.

The things that need to be done are, by and large, decisions which are politically difficult, like deciding that certain areas aren't going to be inhabited anymore, and the governments can't afford to keep up the infrastructure in those places and you relocate people, or pay them to move voluntarily or require temporary adjustments like raising their houses. Alternatively, the U.S. can build large, protective infrastructure, the way the Dutch have done all over their country, or as we have done around New Orleans, which has reshaped that city more than once. You can't make that kind of decision today and complete it tomorrow. The planning takes 10, 20, 30 years, and the thing doesn't get built until the planning, the political consensus, the finance of the construction are done. And in the case of a big project, that's 30 years. So if we want to worry about the storms that are now once in a 100 years happening once a year in 2050, we'd better get going on it——

Mr. BEYER. Thank you, Dr. Oppenheimer. And to my Republican pals on the call, and all who have, you know, the mandate to defend the fossil fuel jobs, we need to be thinking about what happens when fusion energy comes, and the displacement effect that's going to have on all these things. With that, Madam Chair, I yield back.

The CLERK. Mr. Baird is next.

Mr. BAIRD. Well thank you, and thank you, Madam Chair, and Ranking Member Lucas, for holding this session. I want to bring in the perspective of agriculture, and in that I include the forest industry, but I understand that we need to invest in clean energy, and solutions in climate change, but I think we ought to go beyond those that just seem overly idealistic. And so Ranking Member Lucas suggested that we invest in those science-based innovations that improve our ability to produce energy more efficiently. So agriculture, we have a similar conversation about the intersection of agriculture and climate change, highlighting the important contributions that farmers and ranchers can do to help mitigate the impacts of this climate change. One of the most interesting contributions that I found very striking was the fact that 46 percent lower carbon emissions if we use ethanol.

And then I want to catch to what Mr. Garcia had to say, and Mr. McNerney had to say. When you look at forests, forest land and hardwood products, urban trees, they can collectively offset more than 11 percent, or about 3/4 of a gigaton, of CO_2 per year, and that's about 14 percent of the CO_2 emissions. So my point to you is that we have a lot of things taking place in agriculture, and Representative Garcia mentioned that we are not practicing forest management in a lot of our public lands out west, and that contributes to a lot of more BTUs when we do have a fire.

So these are things that we can do immediately, and so I am just interested in the witnesses' comments about using those things that are in place now, and how we might invest more dollars in research, more dollars to incentivize farmers, and ranchers, and forest owners to do management practices that capture carbon in the soil, or capture carbon in the trees. My data would suggest that trees capture almost 6/10 of a metric ton of carbon per hectare per year. So I'll turn it over to the witnesses, and would appreciate your comments about how we might use these existing systems, natural systems, to help us with helping affect climate change. And I guess I might start with Dr. Bontempi, because you mentioned that carbon is captured in cold water, or ice, and sinks to the bottom of the ocean. So let's start there, and then, if we have time, we'll have other witnesses comment.

Dr. BONTEMPI. Yeah, thank you. I appreciate the opportunity to respond to the idea of carbon capture on the land. You know, I think one of the things that we have to be conscious of in this regard is, you know, people on the land, farmers, agriculture, are familiar with things like droughts, the wildfires that were already mentioned, and a few other phenomena that have been occurring at the extremes, as we've been discussing, and these have a huge impact. And these climate extremes have been discussed by some of the other witnesses as well.

It is true that trees, or anything that photosynthesizes, takes up carbon dioxide and goes through that process, and can release oxygen. The questions become how effective are things like trees at permanently storing that carbon, how long does it take to get back in the atmosphere. These are areas of active research, not only in observations but in modeling, and, of course, the Earth isn't infinite. How many trees do we have to plant to actually have an effective drawdown of the deltas that we need in the atmosphere to make it a long-term storage solution?

So I would think at this point I would defer to some of the other witnesses to respond, if that's acceptable, because they have a bit more experience with that carbon drawdown, and permanent capture on land.

Dr. HAUSFATHER. Yeah, if I could add to that, you know, reforestation is one of our best, most cost-effective ways at sequestering carbon, and using nature instead of our energy to do most of the work. At the same time, even if we were to plant a trillion trees worldwide, it would only offset about 8 years of current global emissions. And so it's an important part of the solution, but we need to make sure that we keep it in context, and don't sort of treat it as a replacement for ultimately reducing emissions.

Agriculture is also an area where there's huge potential for building up soil carbon. I can send around a paper that I published in 2018 that covered some of these approaches, but it's an area that we need—to pursue.

Mr. BAIRD. I see I'm out of time, so I would be very interested in the other witnesses' responses, but, Madam Chair, I yield back.

The CLERK. Ms. Ross is next.

Ms. ROSS. Thank you, and thank you, Madam Chair, and Ranking Minority Member for your—for having this hearing. It's so, so important, and it's particularly important for my home State of North Carolina because we've seen the effects of sea level rise on our coast. We have a highway, Highway 12, that's underwater frequently, and we're building bridges, and trying to beat that back. And then we're also No. 2 in solar in the country, and we're dealing with issues of how to get that energy resource on our grid.

My first question is for Dr. Oppenheimer, and I want to build off of some of the things that Mr. Beyer was talking about, about how to incentive local governments to use research. So it's clear that we want to know what's going to happen with sea level rise, though my State legislature in the past hasn't always wanted to know. But once we have these tools, and we know it's hard to make those political decisions, and it's expensive, what could the Federal Government do to incentivize local governments to take the necessary action to protect people and to protect property?

Dr. OPPENHEIMER. Thank you for that question, Representative. There have been discussion for years of developing at the Federal level a climate services, sort of like the weather service, to, you know, turn this information into something that's practical, and that can get into the hands of the decisionmakers that need to make the decisions. Now, I don't know if that's the right answer, but it may be, but it could be done in cooperation with similar sorts of structures at the State and local level. The good—the interesting model is the agricultural extensions, which for over 100 years have developed local solutions for farmers operating in particular States, in particular areas, working through local universities, for instance, and in that—network of information which is designed not for the elite level, but for the people who actually use it. So this is something that is doable that probably isn't that expensive, and the States and the Federal Government together should get on it.

Ms. ROSS. Well thank you very much, and thank you for saying it wouldn't be that expensive. That's very attractive. I have a question for Dr. Hausfather about the grid. So North Carolina is No. 2 in solar. I've actually represented a number of renewable energy companies, I did that in private practice as an attorney, and what we're learning is, you know, now we have these cheaper solar resources, but the biggest issue is interconnection, and who is going to pay for that interconnection, and then who is going to pay to upgrade the grid. And I know that FERC has a cost-sharing model, different States are then left to their own devices for the model, and frequently it's the renewable energy company that has to pay for those upgrades, and those upgrades, though, end up redounding to the benefit of the utility when it comes to dealing with rates.

And so I wanted to know whether you had any creative solutions about how we might do this not just State by State, but on a national scale.

Dr. HAUSFATHER. So I think there is a real role for direct Federal spending in building out a 21st century grid for the U.S., and we need to recognize just how important it will be to enable the clean energy transition at the scale and the speed we need. I'd like to point to a study by the National Renewable Energy Laboratory about—that suggested it'll cost about $80 billion to build a 21st century super grid, it would create hundreds of thousands of jobs, and it would ultimately more than pay for itself in cost savings for people across the country. And, you know, in a time when there really is a need to put people back to work, and when the economy is suffering, infrastructure like long distance transmission is a really important way to get boots on the ground quickly.

Ms. ROSS. Well thank you very much for that. Hopefully we can talk about that in our Energy Subcommittee. Madam Chair, I yield back.

The CLERK. Mrs. Bice is next.

Mrs. BICE. Thank you, Madam Chairwoman and Ranking Member Lucas, for the opportunity, and thank you for the witnesses to join us this afternoon. 30 years ago Sandia National Labs played a huge role in developing PDC bits. They were developed and sustained through specific technology research, and they had an immediate impact on the oil and gas industry. We talked a little bit earlier about how technology plays an important role in helping climate change. These are the types of investments that we should be making to ensure that we're looking toward the future and not just focusing on what's happening today. You know, according to the Acting Undersecretary for Science and Energy, Kathleen Hogan, she said there's an enormous amount of untapped potential for enhanced geothermal systems to provide clean, reliable electricity to power tens of thousands of homes across the country.

I'll start with Dr. Hausfather. Is it safe to say that global economic development can rely on fossil fuel, at least in the near term, but, in your opinion, when we're looking toward the future, would it be better to give developing countries money to combat climate change, or the technological tools that we may be developing here in this country to reduce greenhouse gas emissions?

Dr. HAUSFATHER. So I think it is important to recognize that we're not going to get rid of fossil fuels anytime in the near future. But at the same time, there's sort of an order of operations for fossil fuels, right? Coal is by far the most carbon intensive, then comes oil, then comes natural gas. And so if you look at the type of models that we developed that look at how the globe might be carbonized, you see a transition away from coal first, then away from oil, and then ultimately away from natural gas.

As to your second question, you know, I think geothermal's a really exciting area right now. You know, I think it's, in many ways, in a similar position to where the fracking revolution was 2 decades ago, and, you know, diamond drill bits, which you mentioned in your opening, are actually playing a huge role in unlocking enhanced geothermal today. And so this is one of the type of technologies, you know, renewables are obviously another, advanced nuclear is a third, where making them cheap enough so that they can compete with fossil fuels on the market is going to go a huge way to get them adopted by the rest of the world. You know, direct support is important in some occasions, particularly for adaptation health, but ultimately, given the scale of the energy transition needed, particularly in middle income countries like India and China, it's making clean energy cheap that is the single biggest lever we have to drive adoption and emission reductions by the rest of the world.

Mrs. BICE. Anyone else like to comment on that?

Dr. DIFFENBAUGH. Yeah, I would add that—go ahead, Professor Oppenheimer.

Dr. OPPENHEIMER. Quickly, I'd just like to add, you know, I actually agree with Dr. Hausfather said, with the caveat that—be careful with the ordering of fossil fuels. They all have problems, and in particular, unless the leaks of natural gas due to drilling, transmission, and distribution are eliminated, then the benefits of using natural gas for greenhouse gas emissions reduction are largely eroded.

Dr. DIFFENBAUGH. Yeah, I would add—I really appreciate, Congresswoman, your emphasis on looking both at the present and forward in the future, and when we look over the coming decade, the world will need to supply more energy than it's supplying now, and with greater access. That's true both in the U.S. and globally, and on the order of doubling of energy supply. To stabilize the climate system at any level will require reaching net zero emissions. That's not a political statement or a policy statement, it's simply the fundamental energy balance of the planet.

Mrs. BICE. Which I don't disagree with your statement, but I think one of the challenges that we should all be thinking about is that the United States can become net zero, or even net negative, but that doesn't affect the issues that we're facing in China and India with them using high amounts of coal, as a matter of fact building coal-powered plants, and increasing those emissions into the environment, which is really causing what we're doing here to be irrelevant.

Dr. DIFFENBAUGH. Well, all of the emissions aggregate to affect the global energy balance. So the global—the fundamental physics of the planet are that the emissions, from wherever they are, the greenhouse gas emissions are mixed in the atmosphere, and affect the global temperature, and the climate around the world. So I actually am supporting your statement, but the reality is, regardless of the level of global warming, to stabilize the climate system at any level requires reaching net zero, and that's more global warming than we've already had, which means adaptation will be necessary. We're not adapted to the climate change that's already happened. Further climate change will require further adaptation. The U.S. can be an innovator and a leader in all three of those dimensions. All three of those dimensions are needed here in the U.S. to manage climate risk, and we can do exactly what you described, in terms of supporting the rest of the world through innovation in each of those dimensions.

Mrs. BICE. But without a focus from India and China on this very issue, what we're going to be doing in this country won't be an impact globally. Madam Chairwoman, I appreciate the time, and I yield back.

The CLERK. Mr. Foster is next.

Mr. FOSTER. Thank you. Am I audible and visible here?

The CLERK. Yes, sir.

Mr. FOSTER. All right. Well, let's see, I'd like to start by asking—maybe getting reactions to what are sometimes called Bill Gates's five questions, and whether you think that's an appropriate way to look at this problem. You know, his questions are, you know, first off, for any proposed solution, how much of the 51 billion tons are we really talking about, that we want to make sure we do our research in the areas which will really take a big bite out of that, instead of sort of boutique solutions.

Second question is what's your plan for cement? By cement he means cement steel, you know, the other boring ways that we make—we put a lot of carbon in the atmosphere, but are—don't seem to be doing as much research toward lowering the footprint there. How much power are we talking about, how much space do we need, and most fundamentally, how much is this going to cost? This is what Bill Gates referred to as a green premium. A decade ago this was the formalism of the McKinsey plot, where you look at the number—the cost per dollar of carbon mitigated, and you line up just everything you might do to mitigate carbon, and you start with the ones that cost the least, and you get them down until you've solved the problems, marched down the list, which I always thought was a pretty good way of analyzing this problem.

So I was wondering if any of you have a reaction to that, if that's really the best way for Congress to think about this problem, or are there holes in that methodology?

Dr. OPPENHEIMER. Well, let me just answer that first in this way. I think that the idea of looking at where the big bang for the buck is—if that's what Mr. Gates meant—it's a little hard sometimes to know exactly what he means—that that's in general a good principle in life. So if there are big gains that could be made against a relatively modest sector, take the gains. If there are big gains that could be made against a big sector for, you know, a reasonable cost, take that. The biggest gain that's been made against the greenhouse effect has been actually under the Montreal Protocol, which was not designed to deal with climate change but originally was intended to protect the ozone layer. But those gases happen to be strong greenhouse gases, so they took off the table a lot of what's called climate forcing, and we'd be even in worse shape today than we are if that hadn't been done. So looking for opportunities where you can do two things at once is also a very smart idea.

Where I have trouble with the Gates message is that it can be read as saying there are technological silver bullets, if we're just smart enough to find them, and that's the role of government, and I think that's just wrongheaded. As I mentioned before to Congressman Bowman, you need a combination of appropriate support for technologies and appropriate regulation to put the incentives in front of industry to head in the right direction.

Mr. FOSTER. Um-hum.

Dr. HAUSFATHER. If I can add to that, I'd like to echo Dr. Oppenheimer. You know, I think we have a lot of the technologies that we need today, and we should recognize that we don't have all of them. There is a real need for continued innovation both to drive down the cost of the technologies that we have, and to develop the technologies for hard to decarbonize sectors of the economy like industrial heat, like steel production, glass production, cement production. You know, there we don't really have cost-effective ways to replace fossil fuels today, and so it's sort of a yes, and approach. And also we do need to avoid sort of silver bullet thinking when it comes to energy technology. There's no single technology, be it renewables, nuclear, whatever, that is going to solve this problem by itself. We really need an all of the above approach to clean energy, recognizing that different regions of the U.S. will have very different resource availabilities and different requirements around decarbonizing.

Mr. FOSTER. I was also struck by the difference in your testimony in attitude toward tipping points, you know, that I think—I believe it was Mr. Hausfather's observation that really, you know, as you continue to pour more CO_2 in the atmosphere, it just sort of gradually got worse. There's not some magic point where positive feedbacks took over. But then, on the other hand, you know, there are things like the reversal—the stoppage of the Gulf Stream that seem like they are a really scary near term risk, that there's apparently geological evidence that, you know, in the time scale of a decade, the Gulf Stream has stopped and restarted, and indications that the slowing down may be happening now. You know, if that happens, we don't have 50 years to respond, and, you know, Scotland's going to look pretty different if that happens. And I was just wondering what your—is there, really, a scientific consensus on this issue of tipping points?

Dr. DIFFENBAUGH. So there are absolutely thresholds in the climate system, and, you know, some of them are known knowns, some of them are known unknowns, and surely there are unknown unknowns as well. We're seeing with, you know, the large glaciers non-linearities emerging, you know, in real time. That has huge risk for sea level rise, for example. We certainly see, with the effects of heat, many non-linearities. We heard about the importance of agriculture earlier. There are very clear non-linearities, with very steep declines above temperature thresholds, and global warming is already increasing the frequency of occurrence with which those thresholds are crossed.

And this brings me to my final point, which is it—the importance of adaptation, and research and adaptation. The adaptation gap that Professor Oppenheimer mentioned earlier is large. It's large at present, and it will grow as global warming continues. We—frankly, in order to manage the risk to reduced impacts, we need further research in how to design, develop, and deploy adaptation solutions at scale.

Mr. FOSTER. Thank you. My time is up, and yield back.

The CLERK. Mr. Feenstra.

Mr. FEENSTRA. Thank you, Madam Chair and Ranking Member Lucas. Before I start, I just want to thank each of the witnesses for their testimony and sharing their extensive research and opinions with us.

Dr. Hausfather, in my district, Summit Carbon Solutions and Little Sue Corn Processors are teaming up for a carbon dioxide capture and storage project. The partnership aims to capture 444,000 tons of carbon annually, which will lower the refinery's footprint. It will also be part of an infrastructure network with other vital refineries that will have the capability of capturing 10 million tons of carbon annually. Will large scale partnerships like this be crucial to achieving significant lower carbon emissions? And then, No. 2, they cited 45Q tax credits as being crucial in allowing their companies to invest in these technologies. Could you comment on what types of current or new incentives would help encourage this type of carbon reduction and capture?

Dr. HAUSFATHER. Sure, I'd be happy to. So carbon dioxide removal is a critical technology to meet the climate goals we have today, both because there are some hard to decarbonize parts of the economy where, you know, it simply is going to be the most cost-effective solution to capture the carbon from fossil fuels, rather than replace them with something else. And because, as the other witnesses have discussed, you know, we may want to reduce our global emissions below zero in the future, and we need these sort of carbon capture technologies to be able to do that. And so I think we definitely need to be investing more in these than we are today.

In terms of the types of things that can help, one big one is just long term certainty, and 45Q goes a long way to doing that, to make sure that these companies know that there will be a market for the carbon that they are capturing, so to speak, a price that's being paid to them. The second is more of an investment in the supporting infrastructure around carbon capture. You know, capturing the carbon itself is, in some ways, one of the easiest steps. Then you have to actually have pipelines associated with that, you have to have long term geological storage that proximate, and so making sure that we invest in those infrastructure as well can really enable carbon capture to scale.

Now, carbon capture is not going to be the solution. You know, obviously a number—a lot of sectors it's going to be easier to replace fossil fuels with clean energy sources. But certainly for some sectors it will be a big part of the solution.

Mr. FEENSTRA. OK. So let me just expand on that a little bit. So carbon capture, especially with biorefineries, we can get down to a net negative. With biofuels, this seems like the greenest form of energy, and yet there's this agenda of pushing electric vehicles, which in itself has a lot of problems with, you know, creating batteries, and all this other stuff. How do you see biofuels playing out in this greater plan of reducing carbon?

Dr. HAUSFATHER. So today the dramatic cost declines we've seen in batteries have really unlocked a powerful electric vehicle market for light vehicles, but I think there is, you know, an important role for biofuels, both for some light vehicles, and we'll see how those end up playing out in the market, you know, depends a lot on what happens with these technology costs going forward, but also for things like heavy duty transport over long distances, where, you know, limitations of batteries make that a bit more costly and more challenging, and especially for things like long distance shipping and aviation, where using electricity for those transportation purposes are—you know, possible, but very, very difficult.

And so, you know, biofuels are an important part of the solution as well. You know, we do need to be cognizant of the impacts of growing biofuels if they're offsetting other activities. You know, if you're pushing, say, more deforestation in Brazil by reducing agriculture output in the U.S. by devoting a lot of land to biofuels. We're not really there today, but those secondary effects do need to be considered when looking at impacts of biofuels. But I agree that carbon negative biofuels through carbon capture and storage is a really exciting technology, and it's one that is used at an extremely large scale, and a lot of the energy system models that are used by the IPCC to model some of these emission pathways.

Mr. FEENSTRA. Thank you, Dr. Hausfather. I look at it this way. I am in the Midwest, in Iowa, and we have this corn kernel, or we have this soybean, that holds energy, literally holds energy, and we squeeze it, and we get the energy out. So, to me, it's one of the greatest forms of energy, clean energy, that we can use. So with that I just want to yield back. Thank you.

The CLERK. Mr. Casten is next.

Mr. CASTEN. Thank you so much, and thank you to our witnesses, and I'm really just so pleased to be here with all of this climate science expertise, and geological science expertise, and I'm—I want to get to questions about climate science, but I first just—I just want to raise a concern. There's been a lot conversation in this hearing about economics and energy technology, and, as someone who's spent 16 years building and running clean energy companies, there have been some gross misrepresentations, and I just want to clarify a couple things.

No. 1, clean energy is cheap energy. Anything we do to replace something that uses fossil fuel with something that uses a renewable source, with something that's more efficient, is a source of cheaper energy. It grows our economy. It makes us wealthier as a people. Any conversation we're having about the conversion to a clean energy economy being economically painful is at best economically naïve, and at worst immoral. It's sacrificing a cleaner, cheaper future to look after the fossil fuel industry. The reason those projects aren't deployed isn't because of technology, it's because our regulatory structure grossly distorts economic markets and subsidizes incumbents, because ultimately this transition represents a wealth transfer from energy producers to energy consumers. Let's have that conversation, but let's not misrepresent this.

Now I want to shift to climate science, and, Dr. Oppenheimer, I really, really appreciated your comments about the lag time that happens between when we emit greenhouse gases and when the effects take place. And what I wonder if you could help us out with is—I want to just paint a completely over optimistic view of the world. Let's say we eliminate all CO_2 tomorrow. Explain to us, if you could, what the lag time is before we stop seeing—before that curve saturates. How much more are sea levels going to rise? How much more intense are the derechos in the Midwest going to get? How much more intense are hurricanes going to get before we saturate that curve? Can you speak at all to what your models tell you about that?

Dr. OPPENHEIMER. Well, if you mean if we eliminate all CO_2 emissions, as opposed to all human-made CO_2 that's already put in—been put in the atmosphere——

Mr. CASTEN. Yeah, just on a going forward basis of what we already have.

Dr. OPPENHEIMER. Yeah. So, you know, that's been—that's certainly been looked at, and the—one of the lower conceivable emissions curves was—as a consequence of that—the sea level rise was examined in the report that I had a hand in on oceans and ice, which was mentioned by Paula earlier. And the reality is that the sea level rise you get over this century and beyond is a lot lower than if you just let emissions keep going. I mean, we're talking about meters difference in sea level rise, but, nevertheless, by the end of the century, in any conceivable emissions scenario, we're going to have to deal with a minimum of about one-third of a meter of sea level rise globally.

You know, let me back—actually, what I said was not correct. By—over the next few hundred years we're going to have to deal with a half a meter to a meter. That's because of the very long lags in the system that you asked about. Over this century, we might wind up below half a meter, if we're lucky, and that would be, you know, not great, but it's a safer landing than if we're at or above a meter of sea level rise.

Mr. CASTEN. I appreciate it. And, you know, the fact that even in a best case scenario we're looking at, you know, sea level rise measured in feet, I just think we need to internalize that when we think about what we're doing. Now take—and you correctly sussed out, take the—now the even more optimistic scenario. Let's say we actually not only got to zero CO_2 tomorrow, but invested in all of these negative carbon technologies, and got back to, I don't know, something sustainable in the 350 parts per million zone. Are there hysteresis effects as we go backwards, or what's, you know, what's the lag time? If we get back to where that is, do we anticipate, you know, at some point an end to wildfires, and a heightening—or are some of these changes just fundamentally irreversible at this point?

Dr. OPPENHEIMER. Yeah, there are irreversibilities. For instance, the amount of water that we lose from the ice sheets into the ocean because ice melts, or forms icebergs, we're not going to get that back. We're not going to get it back for 1,000-10,000 years. We may not get it back until we go into another ice age who knows how long in the future. So, yeah, there's some very serious irreversibilities. Whatever amount sea level rises due to loss of ice from Antarctica, Greenland, and mountain glaciers, we have no way to haul that back in a human lifetime.

Mr. CASTEN. You don't—there's no time constant that we start to see greater snowpack and temperatures falling? Is that not in the planning horizons?

Dr. OPPENHEIMER. You would be able to rebuild enough—you know, given what we know, I always want to be careful about the uncertainty. Given what we know, the restoration time for ice lost from Greenland and Antarctica is in the thousands of years——

Mr. CASTEN. Wow.

Dr. OPPENHEIMER [continuing]. So we're not going to be building back a lot of that ice in the—in, you know, human lifetimes. Let's put it that way.

Mr. CASTEN. Wow. Thank you, and I yield back.

The CLERK. Mr. Obernolte is next.

Mr. OBERNOLTE. Well, thank you, everyone, it's been a fascinating discussion. I'd like to further the conversation that we've been having about how we shield disadvantaged communities against the economic effects of transitioning to net zero carbon. And this is something that I know Congressman Lucas mentioned, Congressman Posey, Congresswoman Bice. And so, Dr. Hausfather, you said something that I thought was really fascinating. You said that we should be able to get to a place where clean energy is just as inexpensive as the energy we've been producing, you know, that's carbon intensive. And I'm wondering, you know, how we get there, because in California we've got a very stringent renewable energy standard that, you know, has caused residential electricity rates in California to be double that of adjacent States, and that's one of the reasons why California has the highest poverty rate in the Nation, when you factor that in, is those energy costs. What are we doing wrong here? How do we get to the point where these disadvantaged communities aren't being affected by higher energy prices, and where energy costs aren't driving poverty, as they are in California?

Dr. HAUSFATHER. So that's a great question. You know, California is a complicated system. Energy generation costs in California have actually been going slightly down over the last decade. The transmission and distribution costs have been going significantly up. Some of that is related to grid expansions to support more renewable energy on the grid, some of that is related to dealing with the State's wildfire crisis, and various grid hardening activities around that, but more broadly, you know, there are certainly cases where there are costs to an energy transition, and those costs can be disproportionately felt on poor people, particularly if electricity prices or gasoline prices are going up. You know, for people who have to commute to work every single day, multiple hours, you know, gasoline prices can be a large part of their disposable income. And so we should make sure that in any climate policies we're implementing, be it a carbon price, be it a subsidy for a particular type of energy, we make sure that we are not disadvantaging the people who are the worst hit by that.

So, as an example, if we were to ever put a price on carbon, it would make a lot of sense to make it revenue neutral in a way that makes sure that the people who—for which energy costs are a larger portion of their income, you know, gain from it, they don't lose from it. Another example is, you know, making sure that when we are switching over from one source of energy to another we provide considerable assistance to those communities that will be most impacted, through the loss of jobs in that sector, or through, you know, broader disruptions to local tax revenue, and other factors like that, and so we need to start planning ahead. You know, coal country, in many ways, can be a cautionary tale—right, because technologies can disrupt our energy system very rapidly. Be it natural gas and wind displacing coal, electric vehicles reducing oil demands, reducing production in parts of the U.S. in the future, we see a lot of these things coming, and we need to better understand which communities will be worse affected, and plan ahead to make sure that they're not left behind.

Mr. OBERNOLTE. Sure. Thanks. You know, I think you raise an excellent point about, you know, the economics of carbon pricing, but I just want to raise as a cautionary tale, you know, the fact of political reality intrudes, and when we have tried in the past to try to use that pricing to reduce the impacts on disadvantaged communities and consumers, as we have in California with the cap and trade system, you know, it ends up being a giant government piggy bank. You know, those benefits actually don't make it back to the consumers if we're not careful.

And then one last question for you, since I've got you, Dr. Hausfather, you also mentioned that you thought it was possible to get to a net zero energy mix, and what I'd like to ask about is baseload because all of the estimates that I have seen indicate that when you're talking about just renewables, storage is never going to get us to the point where we can provide base load without some kind of non-renewable source. So, you know, what kind of mix can we do that with?

Dr. HAUSFATHER. So that's a great question. When we look at storage, where storage really excels is bringing power from, say, the midday, when you have a lot of solar on the grid, to the evening, when use ramps up. The challenge you face, though, is around seasonal differences in generation. In California, for example, our solar panels produce half as much electricity in the winter than in the summer, whereas our demand is only 20 percent lower in the winter than in the summer. And as we electrify the economy, as we start replacing natural gas furnaces and water heaters with heat pumps in homes, our winter demand is going to increase even more.

And so there is a real need for clean firm generation on the grid, be that, you know, gas with carbon capture and storage, be that advanced nuclear, be that enhanced geothermal, where there's a lot of really exciting developments. But as I mentioned in my written testimony, if energy system models include a chunk of clean firm generation, tend to be lower cost overall than ones that rely just on variable renewables and storage.

Mr. OBERNOLTE. Sure. Yeah, I completely agree, and especially clean nuclear I think is something we can't ignore. All right. I realize my time is up. Thanks very much everyone, it's been a fascinating discussion. I yield back.

The CLERK. Mr. Kildee is next.

Mr. KILDEE. Thank you so much, and for the witnesses, thank you for a really interesting conversation thus far. I'm sure many of know—at least the Committee Members know I come from Michigan, a State with a really proud heritage of making automobiles, putting the world on wheels, and even we, in this area, in this sector of the economy, recognize that this climate crisis is real, and we have to address emissions. It's a huge polluter. The transportation sector in particular is the largest contributor to climate change, and so American auto companies have been working to transition from internal combustion engines to electric vehicles.

For example, General Motors, which, by the way, was founded right here in my hometown of Flint, Michigan in 1908, GM has invested heavily in electric vehicles, and has committed to stop selling internal combustion vehicles by 2035. And I have been working to expand the 30D tax credit that would provide consumer incentives to purchase electric vehicles, and, just to be clear, to expand it in a way that makes more affordable vehicles available to more people across the economic spectrum, especially folks who are middle income earners.

Some opponents to electric vehicles, however, say that much of the electricity used to power electric vehicles—made from fossil fuels that generate the electricity, fuels such as coal and gas. So starting perhaps with Mr. Hausfather, can you talk a bit, No. 1, about how electric vehicles can help decarbonize the transportation sector, even when electricity, at least for now, is primarily generated using fossil fuels, and just talk about the efficacy of continuing to invest in EVs?

Dr. HAUSFATHER. Sure. So even today, if you get 100 percent of your electricity from coal, which nowhere in the U.S. does right now, an electric vehicle would still be slightly lower carbon than the average conventional vehicle on the road today. So that's the starting point. Now, the U.S. grid is much cleaner than that today, and so you can expect at least 50 percent reductions in life cycle emissions for electric vehicles today in most parts of the country. That includes, you know, taking into account the emissions associated with producing the battery, which is non-trivial.

That said, the real benefit of electric vehicles as a tool of decarbonization is they get better the further along we get in other sectors of the economy. So as we decarbonize the grid, the use emissions from those electric vehicles goes pretty close to zero, and the manufacturing emissions also decreases pretty dramatically. About half of the emissions required to produce the batteries for electric vehicles is in the form of electricity used for the assembly of the battery pack. The other half is for mining and transport of the materials, et cetera. And so, as we reduce the, you know, cleanup the grid, we are also going to decarbonize the manufacturing process for electric vehicles.

Mr. KILDEE. You know, you said something just in the last question that I just wanted to follow up on, because it's been an area of real interest for me, and it has to do with the use of geothermal. Can you talk about how geothermal might be used—because I know this issue of surge, and the imbalance in—particularly in consumer demand for energy is one of the real challenges when it comes to energy storage, but it seems to me, and I've thought about this in the context particularly of urban redevelopment in low income communities, that the use of geothermal not only can reduce consumption, but actually reduces the—some of the inequity, or the problems that we have in terms of imbalance in utilization. Can you discuss whether or not you think there's reason to invest in research around how geothermal might be used to promote affordability of energy?

Dr. HAUSFATHER. I think there is. You know, when we talk about geothermal, we should really differentiate between sort of ground source heat pumps, which is sort of small scale geothermal for homes, and sort of enhanced——

Mr. KILDEE. Yeah, that's really the focus that I'm trying to zero in on, yeah.

Dr. HAUSFATHER. Yeah. So those technologies are still fairly expensive today in most places, but costs have come down a lot. You know, it certainly is a very promising area to continue, you know, research and development and deployment in. I'm less familiar with it than on the power generation side, to be honest.

Mr. KILDEE. Well, I appreciate all of your testimony, and I appreciate the Chairwoman holding this really important hearing. Thank you for that, and I yield back.

The CLERK. Mrs. Kim is next.

Mrs. KIM. Unmute.

The CLERK. We can hear you.

Mrs. KIM. OK. Thank you so much. I want to thank our Ranking Member Lucas and Chairwoman Johnson for this very informative hearing today. You know, the communities that I represent in California's 39th District are keenly aware of the climate change impact. Every year our region is devastated by record setting wildfires caused by increasing temperatures, costing our taxpayers billions of dollars. But rather than looking for a centralized government response to climate change, like Green New Deal, our country should look to unleash market-based solutions. If our country does not take the initiative to implement innovation and new technologies to combat climate change, other countries, like China, will take that initiative away from us.

You know, Mr. Hausfather, in an *L.A. Times* article you noted that fires are not unusual in California, that they're a part of the State's history and landscape, but bad forest management combined with human behavior have contributed to the problem. And as my colleague from California, Mr. Garcia, also mentioned, wildfires are a problem in California. So let me pose this question to all our witnesses. Can you talk to us about the role that forest management and land use play in climate change and emission reduction, and do you think that the monitoring of wildfires by using satellites, and the National Weather Service, along with forest management, would help in preventing some of the tragic effects we've seen from these large fires?

Dr. DIFFENBAUGH. Yeah, I can start. Wildfires result from a confluence of conditions, as you've described. There's certainly never been a wildfire without ignition. There's never been a wildfire without fuel. You know, there's never been a structure threatened or destroyed without habitation. So these all contribute to wildfire risk. And we know that—opportunities to manage those risks in each of those dimensions, so absolutely how we manage fuel is critical. The resources that we have for fire prevention and response are critical, as we've seen, tragically, in recent years, including this past year. The state of the electrical grid, which has been a source of ignitions in California in recent years, is critical for reducing emissions.

And the reality is is that the condition of the fuels is being affected by global warming, and the associated climate change. The area burned in the western U.S. has increased around tenfold in the last 4 decades. About half of the—area burned is attributable to long-term warming and the effect on fuel aridity. My research group had a—published a study this summer documenting that the frequency of extreme wildfire weather in California during the critical autumn seasons is—has more than doubled in the last four decades, so we're in a climate now where high risk is more common, it's more frequent. That will continue to accelerate. We've seen, tragically, year after year the effects of this elevated risk that has stretched our response systems past the ability to prevent those fire, to contain those fires, and to prevent the loss of structures, and, tragically, the loss of life.

Mrs. KIM. Thank you. I would like to reclaim my time so I can put in another important question in there. You know, the United States has the most dynamic private sector in the world, with entrepreneurs, investors, big companies, and capital markets all eager to license technologies and launch startups, but many of these ventures are built on technologies that come from basic research funded by the Federal Government. So can you talk about some of the examples of sustained technology driven research and development the government has started and the private sector has commercialized successfully?

Dr. HAUSFATHER. I'd be happy to take that really quick. So, you know, pretty much every technology that we're using to decarbonize our economy today has its roots in Federal and State R&D, be the—RD&D efforts, be that solar photovoltaics—wind, cheap natural gas, which is one of the biggest factors displacing coal in the U.S. today. Geothermal is really being powered today by diamond drill bits, and horizontal drilling, and hydraulic fracturing technologies that came out of Federal investments. The Federal Government has invested significantly in battery storage technologies in the past, and RD&D there, and our National Labs have played a key role. And so I think that, you know, we really need to recognize the power of technology to help us tackle climate change, and, at the same time, the critical role of the Federal Government in driving that forward.

Mrs. KIM. I think my time is up. I yield back. Thank you.

The CLERK. Ms. Moore is next.

Ms. MOORE. Well, thank you so much, Madam Chairwoman, and Mr. Ranking Member. Of course, this is just like being in school. I've learned so very, very much today.

I am not that efficient with managing my time, so I'm going to get right into it, and maybe I'll start with just mentioning something. I realize I'm not from Flint, Michigan, but I am from Milwaukee, Wisconsin. It's one of the Great Lakes, and I just want to mention that if the Great Lakes were a country, it would be the third largest country in the world. You know, it'd bring $6 trillion a year to our economy, and, of course, Wisconsin, we are the biggest trading partner with Canada, and three million of that trade passes through Wisconsin. I say that to say—because we've spent an awful lot of time talking about disasters on our coasts, and, you know, New Jersey, and New York, and the State of Washington, and California, and I just want to remind people that, you know, we're the fresh coast, and we have a huge economy to protect, and I'm wondering, maybe from Dr. Oppenheimer—you do a lot of stuff with attribution. Do you see—is there any different sort of climate research that needs to be done to maintain and sustain the Great Lakes? I know that the Army Corps of Engineers right now is engaged in a climate resilience project, but they also just get involved with hazard mitigation when, you know, utility lines are knocked down, or something happens. Is there—are the Great Lakes being neglected in the whole scheme of things?

Dr. OPPENHEIMER. Well, I wouldn't say they're being neglected. The hottest temperature ever recorded in the United States, taking together heat and humidity, it's called the wet bulb—was recorded in Appleton, Wisconsin. And so——

Ms. MOORE. That's right.

Dr. OPPENHEIMER [continuing]. You know, extreme heat affects the whole Midwest, you know, right up to the Mississippi Valley, and spreads out. And we know that, and there's been no less focus on that, and I—and it's a real concern, even in the most northerly regions of the low 48 States. The agricultural economy, which is so important in States around the Great Lakes, is a focus of a lot of study. In fact, a study from my research group examined how many people move in and out of those counties if it gets too hot, and the corn doesn't tassel, and people start moving elsewhere. And there have been——

Ms. MOORE. I would love that study. I've got a couple more questions, but I would love to see that.

Dr. OPPENHEIMER. Sure.

Ms. MOORE. I just want to ask a question—maybe Ms.—I just want to appreciate our witness who has served on the Native American—with the Native American lands. I want to ask her if she has seen that climate satellites are useful in monitoring climate, and what does she think that that might do in creating, I think, raison d'être for investing in vulnerable communities, and low-income communities, to demonstrate, maybe by attribution, the benefits of reinvesting in those communities without gentrification to ward off the greatest climate damage?

Dr. BONTEMPI. Yes, ma'am, thank you so much for that question, Congressman Moore—Congresswoman Moore, forgive me. I would say satellites have been absolutely instrumental in enabling us to identify long term trends in climate variability and change on a global scale. What they also allow us to do is reach down to the regional and local levels and actually look at direct impacts of climate variability and change on different populations, particularly along the coast.

You mentioned the Great Lakes. We study, you know, harmful algal blooms in the Great Lakes, water quality in the Great Lakes. This is really important. And I also know, and the IPCC points out, that these communities are disproportionately impacted by climate variability and change. There are agencies that study this. NASA has an applied sciences component with their science division, our colleagues in NOAA, others with real management responsibility take a very hard look at utilizing all pieces of information and blending that into transitioning research into management strategies that can support these communities. The system isn't perfect, and there's a lot of research to do, which is why I stress the hand in hand of research and management.

Ms. MOORE. Well, thank you so much. I have, you know, 5 or 6 seconds left. I just want to, you know, support the comments of Mr. Casten and say that we ought to not pit money and the lack thereof, you know, against our efforts to mitigate climate impacts in vulnerable communities, and I yield back.

The CLERK. Ms. Stevens is recognized.

Ms. STEVENS. Great, thank you so much. I want to just say, I'm from another Great Lakes State, Michigan, and I love what Congresswoman Moore just laid out. I also just absolutely loved these testimonies, and I want to thank you all for bringing your expertise to our Committee, and breadth of knowledge, and fact, and figure, and designation for us today.

In particular, Mr.—or Dr. Hausfather, from The Breakthrough Institute, you provided just a very thorough writeup of—which I soaked with your materials, and want to—I want to recognize—and I know Mr. Casten and Dr. Foster appreciate, and certainly our, you know, Chairwoman, who saw this through to the finish line, which was that you—on Page 31 of your testimony you mentioned the sweeping bipartisan package that we got done that authorized billions of dollars for investment in clean energy, vital energy, R&D, grid modernization, and on, and I loved how you put in quotes that, you know, it's the potential for quiet climate policy. But a big thing on this Committee is how we work together, and produce, and I've spent some time with Sean Casten on this, Congressman Sean Casten, and—how this was really just a sweeping effort, and just part of what we're trying to do, but I appreciated that you included that in your testimony, sir.

And you also mentioned a couple other things. One, I know that Congressman Kildee has talked to you about the electric vehicles here in Michigan. You know, I'm in the heart of automotive land here. We're already seeing industry prepare and get ready for, you know, the arrival of electric, certainly the global demand. We've got a lot to do on the infrastructure side. But you, sir, mentioned peak oil in your—several times in your written documentation. I was just wondering if you could give me your definition of peak oil, and what you mean by that, and also what that means for those of us who are in this manufacturing space, plight toward sustainability, and where—what we should expect in terms of when we're hitting peak oil.

Dr. HAUSFATHER. Thank you, that's a great question. So when I refer to peak oil, I'm not really talking about the peak oil concerns of the 1990's, which was all about running out of cheap oil. You know, clearly that was very wrong. The world has plenty of cheap oil. But rather I'm talking about peak oil demand, the point at which global oil use stops increasing, and starts decreasing, which, you know, is something that seemed out of reach, you know, a decade ago, but now seems pretty close to happening. British Petroleum has already predicted that 2019 was the year of peak oil, and that we'll never recover to that level, even in a current policy world, without, you know, rapid additional climate policies. Other groups suggest that it'll more plateau around current levels, or slightly increase into the future, so there's by no means, you know, universal agreement on this.

But certainly if you look at government targets, it would apply that we're going to either reach peak oil last year, or in the mid-2020's at the latest. And if you look at manufacturer targets, so what companies have pledged to do in terms of their EV sales globally, you know, we'd reach peak oil even sooner, and see larger declines. And so, you know, I think we need to start preparing for a world in which the rapid falling price of electric vehicles is driving down global oil demand. It's not going to—all of it anytime soon, but certainly we're not going to be seeing a world of rapidly expanding oil use that's characterized the last few decades, and that has important implications.

One of these is that in a demand constrained future, it's really going to benefit the cheaper producers, places like the Middle East, which have very low marginal production costs of oil, will be able to capture more of the market when the market size overall is shrinking. And that means we need to be prepared. You know, obviously we can't predict the future perfectly, things might change. Global demand might increase driven by much more rapid economic growth than we all forecast. You know, we simply don't know, but we should prepare for a world in which relatively expensive locations of U.S. oil production become less economical, and prepare for the types of disruptions that might happen there.

Ms. STEVENS. Well, and you've got—we've got to ask ourselves too, you know, in terms of some of these transformations, as we look at peak oil, and to the plastics industry, certainly, or even—and we talk a lot about electric vehicles, but I haven't yet heard about the electric plane, har har. You know—right, and we could look at, you know, what's relying on the, you know, the fuel, and the, you know, the plight, and you very nicely articulated, you know—and all of you, by the way. I mean, these testimonies are just—I mean, I could spend 10 to 15 minutes with each of you, and I'm going to do some follow up questions, because I'm on time—I've hit my time, and I—you know, Zeke, I wanted to get to this agriculture point that you brought up. You know, we've got—obviously talking about the carbon use on agriculture, as well as, you know, these notions of a world without ice. So, if that's OK, I'll just do those for the record, and I'm going to yield back to, you know, the next person in line, but this has just been a remarkable hearing, so thank you all.

The CLERK. Mr. Lamb is next.

Mr. LAMB. Thank you to the witnesses for sticking around this long. I wanted to start with Dr. Hausfather as well. I know that you had done a little bit of work in the past on the transition from coal to natural gas, and the, I guess, percentage of methane leakage that you need to make that advantageous for climate change purposes. Could you say a little bit about that research, and where the industry is now—and this is, like, the most compound question ever, sorry, but—and also reinstating the methane rules that were in place before the Trump Administration repealed them, what that would contribute to this issue of ensuring the climate benefits of the transition from coal to gas?

Dr. HAUSFATHER. So that's a great question. The—comparing methane emissions from natural gas to CO_2 emissions, or coal, or corn natural gas, is really complicated, because methane and CO_2

are very different greenhouse gases. They have very different lifetimes, they behave differently, and a lot of it comes down to how much you value sort of short form effects on the climate versus long term effects on the climate.

That said, in almost all scenarios natural gas is not worse than coal under the types of leakage rates we have today. And if you look at the long term, you'd have to have much higher leakage rates than anything anyone is suggesting we have today to make it worse than coal. But worse than coal is a really low bar, right? You know, we need to make our energy system considerably better than coal, and there there's huge potential in tackling leakage from the oil and gas sector. There's no reason why companies should be losing 2 percent of what they produce to the atmosphere. It means they're losing money, it means it's, you know, harming our climate, it has significant local air pollution impacts. And so better understanding where these leaks are coming from, which involves satellite monitoring, which involves a lot of newer technologies like infrared cameras on drones, for example, which can do a good job of detecting methane leaks. Like, there's a huge amount of technology that can be thrown at this problem effectively.

What we've also found in the work by Adam Brant—Dr. Adam Brant at Stanford is merely instrumental here, is that the leakage in the system is dominated by a long tail of what we call super emitters, a small number of sites that are responsible for a large portion of our overall leakage. And so remote sensing can provide an important detection mechanism there to let us narrow down on those sites. And those super emitting sites are usually places where the operator of the site does not know that a leak's occurring, and could really save money remediating it. And the real cost there isn't so much fixing the leak, it's detecting the leak, and our effort should really focus there.

Mr. LAMB. Now—it sounds like, though, your—that prescription has a lot to do with technology, and deployment of technology, which is good, but are you familiar with what the methane standard was before the Trump Administration sought its repeal? It had to do a lot with the frequency required of inspections, but—I guess what I'm trying to get at is would a replacement of the status quo ante help put us back on the road to something like less than 1 percent emissions, or does it have to be a more technical and rigorous standard——

Dr. HAUSFATHER. I mean, I think inspections are a critical part of getting to the bottom of the problem. At the same time, we want to try to minimize the cost of these inspections as much as possible, and I think that's where technology plays a role. So I think it's a combination of both, and also creating systems. And I think Colorado has really led the way here in some ways of, you know, creating smart inspection regimes where, if there is a problem, you give another inspection relatively soon after that, maybe next year. If there's not a problem, it might be 2 years or 3 years until you get your next inspection, and you have to pay the costs associated with that. So, you know, rewarding companies that do a good job, penalizing those that don't, and, you know, ensuring that we can get to the bottom of where these leaks are occurring on the production side.

Now, there's other challenges around distribution, particularly last mile of distribution, where it's much harder to mitigate leaks, and there, you know, we're ultimately going to solve that moving away from natural gas toward things like heat pumps for space heating and water heating.

Mr. LAMB. Great. I have a minute left. Any other witness want to be heard on those couple questions?

Dr. OPPENHEIMER. Yeah. Let me just add that there's been a tremendous amount of research done in the last 10 years in identifying the sources of the leaks, and it—particularly in the few years since the Trump Administration started taking apart the regulations. We know a lot more now, and so it—I think it's going to have to be looked at again carefully, because, in answer to your question of exactly whether the past regulations were what we needed, and were they strong enough, I don't think we'll know that until there's a thorough review. So just reinstating those regulations might not be good enough at this point.

Mr. LAMB. Well, thank you for that, and thank you all for sticking with us this long time, and for your insights, and I'm—Chairwoman, I yield back.

The CLERK. Ms. Wild is next.

Ms. WILD. Thank you so much. This has been a really interesting hearing, and I appreciate it. I wanted to ask a question—I'm going to start off with Dr. Diffenbaugh. I share with my colleagues, you know, we've all shared stories of our own districts, and how climate change has affected them, and my district is Pennsylvania 7, the Lehigh Valley, and based on a 2018 analysis, NOAA data shows that it is the fastest warming area of our State, and our community sits on the edge of floodplains. We—I've seen firsthand recurring flooding. We are being hit constantly by stronger storms and heavier precipitation which, of course, stresses our local infrastructure, and damages people's homes, and devastates crops. So I think that we really must figure out how we address the climate crisis and invest in community resilience to its impact.

And, Dr. Diffenbaugh, I have a two part question. I'll ask the whole thing. Based on your research, how have advancements in attribution science informed our understanding of climate change's role in extreme storms and precipitation, and the second part is, based on that understanding, how would limiting the global temperature rise to 1.5 degrees Celsius, rather than 2 degrees, limit flooding and extreme storm events for communities on floodplains like mine?

Dr. DIFFENBAUGH. Thank you for that question. Yeah, so I started my Ph.D. in September of 2000, in the Y2K era, and at that point, you know, the overwhelming response of the scientific community to questions about attribution of individual events to global warming was that, you know, the—that we can't attribute any individual event, you know, that that's not something that we're able to do scientifically. That was back 20 years ago. There has been a huge acceleration in our scientific—the ability to answer that question scientifically, and it's, you know, it's thanks in large part to investments in research by the Federal Government, in—at National Labs, and at universities, and outside of those institutions. And what we've learned is that, in fact, the global warming that's already happened is increasing the risk of individual events in many locations, and for many different kinds of events.

And here in the U.S., extreme heat, extreme precipitation, extreme wildfire, weather conditions, extreme storm surge, flooding during landfalling storms, the severity of droughts when low precipitation coincides with high temperature, which is much more likely now as a result of warming, these are some of the many areas where we have now clear confidence that the risks are already elevated, in particular for unprecedented events. And this is really important, right? We're—we now have clear understanding that we're already in a climate where we have substantially elevated probabilities of events that are more severe than any we've experienced, or any that we've observed historically are now more likely.

And so, for the kinds of impacts on communities that you were describing, the lower the level of warming globally, you know, the less intensification of these conditions will occur. And I want to note again that the impacts are non-linear, right? We're—in so many of these examples that you provided, for instance, in agriculture, in flooding losses, we see historically that the impacts are non-linear with—in some cases exponential impacts at higher levels of warming. So there's absolutely benefit to curbing the level of warming, and, in addition, that adaptation gap, again, that—is so critical, and in particular for infrastructure, right? Infrastructure is really where we see that—the nexus of mitigation and adaptation, where we see the nexus of investment and community, you know, benefits to communities, and so updating our design, our operations of—our management of infrastructure has great opportunities for both mitigation and adaptation in communities and for individual localities.

Ms. WILD. Well, thank you. I don't think I have enough time left to ask my next question. Madam Chair, I yield back. But thank you very much, Mr. Diffenbaugh.

The CLERK. Madam Chair, I believe every Member present has asked questions.

Chairwoman JOHNSON. Thank you very much, and thanks for all the participation. Before we bring this meeting to a close, I just need to ask if there's anyone with a hot question that they'd like to ask at this time?

Hearing none, I'd like to thank our outstanding witnesses for participating today, and testifying, and to notify you that the record will remain open for 2 weeks for additional statements from the Members, and for any additional questions the Committee may ask of the witnesses. Our witnesses now are excused, and our hearing is adjourned.

[Whereupon, at 2 o'clock p.m., the Committee was adjourned.]

Appendix I

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Michael Oppenheimer

Michael Oppenheimer - Questions submitted by members for response:

Submitted by Chairwoman Eddie Bernice Johnson

1. The U.S. historic disaster response system tends to incentivize building back to the same standards and not focusing on building resiliently through adaptation measures. a. What has led to the lack of upfront support for adaptation measures versus post-disaster relief by the U.S. government?

b. How can the U.S. government prioritize climate adaptation measures? Especially in the case for vulnerable communities, how can the government provide assistance to help them have the adequate resources to adapt?

c. How can adaptation measures adequately address the varied climate risk landscape across the U.S., and account for disproportionate risks borne by vulnerable populations?

Responses:

1a. The lack of upfront support arises from failure of several Congresses and Administrations to adequately fund FEMA programs for building adaptations in advance of occurrence of disasters and extreme events. At this point, well-funded programs are almost always tied to particular disasters. There is now available limited funding from one program that anticipates rather than follows such events but the amount appropriated pales in comparison to the need.

b. Among the approaches available are the possibility of well-funded programs through FEMA as noted above, rebates on NFIP premiums for actions actually taken by households to build resilience, and stricter enforcement on and by states and localities of existing requirements (e.g., in building codes) to enable eligibility for USACE support for flood control projects and favorable treatment under NFIP. Recent USACE/FEMA moves in this direction of encouraging relocation are modestly encouraging.

c. We need a national adaptation program that comprehensively projects, maps, and assesses climate-related risk and develops guidelines for all actions within the US that fall directly or indirectly under federal jurisdiction and have the potential to increase climate exposure and vulnerability. Among the chief criteria should be that federal support for climate adaptation and resilience building related to projects receiving federal support is contingent on such projects having as their first priority that groups vulnerable by virtue of race, age, gender, etc., should receive top priority for support of adaptation planning, funding, and implementation.

Submitted by Ranking Member Frank Lucas

1. International shipping is key to the world's economy, responsible for 90% of global trade. But the vessels burn about 4 million barrels of oil a day, accounting for almost 3% of the world's carbon emissions, and most ships are built to last about 30 years. So when we cancel something like the Keystone Pipeline, we are not cutting any emissions, we are simply encouraging existing, higher emission methods to take over. Where does the transportation sector stand in terms of innovation to reduce carbon emissions? Are there technologies in a form or scale that are commercially viable for any sector outside of vehicles?

Response:

A detailed response to this question, going beyond the motor vehicle sector, is outside my expertise.

Submitted by Representative Charlie Crist

1. In your testimony, you note that due to sea level rise, "sunny-day," or tidal flooding, now happens regularly along the coast in Miami and that once-per-decade flood levels in New York Harbor now arrive once every five years. a. What do we know about the costs or risks associated with repeat coastal flooding events? How can coastal communities plan to build more resiliently to these changes?

2. In 2020, the U.S. saw a record Atlantic hurricane season with 30 named storms, that predominantly affected the Southeast. You note in your testimony that Hurricane Katrina is an example of how vulnerable communities can be disproportionately impacted by hurricanes. Hurricane Maria is another example. Historic discriminatory policies and regulations can hinder communities of color and low-income communities when it comes to how they are treated during hurricane preparation, response, and recovery. With climate change causing hurricanes to become more intense, this poses even greater threats for vulnerable communities. a. What resources or information do the most vulnerable populations along our coastlines need to make them more resilient to increasingly intense hurricanes due to climate change?

Responses:

1. Repeated nuisance and storm surge flooding at ever higher levels will make many low-lying communities uninhabitable unless vast sums are invested by governments at all levels, to a degree that eventually will not be possible unless sea level rise is slowed by global greenhouse gas emissions reduction. For some communities, relocation will become in evitable. For others, where property values merit expenditure, governments and individuals will likely invest, first in enhancements of drainage, raising houses, and inexpensive protection measure. Eventually, for many areas, these will be insufficient and relocation will become a favored option. For densely populated areas, it seems likely that federal investment in hard protection like surge barriers will become the chosen options. For example, USACE priced one such barrier for NY Harbor at a cost of over $100 billion.

2. I recommend establishment of a national climate adaptation program including an information service akin to agricultural extension programs that function in conjunction with local and community governmental and nongovernmental institutions and can provide direct assistance and access to financial and other support to residents for the purpose of implementing resilience and adaptation measures and facilitate access to such programs for traditionally excluded or under-represented segments of our populations who suffer from diverse vulnerabilities and have limited or no access to financial and other resources.

Submitted by Representative Haley Stevens

1. How seriously do we need to take potential total global ice melt and what would it mean to live in a world without ice?

Response:

1. A world without ice is very unlikely to evolve due to warming during this century although we might reach that state if greenhouse gas emissions continue for hundreds of years and warming approaches ten degree Celsius. Hopefully, we will act to sharply reduce emissions long before then. If this did occur, sea level could rise as much as 200 feet as the entire Antarctic ice sheet would melt slowly, and disappear over several thousand years.

More likely to occur, and perhaps much sooner (~300 years) is a sea level rise of as much as 20 feet due to loss of all of the West Antarctic ice sheet, a minor part of the East Antarctic ice sheet, thermal expansion of sea water, mountain glacier melt, and partial melting of the Greenland ice sheet. This could be triggered by somewhat more than 2-degrees Celsius of warming above preindustrial levels. This is an outcome we are now on track for. The part of it occurring within this century could be more than a meter of sea level rise and cause major problems for all coastal areas.

Responses by Dr. Zeke Hausfather

Response to Ranking Member Lucas

1) Does the cancellation of the Keystone Pipeline (and similar projects) potentially result in increased emissions through increased shipping usage?

The transportation of oil via pipeline is one of the lowest emissions transportation methods, resulting in notably lower transport emissions than shipping oil from the Middle East to the US via oil tankers. Around 3% of carbon emissions come from shipping, and 13% of total maritime emissions come from oil tankers.[1] However, transportation is just a small part of upstream "well-to-tank" lifecycle emissions (e.g. lifecycle emissions of oil production excluding combustion). The figure below, from the International Energy Agency, [2] shows the upstream emissions from oil production across different sources worldwide.

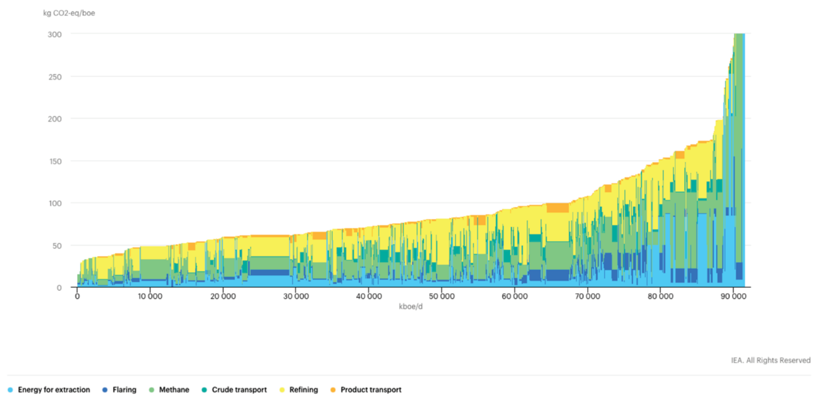

Figure 1: Well-to-tank emissions from global oil production across various sources.

The primary argument against the Keystone Pipeline is that it allows for the development of oil sands in Canada that are among the most carbon-intensive sources of oil, with emissions up to 50% higher than oil produced in the US.[3] The differences between US oil and Canadian oil sands extraction energy use (and emissions) is much higher than transportation-related emissions

[1] International Council on Clean Transportation. 2017. Greenhouse Gas Emissions from Global Shipping, 2013-2015.

[2] International Energy Agency. 2020. Methane Tracker 2020, IEA, Paris. Available: https://www.iea.org/reports/methane-tracker-2020

[3] Liggio, J., et al. 2019. Measured Canadian oil sands CO2 emissions are higher than estimates made using internationally recommended methods. *Nature Communications*. Available: https://www.nature.com/articles/s41467-019-09714-9

regardless of the approach used. For oil produced in the US – such as that from the Bakken shale – there is a stronger case to be made that stopping pipelines may result in larger overall emissions if demand is met by Middle East oil instead.

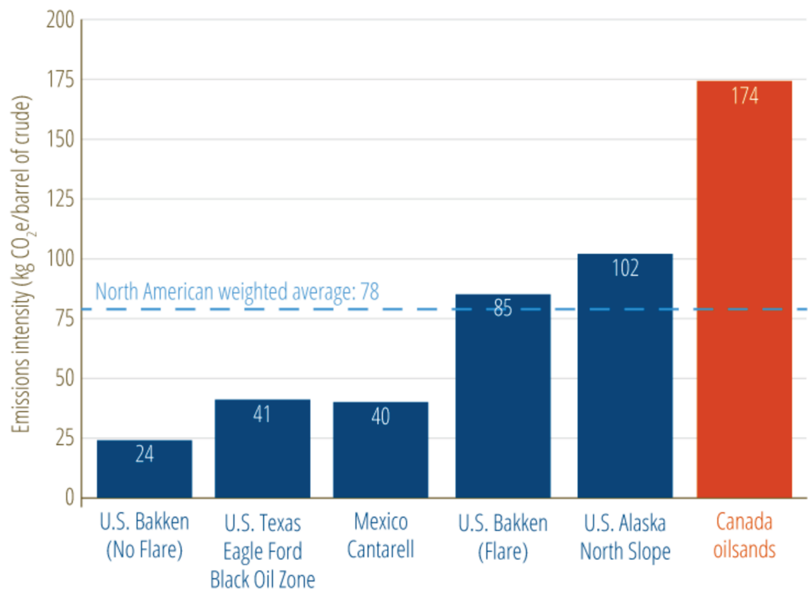

Figure 2: Emissions associated with the extraction and processing of various crudes by production location.[4]

It is also unclear the extent to which restricting the development of pipelines to the US will meaningfully reduce Canadian oil sands emissions; oil sands was already uneconomical before the Keystone Pipeline was canceled, given its high production costs and low global oil prices. Canada was also looking into building pipelines to the Western coast for export to Asia that would serve as an alternative to US exports should oil prices increase in the future. Broadly speaking, restricting supply tends to be an ineffective way to reduce emissions, as any reductions in, say, US oil imports from Canada can be made up for by oil imports from other countries. There is likely not the political will to enact the types of supply restrictions that could meaningfully increase oil prices to the extent that they would have a substantial impact on demand.

[4] Carnegie Endowment for International Peace. 2015. Oil-Climate Index. Available: http://oci.carnegieendowment.org/#total-emissions

Rather, efforts to mitigate emissions and reduce oil use are better focused on the demand side of the equation – in promoting the development and deployment of cost effective alternative technologies like electric vehicles and the transition away from fuel oil use for heating that will actually reduce the amount of oil that is consumed, rather than simply shifting around where the oil we use is produced.

2) What benefit would a "Soil Science Initiative" have for the everyday farmer and rancher?

A soil science R&D initiative could provide modest short-term and substantial long-term benefits for the everyday agricultural producer by enabling them to reduce input use, increase yields, and receive cost-shares or payments for on-farm environmental improvements.

A soil science R&D initiative could reduce the cost and improve the accuracy of measuring soil carbon and soil nutrients, and advance our understanding of the soil microbiome — the set of microorganisms within our soils. This could help improve the efficiency of existing and future programs that pay farmers to adopt environmental beneficial practices. In the near term, improved soil data could enable programs such as USDA's Environmental Quality Incentives Program (EQIP) to provide financial assistance to farmers and regions where it will have the greatest environmental benefit. This would benefit farmers who can provide real ecosystem services and improve the overall environmental impact of U.S. agriculture. In the long-term, advances in soil carbon sequestration knowledge and practices could create opportunities for farmers and ranchers to invest in breakthrough technologies like crops or grasses with root systems[5] that increase the amount of carbon sequestered in the soil. This would improve soil health, which can improve farmer yields and resilience to extreme weather, and would potentially enable them to earn revenue by selling carbon credits to companies or others seeking to offset emissions.

Advances in soil science could also provide the foundation for private sector development of products, such as low-emission microbial seed treatments, that help farmers grow more food with less fertilizer and other inputs. While there are potential short-term advantages, the benefits of a soil science R&D initiative are mainly in the long-run. Advances in soil microbiome research could reduce the use of inputs like synthetic fertilizers and other soil additives — either through improved knowledge leading to more precise application of nutrients, or the replacement of existing fertilizers with more efficient alternatives — without sacrificing yields, potentially

[5] "Harnessing Plants Initiative - Salk Institute for Biological Studies," accessed April 8, 2021, https://www.salk.edu/harnessing-plants-initiative/.

increasing farmers' revenues and reducing their costs.[6,7] For example, Pivot Bio, a start-up based in the Bay Area markets a product that reduces the need for synthetic fertilizer while maintaining or increasing yields in corn production. R&D to apply similar technologies to other types of crops could help producers across the country reduce their costs without losing revenue.

A soil science initiative aimed at advancing soil microbiome R&D would also benefit agricultural producers in the long-term by improving the drought-resistance of both soils and crops, helping farmers protect their investments and maintain productivity despite a changing climate.[8,9,10] This is especially important considering the current state of water supply in the American West and Midwest, and the potential for climate change to increase the risk of droughts.[11] For example, over the first eight months of 2020, much of the U.S. West saw lower rates of precipitation than annual averages.[12] At the same time, soil microbiome research can improve disease-resistance among crops and cropland soils, helping farmers to protect yields and potentially eliminate current losses from crop disease.[13] Such advances could reduce the $21 billion in costs in the United States each year stemming from crop diseases and other deleterious pathogens.[14]

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[6] Deepak Bhardwaj et al., "Biofertilizers Function as Key Player in Sustainable Agriculture by Improving Soil Fertility, Plant Tolerance and Crop Productivity," *Microbial Cell Factories* (BioMed Central Ltd., May 8, 2014), https://doi.org/10.1186/1475-2859-13-66.
[7] "How It Works," accessed April 8, 2021, https://www.pivotbio.com/how-it-works.
[8] Anamika Dubey et al., "Growing More with Less: Breeding and Developing Drought Resilient Soybean to Improve Food Security," *Ecological Indicators* 105, no. February 2018 (2019): 425–37, https://doi.org/10.1016/j.ecolind.2018.03.003.
[9] Anamika Dubey et al., "Soil Microbiome: A Key Player for Conservation of Soil Health under Changing Climate," *Biodiversity and Conservation* 28, no. 8–9 (2019): 2405–29, https://doi.org/10.1007/s10531-019-01760-5.
[10] *Science Breakthroughs to Advance Food and Agricultural Research by 2030*, *Science Breakthroughs to Advance Food and Agricultural Research by 2030* (National Academies Press, 2019), https://doi.org/10.17226/25059.
[11] Benjamin I. Cook, Justin S. Mankin, and Kevin J. Anchukaitis, "Climate Change and Drought: From Past to Future," *Current Climate Change Reports* (Springer, June 1, 2018), https://doi.org/10.1007/s40641-018-0093-2.
[12] "2020 Drought Update: A Look at Drought Across the United States in 15 Maps | Drought.Gov," accessed April 8, 2021, https://www.drought.gov/news/2020-drought-update-look-drought-across-united-states-15-maps.
[13] Bhardwaj et al., "Biofertilizers Function as Key Player in Sustainable Agriculture by Improving Soil Fertility, Plant Tolerance and Crop Productivity."
[14] Christine L Carroll Colin A Carter Rachael E Goodhue C-Y Cynthia Lin Lawell et al., "Crop Disease and Agricultural Productivity," *Bill Waycott*, 2017, http://www.nber.org/papers/w23513.

2a) On top of increasing farmers' soil quality, could an initiative like this sequester enough CO2 to offset the agriculture sector's emissions? What is needed to better understand this topic?

A soil science R&D initiative could help farmers sequester substantially more carbon, but could only plausibly offset the sector's entire emissions if agricultural emissions also fall.

With current technologies, agricultural soils could sequester only a fraction of current agricultural emissions. The National Academies of Sciences estimates that agricultural soils in the US could sequester about 250 million tons CO_2/year at a cost of less than $100/ton CO_2 with current technologies and without large adverse effects, such as on food security.[15] The World Resources Institute estimates less sequestration is plausible: 100-200 million tons CO_2/year of sequestration by 2050, primarily on cropland.[16] This amounts to about 15-30% of the 658.6 million tons CO_2 that U.S. agriculture emitted in 2018.[17] Given the challenges of incentivizing farmers to adopt practices and maintain them over time, which is necessary for long-term sequestration from almost any practice, feasible sequestration levels are likely even lower.

Advances in soil science, soil management practices, and related technology are necessary to increase soil carbon sequestration potential.

Breeding crops with enhanced root systems that sequester more carbon could substantially increase carbon sequestration on farmland, perhaps more than any other approach. Planting crops with enhanced roots on every acre of major US crops (249 million acres) could sequester 100 to 500 million tons CO_2, depending on the change in root depth and carbon input. Sequestering 500 million tons would offset most of agriculture's emissions, but a more plausible sequestration estimate for widespread adoption is about 185 million tons CO_2.[18] Research on crops with enhanced roots is largely still in the laboratory phase. To advance the field, the National Academies of Sciences estimated $40 to $50 million in annual funding would be needed for around 20 years.[19] The Department of Energy's ROOTS program funds research on enhanced roots; however the $35 million total funding it received in 2016 is nearly expended.

With additional research, biochar could also enable farmers to sequester more carbon. Biochar is produced by processing biomass, such as crop residues, at high-temperatures and can be used as a soil amendment where it can increase crop productivity and result in long-term carbon storage.

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[15] *Negative Emissions Technologies and Reliable Sequestration* (Washington, D.C.: National Academies Press, 2019), https://doi.org/10.17226/25259.
[16] James Mulligan et al., "CarbonShot: Federal Policy Options for Carbon Removal in the United States," 2020, www.wri.org/publication/carbonshot-federal-policy-.
[17] "Greenhouse Gas Inventory Data Explorer," EPA, 2019, https://cfpub.epa.gov/ghgdata/inventoryexplorer/#agriculture/allgas/source/all.
[18] Mulligan et al., "CarbonShot: Federal Policy Options for Carbon Removal in the United States."
[19] *Negative Emissions Technologies and Reliable Sequestration*.

However, the climate potential of biochar is limited both by its high cost and by the GHG emissions associated with sourcing and processing biomass.[20] Scientific advances that enable development of low-cost biochar produced with low-carbon energy could sequester on the order of 95 million tons CO_2/year.[21]

Deep soil inversion is another practice requiring further research. It involves burying carbon-rich topsoil and bringing deeper soil to the surface where it can store carbon from crop residues, roots and other organic matter. Initial research in Germany indicates it could sequester 1.5 tCO_2 per acre per year — more than many other farming practices — however, with no research having been conducted in the US, there is very limited understanding of its effectiveness, costs, or potential to be scaled up.[22]

Although plausible levels of carbon sequestration couldn't offset more than three-quarters of current emissions, advances in soil science could also cut agricultural emissions through developing affordable low-emission fertilizers.[23] Nitrous oxide emissions from fertilizer application are responsible for over 100 million tons CO_2e/year.[24,25] Nitrification and urease inhibitors, compounds that can be added to fertilizer mixes, could reduce emissions on the order of 50 million tons CO_2e/year if adopted on all cropland.[26] These products are already commercialized, but additional research could increase adoption by helping reduce costs and illuminate how effective the inhibitors are in reducing emissions and increasing yields for different crops in different regions and conditions.

Additional emissions could be cut through research and development of fertilizers that can be manufactured with a small carbon footprint. Manufacturing conventional nitrogen fertilizer emits about 11 million tons CO2e, according to Environmental Protection Agency data; however, new research suggests that methane emissions from fertilizer manufacturing has been grossly underestimated and that emissions could be over 800 million tons CO_2e.[27] Emerging fertilizer technologies such as microbial seed treatments and soil amendments could meet a substantial portion of farmers' nutrient needs with a lower carbon footprint. Although businesses are developing microbial fertilizer products, the field remains underdeveloped; for example, many

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[20] *Negative Emissions Technologies and Reliable Sequestration.*

[21] Joseph E. Fargione et al., "Natural Climate Solutions for the United States," *Science Advances* 4, no. 11 (November 14, 2018), https://doi.org/10.1126/sciadv.aat1869.

[22] Mulligan et al., "CarbonShot: Federal Policy Options for Carbon Removal in the United States."

[23] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018," 2020.

[24] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018."

[25] Fargione et al., "Natural Climate Solutions for the United States."

[26] Internal calculation, based on Fargione et al. (2018), Norton, J., & Ouyang, Y. (2019). Controls and adaptive management of nitrification in agricultural soils. In Frontiers in Microbiology (Vol. 10, Issue AUG). Frontiers Media S.A. https://doi.org/10.3389/fmicb.2019.01931; Kanter, D. R., & Searchinger, T. D. (2018). A technology-forcing approach to reduce nitrogen pollution. Nature Sustainability, 1(10), 544–552. https://doi.org/10.1038/s41893-018-0143-8

[27] Xiaochi Zhou et al., "Estimation of Methane Emissions from the U.S. Ammonia Fertilizer Industry Using a Mobile Sensing Approach," *Elementa* 7, no. 1 (May 28, 2019), https://doi.org/10.1525/elementa.358.

soil microbes have yet to be identified and understood[28], and microbial products have not been developed for most crops. In addition, federal research is decentralized, with as many as 15 agencies connected to agricultural microbiomes.[29] Given these challenges, coordinated government-funded research, as the Microbiome Interagency Working Group has called for, is critical for accelerating development and adoption of low-carbon microbial products.

<u>Response to Representative Stevens</u>

What opportunities do we have today for carbon capture technologies in ways that would be helpful

There are a wide variety of different technologies being developed today for either capturing carbon from fossil fuel use, or for directly removing carbon from the atmosphere. The former includes ongoing carbon capture and storage efforts associated with coal and natural gas– with much of the current captured carbon going to enhanced oil recovery. The latter includes direct air capture of CO2 (which a wide variety of companies are pursuing through different technological approaches), bioenergy with carbon capture and storage (which has a number of small-to-medium-scale trials), and reforestation. There are additional efforts aimed at enhancing soil carbon sequestration through a combination of organic amendments, cover crops, reduced tillage, improved crop rotations, and improved grazing management.

The Clean Air Taskforce provides a useful tool to track current 45Q recipients and other carbon capture projects around the US. There are currently more than thirty projects either operational or in development capturing significant amounts of CO2, shown in the figure below:

[28] *Sci. Break. to Adv. Food Agric. Res. by 2030.*
[29] "Interagency Strategic Plan for Microbiome Research FY 2018-2022," 2018.

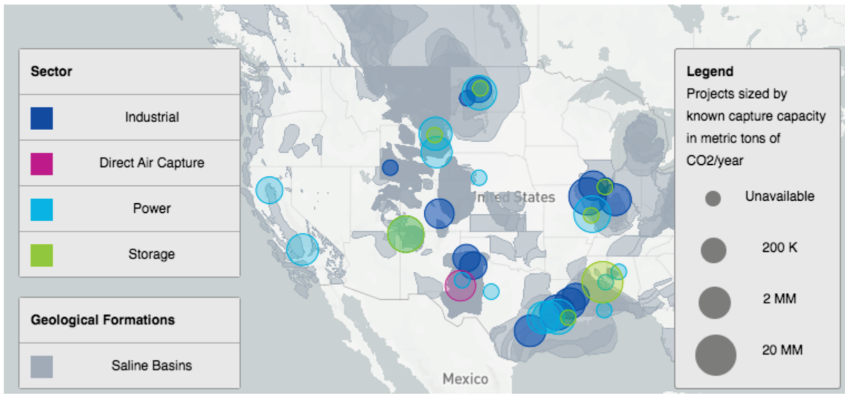

Figure 3: Current carbon capture, utilization, and storage projects in development the US.[30]

Additional steps that would help encourage the development of more carbon removal projects include more research and development spending on promising carbon removal technologies, ensuring long-term predictable payments through 45Q, and ensuring that carbon removal is included in any future technologically-neutral mitigation policies such as carbon prices, clean energy subsidies, or clean energy or electricity standards.

[30] Clean Air Taskforce. 2020. Interactive Map of CCUS Projects in Development in the U.S. Available: https://www.catf.us/2020/07/ccus-interactive-map/

Responses by Dr. Noah S. Diffenbaugh

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"*The Science Behind Impacts of the Climate Crisis*"

Questions for the Record to:

Dr. Noah S. Diffenbaugh
Kara J. Foundation Professor, Department of Earth System Science
Kimmelman Family Senior Fellow, Woods Institute for the Environment
Stanford University

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
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Stanford University
Submitted by Chairwoman Eddie Bernice Johnson

1. The Fourth National Climate Assessment notes that with little or no adaptation, climate change will exact large losses on our economy.
   a. How are climate scientists and economists working to assess the economic risks of climate change?
   b. How do the costs of climate inaction measure up against the needed investments in climate science for adaptation and mitigation solutions?

RESPONSE: This has been an area of very active research in recent years. This research includes both "bottom up" quantification of the response of individual sectors to historical climate variations,[1] as well as "top down" quantification of the response of aggregate economic activity to historical climate variations.[2] It also includes analyses of the economic impacts of the climate change that has already occurred,[3] as well as projections of economic impacts at different levels of global warming.[4]

As I mentioned in my written testimony, this research confirms that the economic impacts of climate change are indeed large. For example, changes in precipitation – particularly intensification of extreme wet events – account for approximately one third of the cumulative flood damages in the U.S. over the past three decades,[5] and historical warming has cost the aggregate U.S. economy approximately 5 trillion dollars within the past two decades.[6] These economic impacts are likely to accelerate in the U.S. at higher levels of global warming, with the poorest counties being harmed around twice as much as the richest counties, exacerbating existing economic inequality.[7] As a result, reductions in the trajectory of global warming are likely to save the U.S. substantially in avoided climate damages. For example, the aggregate damages to the US economy are likely to be trillions of dollars less by the end of this century if the global temperature is held to 1.5°C of warming compared with 2°C of warming.[8]

In order to be accurate, cost-benefit analyses of possible investments in mitigation and adaptation must account for the climate damages that would be avoided by those investments.

2. As environmental and climate justice communities are hit first, worst, and hardest by

[1] Hsiang, et al., *Science*, 356(6345), 1362–1369, 2017.
[2] Burke et al., *Nature*, 557(7706), 549–553, 2018.
[3] For example, Burke and Tanutama, National Bureau of Economic Research, 2019, and Davenport et al., *Proceedings of the National Academy of Sciences*, 118(4), 2021.
[4] For example, Hsiang et al. 2017 and Burke et al. 2018.
[5] Davenport et al. 2021.
[6] Burke and Tanutama 2019.
[7] Hsiang et al. 2017 and Duffy et al., *Science*, 363(6427), eaat5982, 2019.
[8] Burke et al. 2018.

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climate change, it is imperative that these perspectives and disproportionate impacts are included in both research and solutions to climate change.

a. What is our current understanding of the disproportionate impacts of climate change on environmental and climate justice communities in the U.S.?
b. What types of research are needed to better understand the disproportionate impacts of climate change on these marginalized communities?
c. How important is this research in developing and implementing truly equitable climate solutions?

RESPONSE: As my written and spoken testimony emphasized, we have ample evidence that poor and marginalized communities experience disproportionate impacts from the climate change that has already happened, as well as the greatest vulnerability to future climate changes. This includes vulnerability to the impacts of climate change on health, food security, livelihoods and destruction from extreme events. (There is also substantial evidence that poor and marginalized communities also experience the greatest vulnerability to local pollution from the current energy system.)

In my testimony, I stated that a cohesive research agenda that integrates mitigation and adaptation in support of a climate-resilient nation would include the following six themes:

(i) improved observational and modeling capacity for predicting extreme events across weekly, seasonal and decadal timescales;
(ii) R&D for both the technologies and large-scale deployment necessary to transition to a secure, reliable, equitable net-zero-emissions energy system;
(iii) improved understanding of the climate impacts of "overshooting" the Paris Agreement goals, as well as the options for – and risks of – negative emissions technologies;
(iv) R&D for development, implementation and deployment of adaptation approaches across a variety of geographic, climatic and socioeconomic contexts;
(v) information, methodologies and decision support for updating the design guidelines and operational practices for our local, state and national infrastructure to be resilient in the current and future climate; and
(vi) improved understanding of how to generate synergies between mitigation, adaptation and other policy priorities such as economic growth, job creation, environmental conservation, and economic, racial and environmental justice.

Because of the increased vulnerability of poor and marginalized communities to a broad range of climate risks, and the potential for "win-win" synergies between mitigation and adaptation solutions, an integrated research program that includes all of these areas will help to accelerate the development and deployment of equitable climate solutions.

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3. The Intergovernmental Panel on Climate Change Fifth Assessment Report examined four different future greenhouse gas concentration scenarios (Representative Concentration Pathways, or "RCPs") that are driven by different emissions trajectories.

a. What is the most realistically optimistic emissions reduction scenario, and what level of global temperature increase, climate change, and resulting impacts are associated with it?

b. What technological and/or policy measures are needed to achieve this scenario, and when are we mostly likely to achieve it?

RESPONSE: The UN Paris Agreement included the goal of holding global warming well below 2˚C above the pre-industrial baseline, and pursuing global warming of 1.5˚C. The fundamental physics of planet Earth suggest that stabilizing the global temperature at any level will require reaching net-zero emissions (with the total warming being proportional to the total aggregate emissions).[9] Global warming has already exceeded 1˚C above the pre-industrial baseline. According to the 2020 UN Emissions Gap Report, "The levels of ambition in the Paris Agreement must be roughly tripled for the 2˚C pathway and increased at least fivefold for the 1.5˚C pathway."[10]

In addition, as I mentioned during my testimony, the world also faces the intertwined challenges of increasing total energy supply and broadening access to modern energy resources, while simultaneously adapting to a world of accelerating climate stresses that includes increasing occurrence of unprecedented extreme events. Achieving all three of these grand challenges simultaneously will require rapid development and deployment of technologies and policies that ensure broad and equitable energy access through low- and negative-emissions technologies, while also increasing the resilience of climate-sensitive systems including (but not limited to) infrastructure, agriculture, supply chains, and disaster risk management.

Reaching net-zero emissions by 2050 is an ambitious goal that offers a substantial likelihood of avoiding 2˚C of global warming while also ensuring broad energy access and climate resilience. Achieving the level of decarbonization and negative emissions deployment necessary to hold global warming to 1.5˚C is an even more ambitious challenge that may still be attainable.

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[9] IPCC, 2013: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[10] *Key Messages,* 2020 UN Emissions Gap Report, https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/34461/EGR20KM.pdf

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Stanford University
Submitted by Ranking Member Frank Lucas

1. International shipping is key to the world's economy, responsible for 90% of global trade. But the vessels burn about 4 million barrels of oil a day, accounting for almost 3% of the world's carbon emissions, and most ships are built to last about 30 years. So when we cancel something like the Keystone Pipeline, we are not cutting any emissions, we are simply encouraging existing, higher emission methods to take over. Where does the transportation sector stand in terms of innovation to reduce carbon emissions? Are there technologies in a form or scale that are commercially viable for any sector outside of vehicles?

   RESPONSE: Thank you for this question, which highlights the challenges in reaching net-zero emissions. As the question suggests, there are aspects of the economy that will be particularly challenging to fully decarbonize. Shipping and aviation are two areas that have been identified as being among the most difficult. The deep integration of activities such as shipping and aviation in the modern economy and modern lifestyles is one of the primary motivations for negative emissions technologies, such as those discussed during the hearing.

   The fundamental physics of planet Earth suggest that stabilizing the climate system at any level of global temperature will require reaching net-zero greenhouse gas emissions. Deployment of negative emissions technologies offers the potential to reach net-zero emissions while maintaining emitting activities in sectors that are particularly difficult to decarbonize. However, it should be noted that the slower the rate of decarbonization, the greater the scale of negative emissions that will be required to stabilize at lower levels of warming, and we do not currently have the capacity to realize negative emissions at the scale necessary to reach net-zero.

   For a summary of potential negative emissions technologies, and the scale of deployment needed to achieve net-zero emissions in the coming decades, see figures from Rosen (2018)[11] and Anderson and Peters (2016)[12] on the following page.

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[11] Rosen, *Science*, 359(6377), 733-737, DOI: 10.1126/science.359.6377.733, 2018.

[12] Anderson and Peters, *Science*, 354(6309), 182-183, DOI: 10.1126/science.aah4567, 2016.

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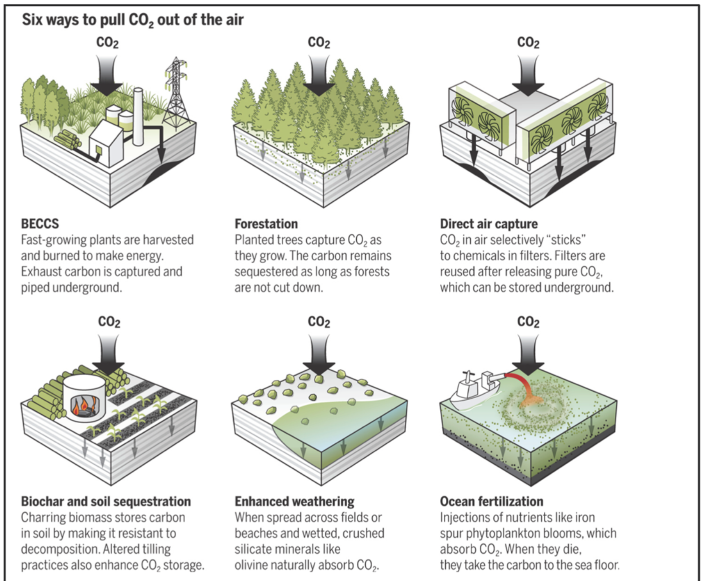

Figure 2 from Rosen, Science, 359(6377), 733-737, DOI: 10.1126/science.359.6377.733, 2018.

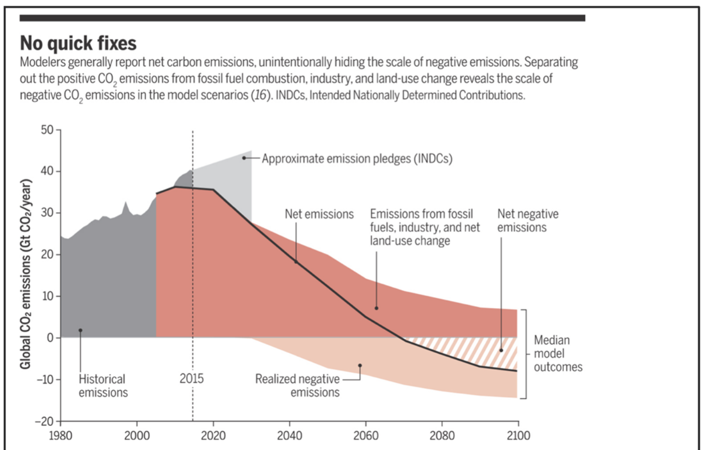

Figure 1 from Anderson and Peters, Science, 354(6309), 182-183, DOI: 10.1126/science.aah4567, 2016.

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Stanford University
Submitted by Representative Ed Perlmutter

1. Climate change is having a real and serious impact in my district, in Colorado, and throughout the country. Last year, Colorado had three of its largest wildfires in the state's history, which torched more than 540,000 acres and forced my constituents to live with unhealthy air quality.
   a. What can we take away from the devastation of the 2020 wildfire season to build resiliency and prepare for the 2021 season?

RESPONSE: In my written testimony, I mentioned results of a recent review that my colleagues and I conducted evaluating the scientific evidence underpinning the EPA's "Endangerment Finding" for greenhouse gases.[13] As is summarized in that peer-reviewed paper, the annual forested area burned in the western United States has increased approximately tenfold since the mid-1980s. Further, evidence shows that "human-caused climate change caused over half of the documented increases in fuel aridity since the 1970s and doubled the cumulative forest fire area since 1984."[14]

Recent wildfires have proved very costly. For example, according to the National Oceanic and Atmospheric Administration (NOAA), multi-billion-dollar firestorms have occurred in the western U.S. in each of the past 6 years, with the 2020 wildfires exceeding $16 billion in CPI-adjusted damages, the 2018 wildfires exceeding $25 billion in CPI-adjusted damages, and the 2017 wildfires exceeding $19 billion in CPI-adjusted damages.[15] And, when the full economic costs are also considered – such as the health costs from smoke pollution and the economic impact of disruption of supply chains – the costs may be several times higher (for example, a full cost accounting of the 2018 wildfires in California totals ~$150 billion[16]).

In addition to the high financial losses caused by catastrophic wildfires, we also know that the historical increases in area burned have been accompanied by rising costs of fire suppression. For example, as reported in the National Climate Assessment, both the total US burned area and federal spending on fire suppression have increased fourfold over the past ~30 years, with suppression costs reaching approximately $2 billion/year in recent years.[17]

A clear message from recent years – punctuated by 2020 – is that the climate has already changed in a way that elevates wildfire risk, and that measures to manage wildfire risk must account for those climate impacts in order to be effective. With respect specifically to 2021: According to the US Drought Monitor, much of the

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[13] Duffy et al. 2019.
[14] Abatzoglou and Williams, *Proceedings of the National Academy of Sciences*, *113*(42), 11770-11775, 2016.
[15] *NOAA Billion Dollar Weather and Climate Disasters*, Table of Events: https://www.ncdc.noaa.gov/billions/events/US/1980-2021
[16] Wang et al., Nature Sustainability, 4, 252–260, 2021.

[17] *Fourth National Climate Assessment*, Chapter 6 "Forests": https://nca2018.globalchange.gov/chapter/6#fig-6-4

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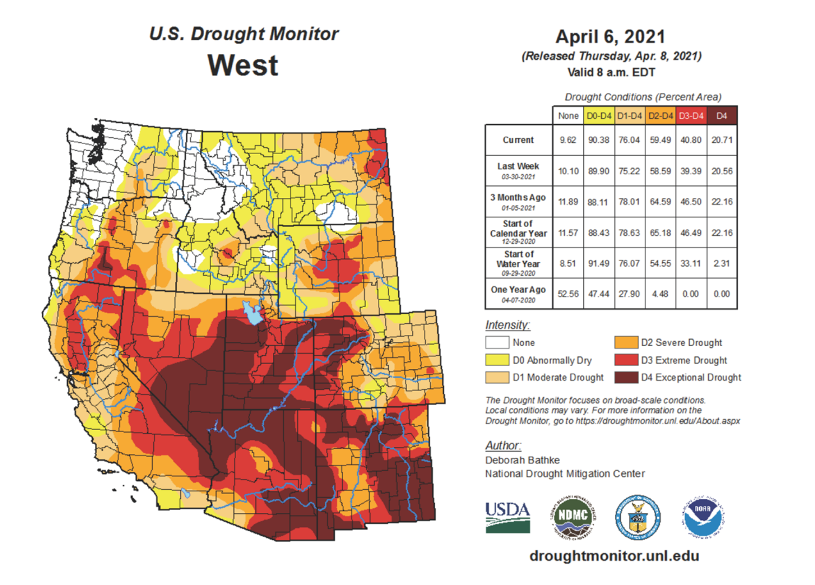
western US is currently in severe, extreme or exceptional drought. (This includes much of Colorado, 100% of which is currently in some form of drought, including >32% in extreme or exceptional drought; see figure below.) While the conditions during the spring and summer will determine the severity of the 2021 wildfire season (including unfolding climatic conditions, as well as natural and human-caused ignitions), the region – including Colorado – is clearly beginning the warm season in a very dry state.

Fortunately, there are measures that can be taken in the near-term to manage wildfire risk, including clearing defensible space around structures; upgrading structures through home-hardening; carefully maintaining, monitoring and managing the electrical grid; and pre-deploying and supporting fire response resources at a scale commensurate with the widespread dryness throughout the region.



US Drought Monitor map for April 6, 2021 (https://droughtmonitor.unl.edu/CurrentMap.aspx).

Responses by Dr. Paula S. Bontempi

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Questions for the Record to:
Dr. Paula S. Bontempi
Dean, Graduate School of Oceanography
Professor of Oceanography
University of Rhode Island

Submitted by Ranking Member Frank Lucas

International shipping is key to the world's economy, responsible for 90% of global trade. But the vessels burn about 4 million barrels of oil a day, accounting for almost 3% of the world's carbon emissions, and most ships are built to last about 30 years. So when we cancel something like the Keystone Pipeline, we are not cutting any emissions, we are simply encouraging existing, higher emission methods to take over. Where does the transportation sector stand in terms of innovation to reduce carbon emissions? Are there technologies in a form or scale that are commercially viable for any sector outside of vehicles?

While research on shipping is a bit outside my area of expertise, the University of Rhode Island Graduate School of Oceanography has a Coastal Resources Center that studies this type of research. Staff there were consulted in this response. As noted in the question, shipping is vital to the global economy with about 90% of manufactured goods traveling by sea. Shipping is also reportedly the most energy efficient way to move cargo, and the industry has put forth significant effort into reducing fuel consumption and associated emissions as well as other "greening" efforts to save costs and minimize ecological impacts. Currently, shipping accounts for 2-3% of carbon emissions globally, and the International Maritime Organization aims to reduce greenhouse gas emissions by 50% by 2050. In order to innovate, the transportation sector has been actively engaged in research and development towards identifying and implementing alternative and renewable energy sources. Additionally, the industry has been investigating and including design modifications and new technology to enhance safe and sustainable shipping.

At the present time, there are many technologies that are commercially viable for the shipping industry. Perhaps the most commonplace is the implementation of renewable energy sources, such as wind and solar. For example, a wind propulsion technology by Norsepower showed a fuel savings of 2.6% using a rotor sail. The successful trial of this wind technology is groundbreaking and indicates the potential for wider development in the near future. Additionally, the application of low loss hybrid (LLH) systems has offered fuel savings and reduced emissions. This system utilizes a mixture of power sources and energy storage devices to optimize performance and limit energy losses. In regard to form and function, design modification such as the alteration of ship's bulbous bow have been used to increase efficiency. Another design modification is the application of fuel-saving propellers; for example, Hyundai Heavy Industries has a propeller attachment that creates counter swirls to improve propulsion. These technologies are just a sample of what is currently available. Additionally, there are ongoing improvements in energy storage, navigation technology, ocean data availability and more that will aid the efficiency and evolution of shipping. The University of Rhode Island's Graduate School of Oceanography has been a leader in "greening the fleet" of research vessels; its ship uses biodiesel where feasible and it is working with its partners in the University-National Oceanographic Laboratory System to learn and share how ships can be cleaner and better for the environment. In summary, continuing research and development are driving technology advances that will continue to improve fuel efficiency and reduce impacts of shipping.

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Atlantic article, "Ten Legitimately Fascinating Facts About the Shipping Industry"
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Article "Greening the Fleet: How URI's Work on R/V Endeavor Can Help You"
https://www.sailorsforthesea.org/programs/ocean-watch/greening-fleet-how-uris-work-rv-endeavor-can-help-you
UNOLS Greening the Fleet Initiative, with links to reports: https://www.unols.org/ships-facilities/unols-vessels/greening-fleet-initiative
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https://www.unols.org/sites/default/files/2018inm_6_Corliss_Bruce_VesselOp_101818_0.pdf
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Dr. Paula S. Bontempi
Dean, Graduate School of Oceanography
Professor of Oceanography
University of Rhode Island

Submitted by Representative Charlie Crist

1. There has been an increasing national focus on the need to significantly expand the monitoring and collection of ocean data, including from coastal areas. Having a robust ocean observation network will contribute highly valuable data to climate models and inform decision-making regarding mitigation and adaptation activities.

a. Please discuss the current state of ocean and coastal observations and monitoring, their importance to improved modeling and prediction capabilities, and what additional infrastructure is required to support the collection of these data?

Ocean and coastal monitoring efforts are crucial in addressing ecosystem-based management from the local to federal level in the face of climate change. The economic valuation of these data is vast, enabling sustainable management of marine resources as well as recreation and tourism. Long-term time series of ecosystems and their properties are invaluable when it comes to understanding the impacts of climate variability and change on highly impacted areas such as polar regions and coastal zones of the US.

Existing infrastructure: There are currently a number of ocean and coastal monitoring efforts throughout the United States, but maintaining them and ensuring continuity among these efforts remains a challenge. NOAA's ocean and coastal monitoring efforts include the National Centers for Coastal Ocean Service (NCCOS), the U.S. Integrated Ocean Observing System (IOOS), and the National Estuarine Research Reserve System (NERRS), which represent impressive monitoring efforts with readily available water quality data. NASA also supports critical monitoring of the U.S. coasts and oceans through the global time series provided by Earth Observing satellites. It is essential to note that most of these global findings would be unconfirmed without the contribution of sustained observations and analyses of Earth observing satellite data (my submitted written testimony highlighted many trends that long-term Earth observing satellite data records highlighted). Satellite observations of the Earth's oceans and coasts are directly fed to managers and policymakers for decision support and to support disaster relief. However, additional regional ocean time series such as the Hawaiian Ocean Time-series (HOT) and Bermuda Atlantic Time Series (BATS), support systematic, long-term time-series studies of selected aquatic and terrestrial habitats that yielded significant contributions to earth and ocean sciences through the characterization of climate trends. Another national monitoring effort is the national network of Long-Term Ecological Research Programs (LTERs), funded by the National Science Foundation, aimed at understanding long-term ecosystem changes in both terrestrial and aquatic environments. Cooperative state and federal monitoring programs are also in place, although more limited, including NEAMAP (Northeast Area Monitoring and Assessment Program) that facilitates the collection and dissemination of fishery-independent information obtained in the Northeast for use by state and federal fisheries management agencies. Finally, there are localized monitoring efforts maintained by continued institutional support. At the University of Rhode Island (URI), the Marine Ecological Research Lab (MERL) has maintained a weekly sampling off the Graduate School of Oceanography Pier for temperature, salinity and nutrients since 1976. This monitoring has documented the response of the economically critical Narragansett Bay to the greater then 50% managed nitrogen reduction accomplished by waste-water treatment facilities in 2012, and revealed consistent declines in nutrient standing stocks, chlorophyll, primary production, and hypoxia in the upper bay. The long-term temperature data document the continued rise in temperature for all seasons in Bay-wide waters. The University of Rhode Island is also home to the Narragansett Bay Long-Term Plankton Time Series. In continuous operation since the 1950s, this monitoring effort represents one of the longest continuing time series of its kind in the world and is funded by the University of Rhode Island, Graduate School of Oceanography.

Knowledge generated: Aquatic monitoring has already yielded major scientific discoveries resulting in the detection of multi-decadal oscillation effects on ecosystems to finer-scale understanding of the food web and biogeochemical pathways through which nutrient pollution affects water quality. Oceanic time series have also been critical in quantifying biogeochemical variability and determining the significance of the ocean in regulating the global carbon cycle, which has direct implications for understanding the effects of climate change. (The oceans take up approximately one third of carbon dioxide in the atmosphere, carbon dioxide being a major input to the atmosphere from fossil fuel combustion). Particularly regarding climate change, which represents a long-term phenomenon influenced by multiple factors, utilizing long-term monitoring data (> 10 years) aids in determining the effects of climate change (i.e., warming, ocean acidification) on an ecosystem. These monitoring efforts also have direct impacts in supporting the Blue Economy by ensuring water quality conditions are favorable for the fishing, aquaculture, and tourism and other industries critical to many states' economies. In addition, high-frequency monitoring data informs predictive capabilities, which can have immediate impacts on coastal communities regarding Harmful Algal Blooms (HABs), Marine Heatwaves (MHW), and storm events (i.e., hurricane preparation). Ocean and coastal monitoring provides an irreplaceable information-stream on environmental processes, dynamics of marine populations and communities of organisms, and emergent properties of ecosystems necessary for conserving the coastal United States for future generations.

Federal investments in time series observations, technologies, approaches, sensors, and modeling facilitate innovation and opportunity and must continue. Supporting a more sophisticated understanding of the ocean's role in the climate system, and the impact of climate change on ecosystems and coastal communities, will require the U.S. to develop a comprehensive observing strategy and a plan for continuity of Earth science observations and data records. Without this coordinated information, scientists and managers may not know the impacts of climate variability and change until it is too late to undo the damage or effectively adapt.

b. How can ocean and coastal monitoring improve our understanding of how climate change is impacting the ecology of coastal zones?

Climate change effects on the ecology of coastal zones occur in addition to the underlying variability and complexity of the oceans. This requires that monitoring and research must operate across many temporal and spatial scales, from individual organisms to annual cycles of ecosystems. An iterative research approach that develops and deploys state of the art monitoring technologies (satellites, platforms, sensors, autonomous and otherwise) to obtain time series data of our oceans and coasts with hypothesis driven investigations that probe specific processes is critical. An example is the North East Shelf Long Term Ecological Research Site (NES-LTER), funded by the National Science Foundation and jointly operated by several North East research institutions, including the University of Rhode Island. The effort leverages a large number of existing time series, including light house weather observations going back to the 1880s. The objective of the NES-LTER is to decipher the functioning of the historic and highly productive fisheries of the North East Shelf region with respect to the food webs that support them, and their sensitivity to both natural and anthropogenic changes.

Such long-term monitoring efforts provide crucial observations that predictive ecosystem models, responsible for forecasting climate change and environmental impacts on ocean and coastal ecosystems, rely on for ground-truthing or validating model results. Long-term and frequent monitoring efforts in some regions, such as the U.S. Northeast Shelf and California Coast, generate volumes of data that can be integrated into ecosystem models, allowing realistic ecosystem predictions to be made and supporting data-driven decision making that sustain marine resources and the local blue economy. However, even the highest resolution monitoring efforts are sparse (short lived or not extensive enough regionally or globally), relative to the complexity and variability in ocean ecosystems.

What could improve ecosystem modeling? Even the most densely populated and accessible regions of the coasts are relatively data sparse, especially when it comes to biological information. This paucity is due both to a lack of sensors available that measure ocean, particularly biological, properties as well as the greater effort required to sample living organisms compared to physical or chemical conditions (e.g. temperature). With this comes an opportunity for investment in infrastructure and technologies that could support commercial partners and industry while forwarding scientific and engineering objectives. Amending passive observational strategies with active sampling and experimentation will generate insights that are hypothesis driven and process focused. Such a two-pronged approach allows for "what if" questions to be addressed. An effort essential to address climate change related management challenges.

Physical infrastructure and an expert, climate literate, work force to support ecological monitoring can be expensive but it is sorely needed, particularly where observational infrastructure already exists to monitor physical and chemical characteristics of an ecosystem (i.e., IOOS). Continued support of integrating sampling strategies from the physical to the biological, with clear data management protocols is critical. Cyberinfrastructure, sensor development and best data management practices are key to the success of coastal monitoring.

Modeling is particularly important for climate change research and impact, adaptation, and mitigation studies. Modeling elements of interdisciplinary research programs must be considered from early planning stages forward. Success stories, such as NASA's Carbon Monitoring System, connect scientists and managers to test real solutions to climate change. Modeling barriers include scientific knowledge and the provision of open source, affordable, robust, and meaningful high-resolution products for user and stakeholder communities. Here, an avenue for advancement may be increased partnering with private entities and enterprise-level cloud-based computing, while simultaneously recognizing issues of repeatability, sustainability, public access, and security that are associated with all climate data records.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
"The Science Behind Impacts of the Climate Crisis"
Questions for the Record to:
Dr. Paula S. Bontempi
Dean, Graduate School of Oceanography
Professor of Oceanography
University of Rhode Island

Submitted by Representative Mikie Sherrill

1. Harmful algal blooms (HABs) are increasing in frequency, duration, and intensity and the effects are exacerbated by climate change. HABs pose a serious economic and social threat. Lake Hopatcong in my district is the largest freshwater lake in New Jersey, and it was closed for most of summer 2019 due to HAB outbreaks.

a. What has led to the improvement in our ability to understand how climate change is impacting HABs?

Investments in local to global research, technology (laboratory and in situ instruments) and modeling, as well as observational approaches have begun to revolutionize our understanding of HABs and their dynamics, enabling better prediction of HABs. However, researchers and managers have not yet fully resolved our understanding of HABs, their evolution, and their prediction and management. HABs are created by small algal organisms that use nutrients and sunlight to grow. These organisms live in both fresh and salt water. Human habitation and agricultural practices supply anthropogenic nutrients into our coastal systems, often stimulating HABs. Climate change is impacting seawater temperature and nutrient inputs are ever increasing – both factors promote HABs. Scientific research focusing on understanding the drivers of plankton ecology in a changing climate will ultimately improve our ability to understand HABs. Recent research has shown that in addition to nutrients, predation can be important for HAB formation. Thus, future research should holistically approach studies of HAB organisms and their toxins in their biological and environmental context, from the organismal to ecosystems. For example, RI researchers are using genetic detection and imaging technologies to discern HAB plankton species from non-HAB relatives and deploying sensitive mass-spectrometry based methods for toxin detection and results have led to predictions in timing and nutrient drivers of when specific algal toxins are likely to occur in the economically critical Narragansett Bay ecosystem.

It is impossible to discern climate change factors on ecosystem change without long-term data sets from time-series sampling efforts for interpretation of present and past events. Data from current and past sampling informs predictive modeling for forecasting HAB events. Congress should continue to support and augment time-series sampling sites and long-term ecological research programs as they are essential for understanding ecosystem change. There are a number of ocean and coastal monitoring efforts throughout the United States but maintaining them and ensuring their continuity remains a challenge. Examples include NOAA's National Centers for Coastal Ocean Service (NCCOS), the U.S. Integrated Ocean Observing System (IOOS), and the National Estuarine Research Reserve System (NERRS) and the NSF funded national network of Long-Term Ecological Research Programs. NASA also supports critical monitoring of the U.S. coasts and oceans through Earth observing satellite observations and research, as do other federal agencies. Finally, there are localized monitoring efforts maintained by continued institutional and state support, including in RI the Narragansett Bay Long-Term Plankton Time Series, one of the longest continuing plankton time series in the world co-funded by the University of Rhode Island, Graduate School of Oceanography that are crucial for collecting information on local waters that allow local agencies to manage HAB outbreaks. Climate change impacts on ocean physical and chemical properties cause additional wide-ranging ecosystem responses, including frequent harmful algal blooms, so these investments must continue to address the evolving HAB challenges.

b. How has satellite monitoring of HABs helped improve early detection and warning of HABs?

Our current ability to monitor HABs are limited by humans' availability and capability to sample, inadequate technology, and limited financial resources to monitor the entirety of the ocean. These limitations are compounded by aquatic phytoplankton's life cycle, which is about 2-6 days, thus requiring near daily or more frequent sampling or monitoring. These issues make management and mitigation of HABs a huge challenge. Increasing ocean surface temperatures, nutrient pollution, and other anthropogenic factors contribute to more frequent harmful algal blooms (HABs) that impact the US's and world's blue economy. Polar orbiting Earth Observing satellite data provide global views of the world's aquatic environments approximately every one to two days at a range of spatial and temporal scales. NASA will soon deploy a new satellite instrument technology that will drastically advance our ability to monitor, study, and predict HABs, protecting the environment and the economy. Satellite observations at high spatial and spectral resolution, such as from NASA's planned PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) mission, will be critical for discerning what types of phytoplankton are blooming, and therefore could be harmful. In situ observations for sea truthing will continue to be critical for validating the remote observations. However, in situ observations alone would not be practical for large water bodies such as Lake Hopatcong.

The PACE observatory will acquire highly specialized data used to examine phytoplankton on a continuous basis and transmit it back to scientists. These data paired with surface water temperature, nutrients, salinity, wind, ocean current, and other aquatic data sets should reveal patterns of bloom occurrence and identify the composition of these blooms, allowing the separation of harmful from other phytoplankton blooms. Using PACE to identify areas of high-pollution from terrestrial runoff and dense algal blooms allows scientists and managers to better handle economically important and populated regions, as well as Marine Protected Areas. In addition, scientists and managers using PACE data might be able to identify locations that show early signs of fish and other commercially viable aquatic species die offs due to HABs, allowing managers to take action to reduce impacts.

According to the NASA PACE mission's early adopters, the hyperspectral resolution of the PACE Ocean Color Instrument will also enable scientists and manages to take an unprecedented look at details on speciation of plankton that may then be related to a particular water-borne pathogen. This will further enhance scientists' and managers' understanding on global coastal and ocean bioecology. The spatial resolution of PACE is optimal for developing protocols to determine risk of potential infections to coastal human communities. Information such as this will help managers to quantify aspects of resilience and sustainability of natural and built infrastructure under current and changing climate scenarios.

Aside from formulating new satellite missions, agencies, such as NASA, also support basic and applied research as well as technology development in cooperation with federal, state, and regional partners to observe, understand, and predict the dynamics of algal blooms, including toxin-producing HABs. Some examples of these partnerships follow.

NASA has funded research in partnership with NOAA, EPA, and USGS that has resulted in the EPA testing an operational CyanoHAB prediction model using optical oceanographic and satellite data. The result of this research is now realized in a monitoring platform of over 2,000 of the Nation's lakes and reservoirs and includes a free downloadable App that local water managers can customize for their areas of concern. https://www.epa.gov/sciencematters/cyan-mobile-app-helps-communities-detect-cyanobacteria-us-water-bodies

NASA, in coordination with NOAA, recently funded a Prototype Model for Improved Forecasts of Respiratory Illness Hazard from Gulf of Mexico Red Tide. As a result of this research and starting in October 2018, people looking to avoid the hazardous effects of toxic red tides around St. Petersburg and Pinellas County, Florida, turned to a new smartphone-based pilot information resource updated several times a day to help them know the risks before they head to the beach. The new 24-hour Experimental Red Tide Respiratory Forecast allows the public to see which beaches are most impacted by red tide.

NASA is funding the University of Florida to collaborate with the Southern Florida Water Management District and the U.S. Army Corps of Engineers to research and develop improved decision tools for water management in Florida's complex freshwater systems, the research seeks to establish potential linkages between water discharge decisions, local forcing, and HAB's.

NASA has supported the development of the California Harmful Algae Risk Mapping (C-HARM) System, providing three-day forecasts of the chance of encountering HAB toxins off the coast of California and southern Oregon. The primary HAB of concern in these waters is caused by certain species of the diatom genus *Pseudo-nitzschia* responsible for domoic acid, a neurotoxin that accumulates in shellfish and small fish ingested by birds, marine mammals, and humans resulting in short-term memory loss, brain damage, and even death. NASA has transitioned operation of C-HARM from academic servers to the West Coast Regional Node of NOAA Coast Watch. Products available to the public include daily nowcast and three-day forecast maps and also a monthly CA HAB Bulletin issued by the Southern California Coastal Ocean Observing System (SCCOOS) with a retrospective analysis of C-HARM output in relation to statewide HAB and shellfish monitoring and marine mammal stranding data.

NASA funding has led to the development of a new sensor configuration for AERONET-OC sites in inland lake systems targeting observation of harmful cyanobacteria blooms. The sites include Lake Erie, Lake Okeechobee (Florida), and Green Bay. These observations are providing new data streams for 1) high-frequency observation of water quality, 2) algorithm development for cyanobacteria bloom detection, and 3) validation match-up data sets with NASA and ESA satellites. Data from these sites are improving our capabilities of cyanobacteria bloom detection and satellite quality needed for long-term trend assessment.

c. What additional improvements in HABs research, monitoring or mitigation do you recommend for improving our understanding of how climate change is impacting HABs and how to mitigate or adapt to the impacts?

As HAB challenges are global, we must foster international coordination and cooperative research to address the scientific and societal challenges of HABs, including the environmental, human health and economic impacts, in a rapidly changing world. Governments must consolidate linkages with broader scientific fields and other regional and international initiatives relevant to HABs. We must foster the development and adoption of advanced and cost-effective technologies, and promote training, capacity building and communication of HAB research to society. International bodies, such as GEOHAB and GlobalHAB, must serve as liaisons among the scientific community, stakeholders and policy makers, informing science-based decision making.

Successful HAB research requires teams comprised of researchers from scientific agencies at all levels (local to federal and international), academics, and training of our next generations of scientists. Investments in continuing long-term data collection are invaluable. Improvements will be realized with investments in human capital first and foremost. Support for sustaining long-term sampling sites going forward and for ecosystem based modeling will improve our ability to predict HABS and to suggest ways of best mitigating them. An example of this is research that made it clear reduction of phosphorus in water bodies is a good way to mitigate HABs and is now monitored by the EPA. As we develop new methods for detecting HAB species and for some that episodically produce toxins, we can better resolve the relationship between climate and toxin production and understand variables to target for mitigation.

According to the GlobalHAB Science and Implementation Plan (2017), there is increasing concern that global change may stimulate geographic expansion and increases in severe impacts of HABs. There is clear evidence that the main drivers of the general dynamics of the causative algae (surface water temperature, ocean stratification, wind and water circulation patterns, precipitation-linked nutrient inputs, and changes in the salinity of estuaries) could lead to expansion of marine HABs by changing ocean and coastal waters in ways that could stimulate more HABs. Further anthropogenic pressures on aquatic ecosystems include surface water acidification derived from increasing CO2 emissions and alteration of natural habitats, especially in the coastal zones.

Forecasting (modeling) the future occurrence of HABs requires continuing our efforts to improve the fundamental knowledge of the mechanisms driving HAB events. A fundamental question is whether the environmental windows of opportunity for HAB species are expanding, or simply shifting geographically and/or seasonally. We are trying to understand these phenomena as the climate is changing. It is, therefore, necessary to investigate the responses of the harmful microalgae (including toxin production) not only in relation to individual natural drivers (i.e., temperature, salinity, nutrients, CO2) but also to changes in the interactions among them under changing climate scenarios.

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Dr. Paula S. Bontempi
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University of Rhode Island

Submitted by Representative Ami Bera

1. There are multiple lines of evidence that climate change has increased the wildfire risk in my home state of California and across the American West. The record-setting 2020 wildfire season is a vivid example of how climate change is making wildfires more frequent and intense, as wildfires last year burned a record 10.3 million acres and caused billions of dollars in damages and cost dozens of lives. Robust forecasting and monitoring of extreme events such as drought and wildfires is critical to helping prepare for and prevent these disasters.

a. What is the role of satellite monitoring in detecting and predicting wildfires?

This question is slightly outside my area of expertise, but I consulted with a few experts and former colleagues at NASA on the topics. Satellite data are critical for detection and prediction of wildfires, their spread, and containment, as well as management of impacts such as burned area and the influx and transport of material in to the atmosphere, such as smoke, that can affect air quality and human health. Satellite data were actively used in management of the California and Australian wildfires last year. NASA's satellite instruments are often the first to detect wildfires burning in remote regions, and the locations of new fires are sent directly to land managers worldwide within hours of a satellite overpass. There are a number of NASA instruments that detect actively burning fires, track the transport of smoke from fires, provide information for fire management, and map the extent of changes to ecosystems, based on the extent and severity of burn scars. These actions are time critical for human life, resources, ecosystems and economics.

Many of NASA's and other space agency Earth-observing instruments contribute to our understanding of fire in the Earth system. Satellites in polar orbit provide observations of the entire planet several times per day, and satellites in a geostationary orbit provide coarse-resolution imagery of fires, smoke and clouds every five to 15 minutes. NASA's satellite, airborne and field research capture the full impact of fires in the Earth system, from rapid detection of actively burning fires, transport of smoke and changes in ecosystems in the days to decades following the fire. Much of the remote-sensing data that NASA collects on wildfires is quickly put to work in aiding disaster response efforts around the world.

Significant research on fire prediction models using satellite data assimilation is being undertaken and supported by USDA, USGS, NSF, NASA, DOE and NOAA. Improved prediction of wildfires could enable firefighters to work more efficiently and safely if they knew exactly how a wildfire was going to spread. We can't forecast exactly where and how quickly a growing fire will move, but computer models used in fire forecasting have vastly improved over the last few decades. To continue improving fire forecasts, researchers need more data on how real fires spread and interact with their environment — but human operations on the ground during fires is too dangerous.

MIT Technology Review had a really comprehensive article on the topic recently:
https://www.technologyreview.com/2021/01/18/1016215/complex-math-fire-modeling-future-california-forests/

Satellite fire detection is relatively mature. NASA's MODIS-Terra, MODIS-Aqua and NOAA's VIIRS sensors are operationally used to do so, as are some geostationary satellites.

Some examples can be found here:

https://firms.modaps.eosdis.nasa.gov/map/#d:2021-04-04..2021-04-05;@0.0,0.0,3z

https://pgefdp.lovelytics.info/pge_fire_app/

These approaches work well for fire *detection*, but not for fire *monitoring*. The primary issue with fire monitoring and polar orbiting satellites is that satellites don't acquire data over the fire frequently enough to derive meaningful fire characteristics from the acquired data. Polar orbiting satellites may not sample at times when the fire is very active, due to their orbit overpass frequency or timing, as well as the fire's evolution.

One challenge with geostationary satellites is that they currently tend to have more coarse spatial resolution relative to polar orbiting satellites, but higher temporal sampling capability (hours versus days from polar orbiters). This approach may be okay for global fire studies, but such information is not detailed enough for operational management of active fires. A figure that demonstrates this can be found here: https://www.mdpi.com/1424-8220/20/18/5081

Predicting fire spread can be done with models such as FARSITE (https://www.firelab.org/project/farsite). Input parameters include characteristics of the fuel bed size and structure, fuel moisture, weather (RH, wind speed, wind direction, etc.), and topography. These types of models are used on active fires to help plan fire response and allocation of firefighting resources, but really have their greatest utility once a fire has started. Predicting fire ignition (i.e., where/when a fire will start) is very complicated. Researchers need a good idea of fuel conditions (structure/moisture), weather, topography, and probability of ignition (e.g., lightning strikes, potential human sources, etc.). Most fire managers look for properties such as fire risk instead. "Fire risk" is essentially maps of areas where fires would become very problematic if ignited. For example, areas of high human value (homes/towns) in proximity to areas with hazardous fuels conditions. Maps of fire risk are used to plan fuels reduction treatments, for example.

Firefighters in command centers worldwide routinely use data streams from satellites to plan firefighting efforts. But satellite data are only one key resource on fire. California's forests were caught between a management regime devoted to growing thick stands of trees—and eradicating the low-intensity fire that had once cleared them—and a rapidly warming, increasingly unstable climate. As a result, more and more fires were crossing a poorly understood threshold from typical wildfires—part of a normal burn cycle for a landscape like California's—to monstrous, highly destructive blazes.

Agencies such as NASA fund research and development for projects that use Earth observations and models to analyze wildfires before, during, and after they occur —improving the accuracy of modelling systems and the methods used to estimate the amount of fuel in a fire-prone area. The agency's airborne and ground-based field campaigns collect valuable data on fire and smoke, including their health effects.

Berkeley and Stanford both have groups doing interesting work:

https://nature.berkeley.edu/stephenslab/lab-members/dr-brandon-collins/
https://woods.stanford.edu/expertise-tags/wildfire

b. What additional investments can be made in satellite or *in situ* monitoring to improve wildfire detection and monitoring?

My previous answer covers some of the areas in which continued and new investments are needed. Our understanding of the mechanics of wildland fire is rudimentary. Our current approach to fire modeling, is built on a particular set of equations nearly half a century old to calculate how fast fire would move, with given wind conditions, through given fuels. What's needed now is less a technique for real-time prediction than a fundamental reappraisal of how fire works—and a concerted effort to to restore California's landscapes to something approaching a natural equilibrium.

Going forward, NASA has a mission in formulation, Surface Biology and Geology (https://sbg.jpl.nasa.gov) that will have thermal bands appropriate for fire related studies, but the temporal resolution will not be sufficient for fire management. Canada is formulating plans for a satellite called WildFireSat, (https://www.asc-csa.gc.ca/eng/satellites/wildfiresat/default.asp). People have been thinking of dedicated satellite constellations to improve upon the limitations I pointed out in #1 above. I'm not convinced this is the way to go for operational fire management. Instead, I think the most promising approaches being discussed include putting thermal sensors on HAPS (high altitude pseudo satellites) that could be deployed over active fires/regions with active fires. A fleet of these would do the trick.

For modeling and prediction: models critically depend upon observations in many ways: 1) to keep our so-called 'forward' models (i.e. those which run free without assimilation of any data) honest by model/observational comparisons; 2) as initial and boundary conditions for those forward models; and 3) for assimilation into our always-too-coarse models. Good observations can also be used in the design of new observatories (locations; spatial and temporal resolution) and the design of new sensors through so-called Observing System Simulation Experiments. A properly designed OSSE can be used for optimizing an observatory for specific processes.

A key challenge in observations and model is that a fire is not a linear system, proceeding from cause to effect. It is a "coupled" system in which cause and effect are comingled.

USDA's Forest Service has a section focused on Predictive Services that supports many types of fire science decisions, including pre-positioning and distribution of firefighting assets; initial and extended attack asset needs; increasing/decreasing assets; fire management strategies; severity funding; and contracting of assets. This is accomplished through analysis of weather and climate, fuels, and fire activity. Predictive Services examines fire weather and climate, fuels and fire danger, and fire activity and firefighting asset intelligence. This department lists their primary needs as: to further improve the basic physical-level models that underlie fire systems, such as those that calculate flame length or rate of flame spread, fuel, weather impacts using investments in computational fluid dynamics that are well suited to fire modeling because it can simulate combustion kinetics, chemistry and heat transfer. The technique requires vast computing investments.

Improving models and establishing their scientific credibility also rest on comparing their outputs against observations of actual fires. The difficulty posed to firefighters and researchers attempting to obtain precise field measurements makes this a challenge in itself. Models will also improve as we get a better handle on the ficklest aspects of a wildfire, such as transitions from surface fires to crown fires, as well as spot fires that are ignited ahead of a flame front by windblown embers.

Appendix II

Additional Material for the Record

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One Earth

Primer

Attributing Extreme Events to Climate Change: A New Frontier in a Warming World

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The emerging field of extreme-event attribution (EEA) seeks to answer the question: "Has climate change influenced the frequency, likelihood, and/or severity of individual extreme events?" Methodological advances over the past 15 years have transformed what was once an unanswerable hypothetical into a tractable scientific question—and for certain types of extreme events, the influence of anthropogenic climate change has emerged beyond a reasonable doubt. Several challenges remain, particularly those stemming from structural limitations in process-based climate models and the temporal and geographic limitations of historical observations. However, the growing use of large climate-model ensembles that capture natural climate variability, fine-scale simulations that better represent underlying physical processes, and the lengthening observational record could obviate some of these concerns in the near future. EEA efforts have important implications for risk perception, public policy, infrastructure design, legal liability, and climate adaptation in a warming world.

Looking beyond the Mean Climate

There is now an extremely high level of scientific confidence that human activities are the only plausible explanation for the observed ~1.2°C rise in global mean temperature, and a human fingerprint has likewise been found in numerous other changes in climate. However, although the mean climate is a useful metric of overall climate change, it remains a statistical construct: no place actually experiences its local mean. Moreover, the aspects of climate change that have the greatest effects on society and ecosystems—such as heatwaves, downpours, hurricanes, droughts, and wildfires—are inherently far from the mean. Therefore, to understand, mitigate, and adapt to climate changes that could harm the health and well-being of humans and ecosystems, it is imperative to understand how (and why) these climate-related extremes are changing in a warming world.

This branch of climate science, often referred to as extreme-event attribution (EEA), has evolved rapidly in recent years. This evolution has faced a number of challenges. In particular, structural limitations in process-based climate models, as well as temporal and geographic limitations of historical observations, lead to substantial challenges in quantification and validation. However, recent methodological advances, coupled with longer observational records and improved climate models, have opened the door to systematically addressing the question of whether climate change has influenced the likelihood and/or severity of individual extreme events.

Viewing Climate Change through an Extreme-Weather Lens

The news media and public often ask: "Did climate change cause this specific extreme weather event?" In a very literal sense, the answer to such a rigidly posed question will always be "no." All events in the dynamically coupled Earth system are ultimately the product of numerous complex, interrelated processes acting across a wide range of spatiotemporal scales. There will thus rarely (if ever) be a traceable singular cause for any specific event, and variability will always play an important role. Indeed, as recently as a decade ago, a common response from scientists was that "no single weather event can be attributed to climate change."

Weather and climate, of course, are not the same. Weather describes variations on very short day-to-day timescales, whereas climate integrates over much longer time horizons. A key step forward in the development of EEA has been the acknowledgment that weather and climate exist on a continuum. Because climate describes the aggregate statistical properties of weather—in other words, the plausible envelope of weather conditions at a particular point in time—it encompasses not only "typical" conditions but also rare, high-magnitude weather extremes. From this perspective, understanding multi-decadal climate change can reasonably be framed as an exercise in quantifying shifts in the overall probability distribution of day-to-day weather conditions.

As a result, climate scientists have increasingly recognized that the strict question of binary causality is ill posed. Because climate is inherently a probabilistic descriptor of largely stochastic underlying weather processes, it stands to reason that scientific investigations into the influence of climate change upon extreme weather events should also be framed in probabilistic terms. Additionally, a considerable body of evidence suggests that human-caused changes in the low-probability, high-consequence "tails" of the weather distribution could be considerably different from what might be inferred from extrapolating shifts in

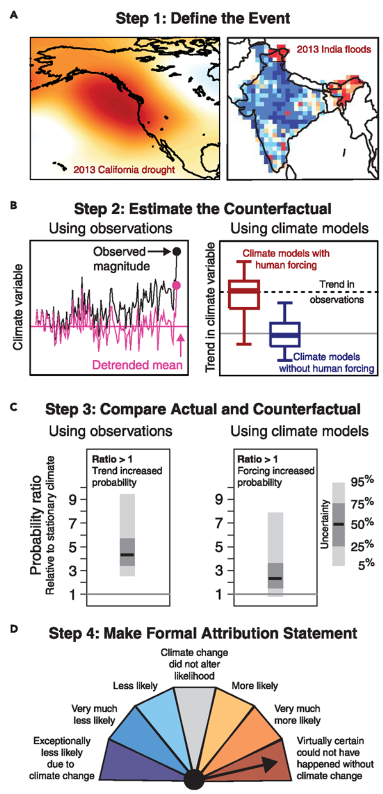

Figure 1. Four Key Steps of EEA

Illustration of the typical EEA workflow using examples from the existing literature.

(A) Define the extreme climate event, here illustrated by the magnitude of anomalous high pressure during a drought event (adapted from Swain et al., 2014, left) and of extreme precipitation during a flood event (adapted from Singh et al., 2014, right).

(B) Calculate the counterfactual climate by using real-world observations and/or climate models (adapted from Diffenbaugh et al., 2017).

(C) Compare actual and counterfactual climates, again by using real-world observations and/or climate models (adapted from Diffenbaugh et al., 2020).

(D) Make a formal attribution statement regarding whether anthropogenic climate change contributed to the likelihood and/or severity of the extreme event (adapted from Lewis et al., 2019).

the mean. Therefore, a growing number of studies have instead begun to ask a more nuanced question: "Has climate change influenced the frequency, likelihood, and/or severity of the extreme event?" This seemingly subtle shift in perspective transforms an essentially unanswerable question about absolute causality into one that is both scientifically tractable and practically actionable—and that can be directly addressed with existing observational and numerical modeling tools.

Diverse Attribution Approaches but Shared Epistemology

As the field of EEA has rapidly expanded over the past decade, different research groups have pioneered a range of novel approaches. Virtually all approaches share a common epistemology: using some combination of real-world observations, numerical climate-model simulations, and rigorous statistical techniques to separate the effects of actual human influence on the climate system from a counterfactual "climate without human influence." It is critical to understand both this general scientific framing and the specific methodological variations because results can be strongly dependent on the assumptions and analysis techniques employed. In the sections that follow, we first outline the basic methodological steps that are shared across most EEA studies (Figure 1) and then more deeply explore the range of approaches and assumptions that have historically been employed in different contexts.

Key Steps in EEA

1. Define the event. What spatiotemporal scale and physical variable(s) best characterize the event? Given an extreme heatwave, for instance, appropriate metrics might include daily maximum temperatures for a specific city, weekly average temperatures for a region, combined heat and humidity metrics, or underlying event drivers such as the strength of the atmospheric underlying high-pressure system.
2. Estimate the "counterfactual" climate. Quantifying the influence of global warming requires quantification of the magnitude and/or likelihood of the event in a counterfactual climate without human influence. One approach is to quantify changes in the probability of the event in climate-model simulations without anthropogenic climate forcing. Alternative approaches include removing the long-term trend from the historical climate time series, using statistical relationships between the climate variable and global temperature, and using observational data from a time period with little anthropogenic influence.
3. Compare actual and counterfactual climate. Are there statistically distinguishable differences in the probability and/or severity of the event between the actual and counterfactual climates? A number of different metrics have been used, including the fractional difference in event magnitude, the ratio of event probability (often called the "risk ratio"), and the portion of the total risk contributed by anthropogenic activities (i.e., the "fraction of attributable risk"). In addition, uncertainty quantification is a critical priority for both model- and observation-focused approaches. Key sources of uncertainty include the statistical quantification of the probability of the event,

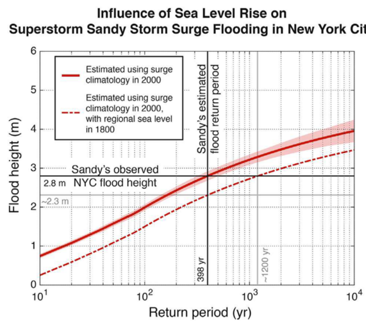

Figure 2. Example of a Conditional and Ingredient-Based EEA Assessment

Results from a conditional and ingredient-based EEA assessment of the influence of one particular aspect of climate change (sea-level rise) upon the observed level of coastal inundation during a specific historical storm event in New York City (Superstorm Sandy during October 2012). The upward and leftward shift of the red curve shows that sea-level rise increased the severity (depth) of the inundation by ~20% but increased the likelihood of the observed level of inundation (i.e., decreased the return period) by ~300%. Adapted from Lin et al., 2016.

the ability of climate models to accurately simulate the observed variability of the climate variable, the magnitude of the "forced response" simulated by different climate models, and the "irreducible uncertainty" in the forced response contributed by internal climate variability.

4. Make a formal attribution statement. Most EEA approaches use a very high bar for attribution: the typical null hypothesis is that human-caused climate change did *not* influence the magnitude or probability of the event, and rejecting that null requires a "beyond a reasonable doubt" standard. If there is sufficient evidence of a statistically distinguishable difference in the actual versus counterfactual climate, the null hypothesis can be rejected, and an affirmative attribution statement can be made at a specific confidence level. Given the multiple sources of uncertainty, attribution statements often include multiple components (i.e., "there is a 95% likelihood that global warming increased the probability of the event by at least a factor of 2.86"). New frameworks have been suggested to simplify the final attribution statement (Figure 1D).

Absolute, Conditional, and "Ingredient-Based" Approaches

Initial decisions regarding how to define the event can influence the entire EEA process described in Figure 1. In addition to the decisions regarding appropriate physical metrics and spatiotemporal scales, there is also a deeper philosophical choice regarding which aspects of the event are most important and how far down the chain of complex physical causality the attribution methodology can be reasonably extended. These decisions can ultimately shape the final EEA conclusion.

Consider an attribution study focused on the coastal inundation produced by a large hurricane making landfall at some specific location. One possible approach would be to consider the full sample of all hurricanes that affected the region and ask whether there has been a change in the likelihood of flooding exceeding the observed threshold. This might be referred to as an "absolute" approach because it considers overall changes in event likelihood without accounting for the specific initial conditions (i.e., the study is not preconditioned on the fact that a large hurricane occurred at that specific location and at that specific time) or the contribution of any particular contributing factor (e.g., sea level, precipitation intensity, and storm strength). As a result, absolute approaches can complicate efforts to understand which specific aspect of climate change has contributed to changes in the probability or severity of the extreme event. For example, without methods to isolate specific conditions, it would be difficult to differentiate between contributions from sea-level rise (which increase background water levels), increasing atmospheric water-vapor content (which contributes to the precipitation intensity of a given storm), and warming ocean temperatures and decreasing vertical wind shear (both of which act to intensify hurricanes).

Another approach, often referred to as the conditional or "storyline" approach, takes certain aspects of the event conditions as given (such as the large-scale atmospheric conditions at the time of the event) and asks whether climate change has had a detectable effect upon modulating the outcome of the event. Often, such attribution studies involve perturbing a subset of relevant physical variables characterizing the state of the real-world atmosphere and/or ocean by an increment commensurate with the effect of climate change. In the hurricane example, a conditional approach might involve using the real-world atmospheric conditions from 5 days before the storm made landfall as initial conditions in a model simulation but prescribing sea surface temperatures with the anthropogenic ocean warming trend removed. A key strength is that the conditional approach can help isolate the influence of specific physical aspects of climate change. A significant weakness is that this approach cannot diagnose changes in the overall probability of the event or the probability of individual constituent physical conditions.

An alternative to the absolute and conditional frameworks is the "ingredient-based" approach (Figure 2). Here, investigators first ascertain the most essential physical conditions known to contribute to the severity of a given event and then assess changes in the probability of these conditions. This approach aims to combine some of the key strengths of the absolute and conditional approaches because it (1) enhances understanding of how anthropogenic climate change is influencing the underlying physical drivers of extreme events, including the probability that they co-occur; (2) makes no assumptions regarding the specific set of initial conditions that produced the event; and (3) potentially enables attribution of event types that are poorly simulated in climate models and/or sparsely sampled in observational datasets.

Magnitude versus Frequency Definitions

Fundamentally, two aspects of extreme events are typically assessed in attribution studies: the probability and the severity

Examples of Collective Attribution

A

	Fraction of global surface area with individual attribution	
	Δ Return interval from historical trend	Δ Magnitude from anthropogenic forcing
Hottest monthly temperature	0.97	0.83
Hottest daily temperature	0.83	0.85
Driest annual precipitation	0.42	0.57
Wettest 5-day period	0.59	0.41

B

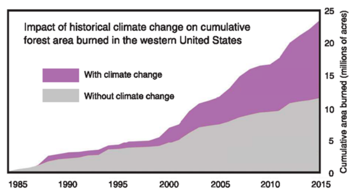

Figure 3. Example of Collective EEA Assessments

(A) Collective EEA for multiple physical event types (hot, dry, and wet events on different timescales) on a global scale with a large climate-model ensemble (adapted from Diffenbaugh et al., 2017).

(B) Collective EEA for a specific event type (wildfire risk, as measured by area burned) directly illustrates the contribution of climate change relative to a counterfactual climate without human influence (adapted from Gonzales et al., 2018).

(Figure 2). The probability of an event is often defined as a rate of exceedance of a fixed threshold defined with a historical baseline—for instance, exceeding the 99.99th quantile of daily precipitation during the years 1920–1980. Conversely, the severity of an event is often defined as a magnitude associated with a given probability, such as "design floods" that are based on the magnitude of the 100-year recurrence interval.

The probability and severity definitions can be two sides of the same analytical coin (Figure 2). However, the differences between these definitions are sometimes highly consequential for both broader communication and practical decision making. For example, regional sea-level rise over the past two centuries increased the severity of Superstorm Sandy's flooding in New York City by 22% (from ~2.3 to ~2.8 m for an event of Sandy's observed probability). According to the same analysis (Lin et al., 2016), that same sea-level rise tripled the probability of the observed flooding (from ~1,200- to ~400-year return period for an event of Sandy's observed severity). In colloquial terms, a ~20% increase might sound modest, whereas a tripling sounds very large indeed—perhaps leading to a wide divergence in public perception regarding a study's outcome.

Yet, both of these are equally valid—and statistically consistent—metrics for quantifying the role of climate change, and both are potentially useful in different contexts. The probability-based metric, for example, could be highly relevant in a civil engineering context. Given that water infrastructure ranging from drainage culverts to large dams is typically designed to accommodate events defined by fixed historical thresholds (e.g., the amount of precipitation associated with a 100-year recurrence interval), increases in the probability of exceeding the original design threshold imply increased risk that the existing design capacity could be exceeded. The magnitude-based metric, on the other hand, is of heightened relevance in a legal and public policy context—instances in which it could be important to know the fraction of known losses contributed by climate change.

Individual versus Collective Event Attribution

Another key point of distinction is the difference between individual event attribution and what can be described as "collective event attribution." Individual event attribution seeks to answer the question: "Has global warming influenced the likelihood or severity of a specific observed historical event?" Conversely, collective event attribution seeks to answer the question: "Has global warming influenced the overall likelihood or severity of extreme events of a certain type?" (Figure 3). Individual event attribution might focus, for example, on whether the vegetation flammability in the vicinity of Paradise, California, in November 2018 (the time and location of California's deadliest and most destructive wildfire in modern history) was made more likely or more severe by global warming. Collective event attribution, on the other hand, might focus on whether climate change has increased the overall likelihood of high vegetation flammability in the western United States (and, hence, that the record-setting vegetation flammability was "consistent with" changes that would be expected from climate change).

Recently, research groups have begun to offer "rapid response" climate attribution targeted toward real-time weather events and sometimes make a formal attribution statement before the event even takes place. Emerging methods that apply an anthropogenic signal to numerical weather forecasts enable evaluations that are highly specific to the conditions of a given individual event. In addition, rapid statements can also be predicated on precomputed metrics via collective event-attribution methodologies that use large samples of observations and climate-model simulations to evaluate a particular type of extreme.

Similar collective attribution methodologies have also been used to quantify the fraction of a region or the globe over which anthropogenic forcing has already influenced the probability of record-setting events (Figure 3) and to verify event-attribution methodologies by using out-of-sample prediction-verification frameworks.

Scientific Stumbling Blocks

Although the science of EEA has advanced dramatically since the benchmark attribution study of the 2003 European heatwave (Stott et al., 2004), several substantial challenges remain. The most prominent relate to uncertainties surrounding the creation and analysis of the counterfactual climate. Researchers have used both statistical and climate-modeling approaches to quantify the counterfactual, although there is no consensus on which of these methods is the most suitable representation of event probability or severity in the absence of human influence.

The challenge of the counterfactual is exacerbated by the fact that, in many cases, it remains difficult to estimate the event probability in the current climate. For sufficiently severe events, the existing observational record might simply be too temporally and/or geographically limited to enable robust probability quantification. One option is to use parametric curve fitting or other statistical techniques from extreme value theory to approximate the

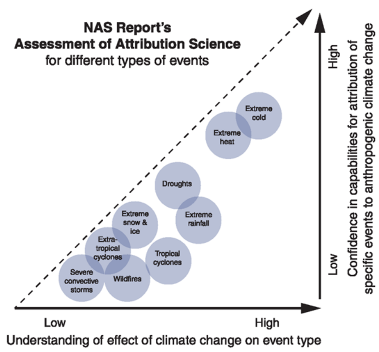

Figure 4. Confidence in EEA by Physical Event Type
Qualitative depiction of the relative levels of confidence in the ability to perform robust EEA as a function of physical event type. Such confidence varies considerably across different atmospheric and Earth system phenomena as a result of differences in understanding regarding how climate change can affect underlying drivers, as well as differences in how these processes are represented in observations and/or climate-model simulations. In general, confidence is highest for events most directly relating to temperature (such as extreme heat) and lowest for events occurring on small spatial scales (such as severe convective storms). Adapted from NASEM, 2016.

recurrence interval of the event. However, multiple studies have demonstrated that such statistical approaches are extremely sensitive to the assumed functional form of the underlying distribution and yield estimates of present-day probability that vary by orders of magnitude. Large climate-model ensembles, which offer much larger sample sizes, can help avoid the need to make such assumptions about the underlying distribution. Yet this alternative is still subject to the major caveat that present-generation climate models cannot always reliably capture the underlying physical processes responsible for certain types of events.

This caveat points to the larger question of whether climate models are fit for purpose in the context of EEA. A major challenge is the trade-off between the fine model resolution that is necessary for resolving the physical phenomena that produce certain types of extreme weather and the large ensembles and long integrations that are needed for fully characterizing internal climate-system variability and distinguish the signal of climate change. For instance, climate models are able to represent $\sim 10^3$-km-scale high-pressure systems responsible for extreme heatwaves, but most are still too coarse to capture the full intensity and behavior of $\sim 10^2$-km-scale tropical cyclones and face even greater challenges in simulating localized extreme precipitation events, which can occur on spatial scales that are smaller than a single global climate model grid cell. These climate-model limitations are a key reason why the level of confidence associated with EEA statements varies considerably by the type of extreme event (e.g., very high confidence for heatwaves versus only moderate confidence for tropical cyclones; Figure 4).

Together, these limitations raise the distinct possibility that studies finding no influence of climate change are simply reflecting the limitations of either the observational record or climate-modeling capabilities. A key philosophical consideration thus emerges: does an "absence of evidence" regarding the role of climate change mean that there is truly "evidence of absence"? Clarifying why it can be difficult to distinguish between these two possible interpretations of a negative attribution result is an important aspect of communicating the results of such studies to decision makers and the public.

The Way Forward

Recent developments in climate modeling and interdisciplinary Earth system science highlight the potential for rapid near-term advancement of EEA. Perhaps the most important development has been the growth of the EEA field, which has expanded the number of researchers developing, testing, and applying attribution methods to a wide variety of extreme events disrupting human and natural systems around the world. Efforts to systematically compare—and independently verify—different methods have begun to emerge. Further codification of these efforts and open access to underlying tools and data will help accelerate EEA capacity. In addition, efforts to develop clear and consistent shared language around communicating the specific characteristics or ingredients of the event being attributed, along with associated scientific uncertainties, will help the public and decision makers better understand the role of anthropogenic climate change.

Growth in supercomputing resources has enabled continued improvement in climate-model resolution, ensemble size, and integration length, allowing for increased physical realism in simulating processes that are critical in the evolution of extreme events. Indeed, targeted studies are now routinely conducted at sufficiently fine resolution that strong vertical motions—such as occur during many extreme precipitation events, severe thunderstorms, and tropical cyclones—can be explicitly represented. Although such "non-hydrostatic" simulations are still generally limited in their spatial and temporal scope, early indications are that this approach offers substantial promise for improving model representation of complex weather and climate phenomena. Similarly, the generation of multiple, single-model large ensembles (which use identical boundary forcings and model physics but perturbed initial conditions) is also a promising development for EEA because it allows for the intercomparison and refinement of predictive skill across individual model variations. It also enables more accurate quantification of the probability of an event within the context of historical climate variability, potentially offering a partial solution to the inadequacies of the existing observational record. Similarly, large "single-forcing" ensembles that isolate the influence of various anthropogenic greenhouse gases, aerosols, and land uses will help distinguish between the respective roles of potentially competing anthropogenic influences.

Given the rising public profile of climate change, the relevance of EEA for real-world applications in the legal, public-policy, and climate-adaptation arenas will only continue to increase. For example, as oil companies and other entities face potential civil liability for global warming, a key question in assigning culpability and subsequent penalties becomes whether climate change has demonstrably increased the likelihood and/or severity of extreme events that have caused loss and damage. Likewise, observed increases in destructive extreme events have increasingly factored into public investment decisions, including infrastructure funding requirements and state and federal disaster declarations. Civil engineering and design considerations are increasingly incorporating new information about the changing characteristics of extremes in order to maintain adequate safety margins and long-term resilience in a rapidly changing world.

Ultimately, it is clear that EEA is more than just a scientific exercise to improve communication of climate risks: it requires rigorous scientific methods to directly and quantitatively address an increasingly wide range of urgent, societally relevant questions that have long-term implications for human well-being. EEA can also help individuals and decision makers make sense of contemporary disasters, helping to contextualize real-world events relative to historical points of reference and aiding in disaster preparedness and climate-adaptation activities. Indeed, as EEA plays an increasingly prominent role in shaping public perception of climate risks, it could ultimately influence collective action to avoid levels of climate change that pose unacceptable risks to human and natural systems.

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CLIMATOLOGY

Unprecedented climate events: Historical changes, aspirational targets, and national commitments

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The United Nations Paris Agreement creates a specific need to compare consequences of cumulative emissions for pledged national commitments and aspirational targets of 1.5° to 2°C global warming. We find that humans have already increased the probability of historically unprecedented hot, warm, wet, and dry extremes, including over 50 to 90% of North America, Europe, and East Asia. Emissions consistent with national commitments are likely to cause substantial and widespread additional increases, including more than fivefold for warmest night over ~50% of Europe and >25% of East Asia and more than threefold for wettest days over >35% of North America, Europe, and East Asia. In contrast, meeting aspirational targets to keep global warming below 2°C reduces the area experiencing more than threefold increases to <10% of most regions studied. However, large areas—including >90% of North America, Europe, East Asia, and much of the tropics—still exhibit sizable increases in the probability of record-setting hot, wet, and/or dry events.

INTRODUCTION

Recognition of the proportional relationship between cumulative carbon emissions and global temperature change represents one of the most important insights of climate science during the past decade (*1–3*). This proportional relationship, which is seen in both the historical record and climate model simulations (*3*), has catalyzed a transition to international policy structures that are built around cumulative emissions (*4*, *5*), culminating in the United Nations (UN) Paris Agreement (*6*). Given the structure of the Paris Agreement, there is a specific need to compare the levels of cumulative emissions identified in the nationally determined contributions (NDCs; which represent the actual country commitments) and the more aspirational targets of "aggregate emission pathways in order to hold the increase in global average temperature to well below 2°C above pre-industrial levels and to limit the temperature increase to 1.5°C above pre-industrial levels" (*6*).

Differences in the mean climate between the UN cumulative emissions targets and the UN cumulative emissions commitments could be large enough to affect natural and human systems (*7*). However, for a number of reasons, it is likely that the highest-impact differences between the UN targets and commitments will be driven by differences in the response of extreme events. First, when observing the historical record, it is clear that the most acute climate vulnerabilities are associated with extremes (*8–10*). These vulnerabilities are seen across human and natural systems, including both wealthy and poor communities, and both terrestrial and marine ecosystems (*10*). Second, assessments of the potential impacts of future climate change identify changes in the frequency and/or intensity of extremes as a primary driver of future risks (*10–13*). This is particularly true for smaller increases in climate forcing, where small changes in the mean can create high-impact changes in extremes (*14–18*). Comparing potential impacts between the UN targets and commitments therefore requires rigorous, observationally based quantification of changes in the likelihood of extremes (*19–21*).

Changes in various quantiles of extremes have been thoroughly explored (*3*, *10*, *13*). However, accurately quantifying the probability that future events exceed the most extreme value found in the historical record poses unique challenges (*22*). For example, the magnitudes of many recent record-setting events have been particularly extreme relative to the length of available historical observations. The limited observational sample, combined with the nonstationarity of the historical time series, creates numerous challenges for quantifying the true underlying variability and hence the true probability of the record event (*23*). Likewise, if the UN's aspirational targets are to be achieved, then emissions will need to be dramatically reduced over the near-term decades (*24*). Those near-term decadal time scales exhibit substantial ambiguity between the signal of climate forcing and the noise of climate variability, particularly on the regional and local scales at which extreme events occur (*22*, *25–27*).

Despite these methodological challenges, the distinct risks posed by unprecedented events create a pressing need to quantify their probabilities at cumulative emissions levels consistent with the UN targets and commitments. We therefore extend the methods of Diffenbaugh *et al.* (*22*), who developed multiple metrics for testing the influence of global warming on the severity and probability of historically unprecedented events. However, whereas Diffenbaugh *et al.* focused exclusively on the historical period using a single climate model, we extend their methods to quantify the probability of record-setting hot, cold, wet, and dry extremes at all available observational grid points, using multiple climate models, for both historical climate forcing and future forcing windows. These future forcing windows are selected to be consistent with global warming of ~1° to 2°C and ~2° to 3°C, allowing us to quantify the differing risks of unprecedented climate extremes associated with the UN aspirational targets versus the UN NDC commitments (*28*).

Although numerous studies and assessments have examined the response of extreme events to changes in climate forcing (*19*, *29–31*), our analyses expand on these previous efforts in a number of ways. First, we compare the influence of human forcing on the probability of unprecedented extremes for multiple metrics, both during the historical period and for future periods consistent with the UN cumulative emissions budgets. This comparison enables quantification of the level of adaptation—in terms of increased climate risk—that will be required if different targets are achieved and of the value—in terms of avoided climate risk—associated with different levels of emissions mitigation.

Second, previous analyses of changes in extreme events have been largely confined to changes in simulated quantile thresholds, which

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often do not represent the record-setting event (*19*, *29–31*). Our analyses provide a new quantification of uncertainty in the probability of unprecedented events that is grounded in the observed historical statistics of multiple extreme climate metrics. Because the UN emissions budgets span overlapping uncertainty in global temperature change (*28*), this observationally based treatment of uncertainty is particularly critical for quantifying differences in unprecedented event probabilities between the UN targets and commitments.

RESULTS

The CLIMDEX project has archived a suite of globally gridded observed and simulated extreme event indices (*29*, *32*). We analyze eight of the CLIMDEX indices, which together provide two metrics each for hot, cold, wet, and dry extremes [Fig. 1 and fig. S1; see Materials and Methods for descriptions of the observations and Coupled Model Intercomparison Project (CMIP5) simulations].

Across the eight extreme indices, the probability of the warmest night exhibits the most widespread response to increasing forcing, with almost half of the global-scale return interval ratios exceeding 5 for cumulative emissions consistent with 2° to 3°C of global warming (Fig. 1B). [In this case, a ratio of 5 means that cumulative emissions of ~3500 gigatons (GT) of CO_2 increase the probability of exceeding the historical maximum warmest night by a factor of 5 relative to the world without human influence.] The hottest day, mildest cold night, and mildest freeze length also exhibit substantial sensitivity, with approximately a quarter of the global-scale return interval ratios exceeding 5 for cumulative emissions consistent with 2° to 3°C (Fig. 1, A, C, and D).

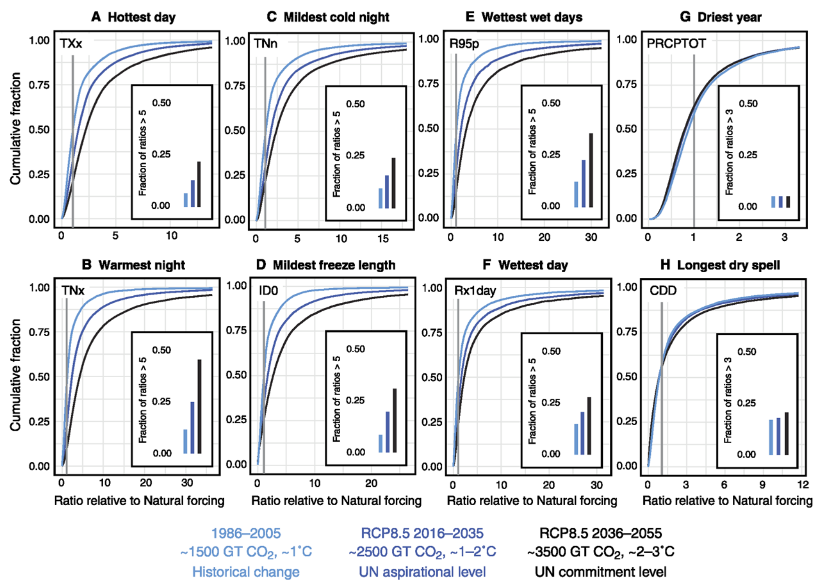
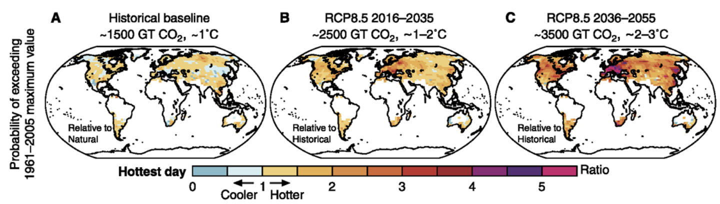


Fig. 1. The global change in probability of exceeding the historically unprecedented event at three levels of forcing. Global-scale cumulative distribution functions (CDFs) are calculated from all bootstrapped return interval ratios at all observationally available grid points for each level of anthropogenic forcing (see Materials and Methods). The horizontal axis is the change in probability calculated as the return interval ratio between the natural and anthropogenic forcing. For example, a ratio of 5 means that, in the anthropogenic forcing, the probability of exceeding the most extreme historically observed value is five times the probability in the world without human influence. The vertical axis is the cumulative fraction of all ratios calculated at all available grid points that are less than or equal to a given ratio. Insets show 1 minus the value on the vertical axis, which gives the fraction of ratios that are greater than a given ratio. For example, if a given CDF curve intersects 5 on the horizontal axis and 0.75 on the vertical axis, then 75% of all calculated return interval ratios are less than or equal to 5, and the inset will show that 25% of all calculated ratios are greater than 5. The dark gray vertical line in each panel shows where the return interval ratio between the natural and anthropogenic forcing is equal to 1, meaning that the probability of exceeding the most extreme historically observed value is equivalent in the natural and anthropogenic forcing. The three levels of anthropogenic forcing are the 1986–2005 period of the Historical simulations (~1500 GT CO_2 emitted and ~1°C of global warming above the pre-industrial), the 2016–2035 period of the RCP8.5 simulations (~2500 GT CO_2 and ~1° to 2°C), and the 2036–2055 period of the RCP8.5 simulations (~3500 GT CO_2 and ~2° to 3°C).

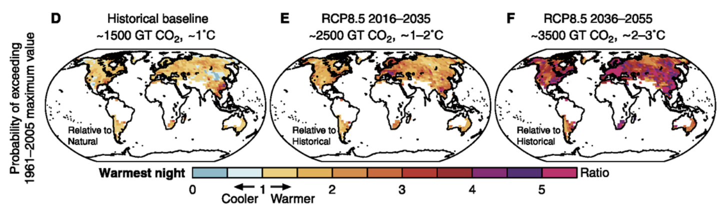
Wet events show more widespread sensitivity than dry events, with more than a quarter of the global-scale return interval ratios exceeding 5 for both extreme wet metrics (wettest day and wettest wet days) for cumulative emissions consistent with 2° to 3°C (Fig. 1, E and F). In contrast, although both the driest year and the longest dry spell already exhibit increases in probability in the current climate, they exhibit little additional increase in global extent for cumulative emissions consistent with either 1° to 2°C or 2° to 3°C (Fig. 1, G and H).

The historical forcing has already increased the probability of both the hottest day and the warmest night over most of the observational area (Fig. 2, A and D, and fig. S2). For the hottest day, the historical forcing has increased the probability relative to natural forcings (that is, ratios >1) for more than half of the available data points in East Asia (56.3%), more than two-thirds in North America (70.9%), and more than three-quarters in Europe (76.7%), Australia (82.4%), and southern South America (85%). The historical increases are even more widespread for the warmest night, with ≥90% of the available data points in North America, Europe, Australia, and southern South America exhibiting ratios of >1, and almost 10% in East Asia exhibiting ratios of >3. Exceeding 2°C of global warming increases the probability of the hottest day substantially. For example, whereas less than 10% of the available data points in Europe exhibit hottest day ratios of >3 (relative to Historical) for cumulative emissions consistent with 1° to 2°C of global warming, more than half (51.7%) exhibit ratios of >3 for cumulative emissions consistent with 2° to 3°C. Similarly, in East Asia, the median hot day ratio remains below 3 (relative to Historical) for all available data points for cumulative emissions consistent with 1° to 2°C of global warming, but more than a quarter of those data points (28.6%) exhibit ratios of >3 for cumulative emissions consistent with 2° to 3°C.

The probability that the coldest events of the year become more mild also increases substantially as cumulative emissions increase (Fig. 3). Most of high-latitude Eurasia and North America have already experienced increased probability that the coldest night of the year exceeds the mildest value on record (Fig. 3A). These increases in probability intensify

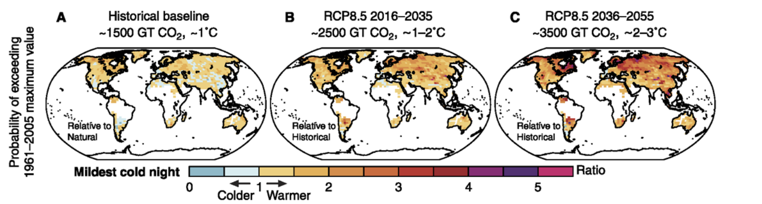


	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5
North America	70.9	0	0	91.7	0	0	98.2	7.6	0
Europe	76.7	0	0	100	7.5	0	100	51.7	16.7
East Asia	56.3	0	0	96.6	0	0	100	28.6	0.8
S. South America	85	0	0	100	0	0	100	0	0
Australia	82.4	0	0	73.5	0	0	67.6	0	0

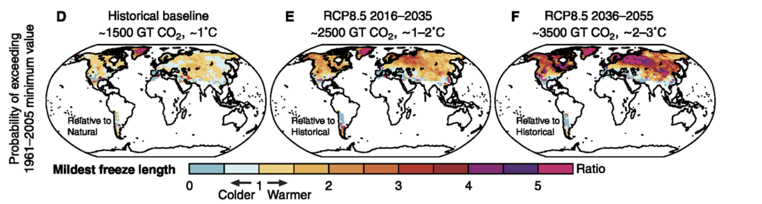


	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5
North America	89.5	1.1	0	99.6	1.4	0	100	69.6	10.9
Europe	90.6	0	0	100	37.6	0.9	100	98.3	48.7
East Asia	73	9.6	0	99.1	7	1.7	100	92.2	25.2
S. South America	100	0	0	100	2.7	0	100	21.6	2.7
Australia	92.9	0	0	100	0	0	100	14.3	0

Fig. 2. The change in probability of exceeding the historically unprecedented hot event at three levels of forcing. Maps show the median value of the bootstrapped return interval ratios between the lower and higher forcing. (Full distributions for all grid points are shown in Fig. 1). For ratios reported as "relative to Natural," the lower forcing is that for a world without human influence; for ratios reported as "relative to Historical," the lower forcing is the combined human and natural forcing that occurred during the historical period (see Materials and Methods). (**A** to **C**) Median return interval ratio for the hottest maximum daily temperature of the year (maximum TXx value; "hottest day"). (**D** to **F**) Median return interval ratio for the warmest minimum daily temperature of the year (maximum TNx value; "warmest night"). As described in Materials and Methods, the analysis is limited to the areas with observed values in the CLIMDEX data set (missing areas shown in white; fig. S1). See fig. S2 for regional boundaries used in the regional summary calculations.



	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5
North America	91.2	0	0	97.9	0	0	99.3	14.4	1.1
Europe	75.6	0	0	81.7	0	0	87.8	20.6	0
East Asia	65.1	0	0	96.8	0.8	0	100	9.5	0.8
S. South America	58.3	0	0	83.3	2.1	0	81.3	14.6	0
Australia	93	0	0	96.5	0	0	96.5	1.8	0



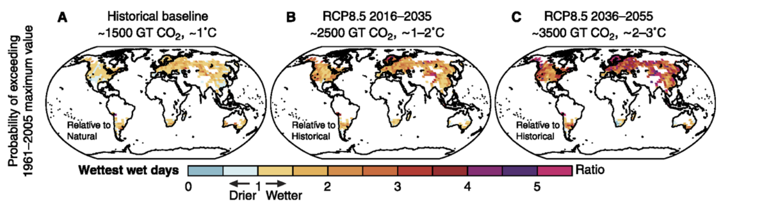
	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5
North America	73.3	1.4	0.7	89.9	3.6	1.4	89.5	46.2	4.7
Europe	47	5.2	5.2	63.9	13.9	2.8	75	34.4	19.8
East Asia	44.8	1	1	76.5	4.9	3.9	76.2	40.6	6.9
S. South America	44.8	10.3	0	52	16	8	44	4	0
Australia	–	–	–	–	–	–	–	–	–

Fig. 3. The change in probability of exceeding the historically unprecedented mild cold event at three levels of forcing. As in Fig. 2, but for coldest minimum daily temperature of the year (maximum TNn value; "mildest cold night") and number of days with maximum temperature below 0°C (minimum ID0 value; "mildest freeze length").

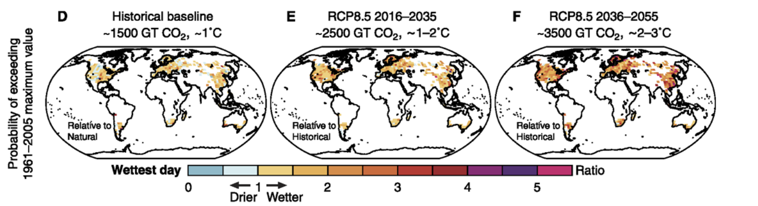
at higher levels of forcing, with return interval ratios of >2 (relative to Historical) for cumulative emissions consistent with 1° to 2°C of global warming (Fig. 3B), and ratios of >3 for cumulative emissions consistent with 2° to 3°C (Fig. 3C). Areas of high-latitude Eurasia and North America also exhibit particularly strong increases in the probability of the mildest freeze length, including return interval ratios of >4 (relative to Historical) over large areas of Eurasia for cumulative emissions consistent with 2° to 3°C (Fig. 3F).

As with temperature extremes, large fractions of the observed area already exhibit increased probability of record-level wet events, including ≥70% of the available data points in North America, Europe, East Asia, southern South America, and Australia for both extreme wet metrics (Fig. 4, A and D). The fraction of available points that exhibit increases in probability of record-level wet events expands for cumulative emissions consistent with 1° to 2°C of global warming (Fig. 4, B and E). However, the intensification of wet event probability is substantially greater for cumulative emissions consistent with 2° to 3°C, with 15 to 60% of the available data points in North America, Europe, East Asia, and southern South America exhibiting ratios of >3 (relative to Historical) for both metrics (Fig. 4, C and F). We note that the increases in probability are generally more substantial and widespread for the fraction of total precipitation falling in wet days ("wettest wet days") than for the magnitude of the wettest single day of the year ("wettest day"). This difference suggests that the risk of increasing extreme wet events is greater than what is indicated by the wettest single event and can occur across a broader range of the precipitation distribution—and therefore potentially result in more sustained wet conditions.

Compared with hot, cold, and wet events, increases in extreme dry probabilities are less widespread (Figs. 1 and 5). This discrepancy is caused primarily by the fact that substantial areas experience decreasing probability of both the driest year and the longest dry spell (Fig. 5). These areas of decreasing dry probabilities are concentrated in the high latitudes, where precipitation increases are most robust (*33*). However, the fact that continued increases in cumulative emissions do not cause substantial increases in extreme dry probabilities at the global scale (Fig. 1) does not mean that the probability of dry events is not responsive to increasing forcing. Large fractions of the northern and southern hemisphere mid-latitudes exhibit increasing probability of eclipsing the historically driest year and longest dry spell (Fig. 5). These include many areas that are currently heavily populated and highly vulnerable, such as the Mediterranean, southern Africa, Southeast Asia, and southern South America. Not only have increases in event probability



	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5
North America	79.6	0.7	0	96.6	4.8	0	97.3	36.1	8.8
Europe	89	0	0	96	13	2	96	59	15
East Asia	70	0	0	100	6.7	0	100	37.8	12.2
S. South America	80.8	0	0	80.8	0	0	80.8	15.4	0
Australia	90.9	0	0	77.3	0	0	72.7	0	0



	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5
North America	73.6	0.8	0	95	3.3	0	97.5	14.9	1.7
Europe	83.2	0	0	93.7	5.3	1.1	100	18.9	6.3
East Asia	81.9	1.4	0	94.4	8.3	1.4	100	30.6	9.7
S. South America	73.3	6.7	0	80	0	0	93.3	20	0
Australia	86.7	6.7	0	93.3	0	0	100	0	0

Fig. 4. The change in probability of exceeding the historically unprecedented wet event at three levels of forcing. As in Fig. 2, but for annual precipitation from days that exceed the 95th percentile (maximum R95p value; "wettest wet days") and wettest day of the year (maximum Rx1day value; "wettest day").

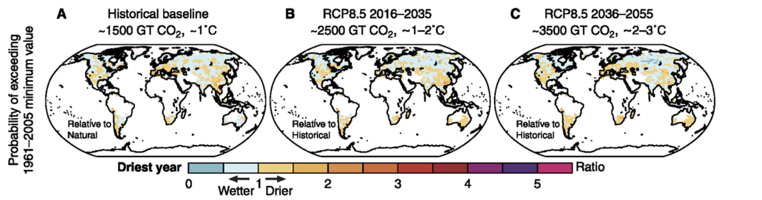
already emerged over most of these regions, but also continued emissions substantially intensify the regional increases. Regional intensification is particularly strong for the longest dry spell, with areas of North America, Europe, southern South America, and southern Africa exhibiting higher probability of record-setting events for cumulative emissions consistent with 2° to 3°C of global warming than 1° to 2°C of global warming (Fig. 5, E and F). The fact that increases in probability are generally more substantial and widespread for the longest dry spell of the year ("longest dry spell") than for the minimum annual precipitation ("driest year") suggests that the risk of increasing extreme dry conditions is greater at subannual than annual time scales and that the probability of prolonged dry conditions within the year can increase even if the probability of the driest year does not.

DISCUSSION

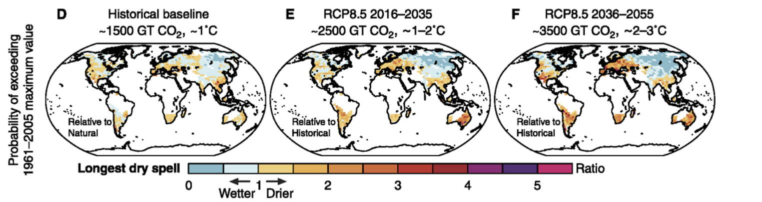
We note a number of important considerations when evaluating our results. One is that although the CMIP5 ensemble accurately simulates the observed variability of most of the extreme indices over most areas, there are areas of disagreement (fig. S1). Although our methodology does use the observed uncertainty in the probability of the record-setting event to implicitly correct errors in the climate model probability (see Materials and Methods), the regions where the climate model ensemble does not accurately simulate the observed variability (fig. S1) should be treated with caution.

In addition, because our methodology is built around the observed statistics of each extreme climate indicator, analyses are limited to areas with observational coverage in the CLIMDEX data set (*22*). Areas that lack observational coverage could exhibit substantial changes in the probability of record-setting events, particularly in the tropics, where the mean warming has been large relative to the historical variability (*21*, *34*, *35*). Not only would inclusion of these areas alter the global-scale CDFs shown in Fig. 1, but also many of these areas coincide with large human populations, high human vulnerability, and/or high biodiversity, whose exposure to changing extreme event probabilities is not represented in our results due to the lack of observational coverage.

We can provide some estimation of the change in probability in these regions by calculating how often the maximum/minimum value of the CMIP5 natural forcing ("HistoricalNat") simulations is exceeded in the CMIP5 historical and future scenarios (figs. S3 to S6). These occurrence frequencies suggest that areas lacking observational coverage are also likely to exhibit substantial increases in the probability of events that fall outside of the historical range. For example, for



	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5
North America	32.4	0	0	28.5	0	0	30.8	0	0
Europe	50.4	0	0	44.3	0	0	55.7	0	0
East Asia	65.9	0	0	48.8	0	0	41.5	0	0
S. South America	55.6	0	0	64.4	0	0	88.9	0	0
Australia	23.5	0	0	79.4	0	0	85.3	0	0



	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5	Ratios > 1	Ratios > 3	Ratios > 5
North America	53.4	0	0	45.1	0	0	47.6	2.9	0
Europe	55.7	0	0	79.2	0	0	84.9	11.3	0
East Asia	47.9	0.9	0	45.3	0.9	0	41.9	0.9	0
S. South America	64.6	0	0	95.8	0	0	95.8	12.5	2.1
Australia	76.7	0	0	100	11.6	0	100	7	0

Fig. 5. The change in probability of exceeding the historically unprecedented dry event at three levels of forcing. As in Fig. 2, but for total annual precipitation (minimum PRCPTOT value; "driest year") and longest consecutive dry spell of the year (maximum CDD value; "longest dry spell").

cumulative emissions consistent with 2° to 3°C of global warming, the occurrence of the hottest day and wettest day is more than five times the recent historical occurrence over most of tropical South America and tropical Africa (figs. S3 and S5). Likewise, for cumulative emissions consistent with both 2° to 3°C and 1° to 2°C, the occurrence of the driest year and longest dry spell is more than three times the recent historical occurrence over substantial fractions of tropical South America and tropical Africa (fig. S6).

We also note that our analysis of cumulative emissions windows within transient climate model simulations is likely to yield conservative estimates of the ultimate climate response, because further regional climate change is likely to occur after emissions are terminated (*36*). The occurrence frequencies of the maximum/minimum HistoricalNat value in the CMIP5 Representative Concentration Pathway (RCP) simulations (figs. S3 to S6) provide a test of the sensitivity to the pathway of cumulative emissions. For example, the cumulative emissions are similar in RCP8.5 and RCP2.6 in the first three decades of the 21st century, after which they diverge sharply, with the mid-21st century cumulative emissions of RCP8.5 exceeding the late-21st century cumulative emissions of RCP2.6 (*3*). The rapid decline in annual emissions in RCP2.6 means that the global temperature remains approximately between 1° and 2.5°C above the pre-industrial for the second half of the 21st century of RCP2.6 (*3*, *33*). Therefore, comparison of the mid-century of RCP2.6 with the late century of RCP2.6 provides an approximation of the sensitivity of the event probability to changes in regional climate that occur after near stabilization of the global temperature. We find that the changes in occurrence between the mid- and late-century of RCP2.6 are broadly similar (figs. S3 to S6). However, a comprehensive quantification of the sensitivity of event probabilities to cumulative emissions pathway will require multiple simulations of multiple stabilization trajectories using multiple climate models.

The conservativeness of our statistical methodology is another reason that our results provide a lower bound on the probability of unprecedented climate events at different levels of forcing identified by global policy-makers. In particular, our methodology selects a parametric distribution that minimizes the return interval ratio (*22*). Comparing our results with the simple occurrence frequencies in the CMIP5 simulations (figs. S3 to S6) provides a comparison of our probability quantification with the kind of ensemble frequency quantification that has been used in previous studies and assessments (*19*, *29*–*31*). This comparison shows that our results do exhibit smaller changes than those calculated based on thresholds from the models themselves. However, it should be reiterated that our method allows calculation of the uncertainty in the probability of the actual observed record-setting event based on the statistics of the observed distribution (*22*), which is distinct from approaches that have analyzed the frequency of occurrence of the simulated quantiles (*19*, *29–31*).

Our analyses also provide an important comparison with the historical attribution analyses of Diffenbaugh *et al.* (*22*). First, we extend the number of extreme event metrics from four in the study of Diffenbaugh *et al.* to eight in the current analysis. Second, whereas Diffenbaugh *et al.* did not differentiate human and natural forcings during the historical period, our analysis isolates the human component of the historical climate forcing. Third, whereas Diffenbaugh *et al.* used many realizations of a single climate model [the National Center for Atmospheric Research (NCAR) "Large Ensemble"], our analysis spans a larger range of uncertainty by analyzing results from multiple climate models.

A high priority of the proof-of-concept study of Diffenbaugh *et al.* (*22*) was to isolate the "irreducible uncertainty" arising from internal climate system variability. In contrast, our emphasis on quantitatively comparing historical and future changes makes spanning both internal variability and model structural uncertainty a key requirement. As shown by Diffenbaugh *et al.*, the historical global warming in the NCAR Large Ensemble falls in the lower half of the CMIP5 multimodel ensemble. Therefore, by using many climate models, our current analysis spans a far greater range of climate sensitivity, which is crucial for comparing climate risks associated with the UN targets versus the UN NDC commitments. Likewise, given the potential for systematic errors in the simulation of the atmosphere and ocean circulation to create errors in the simulated response of temperature and precipitation to changes in forcing (*37*, *38*), the use of multiple climate models also enables our analysis to span a broader range of regional uncertainty.

CONCLUSIONS

Our results provide the first quantitative comparison of the probability of unprecedented climate events in cumulative emissions windows that are consistent with both historical changes and the UN aspirational targets and pledged national commitments. Analysis of cumulative emissions consistent with global warming of 2° to 3°C shows that the commitments outlined in the UN Paris Agreement are likely to lead to substantial and widespread increases in the probability of historically unprecedented extreme events. For example, 15 to 60% of observed locations in North America, Europe, East Asia, and southern South America exhibit return interval ratios of >3 for most of the extreme indices analyzed here. In contrast, analysis of cumulative emissions consistent with global warming of 1° to 2°C shows that achieving the more aspirational UN targets is likely to substantially limit those increases.

However, even if cumulative emissions are sufficiently constrained to ensure that global warming is held to 1° to 2°C, many areas are still likely to experience substantial increases in the probability of unprecedented events. At the global scale, hot, cold, wet, and dry extremes all exhibit prominent changes in event probability within the 2°C target, including more than fivefold increases at ~25% of the observed area for warmest night and wettest wet days and more than twofold increases at ~25% of the observed area for hottest day. These changes encompass substantial fractions of the United States, Europe, East Asia, and the southern hemisphere mid-latitudes. For example, >90% of observed locations in those regions exhibit increases in the probability of record-hot days and/or record-warm nights relative to the current climate, and 45 to 100% exhibit increases in probability of the longest dry spell. Further, although much of the tropics lack long-term observational coverage, analyses of climate simulations indicate increases in record hot, wet, and dry events that are at least as substantial as the increases seen over the mid-latitude regions.

Together, our results suggest that the aspirational UN emissions targets are likely to yield substantial reductions in climate risk relative to the changes arising from pledged national commitments but also that those aspirational targets are likely to produce substantial—and potentially high-impact—increases in the probability of unprecedented extremes relative to the current climate.

MATERIALS AND METHODS

Observations and models

The CLIMDEX project has archived globally gridded extreme event indices for both historical observations and climate model simulations of historical and future forcing trajectories (*29*, *32*). We analyzed eight of the CLIMDEX indices: (i) hottest maximum daily temperature of the year (TXx), (ii) warmest minimum daily temperature of the year (TNx), (iii) coldest minimum daily temperature of the year (TNn), (iv) number of days with maximum temperature below 0°C (ID0), (v) annual precipitation from days that exceed the 95th percentile (R95p), (vi) wettest day of the year (Rx1day), (vii) total annual precipitation (PRCPTOT), and (viii) longest consecutive dry spell of the year (CDD).

We applied the methods of Diffenbaugh *et al.* (*22*) to calculate the probability of exceeding the most extreme observed value of each of these eight indices. For these indices, "exceeding the most extreme observed value" means hotter than the maximum TXx value ("hottest day"), warmer than the maximum TNx value ("warmest night"), warmer than the maximum TNn value ("mildest cold night"), fewer days than the minimum ID0 value ("mildest freeze length"), wetter than the maximum R95p value ("wettest wet days"), wetter than the maximum Rx1day value ("wettest day"), drier than the minimum PRCPTOT value ("driest year"), and longer than the maximum CDD value ("longest dry spell").

CLIMDEX calculated the simulated extreme event indices using output from CMIP5 (*39*). CLIMDEX has archived indices for the CMIP5 Historical, HistoricalNat, and RCP simulations. We analyzed the climate models for which there are matching realizations in the Historical, HistoricalNat, and RCP8.5 simulations. Following the Intergovernmental Panel on Climate Change (IPCC), we used the "r1i1p1" realization from each model (*40*), yielding a total of 15 realizations from 15 models.

Analysis

We followed the analysis of Diffenbaugh *et al.* (*22*), who compared four attribution metrics during the historical period. To extend the historical analysis of Diffenbaugh *et al.* to periods of elevated climate forcing, we focused on their fourth metric, which is the ratio of return intervals at lower and higher levels of climate forcing. (For example, an event that has a probability of 0.01—or a return interval of 100 years—in the lower forcing and a probability of 0.05—or a return interval of 20 years—in the higher forcing has a return interval ratio of 5). To account for uncertainty in the return interval of the observed record-level event, a distribution of return interval ratios was calculated at each grid point. To do so, we block bootstrapped the grid point time series at the lower and higher forcing levels to generate two distributions of return intervals; we then calculated ratios between all combinations of bootstrapped return intervals at lower and higher forcing, yielding a distribution of return interval ratios (*22*).

Some modifications are necessary to apply the methods of Diffenbaugh *et al.* (*22*) to the multimodel CMIP5 ensemble under both historical and elevated levels of forcing. First, because CLIMDEX archived the extreme indices for the CMIP5 HistoricalNat simulations rather than the CMIP5 Pre-Industrial Control simulations, we used the HistoricalNat experiment as the "counterfactual" world without human influence. (The Pre-Industrial Control and HistoricalNat simulations are similar, but whereas the Pre-Industrial Control simulations use constant pre-industrial forcing, the HistoricalNat simulations add the volcanic and solar forcing that occurred during the historical period; the HistoricalNat simulations therefore enable isolation of the anthropogenic forcing during the historical period). We used the 1961–2005 period to calculate the return interval of the most extreme event in both the observations and the HistoricalNat simulations [see the study of Diffenbaugh *et al.* (*22*)].

We compared the return interval of the most extreme observed value between the HistoricalNat forcing and three anthropogenic forcing windows: the 1986–2005 period of the Historical simulations, the 2016–2035 period of the RCP8.5 simulations, and the 2036–2055 period of the RCP8.5 simulations. The 1986–2005 period of the Historical simulations is the baseline period used by the IPCC (*3*, *13*), at the end of which there were ~1500 GT CO_2 emitted and ~1°C of global warming above the pre-industrial (*3*); comparing the return interval of the most extreme observed value between the HistoricalNat simulations and the 1986–2005 period of the Historical simulations quantifies the influence of historical anthropogenic forcing on the probability of the most extreme historical event. The 2016–2035 period of RCP8.5 encompasses a scenario in which there are ~2500 GT CO_2 emitted and ~1° to 2°C of global warming above the pre-industrial (*3*); comparing the return interval of the most extreme observed value between the 1986–2005 period of the Historical simulations and the 2016–2035 period of RCP8.5 thereby quantifies the change in event probability for a future in which the emissions and global warming targets outlined in the Paris Agreement are met. In contrast, the 2036–2055 period of RCP8.5 encompasses a scenario in which there are ~3500 GT CO_2 emitted and ~2° to 3°C of global warming above the pre-industrial (*3*); comparing the return interval of the most extreme observed value between the 1986–2005 period of the Historical simulations and the 2036–2055 period of RCP8.5 thereby quantifies the change in event probability for a future in which the UN NDC emissions commitments—but not the UN emissions targets—are met (*3*, *24*, *28*, *41*).

We note that Millar *et al.* (*42*) have provided a more recent update of the cumulative emissions-temperature relationship shown in the IPCC Fifth Assessment Report (AR5). Because they are based on the same underlying CMIP5 simulations that were used to generate the findings in the IPCC AR5, the cumulative emissions windows are similar between the periods presented here and those by Millar *et al.* For example, the cumulative emissions that Millar *et al.* identify as having a 66% chance of staying below 1.5°C above the pre-industrial fall close to 2030 of RCP8.5, and the cumulative emissions that Millar *et al.* identify as having a 66% chance of staying below 0.6°C above the recent decade occur near 2040 of RCP8.5. Further, the cumulative emissions that Millar *et al.* identify as having a 66% chance of exceeding 1.1°C above the recent decade fall close to 2050 of RCP8.5.

In addition, whereas the proof-of-concept study of Diffenbaugh *et al.* (*22*) analyzed many realizations of a single climate model, the CLIMDEX archive contains output from many climate models but at most a few realizations of each model. Given the importance of sufficient population size for quantifying the probability of rare events (*23*), we pooled the CMIP5 realizations, yielding a total of 300 simulated years in each 20-year forcing period. We found that the pooled climate model output generally agrees with the CLIMDEX observational data (that is, the *P* value using the Anderson-Darling test comparing distributions is >0.10, indicating that the null hypothesis that the simulated and observed values are drawn from the same underlying distribution cannot be rejected at the 1, 5, or 10% significance levels; fig. S1).

Note that the method of Diffenbaugh *et al.* (*22*) includes a bias correction step. As described by Diffenbaugh *et al.*, to evaluate each model's simulation of interannual variability in each climate index, this bias correction is based on the differences between the detrended observations and the climate simulation without human forcings. First, the climate model mean is corrected to be equal to the observational mean (that is, by subtracting the difference between the climate model mean and the observational mean from the climate model time series). In the current analysis, we corrected each CMIP5 realization individually and then pooled the corrected data into a single "bias-corrected" CMIP5 population. This approach allows us to leverage the variability across the full CMIP5 ensemble while simultaneously controlling for the mean biases of the individual climate models. In addition, the method of Diffenbaugh *et al.* also controls for errors in the climate model variability by defining the simulated sample of event return intervals to be identical to the observed sample of event return intervals. That sample of event return intervals is then used to define the sample of event magnitudes in the pool of climate model simulations. This approach of defining the sample of simulated event magnitudes based on the sample of observed event return intervals helps to control for the effect of variability biases on event magnitudes in the tail of the simulated distribution.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/2/eaao3354/DC1

fig. S1. Statistical comparison of observed and simulated climate indices during the historical period.

fig. S2. Regions used in regional summary calculations.

fig. S3. Frequency of occurrence of the maximum "HistoricalNat" hot event value in the CMIP5 RCP8.5 and RCP2.6 simulations.

fig. S4. As in fig. S3, but for mild cold events.

fig. S5. As in fig. S3, but for wet events.

fig. S6. As in fig. S3, but for dry events.

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Unprecedented climate events: Historical changes, aspirational targets, and national commitments

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CLIMATOLOGY

Verification of extreme event attribution: Using out-of-sample observations to assess changes in probabilities of unprecedented events

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Independent verification of anthropogenic influence on specific extreme climate events remains elusive. This study presents a framework for such verification. This framework reveals that previously published results based on a 1961–2005 attribution period frequently underestimate the influence of global warming on the probability of unprecedented extremes during the 2006–2017 period. This underestimation is particularly pronounced for hot and wet events, with greater uncertainty for dry events. The underestimation is reflected in discrepancies between probabilities predicted during the attribution period and frequencies observed during the out-of-sample verification period. These discrepancies are most explained by increases in climate forcing between the attribution and verification periods, suggesting that 21st-century global warming has substantially increased the probability of unprecedented hot and wet events. Hence, the use of temporally lagged periods for attribution—and, more broadly, for extreme event probability quantification—can cause underestimation of historical impacts, and current and future risks.

INTRODUCTION

The field of extreme event attribution has burgeoned since the seminal work of Stott *et al.* (*1*). In that time, numerous event attribution frameworks have been developed (*2*). Although there is heterogeneity in the design of these frameworks, most use a combination of instrumental observations and climate model simulations to quantify the influence of historical anthropogenic climate forcing on the probability and/or severity of individual events. The purpose of this study is to examine whether independent "out-of-sample" observations can be used to assess the accuracy of changes in extreme event return intervals that are either explicitly or implicitly predicted by attribution frameworks.

Since Stott *et al.* (*1*), attribution analyses have been published for many types of events (*2*), including heatwaves [e.g., (*3*–*8*)], cold snaps [e.g., (*3*, *5*, *9*)], heavy rainfall [e.g., (*3*–*6*, *10*)], floods [e.g., (*11*)], droughts [e.g., (*12*)], tropical cyclone precipitation [e.g., (*13*, *14*)], storm surge flooding [e.g., (*15*)], and extremely low Arctic sea ice [e.g., (*4*, *16*)]. In addition, event attribution frameworks have been applied to the underlying physical causes of extremes (*2*, *17*, *18*), including atmospheric circulation patterns [e.g., (*4*, *19*–*22*)], atmospheric water vapor (*4*), ocean heat content (*23*), and wildfire risk factors [e.g., (*24*)]. In recent years, attribution analyses have been applied increasingly quickly following an event [e.g., (*10*, *25*)], with some techniques using forecasts generated before the event [e.g., (*26*, *27*)]. "Precomputed" approaches (*7*) have likewise been used to quantify the influence of global warming on a particular type of event at each area of the globe, using observational data (*4*, *28*), climate model simulations (*6*, *7*), or a combination of the two (*4*, *5*).

Independent verification of event attribution poses a particular challenge. In addition to the reliability of observational data and climate model simulations [e.g., (*29*, *30*)], there are fundamental questions about the appropriate scientific framing through which causation can be measured [e.g., (*2*, *31*–*34*)]. One inherent challenge is that single event attribution is conducted for conditions at one specific place and time; the event only occurs once, and by construction, the attribution quantification pertains only to that event. Further, because extreme events are by definition rare, the available population of events with which to independently verify attribution results is limited, a challenge that is exacerbated for events that are unprecedented in the observational record.

One approach to resolving these challenges is to frame the attribution result as a falsifiable prediction, and then test that prediction using independent observations. Such an approach draws on the many aspects of climate and weather research that routinely use independent verification. For example, daily- and seasonal-scale forecasts are verified after the forecast period has passed [e.g., (*35*)]. This forecast verification includes daily fields such as temperature, precipitation, and winds, as well as extreme event phenomena such as tropical cyclones, severe thunderstorms, and river and storm surge flooding. Further, scientists have been making long-term climate projections for decades (*36*, *37*). Older projections can be verified using current observations [e.g., (*38*)], and such comparisons are now made for global temperature anomalies in quasi-real time.

It is important to emphasize the distinction between verification of falsifiable predictions and evaluation of methodological uncertainty. Researchers have for years taken great care to thoroughly evaluate various aspects of uncertainty within climate attribution systems (*2*). This includes (i) assessing the robustness of the observational record and the fidelity of climate model simulations for different types of events [e.g., (*2*–*4*, *30*)]; (ii) quantifying uncertainty in the climate model simulations, including the sensitivity to historical emissions (*4*), the ability to simulate the statistical properties of the historical observations [e.g., (*4*, *21*, *39*, *40*)], and the ability to simulate the underlying physical processes that cause different types of events [e.g., (*21*, *41*)]; (iii) quantifying uncertainty in the statistical analysis, including the appropriateness of the underlying statistical assumptions (*4*, *42*–*45*); and (iv) applying different attribution methodologies to the same event (*4*, *16*, *46*, *47*), including systematic

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reanalysis of multiple published results (*3*, *33*). However, despite this emphasis on uncertainty quantification, independent observational verification of specific, quantitative attribution results remains elusive.

Central to the analysis presented in this study is the idea that attribution results that are generated from estimates of return intervals in previous historical time periods can be verified using the frequency of extreme events that occur over large geographic domains during subsequent, multi-year, out-of-sample time periods (see Materials and Methods). For example, many attribution analyses have used global climate model simulations from the Coupled Model Intercomparison Project (CMIP5) [e.g., (*4*–*8*, *20*, *38*)]. Because the CMIP5 Historical and Natural simulations were only run through 2005 (*48*, *49*), simulations using the actual climate forcings do not cover the most recent period of observations. Attribution analyses that use CMIP5 can thus either restrict the historical analyses to this pre-2006 period [e.g., (*4*–*6*, *12*, *20*)] or use the early period of the CMIP5 future projections to extend the historical simulations (in which case the anthropogenic and non-anthropogenic simulations cover different time periods) [e.g., (*8*, *38*)]. In the case of previously published global attribution analyses, which used the CMIP5 Historical and Natural simulations to quantify the influence of historical forcing on the probability of unprecedented hot, wet, and dry extremes at each area of the globe, the attribution analysis was limited to the pre-2006 period (*5*). However, this limitation also presents an opportunity, because the frequency of record-setting events during 2006–2017 can now be used to independently verify the published results that used data from 1961 to 2005.

Previous global attribution analyses (*4*) examined four different attribution metrics: (i) the contribution of the observed trend to the event magnitude, (ii) the contribution of the observed trend to the event probability, (iii) the probability of the observed trend in the historical forcing, and (iv) the contribution of the historical forcing to the event probability. This work was recently extended (*5*), using CMIP5 data to quantify the fourth metric for natural and anthropogenic forcing during the historical period, and for future levels of forcing consistent with the United Nations Paris Agreement goals and commitments.

The current study focuses on verifying the second and fourth metrics using out-of-sample observations. The contribution of historical climate change to the event probability is measured using an "attribution ratio" (*AR*), which is calculated as the ratio between the return interval in a counterfactual world without climate change and the return interval in the actual observed world with climate change (*4*, *5*). For the contribution of the observed trend to the event probability, observational data are used to estimate the return intervals of extreme events, with the attribution ratio ($AR_{\text{Obs-dt}}$) calculated from the return interval in the actual time series (RI_{Obs}) and the return interval in the detrended time series ($RI_{\text{Obs-dt}}$)

$$AR_{\text{Obs-dt}} = (RI_{\text{Obs-dt}}) \div (RI_{\text{Obs}})$$

For the contribution of the historical forcing to the event probability, observational data are used to correct systematic biases in the climate model simulations, which are then used to estimate the change in return intervals under historical (HIST) and natural (NAT) climate forcing

$$AR_{\text{Forcing}} = (RI_{\text{Obs-dt}}) \div (RI_{(\text{HIST-NAT}) + \text{Obs-dt}})$$

An attribution ratio of 1 indicates equal probability with and without global warming. Because return intervals are the inverse of event probabilities, larger ratios indicate greater influence of global warming (e.g., a ratio of 2 indicates that the probability of an event is twice as large with global warming). Block bootstrapping of the time series at each location is used to quantify a distribution describing the uncertainty in the event probabilities at each location (*4*, *5*).

The present study is focused on two objectives. The first phase of the analysis uses specific, previously published predictions to demonstrate the framework for verifying extreme event attribution results. Independent data (i.e., observations over the 2006–2017 time period) are used to derive the return intervals of unprecedented events over different regions, based on the regional frequency of record-setting events. These out-of-sample return intervals are then compared with the regional-mean distributions of return intervals (e.g., 5th, 25th, 50th, 75th, and 95th percentiles) that were predicted from the detrended 1961–2005 observational data at each grid point in the region. The ratio is referred to as a "verification ratio" (*VR*)

$$VR_{\text{Obs:2006–2017}} = RI_{\text{Obs-dt:1961–2005}} \div RI_{\text{Obs:2006–2017}}$$

where $RI_{\text{Obs-dt:1961–2005}}$ is the regional-mean of the return intervals in the detrended 1961–2005 time series at each grid point, and $RI_{\text{Obs:2006–2017}}$ is the regional-mean return interval implied by the frequency of record-setting events in the region during the out-of-sample 2006–2017 verification period. These verification ratios are compared with attribution ratios that quantify the contribution of historical climate change during the 1961–2005 attribution period, calculated from both the observational record ($AR_{\text{Obs-dt}}$) and the CMIP5 global climate model ensemble (AR_{Forcing}). Thus, by construction, the out-of-sample comparison tests the stability of the attribution results over time, within the context of a nonstationary climate.

The second phase of the analysis attempts to understand discrepancies between the verification and attribution ratios. This analysis tests whether any such discrepancies are due to structural mismatches between the attribution and verification methods. It also tests whether there have been changes in the frequency of record-setting events between the attribution and verification periods, and whether any changes are due primarily to external climate forcing or to internal climate variability. Understanding discrepancies in the predicted probabilities of record-setting events and the actual out-of-sample occurrence is important not only for verifying extreme event attribution but also for evaluating the durability of design and planning guidelines that use similar return interval quantification when conducting risk analysis (such as for infrastructure design, land use planning, and disaster management).

In principle, this verification framework could be applied to any type of extreme event. The focus of this initial application is on events that are unprecedented in the baseline historical period (1961–2005). Unprecedented events pose important challenges for event attribution (*4*). First, statistical uncertainty increases as values reach further into the tails of the distribution. Events that fall outside of the historical range are, by definition, in the extreme tail, amplifying the challenges posed by small samples. Second, climate change is increasing the probability of unprecedented events (*4*). Quantifying the effects of this nonstationarity is a general challenge for risk assessment [e.g., (*50*, *51*)] and poses specific challenges for event attribution (*4*). Third, climate models are the only available tool for systematically testing the influence of global warming on the physical processes that shape extremes, making climate models a necessary component of event attribution frameworks (*2*). However, because historically unprecedented events often arise from rare combinations of physical ingredients, they generally pose the greatest challenge for accurate climate model simulation (*2*, *17*, *18*, *30*).

Despite these potential barriers, events that fall outside of the historical experience are critical for a suite of design and management decisions [e.g., (*50*, *52*–*54*)], as well as climate change mitigation and adaptation considerations [e.g., (*4*, *5*, *54*, *55*)]. Given both the societal relevance and methodological challenges, this initial verification study focuses on the attribution of events that are unprecedented in the historical observations.

RESULTS

The regional verification ratios for 2006–2017 frequently exceed the published attribution ratios calculated from the 1961–2005 data (Fig. 1), suggesting that the attribution framework underestimates the influence of historical global warming. For example, for the influence of anthropogenic forcing, the median attribution ratio is less than 2.0 for all three extreme indices (hottest days, wettest days, and longest dry spell) over the United States, Europe, and East Asia. In contrast, the median verification ratio for the hottest days exceeds 4.0 over Europe and 2.5 over East Asia, with >95% of the verification ratio distribution exceeding the median attribution ratio. Likewise, the median verification ratio for the wettest days exceeds 3.0 over the United States and Europe, with >95% of the verification ratio distribution again exceeding the median attribution ratio.

Although the trend-based attribution ratio is generally larger than the forcing-based attribution ratio (Fig. 1), the verification ratio for 2006–2017 still frequently exceeds the trend-based attribution ratio (Fig. 1). For example, for the hottest days, >95% of the verification ratio distribution exceeds the median trend-based attribution ratio over Europe, and ~75% exceeds the median trend-based attribution ratio over East Asia. Similarly, for the wettest days, >95% of the verification ratio distribution exceeds the median trend-based attribution ratio over the United States and Europe.

In a number of cases, the median values of both the attribution and verification ratios are close to 1.0 (Fig. 1). For the hottest days, both the forcing- and trend-based attribution ratios exhibit median values just above 1.0 over the United States, while the median verification ratio is just below 1.0. Likewise, for the longest dry spells, the attribution and verification ratios are near 1.0 over the United States, Europe, and East Asia. In these cases, the range of values is larger for the attribution ratios than for the verification ratios, including greater likelihood of large increases in extreme event probability. However, the attribution and verification distributions largely overlap.

The discrepancies between the attribution and verification ratios for record-setting events (Fig. 1) are reflected in discrepancies between the probabilities predicted from the 1961–2005 observations and the frequencies observed in 2006–2017. For example, the 2006–2017 frequency of record-setting hottest days exceeds the 99th percentile of predicted probabilities over both Europe and East Asia (Fig. 2). Similarly, the 2006–2017 frequency of record-setting wettest days exceeds the 99th percentile of predicted probabilities over both the United States and Europe (Fig. 3). Further, in cases where the discrepancies between the verification and attribution ratios are less pronounced, such as the hottest days over the United States and wettest

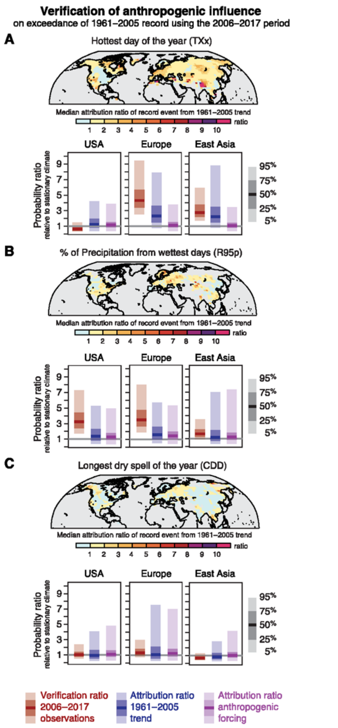

Fig. 1. Verification of the anthropogenic influence on unprecedented hot, wet, and dry events. The verification framework is based on the probability, during the out-of-sample verification period (2006–2017), of exceeding the most extreme value found in the period for which the attribution metrics were calculated (1961–2005). The framework is used to verify the attribution metrics published in (*4*) and (*5*), for (**A**) hottest day of the year (TXx), (**B**) percentage of annual precipitation falling in days that are wetter than the 95th percentile of the 1961–1990 period (R95p), and (**C**) longest consecutive dry spell of the year (CDD). Maps show the median attribution ratio calculated from the 1961–2005 trend at each northern hemisphere grid point for which there are continuous data in the CLIMDEX dataset (see Materials and Methods). The blue distribution shows the uncertainty in the attribution ratio calculated from the 1961–2005 trend (i.e., the metric shown in the map) over the United States, Europe, and East Asia. The purple distribution shows the uncertainty in the regional attribution ratio calculated from anthropogenic climate forcing. The red distribution shows the uncertainty in the regional verification ratio calculated from the 2006–2017 observations. Uncertainty in each ratio is depicted by the 5th, 25th, 50th, 75th, and 95th percentile values of the bootstrapping described in (*4*) and (*5*).

days over East Asia (Fig. 1), the 2006–2017 frequency still falls in the tail of predicted probabilities (Figs. 2 and 3).

There are at least two possible explanations for these discrepancies between the probabilities predicted during the attribution period (1961–2005) and the frequencies observed during the verification period (2006–2017). The first possibility is a structural discrepancy in the comparison, such as if the regional-mean of the probabilities calculated from the 1961–2005 grid-point time series did not accurately predict the regional frequencies during an overlapping time period. A second possibility is that there have been changes in the probabilities of record-setting events between the attribution and verification periods.

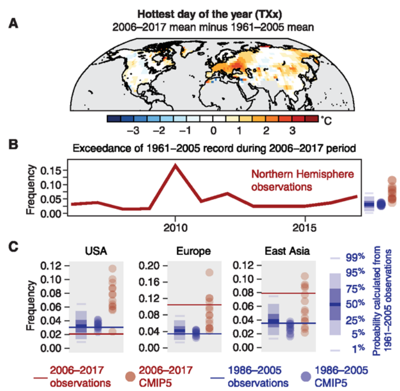

Fig. 2. Observed and simulated regional extreme event frequencies for the hottest day of the year (TXx). (**A**) The map shows the difference in the mean value between the out-of-sample verification period (2006–2017) and the period for which the attribution metrics were calculated (1961–2005). (**B**) The red line shows, for each year of the 2006–2017 verification period, the observed northern hemisphere frequency of events in which the grid-point value exceeded the maximum grid-point value during the period for which the attribution metrics were calculated (1961–2005). The blue distribution shows the uncertainty in the hemispheric mean probability of exceeding the most extreme value found in the period for which the attribution metrics were calculated (1961–2005). The probability of the record-setting event is calculated by fitting an extreme value distribution to the 1961–2005 time series at each grid point, as described in (*4*); uncertainty is depicted by the percentile values of the bootstrapping described in (*4*). The blue circles show the regional frequency simulated by the CMIP5 climate model ensemble during the IPCC's baseline period (1986–2005). The red circles show the regional frequency simulated by the CMIP5 climate model ensemble during the verification period (2006–2017). (**C**) The blue distribution shows the uncertainty in the regional-mean probability of exceeding the most extreme value found in the period for which the attribution metrics were calculated (1961–2005). The blue horizontal line shows the observed regional frequency during the IPCC's baseline period (1986–2005); blue circles show the regional frequency simulated by the CMIP5 climate model ensemble during the IPCC's baseline period. The red horizontal line shows the observed regional frequency during the out-of-sample verification period (2006–2017); red circles show the regional frequency simulated by the CMIP5 climate model ensemble during the verification period.

The results favor the second possibility. For example, the actual regional frequencies that occurred during the Intergovernmental Panel on Climate Change (IPCC's) baseline period (1986–2005) all fall within the 5th to 95th percentile uncertainty range predicted from the 1961–2005 observations, and the majority fall within the 25th to 75th percentile uncertainty range (Figs. 2 to 4). Further, the CMIP5 climate model ensemble, which is an independent dataset with which to predict the frequency of record-setting events at a given level of climate forcing, exhibits close overlap with the predicted probabilities and the observed 1986–2005 regional frequencies (Figs. 2 to 4). Even in the cases where the 1986–2005 CMIP5 ensemble spread is furthest from the median of the predicted probabilities (such as the longest dry spells over the United States, Europe, and East Asia), the ensemble range still falls within the distribution of predicted probabilities (Fig. 4). The fact that the observed and simulated 1986–2005 frequencies fall well within the distributions of probabilities predicted from the 1961–2005 observations (Figs. 2 to 4) suggests that discrepancies between the attribution and verification ratios (Fig. 1) are not caused by structural discrepancies between the underlying metrics.

In contrast, there are substantial differences in the observed frequency of record-setting events between 1986–2005 and 2006–2017. For example, the observed frequency is at least ~50% higher in 2006–2017 for hottest days over Europe and East Asia (Fig. 2), wettest days over the United States and Europe (Fig. 3), and longest dry spells over East Asia (Fig. 4). Likewise, with the exception of the longest dry spells over the United States and East Asia (Fig. 4), the frequency observed during 2006–2017 falls further from the median predicted probability, while the frequency observed during 1986–2005 falls closer to the median (Figs. 2 to 4). These comparisons quantify a substantial increase in the risk of unprecedented events between the attribution and verification periods, particularly for hot and wet events.

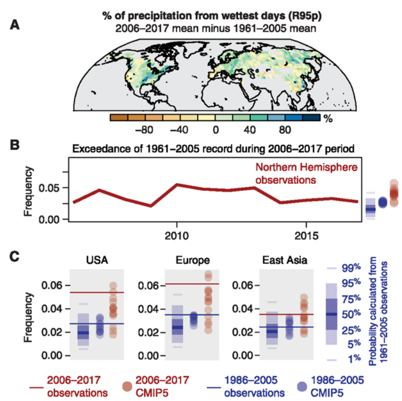

Fig. 3. Observed and simulated regional extreme event frequencies for the wettest days. As in Fig. 2, but for the percentage of annual precipitation falling in days that are wetter than the 95th percentile of the 1961–1990 baseline period (R95p).

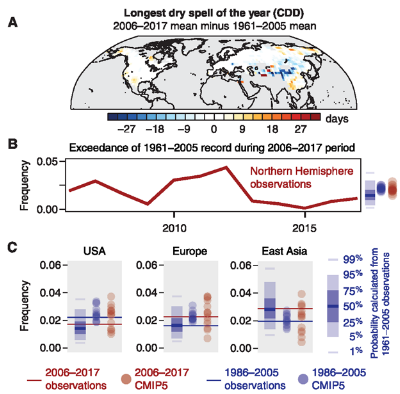

Fig. 4. Observed and simulated regional extreme event frequencies for the longest dry spell. As in Fig. 2, but for the longest consecutive dry spell of the year (CDD).

One concern about this analysis is that the verification period is relatively short (12 years) compared to a standard climatological baseline period (nominally 30 years). To test the robustness of the results to a longer period, the verification period can be extended to include the period from the beginning of the IPCC baseline (1986) to the end of the out-of-sample verification period (2017). As would be expected, mixing the out-of-sample verification period (2006–2017) with the end of the attribution period (1961–2005) to form an extended verification period (1986–2017) yields verification results that generally fall between the original attribution results and the out-of-sample verification results (tables S1 to S3). However, in a number of cases, the verification results for this modified period still exceed the original attribution results, including hot events over Europe (table S1) and wet events over the United States and Europe (table S3).

By generating multiple realizations of the climate system within a given level of forcing, the CMIP5 simulations can also provide an independent evaluation of whether the change in frequency of record-setting events is due primarily to climate variability, or has instead been influenced by the increase in climate forcing between the attribution and verification periods. For the hottest days over Europe and East Asia (Fig. 2) and the wettest days over the United States, Europe, and East Asia (Fig. 3), both the observations and the CMIP5 ensemble exhibit higher probability of record-breaking events in 2006–2017 than in 1986–2005. Likewise, for the hottest days over Europe and East Asia (Fig. 2), wettest days over the United States, Europe, and East Asia (Fig. 3), and longest dry spells over the United States and East Asia (Fig. 4), the frequency of record-breaking events observed in 2006–2017 has a higher likelihood of occurring in 2006–2017 of CMIP5 than in 1986–2005 of CMIP5. These patterns are also true at the scale of the northern hemisphere for both the hottest and wettest days, where the CMIP5 ensemble exhibits higher frequency of record-setting events in 2006–2017 than in 1986–2005, and the observed 2006–2017 frequencies have a higher likelihood of occurring in 2006–2017 of CMIP5 than in 1986–2005 of CMIP5 (Figs. 2 and 3). The fact that the frequency of record-setting hot and wet events observed during the 2006–2017 verification period generally falls within the CMIP5 ensemble spread for 2006–2017 and generally outside the CMIP5 ensemble spread for 1986–2005 suggests that the observed increase in occurrence was likely influenced by the increase in forcing between the attribution and verification periods.

In contrast, the verification of record-setting longest dry spells suggests that, at both the regional and hemispheric scales, global warming has not had a clear influence on the probability of record-setting events. This lack of attribution was already suggested by the high fraction of attribution ratios near 1.0 (Fig. 1) (*5*). The fact that the verification ratios are also clustered near 1.0 (Fig. 1) strengthens that conclusion. Further, the close overlap between the observed and simulated frequencies for 1986–2005 and 2006–2017 (Fig. 4) suggests that, in contrast to hot and wet events (Figs. 2 and 3), the recent increase in climate forcing has not altered the probability of record-setting longest dry spells over the analysis regions. However, it is important to note that other areas of the globe may have experienced verifiable increases in the probability and/or intensity of dry spells [e.g., (*4*)].

DISCUSSION

The fact that the verification framework reveals the published global attribution results to be overly conservative for hot and wet events carries a number of implications. For example, those attribution results suggested that global warming had already influenced the magnitude and probability of unprecedented events at large fractions of the globe, including >80% for hot events and >50% for wet events (*4*). This includes 71% of North America, 77% of Europe, and 56% of East Asia for the record hottest day of the year, and 80% of North America, 89% of Europe, and 70% of East Asia for the record percentage of annual precipitation falling in the wettest days (*5*)). The verification results presented here suggest that the influence of global warming on these events has been even more pervasive than suggested by those original attribution results.

Likewise, because many of the impacts of global warming are felt through extremes (*54*), attribution of the influence of global warming on record-setting events is highly relevant for quantifying the impacts of historical anthropogenic climate forcing on natural and human systems. In revealing previously published attribution results to be largely conservative, the verification results suggest that the impacts of global warming have been even larger than originally implied (*4*, *5*). Further, attribution quantification is now being used to assign specific responsibility for the damages resulting from individual events (*55*). The results presented here highlight the importance of independent verification of the attribution frameworks that are used to assign responsibility for damages.

The underestimation of the probability of record hot and wet events during the verification period implies a rapid intensification of extreme event probability—and therefore risk—resulting from relatively small increases in climate forcing. This intensification has important implications both for extreme event attribution and for accurately quantifying probabilities of extreme values in the current and near-term climate. Although the calculation of record-setting probabilities attempts to account for nonstationarity in the observational time series (*4*), the verification results suggest that even one to two additional decades of global-scale climate forcing can lead to substantial underestimation of the probability of record-setting hot and wet events (Figs. 2 and 3).

The fact that the observed and simulated frequencies of record-setting events exhibit such large nonstationarities between the baseline period (ending in 2005) and the verification period (2006–2017) suggests that extreme event attribution assessments—as well as other risk assessments—should take particular care to use techniques that capture conditions in the current time period. Researchers have used a number of approaches to extend the period of the attribution analysis. For metrics that rely only on observational data, researchers have used the period of available data at the time of the event [e.g., (*4*, *10*, *28*, *46*)]. Other researchers have calculated statistical relationships between the event probability and the global mean temperature (*10*, *13*, *14*). For metrics that rely on climate model simulations (including coordinated archived experiments such as CMIP5), researchers have used climate model projections to extend the period of analysis up to the time of the event [e.g., (*38*)] or to generate attribution results for different levels of global warming (including projected future levels) [e.g., (*5*, *6*, *8*, *13*)]. For the attribution results evaluated here, the original study (*5*) included projections of return interval ratios for 2016–2035 and 2036–2055 in the CMIP5 RCP8.5 experiment, enabling comparisons with 1° to 2°C and 2° to 3°C of global warming.

Extending probability predictions under higher levels of global warming has been less common in other applications that rely on extreme event probability quantification, such as infrastructure design and risk assessment [e.g., (*52*)]. The verification results suggest that those applications could benefit from such approaches, particularly given that those planning decisions are more explicitly future-oriented than attribution analysis. For example, the underprediction of occurrence of record-setting events during the out-of-sample verification period provides evidence in support of dynamic design guidelines that can be updated as new observational data become available [e.g., (*50*, *52*–*54*)]. Likewise, the fact that the CMIP5 projections for 2006–2017 most accurately capture the actual 2006–2017 frequency of record-setting hot and wet events (Figs. 2 and 3) suggests that ensemble climate model projections could be used to improve probability quantification for applications that have traditionally relied solely on historical observations.

In addition to capturing the response of extreme events to increasing climate forcing, ensemble climate model projections can also help to quantify the influence of variability on future extreme event probabilities. For example, the 1961–2005 attribution metrics suggest >50% likelihood that global warming has increased the probability of record-setting hottest days over the United States (Fig. 1). Further, comparison of the CMIP5 simulations for 2006–2017 and 1986–2005 predicts very high likelihood of a substantial increase in the frequency of record-setting hot events in the later period (Fig. 2). However, 75% of the verification ratio distribution is less than 1.0 over the United States (Fig. 1), driven by a 2006–2017 frequency that is in the lowest quartile predicted from the 1961–2005 observations (Fig. 2).

This relatively low frequency of record-setting hottest days over the United States is consistent with the well-documented "warming hole," a pattern of reduced warming over the central and southeastern United States that has been attributed alternatively to atmosphere-soil moisture feedbacks (*56*), the aerosol-indirect effect (*57*), and internal ocean-atmosphere variability (*58*). Although high levels of global warming are projected to cause substantial warming throughout North America, the lower rates of warming associated with the warming hole are projected to persist over the near-term decades, with relatively high summer temperature variability over the central and southeastern United States persisting throughout the 21st century (*59*). Although there is some indication that the mechanisms causing the warming hole may have reversed early in the 21st century (*58*), the pattern of reduced warming over the central and southeastern United States is present in the mean hottest day of the year for 2006–2017 relative to 1961–2005 (including negative anomalies over the central United States; Fig. 2). Notably, although the observed frequency of record-setting hottest days is lower over the United States in 2006–2017 compared to 1986–2005 (Fig. 2), the 2006–2017 frequency does overlap with the lowest CMIP5 value, highlighting the importance of climate variability within the context of increasing forcing.

CONCLUSIONS

The motivation for this study is to introduce and demonstrate a framework for independent verification of extreme event attribution results. The field of extreme event attribution has expanded rapidly in the past two decades. Results are now the subject of frequent public interest (*2*). This interest has extended into various public decision-making processes, both as motivation for incorporating climate change into decisions [e.g., (*52*)] and as a basis for assigning responsibility for damages (*55*). The use of attribution results raises the burden for scientists to independently verify those results, particularly for events that are unprecedented in the historical experience (and therefore pose the most acute risks).

Numerous methods for event attribution have been developed (*2*). Although different dimensions of methodological uncertainty have been thoroughly evaluated, and in some cases the results of different methods have been systematically intercompared, extreme event attribution results have not yet been independently verified within a framework of scientific falsifiability. To fulfill that need, this study presents a framework for using the attribution calculation to create falsifiable predictions of the frequency of record-setting events and then uses out-of-sample observations to test those predictions. As an initial proof of concept, the verification framework is applied to previously published attribution results for record-setting hot, wet, and dry events at different areas of the globe (*4*, *5*).

Independent verification suggests that those published attribution results frequently underestimate the influence of global warming on the probability of unprecedented hot and wet extremes, with greater uncertainty for dry extremes. The discrepancy between the attribution and verification ratios can be most explained by the increase in climate forcing since the end of the period in which the attribution ratios were generated. This is particularly true for hot events and wet events, for which the discrepancies between the attribution and verification ratios are greatest. Overall, the verification results suggest not only that historical global warming has increased the probability of unprecedented hot and wet events over the northern hemisphere but also that the magnitude of this effect has increased during the 21st century.

Although this study focuses on record-setting hot, wet, and dry events over land areas of the northern hemisphere, the verification framework could also be applied to a suite of other extreme climate variables [e.g., (*49*)] and physical ingredients [e.g., (*4*)], with different data sources providing coverage for different areas of the globe. Further development and application of this and other frameworks will provide a more comprehensive verification of the magnitude of anthropogenic influence on different types of extreme events in different regions of the world.

The verification of previously published results from one attribution method does offer some generalizable lessons. The first is that although many attribution analyses have leveraged the unique insights available from multi-institution climate model archives such as CMIP5 [e.g., (*4–8*, *20*, *38*)], such "ensembles of opportunity" also present limitations. For example, because the coordinated experiments require multiple years to plan and run, the simulations that use historical forcings do not extend to the present at the time that a new event occurs (*48*). This means that analyses must either cover historical periods that do not extend to the present [e.g., (*4–6*, *12*, *20*)] (which, as this study shows, results in an underestimation of the influence of global warming on hot and wet events) or use approaches to extend the calculation past the period of the historical simulations [e.g., (*8*, *10*, *14*, *38*)]. The commonly implemented approach of using the early period of climate model projections to extend the calculation still presents limitations, both because researchers must compare the extended simulations with counterfactual simulations that do not reach up to the present [e.g., (*8*, *38*)] and because the early period of the climate model projections does not include the actual forcings that occurred, which can hamper accurate attribution (*60*).

Another generalizable conclusion is that although precomputed approaches remove bias in the selection of events that are studied and enable unified analysis of multiple types of events across multiple regions of the world, the fact that the precalculation necessarily limits the analysis to an earlier baseline period likely leads to an underestimation of current probabilities. As a result, other precomputed calculations [e.g., (*6*, *7*)] are likely also subject to a similar underestimation of the influence of historical forcing on the probability of events in the current climate. The verification results presented in this study highlight the importance for precomputed event attribution analyses to include calculations for higher levels of forcing [e.g., (*5*, *6*, *8*)] and to update the precomputed results as new observations become available. These results also suggest that "rapid" attribution approaches [which produce analyses soon after a specific event has occurred; e.g., (*10*, *14*, *25*)] should likewise continue to use methods that align the climate forcing in the attribution analysis with the forcing at the time of the event. Efforts to develop and deploy "operational" attribution systems [e.g., (*27*)] that update observations and simulations in real time will also help to address this limitation.

Last, the verification results have general implications beyond extreme event attribution. Historical climate observations are widely used as the basis for risk management decisions in areas as diverse as land use, infrastructure, water resources, supply chain management, disaster relief, finance, insurance, and liability. In many of these cases, decisions must be robust to both current and future probabilities of extreme events. Although decision-makers have been aware of the challenges posed by climate nonstationarity for a number of years [e.g., (*50*, *51*)], many of these decisions still rely primarily on historical observations for calculating extreme event probability [e.g., (*52*)]. The methods for calculating those probabilities from historical data are closely linked to the methods used in the attribution framework evaluated here (*4*, *5*). The out-of-sample verification results presented in this study thus highlight the importance of incorporating present and future nonstationarity into the extreme event probability quantification that underlies a broad suite of climate-sensitive risk management decisions.

MATERIALS AND METHODS

Data

The analysis uses data from the CLIMDEX project, which has archived observational and climate model values for multiple extreme climate indices (*49*). The observational values are calculated from station observations and gridded to a global grid, based on data continuity criteria. The climate model values are calculated from the CMIP5 climate model experiments (*48*).

The current study uses the observational data, along with the Historical and Natural climate model simulations. The Historical simulations include both natural forcings (such as volcanic aerosols and variations in solar output) and anthropogenic forcings (such as greenhouse gases and aerosols); the Natural simulations include only the natural forcings. The Historical and Natural simulations were run through the year 2005 (*48*). Comparison of the Historical and Natural simulations thus quantifies the influence of anthropogenic forcings during the historical climate period through 2005.

Attribution metrics

This study evaluates the extreme event attribution analyses that were published by Diffenbaugh *et al.* (*5*). The study focuses on three of the CLIMDEX indices included in that analysis, which together measure hot, wet, and dry events: the hottest day of the year (TXx; "hottest day"), the percentage of annual precipitation falling in days that are wetter than the 95th percentile of the 1961–1990 period (R95p; "wettest days"), and the longest consecutive dry spell of the year (CDD; "longest dry spell").

Diffenbaugh *et al.* (*5*) calculated the attribution ratio described in (*4*), using the CMIP5 Historical and Natural simulations over the 1961–2005 period. This attribution ratio ($AR_{\text{Forcing:1961–2005}}$) quantifies the influence of anthropogenic forcing on the probability of exceeding the most extreme value observed at each grid point during the 1961–2005 period. The metric is calculated as the ratio between the return interval of the observed record value in the lower level of forcing ($RI_{\text{NAT:1961–2005}}$) and the return interval of the observed record value in the higher level of forcing ($RI_{\text{HIST:1961–2005}}$). For example, if the most extreme observed value has a return interval of 100 years in the Natural forcing (probability = 0.01) and a return interval of 50 years in the Historical forcing (probability = 0.02), then the attribution ratio ($AR_{\text{Forcing:1961–2005}}$) is 2, suggesting that anthropogenic forcing has doubled the probability of exceeding the most extreme observed value.

Diffenbaugh *et al.* (*4*) also calculated the contribution of the historical trend at each grid point to the probability of exceeding that grid point's most extreme observed value. This metric ($AR_{\text{Obs-dt:1961–2005}}$) is calculated as the ratio of the return interval of the observed record value in the detrended historical time series ($RI_{\text{Obs-dt:1961–2005}}$) and the return interval of the observed record value in the actual historical time series ($RI_{\text{Obs:1961–2005}}$)

$$AR_{\text{Obs-dt:1961–2005}} = (RI_{\text{Obs-dt:1961–2005}}) \div (RI_{\text{Obs:1961–2005}})$$

This second metric ($AR_{\text{Obs-dt:1961–2005}}$) thus relies only on observational data (without any climate model simulations) and is agnostic about the cause of the historical trend.

The current study evaluates both the attribution ratio due to anthropogenic forcing ($AR_{\text{Forcing:1961–2005}}$) and the attribution ratio due to the observed trend ($AR_{\text{Obs-dt:1961–2005}}$). Both attribution metrics report an uncertainty distribution of attribution ratios. These distributions are based on the uncertainty distribution of return intervals for the record setting event ($RI_{\text{Obs:1961–2005}}$), which are calculated from the observational time series using a block bootstrapping approach.

Verification framework

To verify the previously published attribution ratios, the uncertainty distributions calculated for 1961–2005 are compared with the frequency of occurrence of record-setting events observed during 2006–2017. This verification approach is conceptually similar to the attribution calculation of Coumou *et al.* (*28*), except here the verification data are kept out of sample (i.e., the verification data are not used in the calculation of the counterfactual time series from which the counterfactual probabilities are quantified).

First, the maximum value of each climate index is calculated at each grid point during the 1961–2005 period of the CLIMDEX observations. Then, for each grid point, all events during 2006–2017 that exceed the respective 1961–2005 grid-point maximum are identified. The frequency of occurrence of record-setting events in 2006–2017 ($F_{\text{Obs:2006–2017}}$) is then calculated over the Northern Hemisphere, the United States (30–50°N, 120–60°W), Europe (30–60°N, 0–50°E), and East Asia (20–45°N, 90–135°E), where

$F_{\text{Obs:2006–2017}}$ =
[the total number of exceedances in the region in 2006-2017] ÷
[(the number of grid points in the region) ×
(the number of years in 2006-2017)]

This regional frequency of occurrence ($F_{\text{Obs:2006–2017}}$) is then converted to a regional verification ratio ($VR_{\text{Obs:2006–2017}}$) that can be compared with the attribution ratios described in (*5*) and (*4*). First, the regional frequency of occurrence is converted to a "regional return interval" ($RI_{\text{Obs:2006–2017}}$) using the formula for the return interval

$$RI = 1 \div (1 - P)$$

but using the regional frequency of occurrence ($F_{\text{Obs:2006–2017}}$) as the measure of probability

$$RI_{\text{Obs:2006–2017}} = 1 \div (F_{\text{Obs:2006–2017}})$$

The regional-mean return interval of the observed record value in the detrended historical time series ($RI_{\text{Obs-dt:1961–2005}}$) is then computed by first calculating the mean of the grid-point probabilities in the detrended time series ($P_{\text{Obs-dt:1961–2005}}[i,j]$) and then calculating the regional-mean return interval from that regional-mean probability. (Note that the order of operations matters: It is important to first calculate the regional-mean of the grid-point probabilities to avoid the regional-mean return interval being dominated by any single grid-point return interval value.) The uncertainty in the regional-mean return interval ($RI_{\text{Obs-dt:1961–2005}}$) is quantified by calculating the regional-mean at each quantile of the uncertainty distribution of grid-point probabilities ($P_{\text{Obs-dt:1961–2005}}[i,j]$).

Last, the uncertainty distribution of regional-mean return intervals in the detrended 1961–2005 time series ($RI_{\text{Obs-dt:1961–2005}}$) is divided by the regional-mean 2006–2017 return interval ($RI_{\text{Obs:2006–2017}}$), generating an uncertainty distribution of verification ratios ($VR_{\text{Obs:2006–2017}}$) for each region

$$VR_{\text{Obs:2006–2017}} = RI_{\text{Obs-dt:1961–2005}} \div RI_{\text{Obs:2006–2017}}$$

This distribution of verification ratios ($VR_{\text{Obs:2006–2017}}$) is compared with the regional-means of the grid-point distributions of attribution ratios from anthropogenic forcing ($AR_{\text{Forcing:1961–2005}}$) and attribution ratios from the observed trend ($AR_{\text{Obs-dt:1961–2005}}$).

To understand the comparisons between the published attribution ratios and the regional verification ratios, a number of regional extreme event frequencies are calculated using the IPCC's baseline period (1986–2005). These include the regional frequency of events that exceed the observed 1961–2005 maximum during the 1986–2005 period of the observations ($F_{\text{Obs:1986–2005}}$), the regional frequency of events that exceed the simulated 1961–2005 maximum during the 1986–2005 period of the CMIP5 Historical simulations ($F_{\text{CMIP5:1986–2005}}$), and the regional frequency of events that exceed the simulated 1961–2005 maximum during the 2006–2017 period of the CMIP5 RCP8.5 simulations ($F_{\text{CMIP5:2006–2017}}$). For each observed or simulated climate realization, the regional frequency is calculated as the number of times during the evaluation period (1986–2005 or 2006–2017) that a grid-point value within the region exceeds the respective 1961–2005 grid-point maximum, divided by the number of grid points in the region, divided by the number of years in the evaluation period.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/12/eaay2368/DC1

Table S1. Verification metrics for the hottest day of the year (TXx), calculated for different time periods.

Table S2. Verification metrics for the percent of precipitation from wettest days (R95p), calculated for different time periods.

Table S3. Verification metrics for the longest dry spell of the year (CDD), calculated for different time periods.

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Climate change is increasing the likelihood of extreme autumn wildfire conditions across California

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Abstract

California has experienced devastating autumn wildfires in recent years. These autumn wildfires have coincided with extreme fire weather conditions during periods of strong offshore winds coincident with unusually dry vegetation enabled by anomalously warm conditions and late onset of autumn precipitation. In this study, we quantify observed changes in the occurrence and magnitude of meteorological factors that enable extreme autumn wildfires in California, and use climate model simulations to ascertain whether these changes are attributable to human-caused climate change. We show that state-wide increases in autumn temperature (~1 °C) and decreases in autumn precipitation (~30%) over the past four decades have contributed to increases in aggregate fire weather indices (+20%). As a result, the observed frequency of autumn days with extreme (95th percentile) fire weather—which we show are preferentially associated with extreme autumn wildfires—has more than doubled in California since the early 1980s. We further find an increase in the climate model-estimated probability of these extreme autumn conditions since ~1950, including a long-term trend toward increased same-season co-occurrence of extreme fire weather conditions in northern and southern California. Our climate model analyses suggest that continued climate change will further amplify the number of days with extreme fire weather by the end of this century, though a pathway consistent with the UN Paris commitments would substantially curb that increase. Given the acute societal impacts of extreme autumn wildfires in recent years, our findings have critical relevance for ongoing efforts to manage wildfire risks in California and other regions.

1. Introduction

California has recently endured a multi-year period of unprecedented wildfire activity. The state's single deadliest wildfire, two largest contemporary wildfires, and two most destructive wildfires all occurred during 2017 and 2018 [1]. Over 150 fatalities were directly attributed to these fires [2]—a total greater than during any California earthquake since San Francisco's 'Great Quake' of 1906 [3]. Over 30 000 structures and >1.2 million ha burned in 2017–2018, including nearly the entire Sierra Nevada foothill town of Paradise (population 27 000). State-level fire suppression expenditures exceeded $1.6 billion in 2017–2018 [1], and estimated economic losses exceeded $40 billion [2]. Wildfire smoke was transported across the state, exposing millions to prolonged periods of degraded

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air quality, leading to public health emergencies and the extended closure of thousands of schools and businesses [4]. In the wake of these events, California's largest electricity utility has implemented a policy of pre-emptive 'Public Safety Power Shut-Offs' during periods of severe wildfire risk to reduce the probability of ignitions—resulting in widespread and disruptive California power outages in autumn 2019 [5, 6].

The recent California wildfires have garnered widespread attention, with an especially high level of interest from policymakers and emergency responders seeking to understand the multiple contributors to the increase in wildfire disasters. Quantitative assessments of changing wildfire risk factors have thus become critical as California moves beyond the initial stages of short-term disaster recovery and begins to develop risk mitigation, land management, and resource allocation strategies.

Changing demographic factors have undoubtedly played a substantial role in community exposure and vulnerability [7]—including the expansion of urban and suburban developments into the 'wildland-urban interface' [8]. In many forested regions that historically experienced frequent, low-intensity fire, a century-long legacy of fire suppression has promoted the accumulation of fuels, likely contributing to the size and intensity of some fires [9, 10]. Nevertheless, the broad geographic extent of increased burned area in California and the western United States (U.S.)—across geographies and biomes [11, 12], and even when limited to lightning-caused fires [13, 14]—suggests that demographic and forest management factors alone are insufficient to explain the magnitude of the observed increase in wildfire extent over the past half-century.

California's climate has changed considerably over the past several decades [15]. The state's five warmest years on record occurred in 2014–2018 (figure S1 (stacks.iop.org/ERL/15/094016/mmedia)). In addition, over the past century, robust statewide warming occurred during all 12 months, with the most pronounced warming in the late summer and early autumn (figure S1). This warming has increased the likelihood and magnitude of hydrological drought [16–18], decreased mountain snowpack [19], and increased vegetation moisture stress and forest mortality [20]. Rising temperatures and declining snowpack—in combination with precipitation deficits that are consistent with emerging evidence of mechanisms that support decreasing precipitation in autumn and spring [21–23]—have acted to extend California's fire season [13, 24, 25]. As global warming continues in the future, regional warming and snowpack loss are expected to accelerate [26–28], concurrent with a regional increase in the frequency of both wet and dry precipitation extremes [17, 21, 29–32]. Therefore, even absent substantial changes in average precipitation, warming and seasonal shifts in hydroclimate will likely yield pronounced aridification across most of California [16].

Over the past decade, numerous studies have provided substantial insight into the influence of historical climate change on wildfire risk (e.g. [12, 33, 34]). Studies have identified spring and summer warming and earlier melting of snowpack [13, 24]—accompanied by declines in precipitation and wetting rain days during the fire season [35]—as important influences on large wildfires in the western U.S., and demonstrated a 'detectable influence' of historical anthropogenic climate forcing on long-term increases in area burned in Canada [36]. Additional recent studies have attributed approximately half of the increase in annual forest fire area in the western U.S. since the early 1980s to warming-induced increases in fuel aridity [37, 38], and found that anthropogenic climate forcing has greatly enhanced the probability of recent extreme fire seasons (e.g. [39–41]).

Recent autumns have been characterized by multiple large and fast-spreading wildfires burning simultaneously across California. This simultaneous occurrence can quickly compromise the efficacy of local, regional, and even national suppression efforts. Indeed, autumn fires in particular may expose an additional vulnerability: many of the temporary firefighting resources deployed during the core summer fire season—including personnel, vehicles, and aircraft—become unavailable as winter approaches. This is because funding for fire suppression activities has historically been aligned with the 20th century seasonality of wildfire, which typically decreases across most of the American West in the autumn (e.g. [42]). As the seasonality of the fire season broadens in a warming climate, a mismatch can emerge between firefighting resource availability and actual needs [43].

The consequences of such a confluence of events were starkly evidenced in 2018, when large late-autumn fires burning simultaneously in northern and southern California created major logistical challenges, and the heavy commitment of resources simultaneously in both regions required national resources to be ordered [44]. The scope of the resulting wildfire disasters motivates formal analysis of possible changes in the likelihood of warm, dry autumns that enable widespread late season fire activity simultaneously in both northern and southern California.

We therefore focus primarily on climatic factors that contribute to extreme wildfire conditions during autumn, including during two particularly devastating November 2018 events: the Camp Fire, which occurred in a transitional oak woodland in the northern Sierra Nevada foothills; and the Woolsey Fire, which occurred in the coastal chaparral shrub regime near Los Angeles. Both fires ignited during strong and dry 'offshore' downslope wind events, known locally as the Santa Ana winds in Southern California and

Diablo winds in parts of Northern California. The frequency and strength of Santa Ana winds peaks in winter [45], but such winds in autumn that co-occur with dry fuels are responsible for a disproportionate fraction of both area burned [46] and wildfire losses in much of California [47, 48]. While offshore winds in November are not unusual, much of interior northern California and coastal southern California experienced the hottest summer on record in 2018, and autumn rainfall did not arrive across much of the state until mid-to-late November—thus predisposing the region to extreme fire danger conditions.

Motivated by the conditions that led to extreme autumn wildfire activity in 2018, we investigate changes in autumn temperature, precipitation, and daily fire weather indices, with a particular emphasis on the simultaneous co-occurrence of extreme conditions in northern and southern portions of the state. Analyzing both observational and climate model evidence, we seek to quantify (i) whether the occurrence of climate conditions contributing to extreme autumn wildfire potential has changed in recent decades; (ii) whether anthropogenic climate forcing has contributed to any detected changes in extreme fire weather; and (iii) how continued global warming could alter the probability of extreme fire weather in the future. We emphasize that the present investigation only considers changes in climatic contributions to wildfire risk, irrespective of changes in fire ignitions, vegetation, land use or management strategies.

2. Materials and methods

2.1. Historical observations of climate, fire weather, and area burned

We analyze gridded meteorological data (1/24° spatial resolution) from the gridMET database [49] during 1979–2018. We calculate seasonal-mean temperature, precipitation, and Fire Weather Index ('FWI') for each autumn season (September through November; 'SON') from 1979 to 2018 (shown in figures 1 and 2).

The FWI (from the Canadian Forest Fire Danger Weather Index System) is a widely-used generalized measure of fire potential that incorporates both fuel aridity and fire weather (using maximum temperature, minimum relative humidity, wind speed, and precipitation), irrespective of fuel type and abundance [51]. FWI closely tracks interannual variability of other commonly used fire danger metrics such as Energy Release Component (ERC) [37], and exhibits strong empirical links to individual high-intensity fire events (e.g. [48]) and interannual variability in burned area for much of the globe (e.g. [52]).

At each grid point in California, we calculate (i) seasonal-mean temperature by averaging the daily maximum and minimum temperatures in SON of each year; (ii) seasonal total precipitation by summing the daily precipitation accumulation in SON of each year; and (iii) seasonal-mean FWI by averaging the daily FWI values in SON of each year (shown in the maps in figure 2). In addition, we calculate spatially averaged values of SON temperature, precipitation and FWI over the land grid points of three domains: (i) state-wide, encompassing land grid points in California (shown in figure 1); (ii) a Northern Sierra region (38.75–40.75 °N, 122.875–120.375 °W) encompassing the city of Paradise and the Camp Fire footprint (shown in figure 2); and (iii) a South Coast region (33–35 °N,120–117.5 °W) encompassing the city of Malibu and the Woolsey Fire footprint (shown in figure 2).

In addition to these climate observations, we analyze burned area data from the Monitoring Trends in Burn Severity dataset during 1984–2016 [53] that includes all large fires >404 ha; these data have been extended through 2018 using burned area from MODIS [54] and applying bias adjustments to the MODIS records [37]. Data include burned area by wildfires that had fire discovery dates between September 1 and November 30, and do not include wildfire events that began prior to September. It is possible to separate burned area by vegetation class (e.g. [12]), and because we find that only 43% of SON burned area over the period of record occurred in forests, we use total burned area for the state-wide analysis shown in figure 1.

For each of the regional-mean climate and area burned time series, we quantify the linear trend and statistical significance using the nonparametric bootstrap resampling approach described in Singh *et al* [50], using n = 10 000 iterations. This resampling approach has two key strengths. First, as a nonparametric resampling method, it is applicable even in cases where the underlying distribution is non-Gaussian. Second, it allows us to account for potential temporal autocorrelation in the raw time series by using a block length greater than that of any statistically significant autocorrelation. The resampling approach, along with the calculation of statistical significance, is described in detail in the supplementary materials of Singh *et al.*

2.2. Relationship between extreme autumn fire weather and area burned

The area burned dataset described in the previous section allows us to quantify the trend and interannual climate-burned area relationships. In addition, to quantify the relationship between extreme daily-scale autumn fire weather and the area burned by individual wildfires, we use the fire database of individual wildfires occurring in non-desert and non-agricultural regions of California from Williams *et al* [12]. We query this dataset from 1979–2018 to identify relationships between daily FWI exceeding the locally-defined 95th percentile (FWI_{95}; 'extreme fire weather') and the occurrence of very large autumn fires (herein defined as the largest 1%

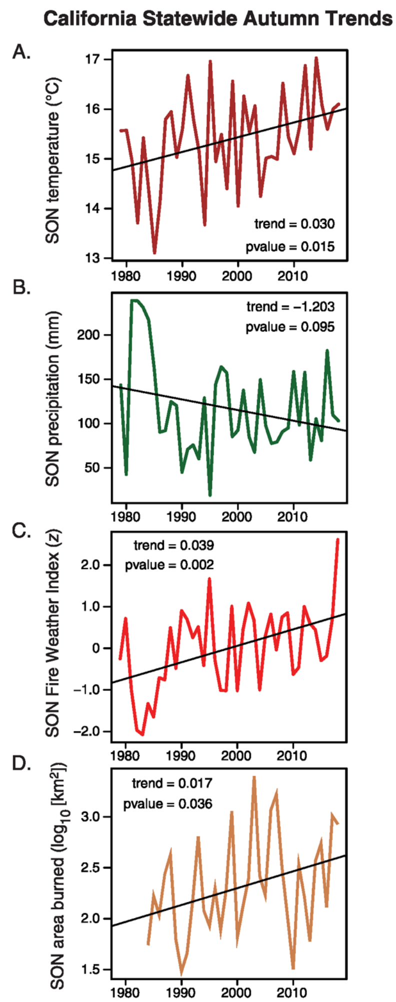

Figure 1. Observed state-wide trends in autumn climate and area burned over California. Time series show each year's value for SON (A) temperature, (B) precipitation, (C) FWI, and (D) $\log_{10}$(burned area). Fitted trends and p-values are calculated using the block bootstrapping approach of Singh *et al* [50], which accounts for time dependency (see Methods).

of autumn fires, or 54.25 km^2). We calculate the 95th percentile threshold using data pooled over the calendar year during 1979–2018. We tabulate the maximum FWI over the first three days of each fire at the fire ignition location, as this often comprises a critical period where fires escape initial attack [55].

In addition, we quantify seasonal relationships between autumn area burned and the number of

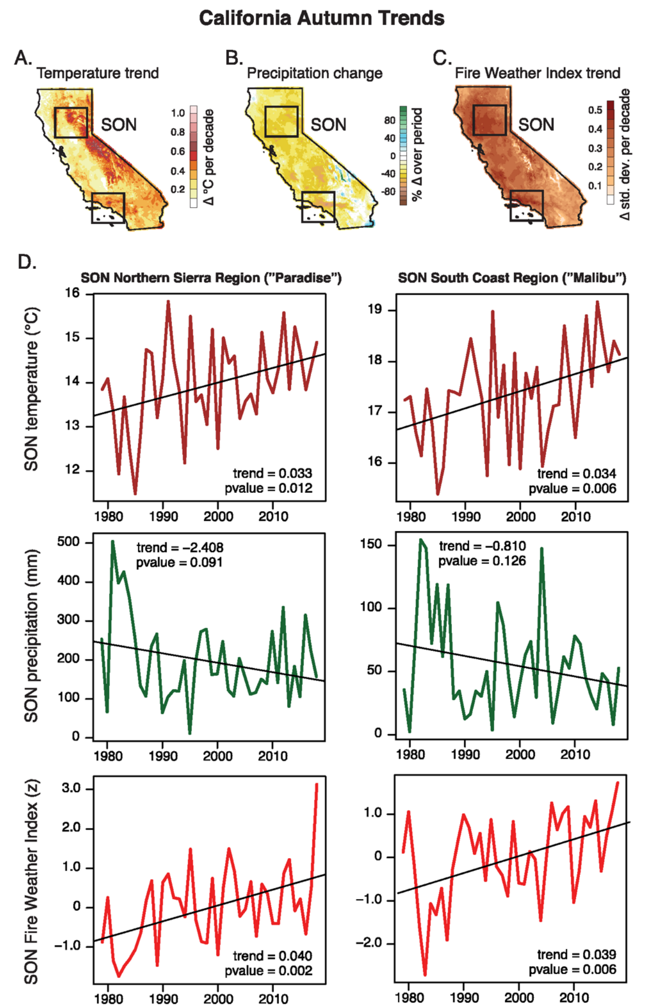

Figure 2. Observed climate trends across California. Maps show 1979–2018 trends in observed autumn-mean (A) surface air temperature (°C per decade), (B) precipitation (% change over period), and (C) FWI (units per decade). For precipitation, trends are displayed for each grid point as change relative to the 1979 value. Black boxes on each map indicate the boundaries of the Northern Sierra ('Paradise') and South Coast ('Malibu') regions discussed in the text. (D) Time series plots show observed autumn mean temperature, precipitation, and FWI for the Northern Sierra ('Paradise'; left) and South Coast ('Malibu'; right) regions for 1979–2018. Fitted trends and p-values are calculated using the block bootstrapping approach of Singh *et al* [50], which accounts for time dependency (see Methods).

FWI_{95} days. Both measures are aggregated state-wide over the geographic region from Williams *et al* [12] to create annual time series. We calculate bivariate interannual correlations between the logarithm of autumn burned area and the number of FWI_{95} during 1984–2018 using both Pearson and Spearman correlation coefficients. As in previous studies, we use logarithms of burned area to overcome the exponential distribution of burned area records. Correlations are additionally calculated using detrended data to assess whether interannual relationships were strongly contingent on trends. Finally, we estimate average annual SON burned area for years where the state-wide FWI_{95} was above and below the 1984–2018 median (approximately 5.5 d). Given the heavily right skewed nature of burned area, we quantify uncertainty of these estimates through bootstrap resampling with replacement ($n = 1000$).

2.3. Simulated occurrence of extreme fire weather during the 20th and 21st centuries

We calculate daily FWI using the statistically downscaled (1/24th degree) maximum temperature, minimum relative humidity, wind speed, and precipitation fields from 18 CMIP5 models, described in [56]. These high-resolution fields are available for 1950–2005 in the CMIP5 Historical forcing, and 2006–2099 in the CMIP5 RCP4.5 and RCP8.5 forcing pathways. Together, they represent a unique, extremely high-resolution, daily-scale version of the CMIP5 ensemble. Although these high-resolution fields do not extend back to the late-19th/early-20th century (and therefore cannot be used to calculate changes in the probability of extreme autumn fire weather conditions since the Industrial Revolution), they do enable an unprecedented analysis of the spatial response of extreme fire weather to increases in climate forcing over the past half century, and projection of changes in multiple future climate forcing scenarios.

This high-resolution version of the CMIP5 dataset allows us to examine responses to two distinct future anthropogenic emissions scenarios: (i) a 'high emission' scenario (RCP8.5, which is the forcing most closely matching actual emissions over the past decade [57]), and (ii) a 'stabilization' scenario (RCP4.5, which is a forcing scenario slightly lower than that which would result from adherence to existing national commitments made as part of the Paris Agreement [58, 59]). While the RCP8.5 'high emissions' scenario is viewed by some as implausible, we include it in our analysis because, while the underlying socioeconomic assumptions and resultant energy portfolio underpinning the RCP8.5 scenario may be implausible, attainment of 'RCP8.5-like' warming may be possible even under lower emission trajectories if carbon cycle feedbacks are stronger than anticipated (e.g. [60]), and/or if climate sensitivity is higher than had previously been projected—as preliminary results from new CMIP6 simulations suggest is possible [61].

We harmonize this CMIP5 analysis with the analysis of observed extreme daily FWI (see previous section) by calculating the 95th percentile FWI value at each grid point across all calendar days during the CMIP5-simulated 1979–2018 period. We then calculate the mean frequency of occurrence of SON days that exceed the respective grid-point FWI_{95} threshold during 1950–2005 of the CMIP5 Historical simulations, along with 2006–2099 of the CMIP5 RCP4.5 and RCP8.5 simulations.

We use these high-resolution grid-point time series of autumn FWI_{95} days to conduct four analyses (shown in figures 4 and 5):

First, for each of the individual CMIP5 realizations, we calculate the 1979–2018 trend in autumn FWI_{95} days over the Northern Sierra (Paradise) and South Coast (Malibu) regions. As described in [62], we use a binomial test to compare the frequency of positive trends with the null hypothesis that in a stationary climate the probability of a positive multi-decadal trend is 0.5.

Second, for each year between 1950 and 2099 in the CMIP5 Historical, RCP4.5 and RCP8.5 simulations, we calculate the number of autumn FWI_{95} days in the Northern Sierra region, and the number of autumn FWI_{95} days in the South Coast region. Then, for each region, we calculate the mean of the CMIP5 values in each year, yielding an annual time series of CMIP5-mean autumn FWI_{95} occurrence for the Northern Sierra and South Coast regions.

Third, for each year between 1950 and 2099 in the CMIP5 Historical, RCP4.5 and RCP8.5 simulations, we identify each of the CMIP5 realizations for which both the Northern Sierra and South Coast regions experience >5 FWI_{95} days during autumn. We then calculate the fraction of the CMIP5 realizations meeting this criterion in each year, yielding an annual time series of the probability that both the Northern Sierra and South Coast regions experience >5 FWI_{95} days in the same autumn season.

Fourth, we calculate the mean occurrence of autumn FWI_{95} days at each of the high-resolution grid points during three 30-year periods of the CMIP5 RCP4.5 and RCP8.5 simulations: 2006–2035, 2036–2065 and 2066–2095. Together, these three periods span the cumulative emissions and global temperature changes of similar periods in RCP2.6 and RCP6.0, with all four RCPs overlapping closely during the early period [63].

3. Results and discussion

3.1. Observed trends in climate, fire weather, and area burned

Between 1979 and 2018, state-wide autumn trends were +0.30 °C/decade ($p = 0.015$) for temperature, −12.03 mm/decade ($p = 0.095$) for precipitation, and +0.39 standard deviations/decade ($p = 0.002$) for FWI (figure 1). Likewise, the trend in state-wide autumn burned area corresponded to an increase of ~40% per decade during 1984–2018 ($p = 0.036$).

These state-wide trends are reflected more broadly throughout California, with most areas having experienced positive temperature trends (figure 2(A)), negative autumn precipitation trends, and positive autumn FWI trends (figure 2(C)) during 1979–2018. The Northern Sierra (Paradise) and South Coast (Malibu) regions have exhibited autumn temperature trends of +0.33 °C/decade ($p = 0.012$) and +0.34 °C/decade ($p = 0.006$), respectively, along with autumn precipitation trends of −24.08 mm/decade ($p = 0.091$) and −8.10 mm/decade ($p = 0.126$) (figure 2(D)). Further, strongly positive FWI trends have been observed for both the Northern Sierra (+0.40 standard deviations/decade; $p = 0.002$) and South Coast (+0.39 standard deviations/decade; $p = 0.006$) regions.

The autumn 2018 FWI value was the highest in the observed record for both the Northern Sierra and South Coast regions (figure 2(D)). However, those record FWI values were not associated with record SON temperature or precipitation in either region (figure 2(D)). This discrepancy highlights the fact that FWI incorporates build-up factors (e.g. summer aridity) that entrain some memory of summer conditions into early autumn, as well as the multivariate and nonlinear nature of FWI calculations.

The seasonal mean precipitation from the full October-November period may also not always represent on-the-ground moisture conditions coincident with fire activity, since individual large storms during mid-late November can occasionally offset critically dry antecedent conditions. In 2018, a series of Pacific storm systems brought widespread heavy rainfall and anomalously cool temperatures to California in the final ~10 d of November. However, conditions from September through the first half of November were very warm and dry, which produced a period of extraordinarily high wildfire potential (figure 2(D)) during which both the Camp and Woolsey fires ignited and spread. Additionally, the record downslope-wind-driven Thomas Fire in 2017 ignited in early December [46], suggesting that future analyses may need to consider September-December, as the later onset of precipitation extends the autumn fire season later into the year. Although further research is needed to fully assess changes in the precise timing of cool-season precipitation onset, recent work suggests that projected sub-seasonal shifts in California precipitation ([17, 21–23, 29]; figure S2) have significant potential to interact non-linearly with changes in the seasonality of autumn offshore winds [64].

3.2. Observed relationships between extreme autumn fire weather and area burned

We find moderate interannual correlations between SON area burned and the mean number of SON days in which FWI exceeds the locally-defined 95th percentile (FWI_{95}) (e.g. $r > 0.35$ for forest and non-forest area; Table S1). Correlations between SON burned area and FWI_{95} days are stronger than those between SON burned area and seasonal FWI, temperature, or precipitation. These weaker relationships to total SON burned area are consistent with prior studies [12, 65]. A matrix of additional factors ultimately shape autumn fire potential and realized fire activity, including live fuel moistures; sensitivity of short-term fuel abundance in grassland regions to the preceding winter/spring moisture availability (e.g. [66]); and the stochastic nature of synchronization between predominantly human-caused ignitions, critical fire weather conditions, and dry fuels.

Given the inherent limitations of the relationships between seasonal-scale climate variables and wildfire activity, we also analyze relationships with daily-scale fire weather conditions at the individual fire event level. Approximately 60% of the largest 1% of autumn fires during 1979–2018 started or were immediately followed within the first two days by extreme fire weather conditions. Further, we find substantially more area burned in SON seasons with greater frequency of FWI_{95} days. For instance, over the 1984–2018 period, the mean area burned for SON seasons in which the number of FWI_{95} days exceeded the median FWI_{95} frequency (5.5 d) was 528 km^2 (95% range: 300–920 km^2), compared with 222 km^2 (95% range: 121–574 km^2) for SON seasons in which the number of FWI_{95} days was less than the median frequency (figure 3(B)).

The occurrence of autumn FWI_{95} days has increased substantially in recent decades (figure 3(A)). Over the 1979–2018 period, the regional average number of SON FWI_{95} days exhibits a trend of +2.34 d/decade ($p < 0.001$). As a result, the mean number of days with extreme fire weather during the autumn season has more than doubled since the late 1970s. Further, 2005 was the last year in which the regional average fell below the 1979–2018 median value.

3.3. Response of extreme autumn fire weather to historical and future changes in climate forcing

Given the elevated probability of extensive area burned for autumn seasons with >5 FWI_{95} days (figure 3), we compare the frequency of FWI_{95} days—and seasons with >5 FWI_{95} days—for different periods of the CMIP5 historical and future climate simulations. During the 1979–2018 period, both the Northern Sierra and South Coast regions exhibit simulated increases in frequency of autumn FWI_{95} days, both in the mean of the CMIP5 realizations (fig-

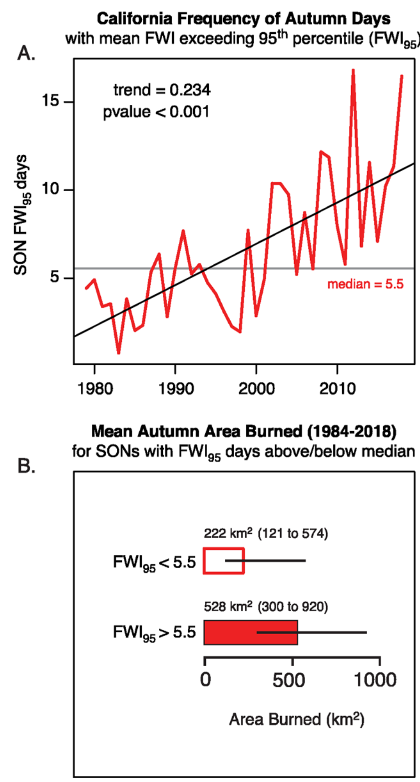

Figure 3. Observed relationship between extreme autumn fire weather days and autumn burned area. (A) The mean number of days in each autumn from 1979–2018 in which the daily FWI exceeded the locally-defined 95th percentile (FWI_{95}). Fitted trend and p-value are calculated using the block bootstrapping approach of Singh *et al* [50], which accounts for time dependency (see Methods). (B) The mean SON burned area for years in which the mean autumn FWI_{95} frequency was above/below the median value (approximately 5.5 d). Uncertainty of the estimates is quantified using bootstrap resampling with replacement (see Methods).

ures 4(C), (D)), and in a majority of the individual realizations (figures 4(A), (B)). These increases in FWI_{95} days result in increases in the joint occurrence of years in which both the Northern Sierra and South Coast regions experience high FWI_{95} occurrence during the same autumn (figure 4(E)). For example, the CMIP5-mean simulated fraction of SON seasons in which there are >5 FWI_{95} days in both the Northern Sierra and South Coast regions increases from ~0.35 to >0.40 between 1950 and 2018.

Simulated future changes in extreme FWI days are projected in both 'high warming' (RCP8.5) and 'warming stabilization' (RCP4.5) scenarios. Both the Northern Sierra and South Coast regions exhibit increases in mean FWI_{95} occurrence of >25% over the remainder of the 21st century in RCP8.5, reaching a mean of ~10 d/autumn over the Northern Sierra and ~9 d/autumn over the South Coast (figure 4(B)). The multi-model mean increases are reduced in RCP4.5, reaching a mean of ~8 d/autumn over the Northern Sierra and ~7 d/autumn over the South Coast (figure 4(B)). As a result, the projected fraction of autumn seasons in which both the Northern Sierra and South Coast experience >5 FWI_{95} days is reduced from ~0.6 at the end of the 21st century in RCP8.5 to below 0.5 in RCP4.5.

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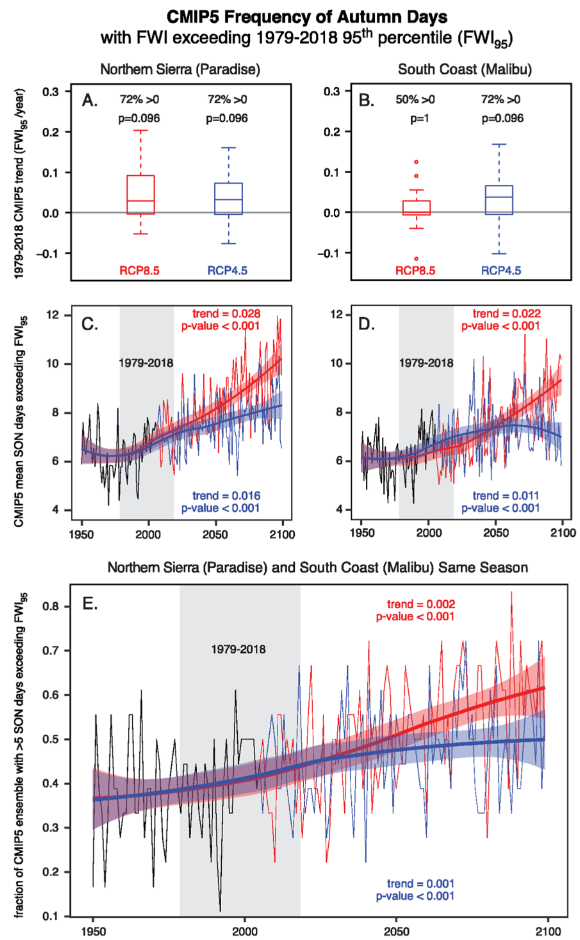

Figure 4. CMIP5-simulated historical change in extreme Fire Weather Index (FWI) values. (A), (B) The distribution of CMIP5 1979–2018 trends in autumn FWI_{95} days over the Northern Sierra (Paradise) and South Coast (Malibu) regions; the p-value compares the frequency of positive trends with the null probability of 0.5, as described in [62]. (C), (D) The CMIP5-mean autumn FWI_{95} occurrence for the Northern Sierra and South Coast regions for each year between 1950 and 2099 in the CMIP5 Historical (black), RCP4.5 (blue) and RCP8.5 (red) simulations. (E) The fraction of CMIP5 realizations for which both the Northern Sierra and South Coast regions experience >5 FWI_{95} days during the same autumn season, for each year between 1950 and 2099 in the CMIP5 Historical (black), RCP4.5 (blue) and RCP8.5 (red) simulations. Trends and p-values are calculated over the full 1950–2099 period using the block bootstrapping approach of Singh *et al* [50], which accounts for time dependency (see Methods). The bold regression lines and associated envelopes show the 95% confidence interval of a locally weighted regression ('loess').

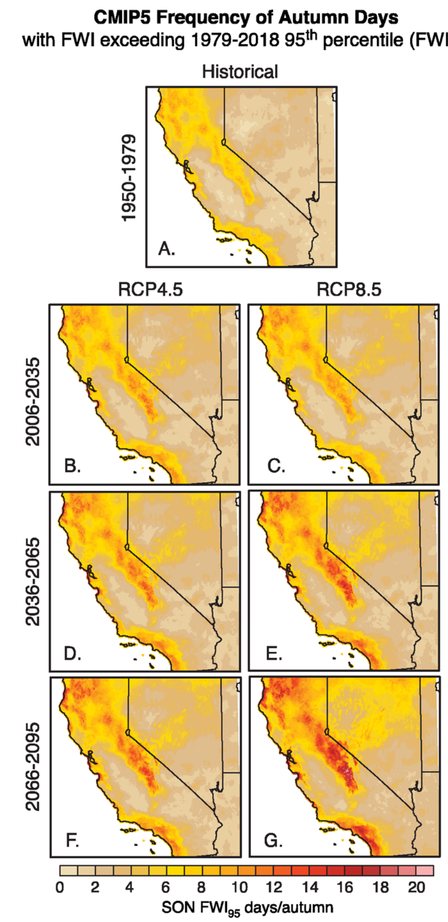

Figure 5. Projected changes in extreme FWI occurrence. Maps depict the ensemble-mean number of days per autumn season during which CMIP5-downscaled FWI exceeds the historical (1979–2018) 95th percentile for the past (1950–1979), present-era (2006–2035), mid-century future (2036–2065), and late-century future (2066–2090). Results are shown for two separate climate scenarios: a 'high warming' (RCP8.5) and 'warming stabilization' (RCP4.5) trajectory.

The greater intensification of extreme wildfire weather in the 'high warming' RCP8.5 scenario is also reflected in much of the rest of California (figure 5). During the present era (2006–2035), RCP8.5 and RCP4.5 show similar increases in FWI_{95} occurrence, with the area experiencing >10 FWI_{95} days/autumn expanding over northern California, the Sierra Nevada, and the Pacific coast relative to the mid-20th century (1950–1979). By the mid-21st century (2036–2065), RCP8.5 exhibits a higher frequency of FWI_{95} days over many of the high-FWI regions, including much of northern California, the Sierra Nevada and the South Coast. These differences between RCP4.5 and RCP8.5 are further exacerbated in the late-21st century. Specifically, the frequency of FWI_{95} days is projected to remain below 15 d/autumn throughout almost all of the state in 2066–2095 of RCP4.5, but it is projected to exceed 15 d/autumn over many of the high-FWI regions in 2066–2095 of RCP8.5.

We emphasize that although the projected increases in extreme FWI are not spatially uniform, they are essentially ubiquitous across vegetated areas of California. In particular, we note 'hotspots' of extreme projected FWI increases in regions with very different vegetation regimes. For example, relative increases in extreme FWI frequency are broadly projected to exceed 50% by the late-21st century of RCP4.5 (relative to 1950–1979), and approach 100% in some regions by the late-21st century of RCP8.5 (figure 5). This finding strongly suggests that—at least from an extreme fire weather perspective—the direct influence of climate change on wildfire risk is not limited to California's forested regions, and instead extends across a diverse range of microclimates and ecoregions as long as fuel abundance is not limiting.

4. Conclusions

We report a substantial and statistically significant historical trend toward autumns which are increasingly conducive to enhanced wildfire risk across most of California. This observed increase in weather-driven autumn wildfire risk coincides with a strong and robust warming trend (+0.30 °C/decade; $p = 0.015$), and a modest negative precipitation trend (−12.03 mm/decade; $p = 0.095$) over the 1979–2018 period. Observations and climate model simulations suggest that the likelihood of Northern and Southern California simultaneously experiencing extreme autumn fire weather conditions has increased since the mid-20th century. Climate model simulations further suggest that continued warming and strengthening of seasonal drying trends in the future will likely result in further increases in extreme autumn fire weather conditions throughout California—even for a future climate scenario similar to that which would result from adherence to commitments made in the UN Paris Agreement [58, 59]. Collectively, this analysis offers strong evidence for a human fingerprint on the observed increase in meteorological preconditions necessary for extreme wildfires in California. Absent a strong decrease in autumn wind patterns, observed and projected temperature and precipitation trends portend increasing risk that autumn offshore wind events will coincide with critically dry fuels—increasing the potential for wildfire catastrophes when fires affect populated areas.

We note several caveats. First, the increases in wildfire probability that we quantify are based on links with FWI, but not on simulations of wildfire frequency. However, there are physical and empirical bases for the relationship with FWI (e.g. [67–69]) and our results help to further refine the linkage between the occurrence of extreme autumn fire weather and autumn area burned (figure 3; table S1). Second, although the high-resolution climate datasets enable analysis of historical and projected changes in extreme fire weather potential, gridded datasets are imperfect approximations of real-world weather conditions, climate trends, and the response of local climate to changes in forcing (including the mesoscale atmospheric dynamics that generate strong wind events). Third, there are uncertainties associated with internal low-frequency climate variability apparent in multi-decadal climate observations of simulations (e.g. [70]), especially with respect to precipitation trends [26], that may alter past and future multi-decadal trajectories of autumn extreme fire weather from those dictated by anthropogenic climate forcing alone. Additionally, we do not account for feedback mechanisms between climate, wildfire, and the biosphere. These could include negative climate-fire feedbacks that result from dynamic vegetation processes that lessen future fuel loads [71]—although positive climate-fire feedbacks are also plausible in some higher-frequency fire regimes and in regions where invasive grasses proliferate [72].

We also emphasize that climate change is only one of several factors driving California's multi-year wildfire disaster. Nearly 88% of fires and 92% of burned area from autumn wildfires in California are human-caused [73], highlighting human ignition sources as key contributors. However, the number of ignitions has declined over the past several decades [74]. In the present study, we do not quantify the relative role of increased urban and suburban incursion into the high-risk wildland-urban interface, nor the contribution of historical land/vegetation management practices to increasing wildfire risk or possible future climate-fire feedbacks. We note, however, that although demographics and vegetation exhibit high spatial heterogeneity, observed and projected climate trends relevant to wildfire risk (including temperature, precipitation, and FWI) are pervasive across California's major ecological zones, vegetation types, and fire regimes (e.g. [75]). California's mean climate is aridifying from a net water balance perspective [12]—primarily due to rising temperatures, but also with some contribution from the potentially narrowing seasonality and shifting temporal characteristics of precipitation [21, 30–32]. Increased aridity in semi-arid landscapes in California may alter fire-climate relationships, resulting in fuel-limited regimes in regions that become increasingly sensitive to interannual variations in biomass abundance, and less sensitive to the aridity of the vegetation itself (e.g. [76, 77]). A key consequence of climate change-driven aridification is that vegetation throughout the state is becoming increasingly flammable, setting the stage for extreme burning conditions given an ignition source and otherwise conducive weather conditions.

Climate change can thus be viewed as a wildfire 'threat multiplier' amplifying natural and human risk factors that are already prevalent throughout California.

Observed and projected trends suggest that anthropogenic climate change has already facilitated conditions that are increasingly conducive to wildfire activity, and that continued global warming will continue to intensify those conditions in the future. Increased synchronicity of extreme fire danger between northern and southern California has the potential to hamper fire suppression and risk-reduction efforts, particularly as longer fire seasons increase fatigue among firefighters and evacuated residents alike. Absent substantial interventions, our results portend even greater potential for future wildfire disasters in California, placing further burdens on an already stressed global fire suppression network. In the long-term, reduction of global greenhouse gas emissions is the most direct path to reducing this risk, though the near-term impacts of these reductions may be limited given the many sources of inertia in the climate system [78]. Fortunately, a broad portfolio of options already exists, including the use of prescribed burning to reduce fuel loads and improve ecosystem health [79], upgrades to emergency communications and response systems, community-level development of protective fire breaks and defensible space, and the adoption of new zoning rules and building codes to promote fire-resilient construction [80]. Assessment of those options will require integration of perspectives from multiple disciplines in order to fully understand the complex ecological, meteorological and human interactions revealed during the recent wildfires in California.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Observed temperature, precipitation and FWI data were obtained from the gridMET dataset (www.climatologylab.org/gridmet.html). Climate model temperature and precipitation data, as well as all other underlying variables required to calculate FWI, were obtained from the CMIP5 archive (accessible via the Earth System grid at https://esgf-node.llnl.gov/projects/cmip5/). Downscaled climate data used to calculate FWI were obtained from the Multivariate Adaptive Constructed Analogs archive (www.climatologylab.org/maca.html). A database of daily downscaled FWI covering the region 32.5-42N, 113-125W will be made available at www.climatologylab.org. Time series of temperature, precipitation, Fire Weather Index and burned area plotted in figures 1 and 2 are available in supplementary data file 1 of this paper.

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Contribution of historical precipitation change to US flood damages

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Precipitation extremes have increased across many regions of the United States, with further increases anticipated in response to additional global warming. Quantifying the impact of these precipitation changes on flood damages is necessary to estimate the costs of climate change. However, there is little empirical evidence linking changes in precipitation to the historically observed increase in flood losses. We use >6,600 reports of state-level flood damage to quantify the historical relationship between precipitation and flood damages in the United States. Our results show a significant, positive effect of both monthly and 5-d state-level precipitation on state-level flood damages. In addition, we find that historical precipitation changes have contributed approximately one-third of cumulative flood damages over 1988 to 2017 (primary estimate 36%; 95% CI 20 to 46%), with the cumulative impact of precipitation change totaling $73 billion (95% CI 39 to $91 billion). Further, climate models show that anthropogenic climate forcing has increased the probability of exceeding precipitation thresholds at the extremely wet quantiles that are responsible for most flood damages. Climate models project continued intensification of wet conditions over the next three decades, although a trajectory consistent with UN Paris Agreement goals significantly curbs that intensification. Taken together, our results quantify the contribution of precipitation trends to recent increases in flood damages, advance estimates of the costs associated with historical greenhouse gas emissions, and provide further evidence that lower levels of future warming are very likely to reduce financial losses relative to the current global warming trajectory.

precipitation | flooding | climate change

Flooding is one of the most costly natural hazards, causing billions of dollars in damage each year (1). Both the total cost of flood-related damages and the frequency of "billion-dollar disasters" have been growing over time (2–4) (Fig. 1*A*). Simultaneously, extreme, short-duration precipitation has been increasing in many areas (5–7). Many historical trends in precipitation intensity—including of individual extreme events—have been attributed to climate change (8–11), and continued global warming is very likely to yield further increases in extreme precipitation (12–15). Quantifying the impact of these precipitation changes on flood damages is a critical step toward evaluating the costs of climate change and informing adaptation and resilience planning (16).

However, the effect of changes in precipitation on historical flood damages—and the potential attribution of these damages to anthropogenic climate change—remains poorly quantified (17, 18). Such attribution requires isolating the impact of changes in precipitation from changes in other factors such as exposure and vulnerability, as well as from changes in reporting of damages. Previous studies have argued that increases in exposure (e.g., increases in property values or the number of structures) could explain most or all trends in disaster losses (19–22). While much of the research on trends in the cost of flood damage has been conducted at the national scale (2, 4, 19, 20), both the processes that cause damaging precipitation and the factors that control exposure and vulnerability occur at smaller spatial scales. Analyzing the national precipitation trend is thus not sufficient to understand historical drivers of flood damage, which result from regionally varying trends in flood hazard, exposure, and/or vulnerability. As a result, there remains critical uncertainty in the contribution of historical precipitation trends to the observed national-level increase in flood damages.

"Bottom-up" flood risk assessments (23–25)—which integrate higher-resolution socioeconomic and flood hazard information—can provide greater detail, but are often limited in temporal and geographic extent. Further, these approaches may require assumptions about the relationship between flood hazard and damage that cannot be easily verified. For example, existing flood depth–damage curves are often poor predictors of observed flood damage (26) but are commonly used in flood risk assessments. The attribution of historical precipitation trends also becomes more uncertain at finer spatial scales because of the progressively stronger influence of climate variability (27), particularly over the United States, where there is uncertainty in the signal-to-noise ratio of mean precipitation change during the historical period (17).

Here we quantify the impact of historical global warming on flood damages by combining 1) empirical approaches that integrate historical flood damages and precipitation at the subnational scale, 2) an analysis of historical changes in precipitation, and 3) ensemble climate model simulations that quantify the contribution of anthropogenic forcing to historical and future

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Significance

Precipitation extremes have increased in many regions of the United States, suggesting that climate change may be exacerbating the cost of flooding. However, the impact of historical precipitation change on the cost of US flood damages remains poorly quantified. Applying empirical analysis to historical precipitation and flood damages, we estimate that approximately one-third (36%) of the cost of flood damages over 1988 to 2017 is a result of historical precipitation changes. Climate models show that anthropogenic climate change has increased the probability of heavy precipitation associated with these costs. Our results provide information quantifying the costs of climate change, and suggest that lower levels of future warming would very likely reduce flooding losses relative to the current global warming trajectory.

Author contributions: F.V.D., M.B., and N.S.D. designed research; F.V.D. performed research; F.V.D. contributed new analytic tools; F.V.D., M.B., and N.S.D. analyzed data; and F.V.D., M.B., and N.S.D. wrote the paper.

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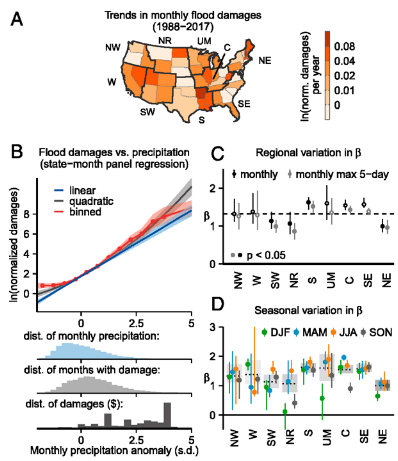

Fig. 1. Effect of state-level precipitation on flood damages. (*A*) Historical state-level trends in monthly flood damages. The nine National Centers for Environmental Information (NCEI) climate regions are outlined in dark gray: Northwest (NW), West (W), Southwest (SW), Northern Rockies and Plains (NR), South (S), Upper Midwest (UM), Central (C), Northeast (NE), and Southeast (SE). (*B*) Relationship between normalized flood damages and monthly precipitation at the state level using linear (blue line), quadratic (gray line), and binned (red line) models. Shading indicates the 95% CI estimated by bootstrapping states. Response functions are centered at mean monthly precipitation (0.04 SD) and mean log-normalized damage (1.8). Histograms show the distribution of monthly precipitation anomalies across all state-months (blue), the distribution of monthly precipitation anomalies during months with flood damage (light gray), and the distribution of total damages (in 2017 dollars) across monthly precipitation anomalies (dark gray). (*C*) Effect of precipitation on flood damages within each NCEI climate region (shown in *A*), for two precipitation variables: total monthly precipitation (black) and monthly maximum 5-d precipitation (gray). Effects are measured as the change in ln(normalized damages) per SD change in precipitation. Points show median coefficient estimates and vertical lines show the 95% CI around each point estimate. Filled circles indicate statistically significant ($P < 0.05$) differences between the regional coefficients and a pooled model (shown as a black dashed line for total monthly precipitation, same as the blue line in *B*). (*D*) Seasonal variations in the effect of monthly precipitation on flood damages for each region. Points show the median coefficient estimates for each season and region, and vertical lines show the 95% CI around each point estimate. Seasons are defined as December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON). Black dotted lines show the median coefficient estimate for each region (the same as black points in *C*), and gray shading shows the 95% CI (black lines in *C*).

precipitation change within the context of climate variability (*SI Appendix*, *Text*).

We use historical observations from 1988 to 2017 to model the relationship between precipitation and flood damages at the state-month level using fixed-effects panel regression analyses. We control explicitly for changes in income in each state, and include fixed effects that account for 1) year-to-year variations in precipitation and flood damages within each state and 2) state-specific seasonality in precipitation and flooding. In essence, we compare the effect of a relatively wet month in one state with a relatively dry month in the same calendar month and state, while accounting for year-to-year changes in average flood damage in that state. Over shorter (i.e., monthly or submonthly) timescales, variations in precipitation within each state are plausibly uncorrelated with variations in exposure or vulnerability, meaning that the regression analyses isolate the effect of a precipitation anomaly from other confounding variables that also affect flood damages.

Results and Discussion

We find a significant, positive relationship between monthly precipitation and flood damages, with a 1-SD increase in the monthly precipitation anomaly corresponding to a >3-fold increase in flood damages (Fig. 1*B*). Variation in monthly, state-level precipitation (after accounting for state-month and state-year fixed effects) explains 21% of the observed variation in monthly flood damages. The log-linear response suggests exponential growth in flood damages for a given increase in monthly precipitation, and we find a similar shape and magnitude of response using either a quadratic or nonparametric binned model (Fig. 1*B*). We also show that the presence of reporting errors in the data (such as missing damages) is unlikely to cause an overestimation of the effect of precipitation on flood damage (*SI Appendix*, *Text* and Fig. S1).

Although months with flood damages occur at a range of precipitation anomalies, the largest damages primarily occur at precipitation anomalies >2 SDs (Fig. 1*B*). As expected, the slope of the relationship is flatter across negative monthly precipitation anomalies when using a nonlinear functional form. Smaller flood damages do occur during months with negative statewide precipitation anomalies (Fig. 1*B*), possibly due to lagged effects from snowmelt, precipitation in adjacent states, or short-duration and/or localized precipitation during months that are relatively dry at the state-month scale. (We include additional models to test for some of these effects, as described below.)

Given the range of temporal and spatial scales at which flooding occurs, we compare our primary monthly, state-level regression model with regression models that use shorter- or longer-duration precipitation, or precipitation over large watersheds that span multiple states. Monthly maximum 5-d precipitation has a positive effect on monthly flood damages, but the effect is smaller compared with that of total monthly precipitation (Fig. 1*C*). Using a lagged precipitation model, we find that precipitation in previous months has a positive effect on flood damages (*SI Appendix*, Fig. S2*A*) but that these effects are much smaller than the effect of the current-month precipitation. Further, although there are additional effects from precipitation that occurs out-of-state (*SI Appendix*, Fig. S3), these effects are small compared with that of within-state precipitation. Combined, these analyses indicate that results based on the state-month regression are consistent with models that account for the effects of shorter- or longer-duration precipitation, or large-scale flooding processes.

We do find regional differences in the magnitude of the effect of monthly precipitation on flood damages (Fig. 1*C*), reflecting both regional differences in the conditions creating flood hazards (e.g., the type of weather events associated with extreme precipitation, and the primary flooding processes) and regionally specific patterns of exposure and vulnerability (e.g., patterns of land use and development). Additionally, some regions show seasonal variations in the effect of precipitation on flood damages (Fig. 1*D*). For example, there are smaller effects of precipitation on flood damages during the winter (December through February) season in the Northern Rockies, Upper Midwest, and Northeast regions. This result could reflect the fact that these cold regions receive snow in the winter, which would not have the same immediate impact on flooding as rain during

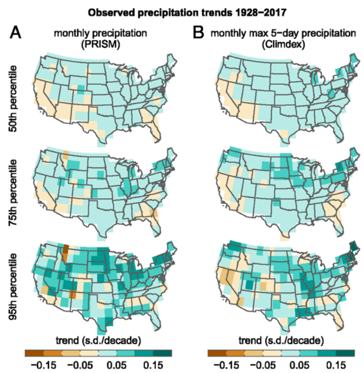

Fig. 2. Observed trends in monthly total and maximum 5-d precipitation. (*A*) Observed 1928-to-2017 trends in the 50th, 75th, and 95th percentiles of monthly precipitation, measured in SDs per decade. Trends are calculated on a 2.5 × 2.5° grid using quantile regression and the PRISM monthly precipitation product. (*B*) Same as *A*, but for monthly maximum 5-d precipitation. Trends are calculated on a 2.5 × 2.5° grid using quantile regression and the Climdex HadEX3 monthly Rx5day product.

warmer seasons. We use the regional, monthly regression model (Fig. 1*C*) as our primary model for later analyses, but we test the sensitivity of our results to these seasonal effects (see Fig. 3*B*).

We use our regression model results as a framework to understand the effect of historical precipitation changes on flood damages. Because monthly total and maximum 5-d precipitation have a similar effect on monthly flood damages (Fig. 1*C*), and because previous studies have detected changes in short-duration (e.g., daily or 5-d) precipitation extremes (5, 28), we analyze trends in both monthly total (Fig. 2*A*) and maximum 5-d precipitation (Fig. 2*B*). Further, given existing evidence that trends in extreme precipitation are larger and sometimes of opposite sign compared with trends in mean precipitation (29), we calculate trends at multiple quantiles within the distributions of monthly total and maximum 5-d precipitation. This approach allows us to distinguish between changes in the wettest months (which are associated with the largest flood damages; Fig. 1*B*) and changes in the median or drier months.

Fig. 2 shows trends in the 50th, 75th, and 95th percentiles of the monthly total and maximum 5-d precipitation distributions from 1928 to 2017. These analyses confirm that historical precipitation trends are not uniform across the distribution, with the 95th percentile exhibiting the largest trends. The spatial pattern of changes in monthly precipitation is very similar to that of monthly maximum 5-d precipitation. Most of the northwestern, central, and eastern United States have seen increases in median (50th percentile) monthly precipitation, whereas the Southwest has experienced decreases in median monthly precipitation. This spatial pattern is very similar to reported changes in annual mean precipitation over the United States, which results from changes that vary by region and season, including increases in fall precipitation in the Southeast, Northeast, and Great Plains and decreases in spring precipitation in the Southwest (29).

Precipitation during the wettest months (i.e., the 95th percentile) has increased across most of the country, even in some areas where median monthly precipitation is decreasing (Fig. 2). This pattern is also true for monthly maximum 5-d precipitation, and is consistent with previously identified increases in short-duration (e.g., daily or 5-d) precipitation extremes (29). The largest increases in the 95th percentile have occurred in the Midwest and Northeast.

Based on the regional regression coefficients, expected state-level flood damages have increased by an average of 35, 50, and 70% for precipitation at the 50th, 75th, and 95th percentiles, respectively (*SI Appendix*, *Text* and Fig. S4). In some states, we calculate that damages from the wettest 5% of months are now more than three times what would be expected in the absence of the observed precipitation changes (*SI Appendix*, Fig. S4).

Removing the historical quantile-specific monthly precipitation trends in each state allows us to estimate the effect of state-level precipitation changes on cumulative national-level damages (Fig. 3*A* and *Methods*). We find that precipitation changes have contributed 36% ($73 billion) of the 1988-to-2017 cumulative US flood damages. Uncertainty in the regional regression coefficients (Fig. 1*C*) and observed precipitation trends (*SI Appendix*, Figs. S4 and S5) yields a 95% confidence range of 20 to 46% (39 to $91 billion) contributed by state-level precipitation trends.

Our results are robust to using alternative regression models that account for lagged and seasonal effects (Fig. 3*B*), and to calculating precipitation trends over different time periods

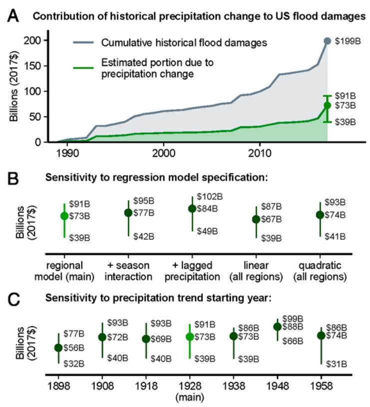

Fig. 3. Cumulative damages due to historical precipitation change. (*A*) Cumulative observed flood damages (gray) and estimated portion due to historical precipitation change (green) from 1988 to 2017. Error bars show the 95% CI for cumulative damages in 2017 (based on precipitation trends from 1928 to 2017). (*B*) Impact of historical precipitation change on cumulative flood damages in 2017 using various regression model specifications. From left to right, the models are the regional model (same as *A*), the regional-seasonal model (Fig. 1*D*), a regional model with lagged precipitation (*SI Appendix*, Fig. S2*A*), a linear model (Fig. 1*B*), and a quadratic model (Fig. 1*B*). (*C*) Sensitivity of cumulative damages from precipitation change to starting year of precipitation trend calculation. All estimates use the same regional regression model used in *A*.

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(Fig. 3*C*). They are also robust to using different assumptions about possible unreported damages (*SI Appendix*, Fig. S6); further, the fact that the historical flood damage values are likely underestimated and/or unreported in earlier years (1) would cause the effect of precipitation on damages to be underestimated, and thus make our estimate of the contribution of historical precipitation change conservative (*SI Appendix*, *Text* and Fig. S1*A*).

There are limitations to using the state-month as the unit of analysis, because flooding can occur on shorter or longer timescales, and over smaller or larger areas. However, we find that our primary regression model yields a similar (although slightly lower) estimate of the contribution of historical precipitation change compared with versions of the model that include effects of precipitation over longer timescales (Fig. 3*B*) or larger spatial scales (*SI Appendix*, Fig. S3). The strong similarity between historical trends in monthly total and monthly maximum 5-d precipitation (Fig. 2), as well as similarity in their effect on damages (Fig. 1*C*), indicate that an analysis based on 5-d precipitation would yield a similar estimated contribution of historical precipitation change. Together, these sensitivity analyses suggest that our primary estimate of the contribution of historical precipitation trends to total US flood damages is both robust and conservative.

Prior studies have attributed increases in short-duration precipitation extremes over the United States to anthropogenic climate forcing by comparing historical trends with climate model simulations (10, 30), isolating forced changes from those driven by modes of natural climate variability (31–34), or calculating the probability of extreme events (i.e., "risk ratio") with and without anthropogenic climate forcing (9, 35, 36). While the general circulation models that comprise the Coupled Model Intercomparison Project (CMIP5) ensemble show a thermodynamic response to warming (37, 38) (Figs. 4 and 5), they do not explicitly resolve the precipitation processes that cause flood damages (such as severe thunderstorms and tropical cyclones), and may underestimate the magnitude of extreme precipitation change (10, 28, 29, 31). Given the large uncertainties in modeled precipitation trends, particularly at the spatial scale of individual events, we do not use our regression analysis to explicitly separate the contributions of forced climate change and unforced climate variability to cumulative flood damages.

However, we do use the CMIP5 global climate model simulations to assess changes in the probability of monthly total and maximum 5-d precipitation thresholds over the recent historical period (1988 to 2017) compared with an early-industrial baseline (1860 to 1920; *SI Appendix*, *Text*). The probability of exceeding the baseline 50th and 75th percentiles of monthly precipitation has increased slightly across the central and eastern United States in the recent historical period, and decreased slightly across the Southwest (Fig. 4). In contrast, the probability of exceeding the baseline 95th or 99th percentiles has increased across most of the United States, especially for monthly maximum 5-d precipitation (Fig. 4). This analysis suggests that anthropogenic climate forcing has increased the frequency of extreme monthly precipitation, with the ensemble mean response (Fig. 4) showing many similarities to the observations (Fig. 2). However, despite the mean wetting in response to anthropogenic forcing, there is some disagreement across models on the direction of change over the recent historical period, particularly at the higher-percentile thresholds (Fig. 4). We must therefore conclude that the estimated flood damages due to precipitation change (Fig. 3) represent the combined effects of anthropogenic forcing and natural variability, and cannot be entirely attributed to anthropogenic climate change.

To understand the implications of additional global warming for the cost of future flood damages, we evaluate future precipitation change in the "high-" (RCP8.5) and "low-" (RCP2.6) emissions scenarios analyzed in the assessment of impacts, adaptation, and vulnerability in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report [IPCC AR5 (16)]. In both scenarios, the 95th and 99th percentiles of monthly total and maximum 5-d precipitation are projected to increase across most of the United States by midcentury (2046 to 2065) relative to the recent historical period (*SI Appendix*, Fig. S7). Under the high-emissions scenario (RCP8.5), there is strong model agreement that the wettest months (both in total precipitation and maximum 5-d precipitation) will continue to intensify through the end of the century (Fig. 5). In some parts of the northeastern and western United States, the 99th percentile of monthly maximum 5-d precipitation is projected to increase by more than 1 SD (Fig. 5*B*). Combined with our regression model, these analyses suggest that—absent changes in exposure or vulnerability—future global warming is very likely to increase the costs of flooding, but that those increases could be greatly reduced under a low-emissions scenario consistent with the UN Paris Agreement.

Overall, our findings are consistent with prior conclusions that flood damages are sensitive to variations in weather (39–41), and that climate change has likely increased historical damages from

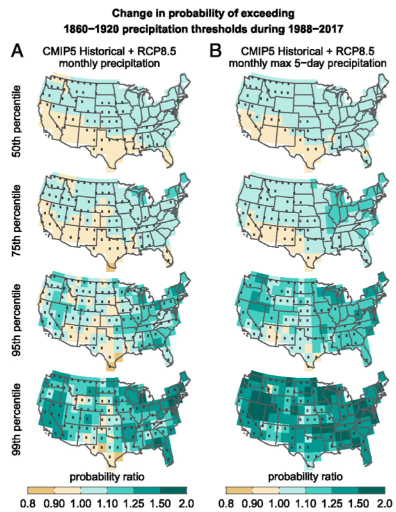

Fig. 4. Change in probability of exceeding early industrial baseline precipitation thresholds during the recent historical period, simulated by the CMIP5 global climate model ensemble. (*A*) Probability of exceeding the early industrial baseline (1860 to 1920) 50th, 75th, 95th, and 99th percentile monthly precipitation thresholds during the recent historical period (1988 to 2017). Probabilities are shown as a ratio relative to the probability during the baseline period, and are based on a 24-model ensemble (*SI Appendix*). Solid colors indicate strong model agreement (following the IPCC AR5 definition, when ≥66% of models agree with the direction of change shown on the map). Black stippling indicates <66% of models agree with the direction of change shown. (*B*) Same as *A* but for monthly maximum 5-d precipitation.

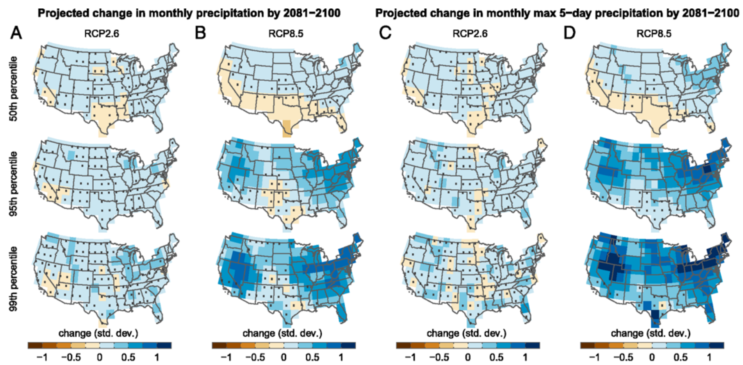

Fig. 5. Projected changes in monthly total and maximum 5-d precipitation. (*A*) Projected change in the 50th, 95th, and 99th percentiles of monthly precipitation by 2081 to 2100 for RCP2.6. Changes are relative to the recent historical (1988 to 2017) period. Maps show the mean change across a 17-model ensemble (*Methods*). Solid colors indicate strong model agreement (following the IPCC AR5 definition, when ≥66% of models agree with the direction of change shown on the map). Black stippling indicates <66% of models agree with the direction of change shown. (*B*) Same as *A* but for RCP8.5. (*C*) Same as *A* but for monthly maximum 5-d precipitation. (*D*) Same as *B* but for monthly maximum 5-d precipitation.

flooding and/or tropical cyclones (42, 43). While some studies have not found an impact of climate change on historical flood damages (20, 21), this contrast may be explained by different methodology, including 1) the scale of the analysis (for example, country-year in previous studies vs. state-month in our study); 2) our use of fixed effects to isolate precipitation variation from the many other time-invariant and time-varying factors that might also affect flood damages (such as variations in exposure and vulnerability); and 3) our use of precipitation trends at different percentiles of the distribution to isolate trends affecting the wettest months (in which damages are most likely to occur).

Conclusions

Our results show that historical increases in precipitation are very likely responsible for a substantial fraction of recent increases in US flood damages. Not only does precipitation in the upper tail of the distribution cause the largest historical damages (Fig. 1*B*) but the most intense precipitation has also shown the greatest increase over the historical period (Fig. 2), along with the strongest imprint of anthropogenic climate forcing (Fig. 4). Our panel regression models, combined with our analyses of quantile-specific precipitation trends, provide an empirical framework for quantifying the contribution of historical precipitation changes to recent increases in flood damages, and more broadly the costs associated with global warming.

This framework provides empirical evidence that climate change has affected the cost of flood damages at the national scale, along with comprehensive quantification of the magnitude and uncertainty of that impact. The framework could be extended to calculate the costs due to changes in other natural hazards, or to calculate the global costs of regional precipitation change. Given the importance of evaluating the costs of climate change versus the costs of mitigation options (44), the empirical quantification of losses due to changing natural hazards provides critical information to inform policy and decision making.

Methods

Precipitation and Flood Damage Data. We calculate historical monthly precipitation in each state using 4-km gridded monthly precipitation observations from the PRISM (parameter-elevation regressions on independent slopes model) Climate Group (45, 46) and state boundaries from the US Census Bureau. Monthly precipitation for each state is calculated as the average of all grid cells within each state boundary. We standardize the precipitation time series in each state by subtracting the mean monthly precipitation and dividing the anomaly by the SD of monthly precipitation, with the mean and SD for each state calculated over the IPCC's 1986-to-2005 baseline period (16). To test the regression model with shorter-duration precipitation, we also calculate monthly maximum 5-d precipitation in each state using the PRISM daily precipitation data. The maximum 5-d precipitation in each month is defined as the maximum total precipitation over 5 consecutive days within each calendar month. We standardize the monthly maximum 5-d precipitation time series in each state using the same procedure described above.

We analyze monthly, state-level flood damage estimates over 1988 to 2017 from the Spatial Hazard Events and Losses Database for the United States (SHELDUS) version 17.0 (47). SHELDUS compiles flood damage estimates from the National Climatic Data Center *Storm Data* publications. Details of the SHELDUS dataset, including a comparison with other flood damage datasets and discussion of how uncertainty in reported damages could impact our results, are included in *SI Appendix*.

Regression Model. To estimate the relationship between monthly precipitation and flood damages (Fig. 1*B*), we use a least-squares log-linear regression model:

$$\ln(y_{ilm}) = \beta P_{ilm} + \delta_{il} + \mu_{im} + \varepsilon_{ilm}, \quad [1]$$

where y_{ilm} is normalized flood damages in state i during month m of year l, P_{ilm} is the standardized precipitation anomaly during the same state-month, δ_{il} and μ_{im} are state-year fixed effects and state-calendar month fixed effects, respectively, and ε_{ilm} is an error term. We normalize flood damages by annual state income, which is strongly correlated with exposure (see details in *SI Appendix*). The fixed effects in Eq. **1** subtract out year-to-year and seasonal variations in average damages in each state, allowing us to estimate the effect of monthly precipitation on flood damages after controlling for

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long-term changes in flood damage in each state. In other words, we can directly compare flood damages during a relatively wet month in a given state (e.g., June 2008 in Iowa) with flood damages during a relatively dry month in the same calendar month and state (e.g., June 2012 in Iowa), after accounting for average differences in flood damages and precipitation between the two different years (e.g., 2008 and 2012) that could have arisen from simultaneous changes in exposure or vulnerability. We calculate CIs around the estimated coefficients using bootstrap resampling (*SI Appendix*).

We test a number of variations of Eq. **1** by including additional interaction terms and testing nonlinear functional forms. The remaining regression models (including those shown in Figs. 1 *C* and *D* and 3*B*) are described in *SI Appendix, Text*.

Impact of Historical Precipitation Trends on Flood Damages. Following the approach of Diffenbaugh and Burke (48), we estimate the impact of historical precipitation trends on cumulative flood damages by calculating the "counterfactual" flood damages that would have occurred in the absence of precipitation changes. To create the counterfactual monthly precipitation time series, we remove observed trends at each decile of the distribution, which allows us to account for nonuniform changes in the distribution of monthly precipitation (*SI Appendix*). We next estimate counterfactual flood damages associated with this counterfactual precipitation time series. For each month with flood damages, we calculate the difference between the observed and detrended precipitation. While there are limitations to using counterfactual "treatments" and fixed-effects regression models to extrapolate impacts of large within-unit changes (49), in this case the changes in precipitation due to the historical trends are much smaller than the historical precipitation variability within each state (*SI Appendix*, Fig. S9). Because many of the observed trends are positive (Fig. 2), the detrended precipitation anomalies in the counterfactual scenario are less extreme than the observed precipitation anomalies, and this analysis does not require extrapolating the regression model beyond the observed data.

Based on the difference between the observed and detrended precipitation anomalies, we estimate counterfactual damages using the regional regression coefficients (*SI Appendix*, Eq. **S4**). We calculate the cumulative damages due to precipitation change as the sum of all observed damages minus the sum of the counterfactual damages. We calculate a 95% confidence range for our estimate of cumulative counterfactual damages based on 1) uncertainty in the regional regression coefficients and 2) uncertainty in the observed precipitation trends (*SI Appendix, Text*). We also evaluate the sensitivity of the counterfactual damage analysis to using other regression models, or using precipitation trends over shorter or longer time periods (*SI Appendix, Text*). The various alternatives lead to slightly higher or lower estimates of counterfactual damage, with our main result falling in the middle of the distribution (Fig. 3 *B* and *C* and *SI Appendix*, Fig. S6).

Climate Model Analysis. We analyze historical and future climate model simulations from CMIP5 (50) to understand the impacts of anthropogenic climate forcing on extreme monthly and 5-d precipitation. To assess the influence of anthropogenic climate forcing on historical changes, we calculate risk ratios (i.e., changes in the probability of exceeding various monthly total or maximum 5-d precipitation thresholds) for 24 simulations over the recent historical period (1988 to 2017) compared with an early-industrial baseline (1860 to 1920). To understand the impact of additional global warming on the future costs of flooding, we analyze changes in monthly total and maximum 5-d precipitation by 2046 to 2065 and by 2081 to 2100 in 34 simulations and two future emissions scenarios (17 simulations with the RCP2.6 forcing and 17 simulations with the RCP8.5 forcing). A detailed description of the CMIP5 simulations and analyses, including the limiting factors on the number of simulations analyzed, is provided in *SI Appendix, Text*.

Data Availability. The PRISM monthly and daily precipitation products are available from the PRISM Climate Group (http://www.prism.oregonstate.edu/). The SHELDUS dataset is a subscription-based dataset available from the Center for Emergency Management and Homeland Security at Arizona State University (https://cemhs.asu.edu/sheldus). State boundary files are available from the US Census Bureau (https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html). Watershed boundary files can be downloaded from the Watershed Boundary Dataset (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/watershed-boundary-dataset). Data on annual state income and national net stock of reproducible fixed assets are available from the US Bureau of Economic Analysis (https://www.bea.gov/). Data on state-level housing values and number of housing units are available from the US Census Housing Tables (https://www.census.gov/topics/housing/data/tables.html) and the American Community Survey (https://www.census.gov/programs-surveys/acs). The Climdex HadEX3 gridded monthly Rx5day product is available from the Climdex project archive (https://www.climdex.org/access/), and the Climdex CMIP5 data are available through Environment Canada (https://crd-data-donnees-rdc.ec.gc.ca/CCCMA/products/CLIMDEX/). CMIP5 data are available from the Program for Climate Model Diagnosis & Intercomparison through the Earth System Grid Federation data portal (https://esgf-node.llnl.gov/projects/cmip5/). Code and data supporting the findings of the study are available in GitHub at https://github.com/fdavenport/DBD2021.

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REVIEW SUMMARY

GREENHOUSE GASES

Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases

Philip B. Duffy*†, Christopher B. Field*, Noah S. Diffenbaugh*, Scott C. Doney, Zoe Dutton, Sherri Goodman, Lisa Heinzerling, Solomon Hsiang, David B. Lobell, Loretta J. Mickley, Samuel Myers, Susan M. Natali, Camille Parmesan, Susan Tierney, A. Park Williams

BACKGROUND: The Clean Air Act requires the Environmental Protection Agency (EPA) to regulate air pollutants when the EPA Administrator finds that they "cause, or contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare." In *Massachusetts* v. *EPA*, the U.S. Supreme Court held that the EPA has the authority to regulate greenhouse gases (GHGs) under the Clean Air Act and that the EPA may not refuse to regulate once it has made a finding of endangerment.

In December 2009, the EPA released its "Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act," known informally as the Endangerment Finding (EF). The EF found that six long-lived GHGs, in combination, should be defined as "air pollution" under the Clean Air Act and may reasonably be anticipated to endanger the health and welfare of current and future generations.

The EF is an essential element of the legal basis for regulating GHG emissions under the Clean Air Act. It provides foundational support for important aspects of U.S. climate policy, including vehicle mileage standards for cars and light trucks and the emissions standards for electricity generation known as the "Clean Power Plan."

The EF was rooted in careful evaluation of observed and projected effects of GHGs, with assessments from the U.S. Global Change Research Program, the Intergovernmental Panel on Climate Change, and the U.S. National Research Council providing primary evidence. The EF was clear that, although many aspects of climate change were still uncertain, the evidence available in 2009 was strong. Since the original EF, scientific information about the causes, historical impacts, and future risks of climate change has continued to accumulate. This Review assesses that new information in the context of the EF.

ADVANCES: The EF was structured around knowledge related to public health and public welfare, with a primary focus on impacts in the United States. The information on public welfare was grouped into sections on air quality; food production and agriculture; forestry; water resources; sea level rise and coastal areas; energy, infrastructure, and settlements; and ecosystems and wildlife.

In this Review, we assess new evidence in the impact areas addressed in the EF, as well as emergent areas that were not addressed in the EF but in which there have been important advances in understanding the risks of climate change. For each area, we characterize changes since the EF in terms of the strength of evidence for a link with anthropogenic climate change, the severity of observed and projected impacts, and the risk of additional categories of impact beyond those considered in the EF.

For each of the areas addressed in the EF, the amount, diversity, and sophistication of the evidence has increased markedly, clearly strengthening the case for endangerment (see Fig. 1 in the full article). New evidence about the extent, severity, and interconnectedness of impacts detected to date and projected for the future reinforces the case that climate change endangers the health and welfare of current and future generations. For the sectors analyzed in the 2009 EF, new evidence expands the range of case studies, deepens the understanding of mechanisms, and analyzes the contribution of climate change to particular types of extreme events. In many cases, new evidence points to the risk of impacts that are more severe or widespread than those anticipated in 2009. Further, several categories of climate change impacts, including effects on ocean acidification, violence, national security, and economic well-being, are now supported by such broad evidence that they warrant inclusion in the framing of endangerment.

OUTLOOK: The EPA Administrator found in 2009 that the EF for six long-lived GHGs was "compellingly" supported by "strong and clear" scientific evidence. Our review of evidence published since the EF shows that the case for endangerment, which was already overwhelming in 2009, is even more strongly justified in 2018.

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PHOTO (FROM LEFT TO RIGHT): NASA; W. MCNAMEE; L. DEGUIRA.

New evidence relevant to the EF. New evidence strengthens the link with anthropogenic climate change (category 1); suggests more severe observed and/or projected impacts (category 2); or identifies new types of risks beyond those considered in the EF (category 3). Examples discussed in this Review include, for category 1, wildfire (left); for category 2, coastal flooding (center); and for category 3, ocean acidification (right).

REVIEW

GREENHOUSE GASES

Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases

Philip B. Duffy[1]*†, Christopher B. Field[2,3]*, Noah S. Diffenbaugh[2,3]*, Scott C. Doney[4], Zoe Dutton[5], Sherri Goodman[5], Lisa Heinzerling[6], Solomon Hsiang[7,8], David B. Lobell[2,3], Loretta J. Mickley[9], Samuel Myers[10,11], Susan M. Natali[1], Camille Parmesan[12,13,14], Susan Tierney[15], A. Park Williams[16]

We assess scientific evidence that has emerged since the U.S. Environmental Protection Agency's 2009 Endangerment Finding for six well-mixed greenhouse gases and find that this new evidence lends increased support to the conclusion that these gases pose a danger to public health and welfare. Newly available evidence about a wide range of observed and projected impacts strengthens the association between the risk of some of these impacts and anthropogenic climate change, indicates that some impacts or combinations of impacts have the potential to be more severe than previously understood, and identifies substantial risk of additional impacts through processes and pathways not considered in the Endangerment Finding.

The Clean Air Act (CAA) requires the U.S. Environmental Protection Agency (EPA) to regulate air pollutants when the EPA Administrator finds that they "cause, or contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare" (*1*). In *Massachusetts* v. *EPA*, the U.S. Supreme Court held that the EPA has the authority to regulate greenhouse gases (GHGs) under the CAA and that the EPA may not refuse to regulate these pollutants once it has made a finding of endangerment (*2*). In this decision, the Supreme Court characterized an endangerment finding on GHGs as a "scientific judgment" about "whether greenhouse gas emissions contribute to climate change."

The courts have long held that the CAA embraces a precautionary approach to findings of endangerment. For example, the federal court of appeals in Washington, DC, has held that "evidence of potential harm as well as actual harm" meets the endangerment threshold and that the EPA's degree of certitude may be lower where the hazards are most grave (*3*). Moreover, public health and welfare are broad concepts under the act, encompassing not only human morbidity and mortality but also effects on soils, water, crops, vegetation, animals, wildlife, weather, and climate (*4*).

In December 2009, the EPA released its "Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act," known informally as the Endangerment Finding (EF). The EF found that six long-lived GHGs, in combination, should be defined as "air pollution" under the CAA and may reasonably be anticipated to endanger the health and welfare of current and future generations. In addition, the EPA explained that "it is fully reasonable and rational to expect that events occurring outside our borders can affect the U.S. population" (*5*).

The EF is an essential element of the legal basis for regulating GHG emissions under the CAA. It provides foundational support for important aspects of U.S. climate policy, including vehicle mileage standards for cars and light trucks and the emissions standards for fossil fuel–fired electric utility generating units (the "Clean Power Plan").

As the DC Circuit held in affirming the EF, the EPA may not decline to find endangerment on the basis of the perceived effectiveness or ineffectiveness of the regulations that may follow in the wake of an endangerment finding or on the basis of predictions about the potential for societal adaptation to climate change (*6*). The DC Circuit held that arguments to the contrary were "foreclosed by the language of the [Clean Air Act] and the Supreme Court's decision in *Massachusetts* v. *EPA*." The court also rejected the argument that the EPA must find that the air pollutants it regulates are the dominant source of the harms it identifies, as the act provides that the pollutants being regulated need only contribute to (or, under some provisions of the statute, "significantly" contribute to) (*7*) harmful air pollution.

The EF was rooted in careful evaluation of the observed and projected effects of GHGs, with assessments from the U.S. Global Change Research Program, the Intergovernmental Panel on Climate Change (IPCC), and the U.S. National Research Council providing primary scientific evidence. The EF was clear that, although many aspects of climate change were still uncertain, the evidence available in 2009 strongly supported the finding. Since the original EF, scientific information about the causes, historical impacts, and future risks of climate change has continued to accumulate. This Review assesses that new information in the context of the EF. We find that the case for endangerment, which was already overwhelming in 2009, is even stronger now.

The EF was structured around knowledge related to public health and public welfare, with a primary focus on effects in the United States. The information on public welfare was grouped into sections on air quality; food production and agriculture; forestry; water resources; sea level rise (SLR) and coastal areas; energy, infrastructure, and settlements; and ecosystems and wildlife. We follow that organization here. In addition, some of the most important advances in understanding the risks of climate change involve sectors or impact types not highlighted in the EF. We summarize the evidence for four of these that are broadly important: ocean acidification, violence and social instability, national security, and economic well-being. We characterize changes since the EF in terms of the strength of the evidence for a link with anthropogenic climate change, the potential severity of observed and projected impacts, and the risks of additional kinds of impacts beyond those considered in the EF (Fig. 1).

Our focus is on the evidence for endangerment rather than the potential for adaptation. Although evidence that a risk might be reduced by some future action is certainly relevant for developing an effective portfolio of responses, the DC Circuit has affirmed that such evidence does not change the core question of whether long-lived GHGs endanger public health and welfare (*6*). In addition, adaptation options are often limited or impose economic costs that reduce adoption (*8*). Even ambitious adaptation rarely eliminates risk. For 32 specific risks evaluated by the IPCC in its recent special report,

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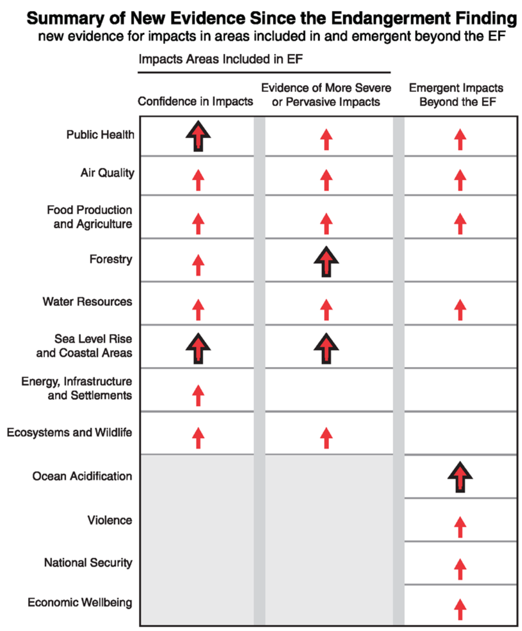

Fig. 1. New evidence since the EF. The columns summarize changes in the amount and implications of new evidence since the EF for each of the impact areas discussed in the EF and four additional impact areas where evidence of climate sensitivity has matured since the EF. An upward-pointing arrow indicates increasing evidence of endangerment. A downward-pointing arrow would indicate decreasing evidence of endangerment. A plain red arrow indicates that the new evidence is abundant and robust. An outlined arrow indicates that the new evidence, in addition, comes from multiple approaches, is derived from independent lines of information, or builds on a new level of mechanistic understanding. The left column refers to confidence in the impacts discussed in the EF. The middle column refers to impact areas that are discussed in the EF but where new evidence points to specific impacts that are fundamentally more severe or pervasive than those discussed in the EF. The right column refers to types of impacts not discussed in the EF.

the potential for adaptation was assessed as low or very low for 25% of risks at a warming of 1.5°C and 53% of risks at 2°C (*9*).

One area of scientific progress since the EF is the attribution of extreme weather events (and some of their consequences) to human-caused climate change. This includes observed effects on human health and security, agriculture, and ecosystems (see below), as well as the probability and/or intensity of specific extreme weather events (*10*, *11*). For extreme event attribution in North America, this includes more than 70% of recent record-setting hot, warm, and wet events and ~50% of record-setting dry spells (*12*), along with the recent California drought (*13*, *14*), the storm-surge flooding during Superstorm Sandy (*15*) and Hurricane Katrina (*16*), and heavy precipitation during Hurricane Harvey (*17*–*19*). Although the realization of risk is not required for a finding of endangerment, cases where extreme events can be confidently attributed to historical emissions reinforce the understanding that we are already seeing impacts and the risks they bring.

Public health

Since the EF, numerous scientific reports, reviews, and assessments have strengthened our understanding of the global health threats posed by climate change [e.g., (*20*, *21*)] (Fig. 1, left column). New evidence validates and deepens the understanding of threats, including increased exposure to extreme heat, reduced air quality, more frequent and/or intense natural hazards, and increased exposure to infectious diseases and aeroallergens. New evidence also highlights additional health-related threats not discussed in the EF, including reduced nutritional security, effects on mental health, and increased risk of population displacement and conflict (Fig. 1, right column).

Extreme heat is the most direct health impact (Fig. 2). With future warming, >200 U.S. cities face increased risk of aggregated premature mortality (*22*). In addition, extreme heat is linked to rising incidence of sleep loss (*23*), kidney stones (*24*), low birth weight (*25*), violence (*26*), and suicide (*27*) (Fig. 1, middle column).

New studies also strengthen evidence for health impacts via increased exposure to ozone and other air pollutants (*28*), including smoke from forest fires (*29*). Likewise, evidence for links among climate change, extreme weather, and climate-related disasters is growing rapidly (*30*). These events often lead to physical trauma, reduced air quality, infectious disease outbreaks, interruption of health service delivery, undernutrition, and both acute and chronic mental health effects (*31*).

Changes in temperature, precipitation, and soil moisture are also altering habitats, life cycles, and feeding behaviors of vectors for most vector-borne diseases (*32*), with recent research documenting changes in exposure to malaria (*33*), dengue (*34*), West Nile virus (*35*), and Lyme disease (*36*), among others. Recent work also reinforces the evidence that increased outbreaks of waterborne (*37*) and foodborne (*38*) illnesses are likely to follow increasing temperatures and extreme precipitation. Likewise, recent research reinforces the conclusion that rising temperatures and carbon dioxide (CO_2) levels will increase pollen production and lengthen the pollen season for many allergenic plants (*39*, *40*), leading to increased allergic respiratory disease (*41*).

One area of new understanding not covered in the EF is threats to global nutrition. Staple crops grown at 550 parts of CO_2 per million have lower amounts of zinc, iron, and protein than the same cultivars grown at ambient CO_2 (*42*). These nutrient losses could push hundreds of millions of people into deficiencies of zinc (*43*), protein (*44*), and iron (*45*), in addition to aggravating existing deficiencies in more than one billion people. These effects on nutritional quality exacerbate the impacts of climate change on agricultural yield, discussed below. Together, these effects underscore a substantial headwind in assuring access to nutritious diets for the global population (*46*).

Mental health impacts represent another area of new understanding (*47*). In particular, increased exposure to climate and weather disasters is associated with posttraumatic stress, anxiety, depression, and suicide (*27*, *48*).

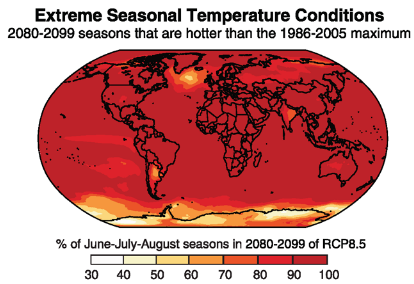

Fig. 2. The frequency of years from 2080 to 2099 of the RCP8.5 scenario in which the June-July-August (JJA) seasonal temperature equals or exceeds the warmest JJA value in the period from 1986 to 2005. [Adapted from (282)]

Lastly, climate change is increasingly understood to function as a threat magnifier, raising the risk of population displacement and armed conflict (discussed below), which can also amplify risks to human health.

Public welfare

Air quality

Evidence for the climate penalty on air quality stressed in the EF has strengthened (Fig. 1, left column). Mechanisms include extreme heat, leading to amplified production of surface ozone (49, 50); strong temperature inversions, leading to increased concentrations of particulate matter (PM) (51, 52); and stagnant atmospheric conditions (53). The most persistent and extreme episodes of elevated temperature, ozone, and PM in the United States have a high incidence of co-occurrence (54). Further global warming is likely to cause air stagnation events to increase over many midlatitude regions, including the western United States (53).

Recent studies confirm the increased risk of higher surface ozone concentrations as climate changes [e.g., (55–57)]. By the 2050s, the United States could experience more ozone episodes (days with 8-hour maximum daily averaged ozone concentrations greater than 75 parts per billion), including three to nine more episodes per year in the Northeast and California (58). By the 2090s, increases could reach 10 episodes per year across the Northeast (59). The U.S. ozone season, typically confined to summer, could also lengthen into spring and/or fall as climate warms (60) (Fig. 1, middle column).

Modeling studies of changes in PM present a mixed picture, arising from the complex responses of PM emissions and chemistry to meteorology [e.g., (61, 62)]. However, as the measurement record has lengthened, more robust estimates have come from observationally based statistical models. By using this approach and assuming no change in emissions of anthropogenic PM sources, one study projected that the annual mean $PM_{2.5}$ (the concentration of particles ≤2.5 μm in diameter) could increase by 0.4 to 1.4 $\mu g\ m^{-3}$ in the eastern United States by the 2050s, with small decreases in the West (58). However, summertime mean $PM_{2.5}$ was projected to increase as much as 2 to 3 $\mu g\ m^{-3}$ in the East because of faster oxidation and greater biogenic emissions.

Warmer and drier conditions in the West and Southwest [e.g., (63)] have implications for wildfire smoke and dust storms, as discussed below. By the 2050s, increased wildfire activity could elevate the concentrations of organic particles across the West by 46 to 70%, depending on the ecoregion (64), and the frequency of smoke episodes could double in California (65) (Fig. 1, right column). Future projections of the frequency of dust storms are mixed [e.g., (66)]. However, seasonal means of fine dust particles are projected to increase 26 to 46% by the 2050s in the Southwest under a scenario of very high GHG emissions (67).

Taken together, these studies imply that the health impacts of changing air quality due to changing climate will vary across the United States, with greater effects from anthropogenic $PM_{2.5}$ in the East and greater effects from dust and wildfire smoke in the West. The effect of changing ozone on health is projected to be greatest in the Northeast and California. Even seasonal exacerbation in pollutants, though relatively short term, would likely have negative consequences for health (68). The projected degradation of air quality could be mitigated to some extent by more stringent restrictions on the anthropogenic emissions of pollution precursors [e.g., (57)].

Food production and agriculture

Research since the EF has confirmed the EF's conclusion that "the body of evidence points towards increasing risk of net adverse impacts on U.S. food production and agriculture over time, with the potential for significant disruptions and crop failure in the future" (Fig. 1, left column). There is still an expectation that certain aspects of increasing CO_2 and temperature will be beneficial in the next few decades for some crops and locations within the United States but that these positive effects are likely to be outweighed by negative impacts, especially in the long term.

There is substantial new evidence quantifying and explaining the mechanisms behind crop yield losses that result from short periods of exposure to high growing-season temperatures (e.g., greater than 30°C, or 86°F) (69, 70) (Fig. 1, middle column). Likewise, warmer winter nights will also negatively affect perennial crops, such as apples and cherries, that require a certain amount of winter chill for high yields (71), an impact not included in the 2009 EF (Fig. 1, right column).

New understanding of weed and pest responses to climate and CO_2 highlights the risks from these biotic stresses [e.g., (72, 73)]. For example, weeds typically respond more quickly than crops to higher CO_2, which "will contribute to increased risk of crop loss due to weed pressure" (70).

Understanding of agricultural vulnerability has also extended beyond the main commodity crops (Fig. 1, right column). For example, national aggregate agricultural total factor productivity (TFP) exhibits strong sensitivity to weather in regions having high-value crops or livestock production or specializing in commodity crops (74). Sensitivity was highest in recent time periods, and projected warming could reduce TFP at a rate faster than that of technological improvement.

Measurements since the EF enable more thorough characterization of ongoing impacts and adaptation responses. Climate changes since 1980 have had net negative impacts on yields of maize and wheat in most major producing regions globally, with less substantial impacts for rice and soybeans (69). Warming trends in the United States have been more muted than those in other regions, resulting in smaller impacts to date. Studies have also assessed the ability of farmers to adapt to ongoing changes, for example, by comparing regions with different rates of warming or by evaluating sensitivity to spatial gradients in temperature at different points in time. These studies generally indicate a limited ability of farmers to simultaneously raise yields and reduce yield sensitivity to warming (75, 76), which is consistent with the increased aggregate sensitivity of TFP. Other adaptations such as switching crops or adding irrigation have been less rigorously tested. Overall, the conclusion of the 2014 National Climate Assessment was that "although agriculture has a long history of successful adaptation to climate variability, the accelerating pace of climate change and the intensity of projected climate change represent new and unprecedented challenges to the sustainability of U.S. agriculture" (Fig. 1, middle column) (70).

Forestry

Evidence available at the time of the EF indicated that anthropogenic climate change would likely bring more harm than benefits for U.S. forests during the 21st century. Research since the EF broadly confirms that forest ecosystems are not in equilibrium with ongoing and projected trends in extreme heat and drought, making large ecological shifts in U.S. forests likely (*77*–*81*) (Fig. 1, left column).

Anthropogenic warming has reduced snowpack across the majority of the montane western United States (*82*, *83*), and Earth system models project reduced summer soil moisture across most of the United States (*63*, *84*). Warming also elevates plant respiration rates and atmospheric evaporative demand, aggravating drought stress and the risk of tree mortality. Further, projected increases in precipitation variability (*85*) are likely to promote increasingly severe droughts even in regions of increased mean precipitation (*13*, *86*).

Whereas CO_2 fertilization, warming-induced lengthening of the growing season, and nitrogen deposition pose potential benefits to trees, models substantially overestimate CO_2-driven increases in global vegetation productivity over recent decades (*87*).

A large body of new evidence points to increasing risks of tree mortality or forest loss in the western United States from wildfire, insect outbreaks, and physiological failure due to drought stress (*88*) (Fig. 1, middle column). Although such disturbances occur naturally, increases in disturbance size, frequency, and severity can have long-term impacts on forest ecosystems (*78*, *89*). Annual western U.S. forest-fire area increased by ~1000% from 1984 to 2017 (*90*, *91*) (Fig. 3). Studies consistently attribute a substantial fraction of this trend to warming-induced fuel drying (*92*–*94*) and suggest continued increases in western U.S. forest-fire activity (*95*, *96*) and resultant tree mortality (*97*) until fuels become limiting (*98*).

Land management has amplified the effects of warming on western U.S. forest-fire activity (Fig. 1, left column). A century of fire suppression caused fuels to accumulate, creating fire deficits in many forested areas (*99*). Accumulated fuels and warming combine to aggravate the risk of large, high-intensity wildfires (*100*–*102*). This risk may be further exacerbated where CO_2 fertilization or precipitation trends enhance biomass (*103*) or where humans add to natural ignitions (*104*).

Recent bark beetle outbreaks in western North America appear to be more massive than those in previous centuries (*105*), with new research since the EF documenting millions of hectares of tree mortality (*106*, *107*) (Fig. 1, middle column). Warming may intensify bark beetle outbreaks by decreasing cold-season beetle mortality, accelerating the beetle life cycle, and weakening tree defenses (*108*). However, the full range of effects of climate change on bark beetle outbreaks remains unconstrained (*109*, *110*).

Heat- and drought-driven tree mortality in western forests may be increasing even in the absence of wildfire or insects, as more intense droughts can damage the water transporting xylem and reduce carbon reserves (*111*, *112*). Quaking aspens in the Rocky Mountains have experienced particularly severe drought-driven mortality since 2002, with the risk of repeated events projected to rise throughout the century (*113*). Some of the impacts of drought intensification may be moderated by adaptation or enhanced capacity for postdrought injury repair (*114*, *115*), but understanding of that potential is limited.

Climate change impacts on eastern forests have been more ambiguous because of the legacy effects of land management, complex competition dynamics, and in some locations, muted warming and/or increased precipitation. Nonetheless, eastern U.S. forests are vulnerable to extreme heat and drought (*116*, *117*). Warming is implicated in the northward expansion of eastern forest pests, including the southern pine beetle (*108*) and nonnative hemlock woolly adelgid (*118*). Recent drought-driven fires in the Southeast may portend warming-exacerbated fire activity in that region (*119*).

The current distributions and assemblages of vegetation species are not in equilibrium with future climate and CO_2 levels. Research over the past decade suggests that the velocity of climate change could exceed the rate of migration of some forest species (*120*, *121*), enhancing the evidence in the EF that rapid 21st-century climate change will profoundly disrupt U.S. forest ecosystems (*78*) (Fig. 1, middle column).

Water resources

Climate change impacts on snow hydrology and water scarcity are especially pronounced in the western United States. Observed trends toward warming-induced reductions in snowpack were first widely reported by Mote *et al.* (*122*). Likewise, up to 60% of climate-related trends in

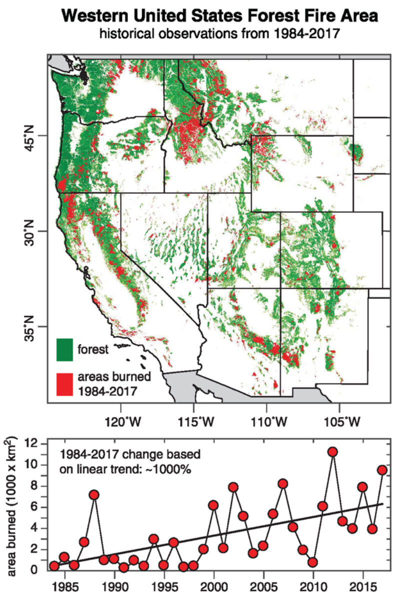

Fig. 3. Western U.S. forest-fire area for 1984 to 2017. (Top) Map of forest-fire areas. **(Bottom)** Annual forest-fire area according to the U.S. Forest Service Monitoring Trends in Burn Severity (MTBS) project for 1984 to 2016 (*90*) and the MODIS version 6 burned-area product for 2017 (*91*). The MODIS burned-area record was linearly calibrated to the MTBS record during overlapping years of 2001 to 2016. The linear trend is derived from least-squares regression.

earlier river flow, warmer winter air temperature, and lower snowpack from 1950 to 1999 are attributed to human activities (*82*).

Since the EF, there has been substantial progress in quantifying trends in snowpack and associated impacts on water availability (Fig. 1, left column). Springtime warming over the past half century has resulted in a higher proportion of precipitation falling as rain versus snow in the western United States (*123*), earlier snowmelt onset by 1 to 2 weeks in the western United States (*124*), reductions in stream flow during the driest part of the year in the Pacific Northwest (*125*), earlier-in-the-year stream flow in snow-fed rivers in North America (*126*), and reductions in snow cover and snowpack over the Northern Hemisphere (*127*).

Climate models project accelerated changes in snow hydrology, both in the western United States and globally. Decreases in midlatitude snowfall (*128*, *129*) are projected to reduce snow cover and depth (*127*, *128*), accelerating hydroclimatic change in snow-dominated regions of the western United States (*130*), including losses in annual maximum water stored in snowpack of up to 60% in the next 30 years (*131*, *132*). Losses of snow cover and water equivalent depth would fundamentally change the sources and timing of runoff in many midlatitude and mountainous regions (*133*), including the western (*134*), midwestern, and northeastern parts of the United States (*135*) (Fig. 1, middle column).

New research highlights risks from snowpack droughts (*133*, *136*). These periods of very low snowpack negatively affect the water supply and other aspects of the Earth system, including rare and endangered species (e.g., salmon, trout, and wolverine) (*137*, *138*) (Fig. 1, right column).

Research since the EF has highlighted the southwestern United States as a region of particular concern. On the Colorado River, elevated temperatures were an important contributor to the drought of 2000 to 2014, and continued warming is projected to drive greater reductions in river flows (*139*, *140*) (Fig. 1, middle column). On the Rio Grande, warming temperatures are contributing to reductions in the fraction of precipitation that becomes river flow (*141*, *142*).

Global urban freshwater availability is threatened by climate forcing and water management practices (*143*, *144*), leading to a projected increase in the number of people living under absolute water scarcity (*144*, *145*) (Fig. 1, right column). In addition, new evidence suggests that further global warming is likely to erode water quality in the United States by increasing nutrient loading and eutrophication, particularly in the Midwest and Northeast (*146*) (Fig. 1, right column).

Sea level rise and coastal areas

Understanding of the present rates of global and regional SLR, the role of contributing processes, the range of future rates, and the observed and projected impacts has improved since the EF (*147*). Evidence of the role of SLR in exacerbating impacts of recent hurricanes (*15*, *17*, *19*) further highlights the risks (Fig. 1, left column).

Recent studies project SLR at greater than 7 mm year^{-1} after ~2050 (*148*). This is a global average SLR rate unprecedented in the last 7000 years (*149*). Recent acceleration of SLR in the U.S. Northeast and Gulf Coast adds to the longer-term trend (*150*). Annual exceedances of flood thresholds are increasing or accelerating at locations along the U.S. coastline (*151*), with the majority of tide gauge locations projected to pass a tipping point for flooding (more than 30 days year^{-1} with water higher than 0.5 m above mean high tide) in the next several decades (*152*). With these rates of SLR, the stratigraphic record and modern analogs that serve as our traditional sources of insight are lacking, limiting our ability to predict the form, magnitude, and spatial extent of future changes to the coastal landscape (*153*, *154*).

Research since the EF documents increased risks of SLR, especially for the higher levels of SLR now within the range of projections (*155*) (Fig. 1, middle column). SLR has and will increasingly expose coastal populations, economies, and infrastructure to hazards such as flooding, erosion, and extreme events. An SLR defined by the National Oceanic and Atmospheric Administration (NOAA) as an "Intermediate Low Scenario" of 0.5 m by 2100 results in tidally forced flooding approximately every other day for much of the East Coast and the Gulf of Mexico, whereas the "Intermediate Scenario" (1.0 m by 2100) leads to daily flooding in all U.S. coastal regions (*156*). In the United States, projected population growth approximately doubles the number of people at risk of inundation by 2100, to 4.2 million for an SLR of 0.9 m and 13.1 million for an SLR of 1.8 m (*157*). By 2110, a high SLR scenario results in the projected loss of more than 80% of West Coast tidal wetlands (*158*).

Coastal erosion and flooding risk are already affecting real estate values. For example, in Miami-Dade County, property subject to high-tide flooding is appreciating at a lower rate than properties at higher elevations, causing displacement through "climate gentrification" (*159*) (Fig. 1, left column). Furthermore, as older and less resilient residential structures are damaged or destroyed by coastal storms and chronic shoreline retreat, they are typically replaced by more resilient but also more expensive structures (*159*, *160*).

New evidence since the EF highlights interactions between the SLR and other sectors (Fig. 1, middle column). The SLR and extreme events threaten the movement of goods among major port cities (*161*), which can lead to economic disruption (*162*), with cascading impacts far from the coastal zone, as well as opportunity costs associated with ensuring the viability of ports and other coastal infrastructure. Likewise, the domestic and international missions of the U.S. military, including disaster relief and humanitarian assistance, are increasingly affected by SLR, as discussed below.

Energy, infrastructure, and settlements

The EF found that "the evidence strongly supports the view that climate change presents risks of serious adverse impacts on public welfare from the risk to energy production and distribution as well as risks to infrastructure and settlements." This evidence has become stronger and broader since the EF, especially on the basis of increased understanding of the relationship between human-caused climate change and extreme events (*10*, *11*) (Fig. 1, left column).

On the basis of analysis by Wilbanks *et al.* (*163*), Dell *et al.* reported that "changes in water availability, both episodic and long-lasting, will constrain different forms of energy production [including those] from fossil fuels (coal, oil, and natural gas), nuclear power, biofuels, hydropower, and some solar power systems …" (*164*). Recent studies indicate that warming water bodies and the reduced availability of water for cooling power plant operations and for hydropower will continue to constrain power production at existing facilities and permitting of new power plants (*163*, *165*). In some parts of the country, electric utilities and energy companies compete with farmers and ranchers, other industries, and municipalities for water rights and availability (*166*).

Recent work documents an increase in energy demand for cooling buildings, with a shift from predominantly heating to predominantly cooling in some regions and a greater reliance on electricity relative to other energy sources (*163*, *167*).

Given that a substantial fraction of America's energy and transportation infrastructure is located in low-lying coastal and riverine areas, much of that infrastructure is vulnerable to flooding from extreme weather events (*168*). Likewise, adverse effects on U.S. military infrastructure and surrounding communities have resulted most notably from drought and flooding, as discussed below.

The Third U.S. National Climate Assessment concluded that "in parts of Alaska, Louisiana, the Pacific Islands, and other coastal locations, climate change impacts … are so severe that some communities are already relocating from historical homelands to which their traditions and cultural identities are tied" (*169*, *170*, *171*). In particular, "physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population, increase the vulnerability of rural communities" (*172*).

The effects of rising temperatures are perhaps most severe in the Arctic, which is warming more than twice as fast as the global average (*173*) (Fig. 1, left column). Communities across the Arctic are experiencing impacts, including effects from the loss of sea ice, SLR, erosion, and permafrost thaw. These changes have been under way for decades, but much of the documentation has occurred since the EF. Arctic warming is endangering human health, destroying public infrastructure, and threatening water resources, cultural resources, and access to subsistence resources and traditional food storage (*174*, *175*).

The risk and severity of climate impacts are particularly high for coastal communities in Alaska, where loss of land-fast sea ice is increasing storm impacts and permafrost thaw is exacerbating coastal erosion rates (176) (Fig. 1, left column). Thirty-one Alaskan villages face imminent threats from flooding, erosion, and permafrost thaw (177). None of these villages have yet relocated, largely because of the lack of a governance framework to facilitate relocation efforts (178).

Permafrost thaw has a substantial economic cost, quantified mainly since the EF. Ground subsidence and collapse, particularly in ice-rich areas, negatively impact the structural integrity of buildings, roads, and industrial infrastructure, including gas and oil development (175). Cumulative projected costs of climate change damages to public infrastructure in the state of Alaska are estimated at $5.5 billion for a high-emissions scenario [Representative Concentration Pathway 8.5 (RCP8.5)] and $4.2 billion for a medium-emissions scenario (RCP4.5) for 2015 to 2099 (179). The greatest economic impact is expected to result from road flooding, followed by building damage as a result of near-surface permafrost thaw.

Ecosystems and wildlife

The first global meta-analyses of climate change impacts on wild species, mostly from terrestrial ecosystems, estimated that about half had responded by shifting their ranges poleward and upward and about two-thirds had responded by advancing their timing of spring events such as tree budburst and bird nesting (180). New studies since the EF have clarified and extended these findings, expanded documentation for marine systems, and illuminated responses at all levels of biological organization (181) (Fig. 1, left column). This new evidence makes clear that prior global estimates underestimated the impacts of anthropogenic climate change on ecosystems and wildlife.

Research since 2009 illuminates new range boundary dynamics that are more complex than simple northward or poleward shifts (182). For example, terrestrial range limits are shifting faster where local warming is stronger (183). Likewise, lower elevation limits set by precipitation can expand downward in response to increased rainfall, despite regional warming (184). Changes in behavior, the timing of activities, or the use of habitat can complement range shifts as a means of matching activity to the range of preferred temperatures (185).

By contrast, marine limits are typically set by physiological thermal tolerances and thus respond more strongly and predictably than equivalent terrestrial limits (186). The mean rate of movement in marine systems (187) reflects the faster poleward movement of isotherms in the oceans than on land (188, 189). The rapid range shift of marine organisms covers many taxa, including phytoplankton (470 km per decade), bony fish (278 km per decade), and invertebrate zooplankton (142 km per decade) (189). Taxa on the move also include important disease organisms, such as *Vibrio* bacteria, which have recently caused unprecedented outbreaks of food poisoning and infection of wounds [reviewed in (190)].

Research since 2009 on the timing of spring events illuminates changes that defy simple expectations (Fig. 1, left column). In plants that require chilling ("vernalization") to determine that winter is over, winter warming slows development whereas spring warming speeds development. Actual changes in timing reflect the combination of these opposing effects, potentially resulting in development that is accelerated, delayed, or unchanged (191).

Before the EF, it was predicted that biological responses would lag behind changes in climate (192). Studies since 2009 have documented that this lag is already occurring. Across Europe, species are responding more slowly than climate is warming, causing bird and butterfly communities to suffer a "climate debt" (193). Likewise, populations of yellow warbler with detectable climate debts had the lowest population growth rates across the United States (194). By contrast, plants that have advanced their timing most strongly have had more positive population growth rates (195).

Similarly, at the time of the EF, there was an assumption that a sensitivity to warming would be most important at the limits of species' ranges. However, several newer studies demonstrate that life history trade-offs can cause species to be constrained by the limits of their climatic tolerances even in central areas of their ranges (196, 197) (Fig. 1, left column).

Biological diversity and the services that ecosystems provide to humans face risks from climate change. The magnitude and timing of these risks are influenced not only by direct effects of climate on organisms but also by compounding effects of other stresses (198, 199), especially land use by humans, changes in disturbance regimes, defaunation (200), and ocean acidification (see below). Biotic interactions related to pollination, food resources, competition, pests, diseases, and predators can also amplify the risks (201). Since the EF, new research has provided additional detail on many of these risks and on the groups of species and ecosystem services that are most vulnerable (202) (Fig. 1, left column).

Extinction risk from climate change is broadly distributed across taxonomic groups, with 21st-century warming threatening about 15% of all species in a world of continued high emissions (202). Risks are especially great for species with small ranges or in habitat types that are spatially limited or rapidly shrinking, including Arctic sea-ice ecosystems (203) and mountaintops (198). Recent large-scale bleaching in warm-water coral reefs (204) and forest mortality events (205) provide clear evidence of risk under current conditions. In the United States, national parks have warmed at twice the national average rate, with precipitation declines at four times the average, highlighting risks to areas of high conservation value (206). Research since the EF underscores risks of climate change for diverse ecosystem services, such as those associated with the role of coral reefs in supporting fisheries (207) (Fig. 1, middle column) and the contribution of forests and soils in GHG balance (208).

Ocean acidification

The removal of anthropogenic CO_2 emissions by air-sea gas exchange and chemical dissolution into the ocean alters the acid-base chemistry of the ocean. Since the EF, scientific understanding of this process and of its possible negative effects on marine life has improved (Fig. 1, right column).

Excess CO_2 gas in the ocean reacts with water, resulting in a series of chemical changes that include reductions in pH, carbonate ion (CO_3^{2-}) concentrations, and the saturation state for carbonate minerals used by many organisms to construct shells and skeletons (209). Such chemical changes are now well documented in the upper ocean. Acidification in coastal waters can be exacerbated by local pollution sources (210). Over the next several decades, trends in near-surface acidification are likely to closely track atmospheric CO_2 trends (211), with acidification hot spots in coastal upwelling systems, the Arctic, and the Southern Ocean (212, 213).

Evidence since the EF reveals a wide range of biological responses to elevated CO_2 and ocean acidification (Fig. 1, right column). For all marine species, the effects of current and future ocean acidification must be framed in the context of a rapidly changing ocean environment with multiple human-driven stressors, particularly ocean warming (214). Warming is reducing open-ocean oxygen levels and exacerbating coastal hypoxia driven by excess nutrients (215), the same nutrient pollution that also causes estuarine and coastal acidification.

Model and data syntheses indicate that acidification may shift reef systems to net dissolution during the 21st century (216). Coral bleaching from ocean warming is already having negative consequences for biologically rich coral reef ecosystems that provide food, income, and other valuable ecosystem services to >500 million people around the world (217), and the combined effects of warming and acidification are expected to worsen in the future (207).

Different kinds of organisms vary substantially in their responses to acidification, with generally negative effects for many mollusks and some plankton to neutral and even positive effects for other species (218). Lower seawater carbonate saturation states reduce calcification and may restrict the geographic habitat for planktonic pteropods (219) that are prey for many fish, marine mammals, and seabirds.

Many shellfish, and perhaps some kinds of crustaceans, are vulnerable to acidification, especially in larval and juvenile stages, with possible repercussions for valuable U.S. and international fisheries (220, 221) (Fig. 1, right column). During the mid-2000s, low-pH waters associated with coastal upwelling led to reduced larval survival of Pacific oysters in some U.S. Pacific Northwest shellfish hatcheries, a problem that has been largely addressable so far through adaptive strategies (222). Wild-harvest fisheries may be more at risk, particularly in regions with combined social and ecological vulnerability (223). Less is known about acidification responses in fish, with most studies indicating weak or no effects

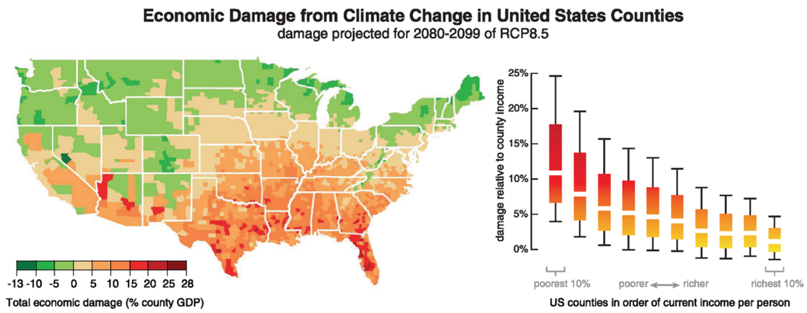

Fig. 4. Total direct economic damage integrated over agriculture, crime, coastal storms, energy, human mortality, and labor in 2080 to 2099 under a scenario of continued high emissions (RCP8.5). **(Left)** Damages in the median scenario for each county. Negative damages indicate benefits. **(Right)** Range of economic damages per year for groupings of U.S. counties, on the basis of income (with 29,000 simulations for each of 3143 counties) as a fraction of county income (white lines, median; boxes, inner 66% of possible outcomes; outer whiskers, inner 90% of possible outcomes). [Adapted from (*238*)]

on growth and reproduction. However, a number of studies report negative effects on fish olfaction and behavior (*224*).

Taken as a whole, acidification will likely exacerbate many of the climate warming effects on marine ecosystems, including shifting species ranges, degrading coral reefs, and expanding low-oxygen zones.

Violence and social instability

Since the EF, a number of studies have used historical data to explore whether changes in environmental conditions influence the risk of violence or instability (*225*). In general, high temperatures and rainfall extremes amplify underlying risks (*26*) (Fig. 1, right column). These effects are not uniform (*226*). Many factors, including political institutions (*227*), income levels (*228*), and local economic structures (*229*), play a role in determining the structure of these effects.

A robust and generalizable finding is an increased risk of threatening and violent interactions between individuals under hot conditions (Fig. 1, right column). In the United States, exposure to high temperatures is associated with higher rates of domestic violence (*230*), rape, assault, and murder (*231*, *232*), as well as greater use of threatening behaviors, such as aggressive language in social media posts (*233*) and horn honking in traffic (*234*), and higher rates of violent retaliation in sports (*235*). Emerging evidence also indicates that hot periods elevate the risk that individuals harm themselves, including by suicide (*27*, *236*). U.S. data indicate no evidence of adaptation (*27*, *232*).

Effects of temperature [+2.4% per SD (σ)] and rainfall (0.6% per σ) on interpersonal violence are both highly statistically significant, according to a meta-analysis (*237*). If these responses to historical fluctuations translate to future climate change, warming of 1°C could lead to an increase in national violent crime (rape, assault, and murder) by 0.88% (±0.04%) (*238*). Under RCP8.5, this trend projects to a warming-caused increase in violent crime of 1.7 to 5.4% by 2080 to 2099. Warming is projected to increase the national suicide rate by 0.6 to 2.6% by 2050 (*27*).

Many studies document a heightened risk of violence between groups of individuals when temperatures are hot and/or rainfall is extreme (*26*) (Fig. 1, right column). The patterns are similar for organized violence, such as civil conflicts (*228*, *239*), and disorganized violence, such as ethnic riots (*240*), with highly statistically significant effects of temperature (+11.3% per σ) and rainfall (3.5% per σ, over 2 years) (*237*).

Political instability is heightened in hot periods, even in contexts where political institutions are sufficiently robust to avoid outright violence (Fig. 1, right column). The probability of political leadership changes, through both democratic process (*241*, *242*) and "irregular" conditions (*243*, *244*), rises in warm periods. Coups are more likely in hot years with extreme rainfall in agriculturally dependent countries (*245*).

By degrading economic conditions, climate events may contribute to out-migrations of populations seeking better opportunities. Drought and soil loss in the Dust Bowl induced mass outmigration from the rural Midwest (*246*), and young working-age individuals left the corn belt during periods of extreme heat in recent decades (*247*). Likewise, periods of high temperatures have been linked to migration from rural regions of Mexico to the United States (*247*, *248*). Population movements after periods of extreme heat or dryness have been documented in multiple regions (*249*–*251*), and high temperatures in agrarian regions elevate international applications for political asylum (*252*).

National security

Since the EF, the American military and intelligence communities have substantially increased their integration of climate change into national security strategies, policies, and plans. These considerations have been reflected in analyses of the national security implications of climate change by the U.S. Department of Defense, with almost 50 reports considering climate security impacts published between 2010 and 2018 (*253*) (Fig. 1, right column).

The National Intelligence Council (NIC) has warned Congress about the security risks of climate change every year since 2008, after the release of the landmark report by the CNA Military Advisory Board, "National Security and the Threat of Climate Change" (*254*). The NIC's "Worldwide Threat Assessment," which reflects the intelligence community's consensus on the most substantial risks to national security, in 2018 for the first time included a robust section titled "Environment and climate change," noting a range of security risks related to environmental concerns (*255*). The 2018 Defense Authorization Act, signed by President Donald J. Trump, stated that "climate change is a direct threat to the national security of the United States ..." (*256*). During the Trump presidency, 16 military leaders, including Secretary of Defense James Mattis (*257*), have voiced concerns about climate change and its security implications. Chairman of the Joint Chiefs of Staff General Joe Dunford stated, "Climate change ... is very much something that we take into account in our planning as we anticipate when, where and how we may be engaged in the future and what capabilities we should have" (*258*).

New studies strengthen the evidence that climate change causes weather patterns and extreme events that directly harm military installations and readiness through infrastructure damage, loss of utilities, and loss of operational capability (Fig. 1, right column). An SLR of 3.7 feet would threaten 128 military bases (*259*). Thawing permafrost exposes foundations to damage, whereas the loss of Arctic sea ice causes coastal erosion near critical facilities. Intensifying wildfires threaten facilities, transportation infrastructure, and utility lines. Fire-hazard days and inclement weather suspend outdoor training, and droughts limit the use of live-fire training. Greater storm frequency and strength put a strain on the resources of the defense support of civil authorities at home, as well as on assistance to humanitarian efforts and disaster relief around the world (*260*). As of 2018, 50% of military installations both at home and abroad had already reported damage due to climate change (*260*). Droughts or unpredictable rainfall could leave armed forces stationed abroad vulnerable to being disconnected from potable water supplies, a cause for concern given that protecting convoys for the "resupply of fuel and drinking water for troops in-theater costs lives" (*261*).

Climate change increasingly disrupts existing international security dynamics in geostrategic environments (Fig. 1, right column). Reduced Arctic sea-ice extent will open the way for more trade, as well as oil and gas extraction, turning a historically neutral territory into a potential political flashpoint. Moreover, the U.S. military now has to operate in an increasingly open water Arctic region as sea ice retreats. As Secretary of Defense Mattis recently stated, "America's got to up its game in the Arctic" (*262*). Both China and Russia have been deepening their Arctic presence through investment and the development of ports. As much as 15 percent of China's trade value could travel through the Arctic by 2030, and between 20 and 30 percent of Russia's oil production will come from deposits in the Arctic shelf by 2050 (*263*). These interests will require further American military and coast guard activity in the region, as well as broader diplomatic and scientific engagement.

Indirectly, climate change has a major effect on national security by acting as a "threat multiplier" (*254*) or "accelerant of instability" (*264*) (Fig. 1, right column). This means that climate change heightens the risk posed by threats the United States is already facing and, in aggregate, fundamentally alters the security landscape (*265*). In both the 2010 and 2014 quadrennial defense reviews (*264*, *266*), the Department of Defense emphasized how seriously the military takes this dangerous dynamic, a commitment that receives meaningful redress every year in its annual strategic sustainability performance plans (*267*).

As discussed in other parts of this Review, an expanding body of evidence reinforces how climate change fuels economic and social discontent, and even upheaval. This includes extreme weather events, which raise the risk of humanitarian disasters, conflict, water and food shortages, population migration, labor shortfalls, price shocks, and power outages (*255*).

Economic well-being

Research on the economic consequences of climate change has advanced substantially since the EF, with important progress on understanding nonagricultural sectors and broad measures of well-being (*225*, *268*) (Fig. 1, right column). In the United States, economic impacts of hot temperatures and changing tropical cyclone environments are clearly documented (*238*), and growing evidence indicates long-term adverse effects on the labor force (*269*–*271*). Other impacts, such as those from water availability or wildfire risks, are thought to be important but remain less well understood (*272*).

Since the EF, new "top-down" analyses of overall macroeconomic performance estimate that warming by an additional 1°C over 75 years can be expected to permanently reduce the U.S. gross domestic product (GDP) by ~3% through direct thermal effects (*273*) and that the U.S. GDP can be expected to be ~4% greater at 1.5°C than at 2°C above preindustrial temperatures (*274*) (Fig. 1, right column). The average projected alteration of cyclone activity under "business as usual" may cost the United States the equivalent of 29% of one year of current GDP (in net present value discounted at 3% annually) (*275*). In one study, the net cumulative market-based cost of thermal effects in RCP8.5 by 2100 should be valued at $4.7 trillion to $10.4 trillion (in net present value discounted at 3% annually) (*276*). Notably, in some cases these top-down analyses are able to account for both the opportunity costs and benefits of adaptations undertaken by populations as they adjust to new climatic conditions (*276*).

"Bottom-up" analyses examining impacts on individual sectors or industries have key advantages, including capturing the value of nonmarket impacts such as the loss of human life or biodiversity (*238*). Evidence from combining sector-specific analyses of impacts such as agricultural output (*277*), the quantity of labor supplied by workers (*278*), energy demand (*167*, *279*), mortality rates (*279*), crime rates (*232*), SLR (*280*) and tropical cyclone damage (*281*) suggests U.S. costs equivalent to 1.2% of GDP for each 1°C of warming, with poorer counties experiencing an economic burden roughly five times that of wealthier counties (*238*) (Fig. 1, right column, and Fig. 4).

Conclusions

The EPA Administrator found in 2009 that the EF for six long-lived GHGs was "compellingly" supported by "strong and clear" scientific evidence (*5*). Since 2009, the amount, diversity, and sophistication of the evidence have increased markedly, clearly strengthening the case for endangerment. New evidence about the extent, severity, and interconnectedness of impacts detected to date and projected for the future reinforces the case that climate change may reasonably be anticipated to endanger the health and welfare of current and future generations. For the sectors analyzed in the 2009 EF, new evidence expands the range of case studies, deepens the understanding of mechanisms, and analyzes the contribution of climate-related extremes. In many cases, new evidence points to the risk of impacts that are more severe or widespread than those anticipated in 2009. Several categories of climate-change impacts, including effects on ocean acidification, violence, national security, and economic well-being, are now supported by such broad evidence that they warrant inclusion in the framing of endangerment. In sum, the EF, fully justified in 2009, is much more strongly justified in 2018.

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Science

Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases

Philip B. Duffy, Christopher B. Field, Noah S. Diffenbaugh, Scott C. Doney, Zoe Dutton, Sherri Goodman, Lisa Heinzerling, Solomon Hsiang, David B. Lobell, Loretta J. Mickley, Samuel Myers, Susan M. Natali, Camille Parmesan, Susan Tierney and A. Park Williams

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The case for endangerment

In 2009, the U.S. Environmental Protection Agency (EPA) established the so-called "Endangerment Finding." This defined a suite of six long-lived greenhouse gases as "air pollution." Such air pollution was anticipated to represent a danger to the health and welfare of current and future generations. Thus, the EPA has the authority to regulate these gases under the rules of the U.S. Clean Air Act. Duffy *et al.* provide a comprehensive review of the scientific evidence gathered in the years since then. These findings further support and strengthen the basis of the Endangerment Finding. Thus, a compelling case has been made even more compelling with an enormous body of additional data.

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Global warming has increased global economic inequality

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Understanding the causes of economic inequality is critical for achieving equitable economic development. To investigate whether global warming has affected the recent evolution of inequality, we combine counterfactual historical temperature trajectories from a suite of global climate models with extensively replicated empirical evidence of the relationship between historical temperature fluctuations and economic growth. Together, these allow us to generate probabilistic country-level estimates of the influence of anthropogenic climate forcing on historical economic output. We find very high likelihood that anthropogenic climate forcing has increased economic inequality between countries. For example, per capita gross domestic product (GDP) has been reduced 17–31% at the poorest four deciles of the population-weighted country-level per capita GDP distribution, yielding a ratio between the top and bottom deciles that is 25% larger than in a world without global warming. As a result, although between-country inequality has decreased over the past half century, there is ~90% likelihood that global warming has slowed that decrease. The primary driver is the parabolic relationship between temperature and economic growth, with warming increasing growth in cool countries and decreasing growth in warm countries. Although there is uncertainty in whether historical warming has benefited some temperate, rich countries, for most poor countries there is >90% likelihood that per capita GDP is lower today than if global warming had not occurred. Thus, our results show that, in addition to not sharing equally in the direct benefits of fossil fuel use, many poor countries have been significantly harmed by the warming arising from wealthy countries' energy consumption.

economic inequality | global warming | climate change attribution | CMIP5

Detection of impacts caused by historical global warming has increased substantially in the past decade, including documented impacts on agriculture, human health, and ecosystems (1). Quantifying these historical impacts is critical for understanding the costs and benefits of global warming, and for designing and evaluating climate mitigation and adaptation measures (1).

The impact of historical warming on economic inequality is of particular concern (2). There is growing evidence that poorer countries or individuals are more negatively affected by a changing climate, either because they lack the resources for climate protection (3) or because they tend to reside in warmer regions where additional warming would be detrimental to both productivity and health (4–6). Furthermore, given that wealthy countries have been responsible for the vast majority of historical greenhouse gas emissions, any clear evidence of inequality in the impacts of the associated climate change raises critical questions of international justice.

More broadly, measuring and understanding the past and present evolution of global economic inequality is an area of active research and policy interest, with ongoing disagreement about the nature and causes of observed inequality trends (7–10). Quantifying any climatic influence on these trends thus has implications beyond climate risk management.

Recent research has identified pathways by which changes in climate can affect the fundamental building blocks of economic production (11, 12). Empirical work has included sector-specific analyses of agriculture, labor productivity, and human health (12), as well as analyses of aggregate indicators such as gross domestic product (GDP) (4, 13). A key insight is the nonlinear response of many outcomes to temperature change, with the coolest regions often benefitting in warm years, and warmer regions being harmed. As a result, empirical evidence combined with projections of future climate change suggests that, although some wealthy countries in cooler regions could benefit from additional warming, most poor countries are likely to suffer (4, 14).

Efforts to apply empirical approaches to explicitly quantify the spatial pattern of aggregate impacts have primarily focused on future climate change (4–6, 14), with quantification of historical impacts being limited to specific economic sectors and outcomes (e.g., ref. 1), or to global GDP (12). Likewise, although a number of researchers have noted that the most robust regional warming has generally occurred in lower-latitude regions that are currently relatively poor (e.g., refs. 15–19), these analyses have not attempted to quantify the distributional impacts of historical temperature change.

Here, we build on past work linking economic growth and fluctuations in temperature (4, 14) to quantify the impact of historical anthropogenic climate forcing on the global distribution of country-level per capita GDP (*Materials and Methods* and Fig. 1). We use the Historical and Natural climate model simulations from the Coupled Model Intercomparison Project (CMIP5) (20) to quantify the temperature trajectory of different countries in the absence of anthropogenic forcing. We then combine these counterfactual country-level temperature trajectories

Significance

We find that global warming has very likely exacerbated global economic inequality, including ~25% increase in population-weighted between-country inequality over the past half century. This increase results from the impact of warming on annual economic growth, which over the course of decades has accumulated robust and substantial declines in economic output in hotter, poorer countries—and increases in many cooler, wealthier countries—relative to a world without anthropogenic warming. Thus, the global warming caused by fossil fuel use has likely exacerbated the economic inequality associated with historical disparities in energy consumption. Our results suggest that low-carbon energy sources have the potential to provide a substantial secondary development benefit, in addition to the primary benefits of increased energy access.

Author contributions: N.S.D. and M.B. designed research, performed research, contributed new reagents/analytic tools, analyzed data, and wrote the paper.

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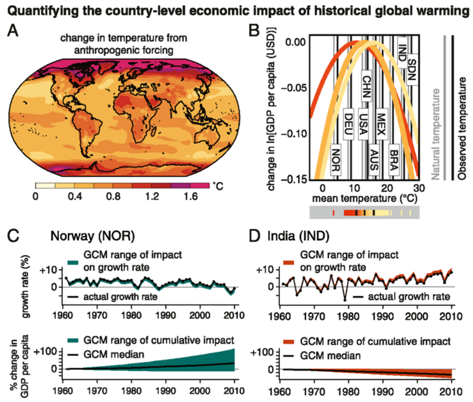

Fig. 1. Response of temperature and per capita GDP to global warming. (*A*) The ensemble-mean difference in annual temperature between the CMIP5 Historical and Natural forcing experiments during the IPCC's historical baseline period (1986–2005). (*B*) The annual temperature for selected countries from historical observations [black; calculated as in Burke et al. (14)] and the world without anthropogenic climate forcing (gray). Overlaid on the country-level temperatures are the response functions containing the 10th (red), 50th (orange), and 90th (yellow) percentile temperature optima, calculated across the 1,000 temperature optima generated by the bootstrap replication of the regression. The full distribution of temperature optima from ref. 14 is shown in the gray box; as in ref. 14, darker red colors indicate cooler temperature optima and thus greater likelihood of negative impacts from warming. (*C* and *D*) The impact of anthropogenic climate forcing on annual economic growth rate, and accumulated impact on per capita GDP, for Norway and India.

with empirically derived nonlinear temperature–GDP response functions to calculate the counterfactual per capita GDP of individual countries over the past half century. Finally, we use those counterfactual country-level economic trajectories to calculate the impact of historical anthropogenic forcing on population-weighted country-level economic inequality, accounting for both uncertainty in the relationship between temperature and economic growth and uncertainty in the climate response to historical forcing.

Results

The estimated parabolic relationship between temperature and economic growth means that long-term warming will generally increase growth in cool countries and decrease growth in warm countries (Fig. 1). For example, for cooler countries such as Norway, warming moves the country-mean temperature closer to the empirical optimum (Fig. 1*B*), resulting in cumulative economic benefits (Fig. 1*C*). In contrast, for warm countries such as India, warming moves the country-mean temperature further from the optimum (Fig. 1*B*), resulting in cumulative losses (Fig. 1*D*).

As a result, anthropogenic climate forcing has decreased economic growth of countries in the low latitudes and increased economic growth of countries in the high latitudes (Fig. 2). The median losses exceed 25% for the 1961–2010 period (relative to a world without anthropogenic forcing) over large swaths of the tropics and subtropics (Fig. 2*A*), where most countries exhibit very high likelihood of negative impacts (Fig. 2 *C* and *D*), including >99% likelihood (*SI Appendix*, Table S1). The median gains can be at least as large in the high latitudes, where many countries exhibit >90% likelihood of positive impacts. Many countries in the middle latitudes exhibit median impacts smaller than ±10%, along with greater uncertainty in the sign of the response (particularly in the northern hemisphere). Thus, the global-scale pattern is of cool countries benefitting and warm countries suffering, with temperate countries exhibiting the greatest uncertainty.

Although this global pattern could be expected from the concave structure of the empirical temperature–growth relationship (Fig. 1*B*), such an outcome is not determined for historical climate forcing, because internal climate variability creates uncertainty in the sign and magnitude of regional temperature change (e.g., refs. 21 and 22). However, because the mean temperature response is positive across all land areas (Fig. 1*A*), and because the differences in temperature change between countries (Fig. 1*A*) are small compared with the range of country-mean temperatures (Fig. 1*B*), the median economic response is that countries that are currently warmer than the median optimum have experienced losses, while countries that are currently colder than the median optimum have experienced benefits (Fig. 3*A*).

Consistent with the strong spatial correlation between temperature and GDP (23), we find a positive relationship between current GDP and impact from historical warming, with lower per capita GDP generally associated with more negative impacts (Fig. 3*B*). Furthermore, at a given level of wealth, warmer countries have tended to experience more negative impacts, while cooler countries have tended to experience less negative—or in some cases more positive—impacts. Because the majority of the world's warmest countries are poor (Fig. 3 *A* and *B*), the majority of large negative impacts have been concentrated in poor countries (Fig. 3 *A* and *B*). Likewise, because the majority of the world's richest countries are temperate or cool, the median likelihood is that the majority of rich countries have benefited.

Consistent with the strong relationship between wealth, energy consumption, and CO_2 emissions (24–26), we also find a positive relationship between per capita cumulative emissions and impact from historical global warming (Fig. 3*C* and *SI Appendix*, Fig. S1). For example, over the 1961–2010 period, all 18 of the countries whose historical cumulative emissions are less than 10 ton CO_2 per capita have suffered negative economic impacts, with a median impact of −27% (relative to a world without anthropogenic forcing) (Fig. 3*C*). Likewise, of the 36 countries whose historical emissions are between 10 and 100 ton CO_2 per capita, 34 (94%) have suffered negative economic impacts, with a median impact of −24%. In contrast, of the 19 countries whose historical emissions exceed 300 ton CO_2 per capita, 14 (74%) have benefited from global warming, with a median benefit across those 14 countries of +13%.

The net effect of these economic impacts is that country-level inequality has very likely increased as a result of global warming (Fig. 4). For example, the ratio between the top and bottom population-weighted deciles [a common measure of economic inequality (9)] has become 25% larger (5th to 95th range of −6% to +114%) during the 1961–2010 period compared with a world

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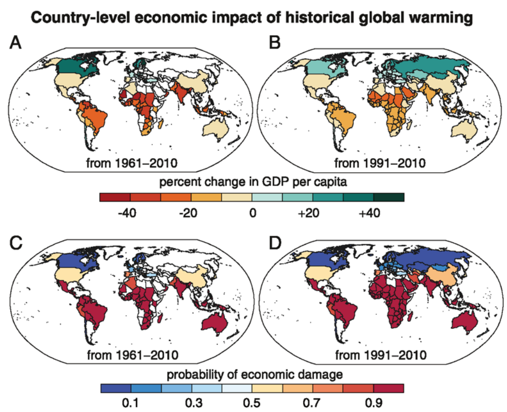

Fig. 2. Country-level economic response to global warming. (*A*) The median impact on country-level per capita GDP across the >20,000 realizations of the world without anthropogenic forcing, calculated for each country over the 1961–2010 period. (*B*) As in *A*, but for the 1991–2010 period. Differences in the presence/absence of countries between the 1961–2010 and 1991–2010 periods reflect differences in the availability of country-level economic data. Differences in the magnitude of country-level values between the 1961–2010 and 1991–2010 periods reflect the influence of accumulation time on the net accumulated economic impact. (*C* and *D*) The probability that historical anthropogenic forcing has resulted in economic damage, calculated as the percentage of the >20,000 realizations that show a decrease in per capita GDP relative to the counterfactual world without anthropogenic forcing.

without global warming, with ~90% likelihood that the ratio has increased (Fig. 4*C*). Likewise, the ratio between the top and bottom population-weighted quintiles [another common measure (9)] has become 45% larger (5th to 95th range of +10% to +99%), with ~99% likelihood that the ratio has increased. As a result, although overall between-country inequality has decreased substantially over the past half century (Fig. 4*A*, refs. 9 and 10), it is "very likely" (27) that global warming has slowed that decrease (Fig. 4 *A* and *C*).

The increase in inequality between countries has resulted primarily from warming-induced penalties in poor countries, along with warming-induced benefits in some rich countries (Figs. 2*A*, 3*B*, and 4*B*). We find that the poorest half of the population-weighted country-level economic distribution has become relatively more poor over the 1961–2010 period, including a median impact of −17% at the poorest decile, and −30% to −31% at the next three poorest deciles (Fig. 4*B*). In contrast, the top half of the population-weighted country-level economic distribution has likely suffered much less—and has a much higher likelihood of having benefited—than the bottom half of the distribution (Fig. 4*B*).

Discussion

Although some canonical uncertainties in quantifying future economic impacts are largely removed when focusing on the historical period—such as future discounting uncertainty (e.g., refs. 14, 28, and 29) and the limits of accounting for future changes that fall well outside of historical experience (14)—other uncertainties must be considered.

For example, uncertainty in the exact magnitude of the temperature optimum creates uncertainty in the sign of the historical climate impact in some countries (Fig. 2*C* and *SI Appendix*, Table S1). However, the sign of the impact on inequality is robust (Fig. 4*C*), primarily because the mean temperature of so many poor countries lies in the extreme warm tail of uncertainty in the optimum (Fig. 3 *A* and *B*). For these countries, it is "very likely" (27) that historical warming has reduced economic growth and lowered per capita GDP (Fig. 2*C* and *SI Appendix*, Table S1). As a result, although uncertainty in the magnitude of the response of regional temperature to historical forcing creates uncertainty in the magnitude of impact at a given decile of the country-level economic distribution (Fig. 4*B*), the sign of the impact on the lower deciles (Fig. 4*B*)—and therefore on inequality (Fig. 4*C*)—is robust.

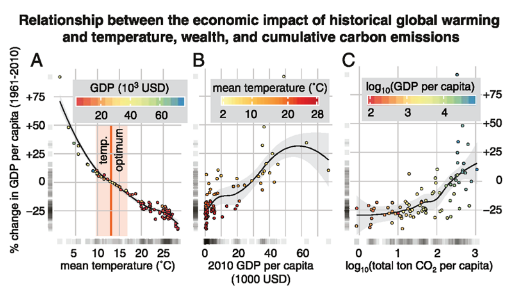

Fig. 3. Relationship between economic impact of global warming and country-level temperature, GDP, and cumulative CO_2 emissions. (*A*) The relationship between country-level mean annual temperature and median economic impact of anthropogenic forcing over the 1961–2010 period. The orange line shows the median temperature optimum reported by Burke et al. (14), and the orange envelope shows the 5–95% range. (*B*) The relationship between per capita GDP in 2010 and median economic impact of historical anthropogenic forcing over the 1961–2010 period. (*C*) The relationship between cumulative emissions over the 1961–2010 period (calculated from ref. 32) and median economic impact of historical anthropogenic forcing over the 1961–2010 period. (*A–C*) Gray strip plots show the density of points along the *x* and *y* axes. The black regression line and gray envelope show the 95% confidence interval of a locally weighted regression ("loess").

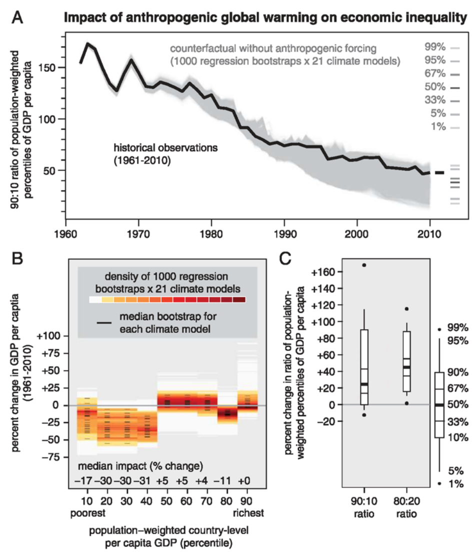

Fig. 4. Impact of global warming on country-level inequality over the past half century. (*A*) The ratio between the population-weighted 90th percentile and 10th percentile country-level per capita GDP for the historical observed time series and each of the >20,000 realizations of the world without anthropogenic forcing. (*B*) The density of the >20,000 realizations at each decile of the population-weighted country-level per capita GDP distribution. (*C*) The distribution across the >20,000 realizations of percent change in population-weighted 90:10 and 80:20 percentile ratios in the year 2010, relative to the present ratio. Calculations include only those countries that have continuous socioeconomic data from 1961 through 2010 ($n = 86$).

The sign of the inequality impact is also robust to the inclusion of lagged responses (*SI Appendix*, Table S2). Lagged responses can compensate the growth effects of temperature fluctuations, leading to decreases in both the growth benefit in cool countries and the growth penalty in warm countries (4). These lagged responses reduce the calculated magnitude and probability of warming-induced increases in economic inequality. However, even with a 5-y lag, there is still 66% likelihood that historical warming has increased country-level inequality.

The availability of socioeconomic data also creates uncertainty. Because growth effects cumulate, the length of time over which economic impacts are evaluated can meaningfully affect results (4, 12, 14). However, data availability creates an inherent tradeoff between evaluating fewer countries over a longer period and evaluating more countries over a shorter period. We repeat our primary analysis using a larger, shorter sample. Overall, the pattern of impact is robust, but the cumulative magnitude is larger over the longer period (Figs. 2 and 3 and *SI Appendix*, Fig. S1). This expansion over longer periods suggests that the full impact of warming since the Industrial Revolution has been even greater than the impact calculated over the past half century.

Our approach to quantifying the impact of global warming on economic inequality is also limited by its reliance on country-level relationships between temperature and economic growth. Our analysis focuses on country-level data because their wide availability (in both space and time) allows us to use empirical relationships to quantify how historical temperature changes have affected economic outcomes around the world. The impact of climate change on the evolution of within-country inequality is a critical question (e.g., ref. 2), but would require either strong assumptions about how within-country income distributions respond to aggregate shocks at the country level, or comprehensive subnational data on incomes (which are currently unavailable for most country-years around the world). Although our population weighting provides some indication of global-scale individual-level inequality (9), documenting the impact of global warming on within-country inequality remains an important challenge.

Many countries in our sample have experienced rapid urbanization and economic development for reasons unrelated to climate, and such trends could plausibly alter how economies respond to subsequent climate change. Because past work did not find statistically significant evidence that higher incomes reduce temperature sensitivities (4), we do not attempt to model this moderating effect here. However, if increasing urbanization or economic development has reduced the temperature sensitivity of economies over our study period, this effect will be implicitly included in our estimated impact of temperature on GDP growth and inequality—that is, we have estimated the effect of temperature on growth for economies that are rapidly urbanizing. Explicitly quantifying the role of these moderating influences is an important avenue for future work, as it will be critical for understanding how future climate change will affect the level and distribution of global income.

Trade between countries has likely already influenced the impacts of global warming on population-weighted inequality. First, a large part of the reduction in historical inequality during our sample period has been due to the unprecedented growth in incomes in East Asia [and particularly China (9, 10)], much of which was built on critical trading relationships with high-income countries. In a no-trade counterfactual, China would likely grow much less rapidly. Thus, because of China's large population and small sensitivity to historical warming (Fig. 2), repeating our analysis in a no-trade counterfactual would likely result in smaller reductions in per capita GDP in the lower deciles of the population-weighted income distribution (Fig. 4*B*). However, trade can also serve as a buffer against climate shocks, particularly in poor countries (e.g., ref. 30). Thus, the economic impacts of global warming—which has substantially increased the occurrence of extremes (e.g., ref. 21)—would likely have been even greater in poor countries in a no-trade counterfactual, amplifying the impact on between-country inequality.

Conclusions

It has been frequently observed that wealthy countries have benefited disproportionately from the activities that have caused global warming, while poor countries suffer disproportionately from the impacts (e.g., refs. 16, 17, 19, 25, and 26). Our results show that, in addition to the direct benefits of fossil fuel use, many wealthy countries have likely been made even more wealthy by the resulting global warming. Likewise, not only have poor countries not shared in the full benefits of energy consumption, but many have already been made poorer (in relative terms) by the energy consumption of wealthy countries. Given the magnitude of the warming-induced growth penalties that poor countries have already suffered, expansion of low-carbon energy sources can be expected to provide a substantial secondary development benefit (by curbing future warming-induced growth penalties), in addition to the primary benefits of increased energy access.

Materials and Methods

Climate Model Experiments. We compare the Historical and Natural climate model simulations from the CMIP5 archive (20). As in Burke et al. (14), we analyze the subselection of CMIP5 realizations analyzed by the Intergovernmental Panel on Climate Change (IPCC) (31). For the Natural experiment, this includes one realization each from 21 of the participating global climate models, which are paired with the 21 corresponding Historical realizations. Note that although the socioeconomic data are available through 2010, the CMIP5 experimental protocol for the Historical and Natural experiments ends in 2005. Thus, as in Burke et al. (14), we use the IPCC's 20-y historical baseline period (1986–2005) as the baseline period for climate model bias correction.

For each country, we create 21 counterfactual historical temperature timeseries $T_{NoAnthro}$, which remove the influence of anthropogenic forcing simulated by each of the 21 climate models. Our approach to creating the counterfactual timeseries follows the widely applied "delta method" of climate model bias correction, in which the model-simulated change in the mean is applied to the observed timeseries. For each country *c*, we first calculate the observed country-level population-weighted mean annual temperature timeseries T_{Obs} for the 1961–2010 time period covered by the socioeconomic data, following Burke et al. (14). Then, for each country *c* and climate model *m*, we calculate the difference in country-level population-weighted mean temperature between the Historical and Natural CMIP5 simulations, both for the 20-y period centered on the beginning of the socioeconomic data (1951–1970), and for the 20-y historical baseline period used by the IPCC (1986–2005). We then linearize the difference between the Historical and Natural simulations over the 1961–2010 period, such that the difference in 1961 is equal to the difference in the Historical and Natural means during the 20-y period centered on 1961 (1951–1970), and the difference in 2010 is equal to the difference in the Historical and Natural means during the IPCC's 20-y baseline period (1986–2005). Finally, for each year *t* in the 1961–2010 observed temperature timeseries, we add the linearized *Natural* minus *Historical* difference ΔT for that year:

$$T_{NoAnthro}[t] = T_{Obs}[t] + \Delta T[t].$$

This process generates, for each country, an ensemble of 21 counterfactual timeseries $T_{NoAnthro}$. This 21-member ensemble reflects a combination of uncertainty in the climate response to external forcings and uncertainty arising from internal climate system variability, but removes biases in the climate model simulation of the absolute temperature magnitude and of the interannual temperature variability. [The $T_{NoAnthro}$ timeseries corresponds to the counterfactual timeseries used in Diffenbaugh et al. (21) to calculate the contribution of the observed trend to the extreme event magnitude, except that in this case the magnitude of the counterfactual trend is calculated from the CMIP5 Natural forcing simulation.]

Impact of Historical Temperature Change on Economic Growth. Burke et al. (4, 14) used historical data to quantify the empirical relationship between variations in country-level temperature and country-level annual growth in per capita GDP, allowing for the marginal effect of annual temperature deviations to vary nonlinearly as a function of country-level mean temperature. As described in detail in Burke et al. (4, 14), the equation for the panel fixed-effects model is as follows:

$$\Delta\log(Y_{it}) = \beta_1 T_{it} + \beta_2 T_{it}^2 + \lambda_1 P_{it} + \lambda_2 P_{it}^2 + \mu_i + \upsilon_t + \theta_{1i}t + \theta_{2i}t^2 + \varepsilon_{it},$$

where Y_{it} is per capita GDP in country *i* in year *t*, *T* is the average temperature in year *t*, *P* is the average precipitation in year *t*, μ_i are country-fixed effects, υ_t are year-fixed effects, and $\theta_{1i}t + \theta_{2i}t^2$ are country-specific linear and quadratic time trends.

In the current study, we repeat the primary regression calculation described in Burke et al. (14), using historical data from 1961 to 2010, and bootstrapping with replacement to estimate a separate response function for each of 1,000 resamples, which we denote f_b. The uncertainty in the magnitude of the temperature optimum (Fig. 1*B*) creates uncertainty in exactly which countries are likely to benefit or be penalized at different levels of warming, and is the largest source of uncertainty in the response of GDP growth to elevated levels of global climate forcing (14).

We quantify the uncertainty in economic damages arising from uncertainty in the temperature optimum (e.g., Figs. 2 and 4 and *SI Appendix*, Table S1), as well as the uncertainty arising from lagged responses to temperature fluctuations (*SI Appendix*, Table S2). We also explore additional aspects of the relationship between temperature and GDP growth. For example, we find that historical temperature fluctuations explain on average 8.6% of the overall variation in country-level annual income growth fluctuations during our study period (*SI Appendix*, Fig. S2). Likewise, given the shape of the temperature–growth response function (Fig. 1*B*), temperature fluctuations around a stable mean will induce a negative trend in per capita GDP. However, we find that the magnitude of this effect is small compared with the impact of long-term warming (*SI Appendix*, Fig. S3).

Whereas Burke et al. (4, 14) projected economic impacts under future emissions scenarios, we calculate the accumulated economic impacts of historical temperature change. For each country *c* in each year *t*, we compare economic growth under historical observed temperatures (T_{Obs}) with predicted growth under counterfactual temperatures ($T_{NoAnthro}$). We repeat this comparison for each climate model *m* and each bootstrap *j*, yielding more than 20,000 realizations of the impact of anthropogenic forcing on economic growth in each country.

We first initialize the analysis in each country with the observed per capita GDP from the starting year $t = 0$ of the socioeconomic data (e.g., $GDPcap_{Obs}[1961]$). Then, for each year *t* and using the temperature–growth response functions *f* estimated above, we calculate the difference in growth rate between the observed temperature and the counterfactual temperature (Fig. 1 *C* and *D*):

$$\Delta Growth[t] = f(T_{NoAnthro}[t]) - f(T_{Obs}[t]).$$

We then add that difference $\Delta Growth[t]$ to the actual observed growth rate $Growth_{Obs}[t]$ to calculate the counterfactual growth rate $Growth_{NoAnthro}[t]$:

$$Growth_{NoAnthro}[t] = Growth_{Obs}[t] + \Delta Growth[t].$$

We then multiply this counterfactual growth $Growth_{NoAnthro}[t]$ by the accumulated counterfactual per capita GDP in the previous year ($GDPcap_{NoAnthro}[t-1]$) to calculate current-year counterfactual per capita GDP:

$$GDPcap_{NoAnthro}[t] = GDPcap_{NoAnthro}[t-1] + (GDPcap_{NoAnthro}[t-1]^{*} Growth_{NoAnthro}[t]).$$

We repeat this process through the last year of the socioeconomic data (2010), for each country in the GDP dataset.

Finally, we calculate the percent difference between the actual observed per capita GDP ($GDPcap_{Obs}$) and the per capita GDP calculated for the counterfactual temperature timeseries ($GDPcap_{NoAnthro}$) in the last year of the socioeconomic data (2010):

$$\Delta GDPcap = [(GDPcap_{Obs}[2010] - GDPcap_{NoAnthro}[2010]) / GDPcap_{NoAnthro}[2010]] \times 100\%.$$

For each country *c*, we calculate $GDPcap_{NoAnthro}$ and $\Delta GDPcap$ for each of the 1,000 bootstrapped response functions f_b, applied to the counterfactual temperature timeseries $T_{NoAnthro}$ from each of the 21 global climate models (thus yielding more than 20,000 values of $GDPcap_{NoAnthro}$ and $\Delta GDPcap$ for each country).

Our primary analysis is focused on quantifying the impacts that historical global warming has had during the full period for which socioeconomic data are available (1961–2010). However, because the socioeconomic data do not extend to 1961 for a large number of countries, we repeat our analysis for the 1991–2010 period. For all analyses that start in 1961, we analyze only those countries that have continuous socioeconomic data from 1961 through 2010 ($n = 86$); for all analyses that start in 1991, we analyze only those countries that have continuous socioeconomic data from 1991 through 2010 ($n = 151$). Observed and estimated counterfactual temperatures and growth rates are the same for the years that overlap between the two periods, but growth rates are cumulated over 30 more years in the longer period, yielding larger (in absolute value) impacts on economic outcomes by the end of the period (Fig. 2).

Quantifying the Impact of Historical Global Warming on Economic Inequality. A number of measures of economic inequality have been developed (9). Given the limited availability of long timeseries of subnational economic data, investigations of changes in global inequality often rely on country-level metrics (e.g., refs. 9 and 10). However, when using country-level metrics, weighting by country-level population is critical to accurately capture trends in global inequality (9).

We measure global economic inequality using the ratio of the top and bottom decile ("90:10 ratio") and top and bottom quintile ("80:20 ratio") of the population-weighted country-level per capita GDP distribution. Both metrics are included among "eight of the most popular" indexes of income inequality identified by Sala-i-Martin (9). According to Sala-i-Martin (9), "The top-20-percent-to-bottom-20-percent is the ratio of the income of the person located at the top twentieth centile divided by the income of the corresponding person at the bottom twentieth centile. A similar definition applies to the top-10-percent-to-bottom-10-percent ratio." Because of the lack of availability of long timeseries of subnational economic data, we calculate these ratios using the respective percentiles of the population-weighted empirical CDF of country-level per capita GDP values (*SI Appendix*, Fig. S4).

We first calculate the percent difference in per capita GDP for each decile of the population-weighted country-level GDP distribution. To do so, we calculate the deciles of country-level population-weighted per capita GDP, using the countries in the 1961–2010 dataset. For each year t in the observed country-level per capita GDP dataset ($GDPcap_{Obs}$), we calculate the pth percentile population-weighted GDP as the country-level per capita GDP below which the sum of the country-level populations represents p percent of the total population of countries in the 1961–2010 dataset (*SI Appendix*, Fig. S4). For example, we calculate the 10th percentile population-weighted GDP as the country-level per capita GDP for which the total population of countries with lower per capita GDP is 10% of the total population of countries in the 1961–2010 dataset, and so on for each decile.

Next, we calculate the deciles of country-level population-weighted per capita GDP in each year t of each bootstrap j and climate model m of the counterfactual world without anthropogenic climate forcing ($GDPcap_{NoAnthro}$). Then, for the year 2010 in each bootstrap j and climate model m, we calculate the percent difference between the observed population-weighted decile value and the counterfactual population-weighted decile value (as described for $\Delta GDPcap$ above). For the differences in each population-weighted decile, we calculate the density distribution across all 1,000 bootstrap regressions from all 21 climate models, as well as the median value across the 1,000 bootstrap regressions for each climate model.

Finally, we quantify the between-country population-weighted economic inequality $GDPcapHigh{:}Low$ as the ratio between the higher percentile (e.g., 90th) and lower percentile (e.g., 10th) population-weighted per capita GDP. We first calculate $GDPcapHigh{:}Low$ in each year t of the observations ($GDPcapHigh{:}Low_{Obs}$), and in each year t of the counterfactual world without anthropogenic climate forcing ($GDPcapHigh{:}Low_{NoAnthro}$). Then, for each bootstrap j and climate model m, we calculate the percent difference between the observed population-weighted inequality $GDPcapHigh{:}Low_{Obs}$ and the counterfactual population-weighted inequality $GDPcapHigh{:}Low_{NoAnthro}$ in the year 2010:

$$\Delta GDPcapHigh{:}Low = [(GDPcapHigh{:}Low_{Obs}[2010] - GDPcapHigh{:}Low_{NoAnthro}[2010]) / GDPcapHigh{:}Low_{NoAnthro}[2010]] \times 100\%.$$

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LETTER

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Large potential reduction in economic damages under UN mitigation targets

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International climate change agreements typically specify global warming thresholds as policy targets[1], but the relative economic benefits of achieving these temperature targets remain poorly understood[2,3]. Uncertainties include the spatial pattern of temperature change, how global and regional economic output will respond to these changes in temperature, and the willingness of societies to trade present for future consumption. Here we combine historical evidence[4] with national-level climate[5] and socioeconomic[6] projections to quantify the economic damages associated with the United Nations (UN) targets of 1.5 °C and 2 °C global warming, and those associated with current UN national-level mitigation commitments (which together approach 3 °C warming[7]). We find that by the end of this century, there is a more than 75% chance that limiting warming to 1.5 °C would reduce economic damages relative to 2 °C, and a more than 60% chance that the accumulated global benefits will exceed US$20 trillion under a 3% discount rate (2010 US dollars). We also estimate that 71% of countries—representing 90% of the global population—have a more than 75% chance of experiencing reduced economic damages at 1.5 °C, with poorer countries benefiting most. Our results could understate the benefits of limiting warming to 1.5 °C if unprecedented extreme outcomes, such as large-scale sea level rise[8], occur for warming of 2 °C but not for warming of 1.5 °C. Inclusion of other unquantified sources of uncertainty, such as uncertainty in secular growth rates beyond that contained in existing socioeconomic scenarios, could also result in less precise impact estimates. We find considerably greater reductions in global economic output beyond 2 °C. Relative to a world that did not warm beyond 2000–2010 levels, we project 15%–25% reductions in per capita output by 2100 for the 2.5–3 °C of global warming implied by current national commitments[7], and reductions of more than 30% for 4 °C warming. Our results therefore suggest that achieving the 1.5 °C target is likely to reduce aggregate damages and lessen global inequality, and that failing to meet the 2 °C target is likely to increase economic damages substantially.

Anticipating the potential impacts of climate change is central to planning appropriate policy responses, including how to allocate resources among mitigation and adaptation options. By committing the international community to holding global warming to "well below 2 °C above pre-industrial levels" and pursuing a 1.5 °C target[1], the UN Paris Agreement increased the need for quantitative analysis of uncertainties in the costs and benefits of achieving highly resolved warming targets. In particular, because mitigation costs are thought to rise rapidly for more stringent targets[9], understanding the value of avoided impacts (what we term 'benefits') is central to evaluating the 1.5 °C target. Quantification of these potential benefits and their uncertainties is needed at the aggregate global level to guide coordinated global policy, as well as at a more local level to understand the distributional impacts of global policy choices[10]. Further, because the current national commitments imply warming[7] of 2.5–3 °C, quantifying the impact of exceeding the 1.5 °C and 2 °C targets is also critical to understanding the implications of policy choices.

Here we estimate the global and country-specific economic impacts of limiting warming to 1.5 °C relative to 2 °C, as well as the global impacts of projected warming under current mitigation commitments, separate from any mitigation costs incurred in achieving those targets. We measure potential global and country-level damages using gross domestic product (GDP), the total value of goods and services produced in a country in a given year. GDP is clearly an incomplete summary of the benefits of mitigation, and it cannot easily diagnose many sector-specific impacts (for example, in crop agriculture versus manufacturing). However, it does capture how sector-specific impacts interact and aggregate—a traditional challenge for sector-specific empirical work and model-based approaches to aggregation[11]. GDP also remains highly relevant to policy discussions, and the level and uncertainty in GDP impacts associated with the UN temperature targets has not been formally quantified.

We construct a probabilistic framework (Fig. 1) that incorporates uncertainty in (1) the historical relationship between temperature variability and economic growth, (2) the spatial pattern of future mean annual temperature change associated with a given level of aggregate emissions, (3) the future rate and pattern of economic development absent climate change, and (4) how future damages should be discounted.

To estimate the historical relationship between temperature and GDP, we use annual measurements of average temperature and growth in GDP per capita from 165 countries over the years 1960–2010. Following Burke et al.[4], we use a fixed-effects estimator that isolates the effect of temperature fluctuations from other time-invariant and time-varying factors that might be correlated with both temperature and economic output, and we estimate nonlinear response functions that allow the marginal effect of warming to differ as a function of countries' average temperatures. To quantify uncertainty in this historical relationship, we employ multiple bootstrapping approaches, estimating a separate response function for each re-sample (see Methods).

All estimated response functions relating GDP growth to temperature display a similar concave shape (Fig. 1a), suggesting that additional warming accelerates growth in cooler regions and slows growth in warmer regions. These findings are consistent with a large body of work demonstrating nonlinear responses of economic outcomes to changes in temperature[12–17]. However, there is uncertainty in the temperature at which additional warming begins to generate damages rather than benefits (the 'temperature optimum'), with a median estimate of 13.1 °C but a 5%–95% range of 9.7–16.8 °C. Because much of today's GDP is produced in areas just beyond the median estimated optimal temperature (density plot, bottom of Fig. 1a), uncertainty in this optimum leads to substantial overall uncertainty in both the magnitude and sign of the impact of additional warming.

We project impacts under different levels of future warming by combining these historical response functions with the Intergovernmental Panel on Climate Change (IPCC) projections of future climate[18]. The climate model experiments used by the IPCC involve dozens of general circulation models (GCMs) run under four forcing pathways (called

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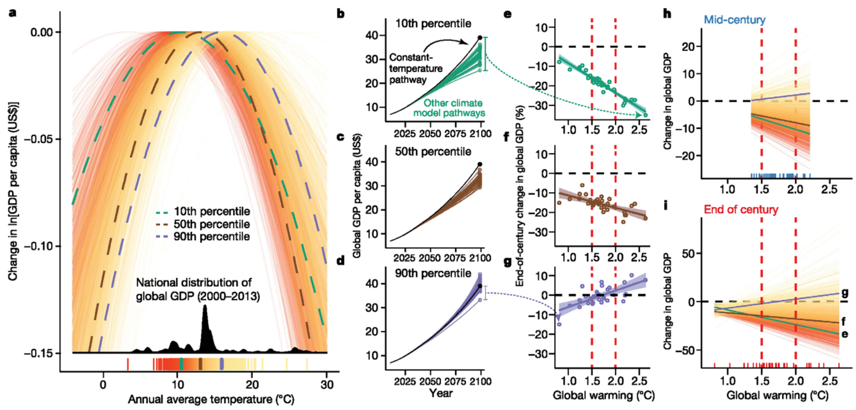

Fig. 1 | Deriving impact projections. a, Historical response of per capita GDP growth rates to temperature. Each curve is the response function estimated from one of 1,000 bootstraps of a historical regression with colour corresponding to the temperature at which it optimizes (redder colours for cooler optima). The green, brown and purple dashed curves highlight bootstraps at the 10th, 50th and 90th percentiles of optimizing temperatures, respectively. The rug plot at the bottom shows the distribution of optimizing temperatures across bootstraps using the same colour scheme. The density plot in black shows the GDP-weighted distribution of baseline average national temperatures. **b–d**, Projected future economic pathways under different historical response functions. Black lines represent the pathway of global GDP per capita, assuming no future warming. Coloured lines are pathways corresponding to the response functions at the 10th, 50th and 90th percentiles highlighted in **a**, under warming projections from 32 GCMs consistent with RCP2.6. Points represent values projected for 2099. **e–g**, Projected climate impact on global GDP per capita by 2099 for the same response functions, equivalent to the percentage difference between the black points and coloured points in **b–d**. The warming on the *x* axes is the global warming projected for 2099 by GCMs running RCP2.6, relative to a pre-industrial benchmark. Red vertical dashed lines mark 1.5 °C and 2.0 °C warming. Linear ordinary least-squares models are fitted for each of the response functions, with the slope estimating the per-degree impact of global warming on global GDP per capita. Shaded areas represent the 95% confidence interval of the ordinary least-squares fit. **i**, The linear fits from **e–g**, but for all bootstrapped response functions instead of just the three highlighted in **b–g**. The colours correspond to the optimizing temperatures of the response functions, as in **a**. The rug plot at the bottom marks global warming for the end of the century (2099) projected by the 32 GCMs consistent with RCP2.6, equivalent to the *x*-axis values of points in **e–g**. **h**, Equivalent to **i** but for mid-century (2049) projections based on 42 GCMs consistent with RCP4.5.

representative concentration pathways, or RCPs). Each GCM realization contains a temperature trajectory for each country and, in aggregate, for the globe. Because temperature affects both the level and the growth rate of economic output[4,11], and because growth effects compound over time, the projected differential impacts of 1.5 °C versus 2 °C are a function of the time horizon. We calculate differential impacts under the two targets using temperature changes for the mid-century (2046–2065) and end-of-century (2081–2100) periods used by the IPCC, focusing on output from those RCPs whose ensemble range spans 1.5 °C and 2 °C for a given time period (Methods). We use projections from the relevant shared socioeconomic pathways (SSPs) to define the secular evolution of population and economic development[6,19], (Fig. 1b–d, Extended Data Fig. 2).

Economic impacts are calculated relative to a constant-temperature counterfactual and are then aggregated globally (weighting by population), resulting in a unique estimate of global impact for each bootstrap–GCM–SSP–year combination. We present two measures of these relative impacts: the percentage difference in annual GDP at the end of the chosen projection period and the discounted present value of absolute GDP differences accumulated over that span. For the second measure we employ a range of discounting schemes, including fixed rates of 2.5%–5% per annum (where a 5% discount rate assumes that society values a given amount of consumption in one year roughly 5% less than it values it today) and time-varying rates that depend on the levels of and uncertainty in realized growth (Methods).

We estimate the benefits of 1.5 °C versus 2 °C by fitting a linear least-squares regression relating either measure of relative economic impact to the global warming projected by each GCM that archives the RCP (Fig. 1e–g). We repeat this procedure for every bootstrapped response function to arrive at a distribution of estimated impacts for the chosen combination of GCM, SSP and projection period. See Methods for a full derivation.

Most response functions generate more negative global impacts at 2 °C than at 1.5 °C (Fig. 1h–i, Extended Data Fig. 2). Cooler estimated historical optima (red colours) generate steeper negative responses to additional warming, implying greater benefits from more stringent mitigation. We estimate that limiting warming to 1.5 °C instead of 2 °C by mid-century would lead to an increase in global GDP of 1.5%–2.0% (median estimate; Fig. 2a) and US$7.7–11.1 trillion in discounted avoided damages under a 3% fixed annual discount rate. Meeting these targets at the end of the century is estimated to lead to median gains in global GDP per capita of 3.4% and discounted avoided damages of US$36.4 trillion.

We use the distributions of bootstrapped estimated impacts to quantify the probability that more stringent mitigation yields benefits of different magnitudes (Extended Data Table 1). We estimate that achieving the 1.5 °C target at mid-century (2046–2065) would lead to a 68%–76% chance of overall cumulative net benefit relative to 2 °C under a fixed 3% discount rate. Under the same discount rate, we estimate a 43%–53% chance of discounted cumulative benefits exceeding US$10 trillion and a 4%–8% chance of exceeding $30 trillion, which is about 40% of current global GDP. For the end of the century (2081–2100), we estimate a >75% chance of net gain in per capita global GDP, an approximately 38% chance that benefits exceed US$50 trillion, and

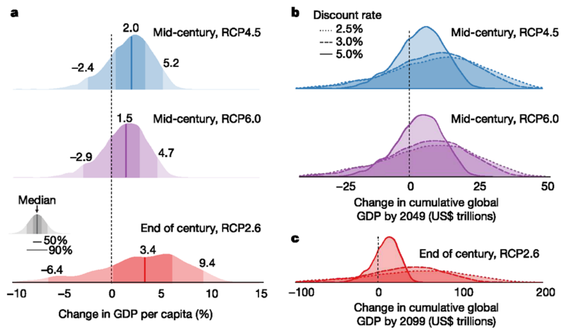

Fig. 2 | Global impact of limiting global warming to 1.5 °C relative to 2 °C. a, Probability distribution of the percentage change in global GDP per capita for 1.5 °C versus 2 °C by mid-century and by the end of the century, as derived from the slopes of the linear fits across response functions illustrated in Fig. 1h–i. Positive values indicate reduced damages at 1.5 °C of global warming as compared to 2 °C. Values above distribution report percentage changes at the 10th, 50th and 90th percentiles of distribution. **b,** Probability distribution of the change in cumulative global GDP by mid-century, assuming discount rates of 2.5% (dotted line), 3% (dashed line) and 5% (filled line). **c,** The equivalent for the end of the century.

an approximately 5% chance that benefits exceed US$100 trillion (3% discount rate; Extended Data Table 2).

While end-of-century estimates of the magnitude of absolute impacts are sensitive to choices about discounting (Extended Data Fig. 3, Extended Data Table 1), estimates of the probability of positive benefits are much less so (Extended Data Tables 2 and 3). Results are also relatively insensitive to alternative bootstrap resampling approaches, to different SSPs, and to alternative assumptions about the time path of future warming for a given RCP (Extended Data Figs. 4, 5). Inclusion of additional lags of temperature in the historical regression—a common

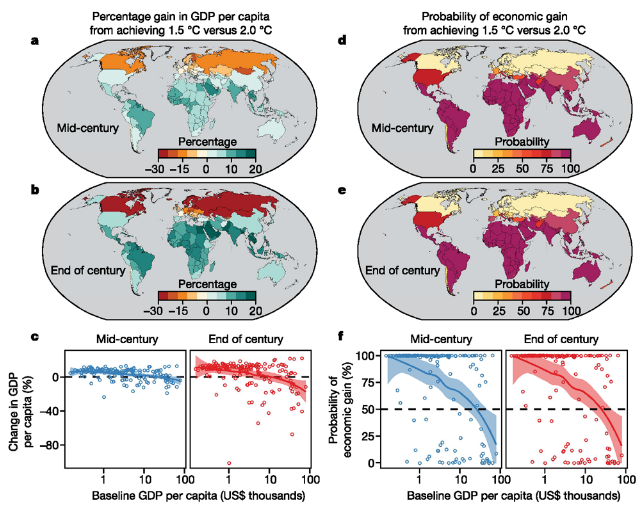

Fig. 3 | Country-level impact of limiting global warming to 1.5 °C relative to 2 °C. a, b, Median estimates of impacts on change in GDP per capita under 1.5 °C versus 2 °C, for mid-century and the end of the century. Positive values indicate reduced damages at 1.5 °C of global warming as compared to 2 °C. **c,** Median estimated impacts as a function of each country's baseline GDP per capita, with each country weighted equally. Lines represent local polynomial regression fits to the data with the corresponding 95% confidence intervals shaded in grey. **d–f,** As in **a–c**, but for the probability of per capita GDP gain, calculated as the percentage of bootstrap response functions projecting a net gain in a country's GDP per capita under 1.5 °C of global warming as compared to 2 °C.

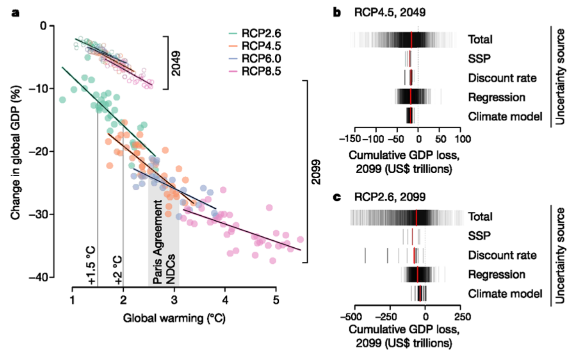

Fig. 4 | The impact of global warming on global GDP per capita, relative to a world without warming, for different forcing levels. a, Projected percentage change in global GDP for different climate models under different RCP forcing scenarios, relative to a no-warming baseline (median bootstrap, SSP1). Colours denote different RCPs. Unfilled points show mid-century projections, filled points show end-of-century projections. Vertical lines show the UN temperature targets as well as the range of estimates of end-of-century warming under current Paris commitments[7]. Warming is relative to pre-industrial levels. **b, c,** Sources of uncertainty in estimates of global warming on cumulative global GDP loss for a given forcing level. Total uncertainty in the impact of warming on global GDP under a given forcing scenario is a combination of uncertainty in how economies respond to warming ('historical regression uncertainty'), uncertainty across climate models in the amount and pattern of warming for a given level of forcing ('climate model uncertainty'), uncertainty in baseline future growth rates across baseline socioeconomic scenarios ('SSP uncertainty'), and plausible alternatives for how to specify the discount rate ('discount rate uncertainty'). Values show cumulative global GDP losses in trillions of US$ for mid-century under RCP4.5 (**b**) and the end of the century under RCP2.6 (**c**), either with all factors allowed to vary ('total uncertainty') or with the listed factor allowed to vary and all others fixed at their median (see Methods). Each vertical line is a point estimate; for example, with 32 climate models running RCP2.6 there are 32 estimates shown for 'climate model uncertainty' in **c**. Red lines are the median estimate across each uncertainty distribution.

approach to capturing persistent growth effects[11]—amplifies the effect of temperature on growth rates and results in larger estimates of benefits under 1.5 °C (Extended Data Fig. 4). Other potential sources of uncertainty, such as uncertainty in the secular rate of growth beyond the scenarios prescribed by the SSPs, were not quantified and could increase overall impact uncertainty.

At the country level, both the magnitude and the uncertainty of potential benefits are highly non-uniform. We find that 71% of countries—encompassing about 90% of projected global population—exhibit a >75% chance of experiencing positive economic benefits at 1.5 °C relative to 2 °C (Fig. 3), and 59% of countries exhibit a >99% chance. These countries include the three largest economies (the USA has a 76% chance of positive benefits; China 85%; Japan 81%) (Fig. 3, maps). They also include a large fraction of the world's poorest countries, with the likelihood of economic gains rising rapidly at lower levels of GDP per capita (Fig. 3c, f). Many of the countries that exhibit a high probability of economic benefits from 1.5 °C are concentrated in the tropics and sub-tropics, where both current and future temperatures are warmer than the economic optimum[4]. As a result, even small reductions in future warming in these countries can generate substantial increases in per capita GDP, with many countries in the tropics exhibiting per capita GDP 10%–20% higher at 1.5 °C than 2 °C by the end of the century (Fig. 3a, b, d, e). The opposite is true for a smaller number of high-latitude countries, where 1.5 °C is estimated to slow growth and generate a high probability of negative impacts relative to 2 °C. Achieving the 1.5 °C target will thus have unequal consequences, with today's poorest countries benefiting the most.

Despite the Paris Agreement's focus on the 1.5 °C and 2 °C targets, its actual Nationally Determined Contributions (NDCs) are instead consistent with 2.5–3 °C of global warming[7]. We estimate that this level of warming could lead to a reduction in global GDP as high as 10% by mid-century and 15%–25% by the end of the century (median estimates across SSPs; Fig. 4 and Extended Data Fig. 6), relative to a world that did not warm beyond 2000–2010 levels. In addition, failing to meet the NDC commitments is likely to lead to reductions in global GDP that exceed 25% by the end of the century. Uncertainty in these estimates is driven much more by uncertainty in economic parameters—namely, the economic response to warming and the discount rate—than by uncertainty in the pattern and magnitude of temperature change reflected in the climate model ensemble (Fig. 4b and c), highlighting the importance of better constraining these economic parameters[20].

Because our future impact estimates are based on observed historical economic responses to temperature variability, our projections will misstate impacts if the relationship between future annual temperatures and climatic extremes differs from what has occurred historically, or if future societies respond differently from societies in the recent past—although there is growing evidence that economic development might not fundamentally alter these economy–environment linkages[4,15–17]. We also cannot account for historically unprecedented changes, such as large-scale loss of land ice and associated sea level rise, which are more likely to occur[8,21] at 2 °C than 1.5 °C and are expected to exacerbate impacts[22,23].

To support policy decisions, our estimates of avoided damages need to be compared against the costs of meeting the UN targets. To our knowledge, no comparable estimates of global abatement costs through to the end of the century currently exist. However, a recent estimate[24] suggests that achieving emissions levels in 2030 that are consistent with the 1.5 °C target will lead to approximately US$300 billion in additional (non-discounted) abatement costs relative to emissions consistent with 2 °C. This estimate of abatement costs is >30 times smaller than our median estimate of (discounted) mid-century avoided damages.

Not accounting for abatement costs, our results suggest that 1.5 °C global warming is "likely"[25] to result in substantial economic benefits relative to 2 °C, with foregone damages probably in the tens of trillions of dollars and 59% of countries "virtually certain"[25] to benefit. Given that most of these countries feature large populations or high poverty rates or both, our results suggest that achieving more stringent mitigation targets will probably generate a net global benefit, with particularly large benefits for the poorest populations.

Online content

Any Methods, including any statements of data availability and Nature Research reporting summaries, along with any additional references and Source Data files, are available in the online version of the paper at https://doi.org/10.1038/s41586-018-0071-9.

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METHODS

Deriving the historical response function. To understand the historical relationship between temperature and economic output, we assemble annual data on country-level GDP per capita from the World Bank's World Development Indicators, using data on 165 countries over the period 1960 to 2010. Growth is computed as the first difference of the natural logarithm of the annual purchasing power parity-adjusted per capita GDP series in each country. These data are then merged with temperature and precipitation data from the University of Delaware[26].The gridded monthly temperature and precipitation data are aggregated temporally to the annual level and spatially to the country level. We then follow ref. [4] and estimate a panel fixed effects model:

$$\Delta\log(y_{it}) = \beta_1 T_{it} + \beta_2 T_{it}^2 + \lambda_1 P_{it} + \lambda_2 P_{it}^2 + \mu_i + \upsilon_t + \theta_{1i} t + \theta_{2i} t^2 + \varepsilon_{it} \quad (1)$$

where y_{it} is per capita GDP in country i in year t, T and P are the average temperature and precipitation in year t, μ_i are country-fixed effects (dummies) that control for time-invariant differences between countries, υ_t are year-fixed effects that account for common global shocks in a given year, and $\theta_{1i}t + \theta_{2i}t^2$ are country-specific linear and quadratic time trends, which allow temperature and growth to evolve flexibly at the country level.

Equation (1) is estimated simultaneously on our global sample of country-years ($N = 6{,}584$). Point estimates for β_1 and β_2 are statistically significant in this regression ($\beta_1 = 0.0127$, standard error 0.0032, $P < 0.001$; $\beta_2 = -0.0005$, standard error 0.0001, $P < 0.001$).

Equation (1) assumes that there is a single response function (described by β_1 and β_2) that specifies the overall global relationship between income growth and changes in temperature, but that individual countries can respond differently to warming as a function of their average temperature (which can be seen by differentiating equation (1) with respect to temperature). Past work has shown that average temperature—rather than other correlated factors such as average income—is the main source of heterogeneity in how countries' income growth responds to changes in temperature and that estimates of β_1 and β_2 are highly robust to alternative specifications of the fixed effects and time controls[4].

An additional concern is that countries trade with one another and that unobserved temperature shocks across a trading network might lead to biased coefficient estimates in equation (1). However, if temperature shocks are uncorrelated across trading partners, then estimates of β_1 and β_2 still represent unbiased estimates of own-country temperature shocks on output; if shocks are correlated across trading partners, then β_1 and β_2 represent reduced-form estimates of the net effect in a given country of correlated shocks across that country's trading network. The main concern for our analysis is if the future pattern of temperature change should not correspond to the spatial pattern of historical shocks; however, we are unaware of any relevant research in climate science.

To quantify uncertainty in estimates of β_1 and β_2, we implement multiple bootstrapping strategies: (1) Sampling by country. From our list of 165 countries, draw (with replacement) a 165-element list of countries—which will omit some countries and contain duplicates of others—and retain all years of data for the selected countries; this is repeated 1,000 times, drawing a new country sample each time, re-estimating equation (1), and retaining estimates of β_1 and β_2. This approach allows for arbitrary correlation in residuals within countries over time. (2) Sampling by year. This allows for potential cross-sectional correlation in residuals in a given year, and is also repeated 1,000 times. (3) Sampling by five-year block. We divide the data into 10 five-year blocks (that is, 1961–65, 1966–70, and so on through 2010), and sample with replacement from these 10 blocks. This allows for both temporal and cross-sectional dependence in residuals, for example, as caused by global recessions that last multiple years.

Our main results use strategy (1) (sampling by country), but we show that our results are robust, regardless of the strategy used. In what follows, the bootstrapped response functions $h^j(T_{it}) = \hat{\beta}_1^j T_{it} + \hat{\beta}_2^j T_{it}^2$ are indexed with j, where $j \in (1, 2, \ldots, 1{,}000)$.

For each $h^j(T_{it})$, we define the 'temperature optimum' as the maximum of the quadratic function, that is, $\frac{-\beta_1^j}{2 \times \beta_2^j}$ (this is always a maximum because all estimates yield $\beta_1^j > 0$ and $\beta_2^j < 0$).

To ensure that equation (1) is capturing growth effects and not just level effects, we re-estimate equation (1) with additional lags of temperature (and their squares)[4,11]. This is important because countries' economic output could 'catch up' in the year following a temperature shock; this catch-up behaviour would not be captured in a model containing only contemporaneous temperature variables, but would be captured in a model that includes lags of temperature and where overall temperature effects are computed by summing contemporaneous and lagged coefficients[11]. We thus estimate equation (1) with up to five lags l of temperature, that is,:

$$h^j(T_{it}) = \sum_{l=0}^{5} \{\hat{\beta}_{1,l}^j T_{it-l} + \hat{\beta}_{2,l}^j T_{it-l}^2\} \quad (2)$$

and re-estimate all calculations below with results from these distributed lag models. Our main results with this sensitivity test are shown in Extended Data Fig. 4.

Climate model simulations. To follow the IPCC protocols, we analyse the exact climate model realizations and time periods used by the IPCC in its most recent assessment report[5]. These climate model realizations were generated by the World Climate Research Program under Phase Five of the Climate Model Intercomparison Project (CMIP5)[18]. For the historical baseline experiment, the CMIP5 protocol ran each climate model from the mid-1800s to 2005, using the historical climate forcings. For the future scenarios, the CMIP5 protocol used the RCPs, which assume different levels of climate forcing going forward in the 21st century. In total, there are four: RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Following the IPCC protocols, we use the same historical baseline period (1986–2005) and RCP future periods (2046–2065 and 2081–2100) as did the IPCC. In our bias correction method (see below), there are three RCPs whose global warming ranges are most consistent with the 1.5 °C and 2 °C targets in these IPCC scenario time periods: RCP4.5 and RCP6.0 during the 2046–2065 period, and RCP2.6 during the 2081–2100 period. (RCP2.6 is the only RCP scenario in which some models project global warming of less than 1.5 °C for the end of the century; for mid-century, none of the RCP2.6 model runs project warming above 2 °C, and so we do not utilize RCP2.6 for mid-century). We therefore calculate the distribution of GDP outcomes in response to the global warming levels projected during the 2046–2065 period of RCP4.5 and RCP6.0, and during the 2081–2100 period of RCP2.6. In addition, to compare the probability of economic impacts for the UN targets with the probability of those for higher levels of greenhouse gas emissions, we also calculate the distribution of GDP outcomes for the 2046–2065 and 2081–2100 periods of RCP8.5.

Uncertainty in the temperature-driven GDP impacts of a given level of greenhouse gas emissions arises from both uncertainty in the level of global warming associated with that level of emissions and uncertainty in the spatial pattern of temperature at that level of global warming. The IPCC climate analysis protocols span these uncertainty dimensions by analysing one realization of each climate model in each RCP scenario[5]. To follow the IPCC protocols, we analyse the same realizations as the IPCC.

However, it should be noted that the CMIP5 ensemble does not span the full range of each uncertainty dimension in a fully uniform framework. Rather, although the experimental conditions for the ensemble were coordinated between the modelling centres, both the models and the implementation of the simulation conditions vary across the ensemble. For example, the ensemble includes simulations from all national modelling centres that chose to participate, but not every modelling centre archived a simulation in each scenario. As a result, the IPCC selection of one realization of each model in each RCP yields different numbers of realizations—and model combinations—in each RCP (42 realizations in RCP4.5, 32 in RCP2.6, 25 in RCP6.0 and 39 in RCP8.5). Likewise, although each modelling centre conformed to a basic set of coordinated experimental conditions, the exact implementation of those conditions varied between the centres. This combination of coordinated but incomplete experimental uniformity has led the CMIP5 ensemble to be known as 'an ensemble of opportunity'. As in the IPCC, we leverage the CMIP5 ensemble of opportunity to estimate an approximate probability distribution; it should be emphasized that this approach is not identical to sampling across a probabilistic ensemble[27].

Because we use GDP data through 2010 and attempt to quantify economic impacts from that year forward, we must also project global and country-level temperature changes forward from the year 2010. To do so, and to control for individual climate model biases in average temperatures, we first calculate the difference between model-projected annual average future temperatures (in 2046–2065 or 2081–2100) and model-simulated annual average temperatures in the baseline 1986–2005 period. We then add those model-projected differences to the actual historical temperature observations.

For each climate model m corresponding to a chosen RCP scenario s at a given time period, we first calculate two quantities: (1). The magnitude of global temperature change ΔT^{sm}, which is the difference in annual average global surface temperature between a 1986–2005 baseline period and a future period (either 2046–2065 or 2081–2100). Gridded temperature projections relative to this baseline period are produced at 2.5° resolution. These are aggregated to a scalar 'global warming' projection by taking an average over all grid cells, with each cell g weighted by the cosine of the latitude of each cell g's centrepoint L (given the convergence of lines of latitude towards the poles):

$$\Delta T^{sm} = \frac{\sum_g \{\cos(\overline{L_g}) \times (T_{g,\text{end}}^{sm} - T_{g,\text{base}}^{sm})\}}{\sum_g \cos(\overline{L_g})} \quad (3)$$

(2). The magnitude of each country i's temperature change ΔT_i^{sm}, analogously computed by taking the average projected temperature change of all cells g but weighted by their share of country i's population P_{ig} rather than by their relative surface area. Gridded population distribution data[28] is provided at 30-arc-sec resolution and is aggregated to 2.5° resolution to match the temperature projection data. Thus, country-level temperature change projections are described by the equation:

$$\Delta T_i^{sm} = \frac{\sum_g \{P_{ig} \times (T_{g,\mathrm{end}}^{sm} - T_{g,\mathrm{base}}^{sm})\}}{\sum_g P_{ig}} \quad (4)$$

To express the future global-scale temperature values relative to pre-industrial values, as in the UN temperature targets, we add these model-projected differences between the future and the baseline to the global-scale warming that occurred between the pre-industrial period and the end of the period of GDP and temperature observations (which extends to 2010). According to the IPCC, the "globally averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C, over the period 1880–2012," and the "total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78 [0.72 to 0.85] °C"[29]. We therefore assume that 0.8 °C of warming took place between the pre-industrial period and the end of our observational period. Thus for the global averages ΔT^{sm}, "global warming relative to pre-industrial" is equal to $\Delta T^{sm} + 0.8$ for all s and m.

To generate annual country-specific time series of projected future changes in temperature for input into the simulations below, we assume that temperatures increase linearly between the base period and the end period, and then add the linearized projected change in temperature to the observed average baseline temperature, thus 'bias-correcting' future national temperature time series. Thus for a given climate model–RCP realization, if the observed average historical temperature during the base period is $\overline{T_{i0}} = \frac{\sum_{t=1986}^{2005} T_{it}}{2005 - 1986}$, then the projected temperature in each future year is:

$$\Delta T_{it}^{sm} = \overline{T_{i0}} + \frac{t - t_{\mathrm{base}}}{t_{\mathrm{end}} - t_{\mathrm{base}}} \times \Delta T_i^{sm} \quad (5)$$

where $t_{\mathrm{base}} = 2010$ is the initial year of our simulation and t_{end} is either 2049 or 2099. (As before, small t indexes time and capital T refers to temperature). The assumed linear temperature increase appears to be consistent with RCP 4.5 or 6.0 through mid-century; it is perhaps less consistent with RCP2.6 through the end of the century, as RCP2.6 warms though mid-century and then stabilizes through to the end of the century. To understand whether our assumed linear warming path distorts our findings for RCP2.6, we conduct an additional experiment in which we assume all warming under RCP2.6 occurs by 2049, and then temperatures stabilize at this new level between 2050 and 2099 (Extended Data Fig. 5). This scenario has the same projected global warming by the end of the century as our baseline RCP2.6 scenario, but all warming is assumed to happen in the first half of the 21st century. As shown in Extended Data Fig. 5, we find that the scenario with rapid initial warming worsens the overall impacts of climate change and increases the cumulative benefits of limiting warming to 1.5 °C versus 2 °C.

Defining counterfactual growth scenarios. To project growth in GDP absent climate change, we use projections from the SSPs, a framework developed to describe conditions associated with various degrees of climate forcing by the end of the century. In all, there are five SSP narratives, each making different assumptions about mitigation and adaptation challenges, demographic trends, and developments in the energy industry[19]. We exploit the time series of projected country-level economic growth and population from 2010 to 2095 associated with the SSP1 narrative, because this appears to be the SSP most consistent with the forcing levels required to achieve 1.5 °C warming in 2049 or 2099[6] (although, as pointed out by ref. [6], with high enough carbon pricing all SSPs could potentially be consistent with 1.5 °C warming by mid-century, and three SSPs could be consistent with 1.5 °C warming by the end of the century). SSP1 is described as an optimistic future with 'low' challenges to adaptation and mitigation. SSP1 is characterized by many developing countries contributing an increasingly large share of global GDP by the end of the century (Extended Data Fig. 1a and b), with a larger share of total global GDP projected to be produced in countries with warmer average temperatures by the end of the century absent climate change (Extended Data Fig. 1c). In addition to using SSP1, we also test the robustness of our results to alternative choices from the other four SSPs (Fig. 4 and Extended Data Fig. 6).

Projecting economic impacts of 1.5 °C versus 2 °C. *Step (1). Assemble input data.* Required input data are the parameters of each response function $h^j(T_{it})$ estimated from each of the j bootstraps of equation (1); projections of country-year average temperature T_{it}^{sm} for each GCM m for a given RCP scenario s through to 2049 or 2099; projections of baseline country-year per capita growth rates λ_{it}^{κ} and populations ω_{it}^{κ} through 2099, for each country i and year t, from a given SSP scenario κ.
Step (2). Calculate country-specific growth trajectories for each bootstrap–RCP–GCM–SSP combination. Projections are initialized using average temperature and GDP per capita between 2000–2010 as the baseline for each of the countries in our analysis. For a given historical bootstrap run j and GCM–RCP–SSP projection $sm\kappa$, GDP per capita y in each future year $t+1$ in country i is projected by the equation:

$$y_{it+1}^{jsm\kappa} = y_{it}^{jsm\kappa} \times (1 + \lambda_{it+1}^{\kappa} + \varphi_{it+1}^{\kappa}) \quad (6)$$

where λ_{it+1}^{κ} is the level of economic growth projected by the data corresponding to the particular SSP series and $\varphi^{jsm} = h^j(T_{it+1}^{sm}) - h^j(T_{i0})$ is the additional estimated change in the growth rate due to the projected temperature increase above baseline for bootstrap run j and GCM projection ms. We also run a counterfactual no-warming scenario where temperatures are fixed at baseline levels, that is, $T_{it+1} = T_{i0}$ and $\phi_{it} = 0$ for all i and t):

$$y_{it+1}^{0,\kappa} = y_{it}^{0,\kappa} \times (1 + \lambda_{it+1}^{\kappa}) \quad (7)$$

With 165 countries, 1,000 bootstrap estimates of the temperature response function $h(\cdot)$, 100 total temperature time series (corresponding to 42, 25 and 32 climate models for mid-century RCP4.5, mid-century RCP6.0, and end-of-century RCP2.6, respectively, plus the constant-temperature series), five SSPs, and five bootstrap resampling schemes, we analysed more than 400 million distinct country-level economic pathways.
Step (3). Calculate global GDP trajectories for each bootstrap–RCP–GCM–SSP combination. For each GCM–bootstrap–SSP combination in a given period t, global GDP per capita is calculated as the average GDP per capita across countries, weighted by share of world population:

$$y_t^{jsm\kappa} = \sum_i \frac{\omega_{it}^{\kappa}}{\omega_t^{\kappa}} \times y_{it}^{jsm\kappa} \quad (8)$$

where $\frac{\omega_{it}^{\kappa}}{\omega_t^{\kappa}}$ is country i's projected share of global population in year t for a given SSP. We similarly produce a time series of total global GDP by replacing $\frac{\omega_{it}^{\kappa}}{\omega_t^{\kappa}}$ with ω_{it}^{κ}, the country i's projected population in that year. This is also calculated for the no-warming scenario, yielding counterfactual global GDP time series $y_t^{0,\kappa}$ and $Y_t^{0,\kappa}$, where Y_t denotes GDP.
Step (4). Calculate projected percentage changes in GDP or global GDP relative to the no-warming counterfactual for each bootstrap–RCP–GCM–SSP combination. For each bootstrap–RCP–GCM–SSP combination, we calculate the warming-induced percentage change in GDP relative to the counterfactual no-warming scenario in each country as:

$$\Psi_{it}^{jsm\kappa} = \frac{y_{it}^{jsm\kappa}}{y_{it}^{0,\kappa}} - 1 \quad (9)$$

This is calculated for $t = 2049$ for RCP4.5 and RCP6.0, and $t = 2099$ for RCP2.6. The percentage impact on global GDP per capita, $\Psi_t^{jsm\kappa}$, is calculated similarly for these endpoint years.
Step (5). Calculate projected discounted absolute changes in GDP or global GDP relative to the no-warming counterfactual for each bootstrap–RCP–GCM–SSP combination. The cumulative absolute dollar impact of warming is calculated for each country by taking the annual difference between the unique bootstrap–RCP–GCM–SSP projected GDP time series and the counterfactual no-warming time series, and discounting these differences back to present:

$$\Theta_i^{jsm\kappa} = \sum_t \frac{Y_{it}^{jsm\kappa} - Y_{it}^{0,\kappa}}{(1 + r_t)^{t - t_0}} \quad (10)$$

where $Y_{it}^{jsm\kappa} = y_{it}^{jsm\kappa} \times \omega_{it}^{\kappa}$ and r_t is the social discount rate that could vary with t. The global absolute impact is calculated by summing country-level impacts: $\Theta^{jsm\kappa} = \sum_i \Theta_i^{jsm\kappa}$.

Given the long-running and unresolved debate over how r should be specified, we calculate $\Theta_i^{jsm\kappa}$ under a range of approaches to specifying r. Specifically, we implement a variety of approaches discussed and implemented by previous authors, including implementations of the Ramsey equation with and without uncertainty and under alternate parameter choices for time preference and the marginal utility of consumption[30–34], calibrations to historical market interest rates in the USA[35,36], and constant discount rates[37] ranging from 2.5%–5%. Choices about the discount rate clearly have large implications for the estimation of damages. For instance, US$1,000 of damages in 50 years is worth US$228 today under a 3% annual discount rate, but only US$87 under a 5% annual rate.

As described by multiple authors[33,34,38], choices about r can be approached from the perspective of a social planner wishing to maximize the welfare of society. The central intuitions in this approach are that extra income or consumption is worth more to poor people than it is to rich people, and that with rising incomes a dollar of additional income is worth less in the future than it is today. Under standard assumptions about the functional form of the 'utility function' that relates changes in consumption to changes in utility, this approach yields the Ramsey formula, which specifies the annual discount rate on consumption as:

$$r = \rho + \eta g \quad (11)$$

where ρ is the pure or social rate of time preference (the rate at which society discounts the utility of future generations), η is the elasticity of marginal utility of consumption (or how fast the utility of consumption declines as consumption increases), and g is the growth rate in consumption. If there is uncertainty about the growth rate in consumption, a third term is added to the Ramsey equation which induces a precautionary savings effect[34]:

$$r = \rho + \eta g - 0.5\eta^2\sigma_g^2 \quad (12)$$

where σ_g^2 is the variance in the growth rate. Uncertainty in future consumption growth enters negatively as the social planner, facing the possibility of slow future growth, wishes to transfer more resources to the future.

Using equations (11) and (12) and parameter choices about ρ and η from three benchmark studies[30–32] (Stern $\rho = 0.1, \eta = 1$; Nordhaus $\rho = 1, \eta = 2$; and Weitzman $\rho = 2, \eta = 2$; see Extended Data Fig. 1), we implement six versions of the Ramsey approach—three without uncertainty in future growth and three with uncertainty. For each bootstrap–RCP–GCM–SSP run, we define the growth rate g_t as the population-weighted average growth rate of GDP per capita:

$$g_t^{jsm\kappa} = \sum_i \frac{\omega_{it}^{\kappa}}{\omega_t^{\kappa}}(1 + \lambda_{it}^{\kappa} + \varphi_{it}^{jsm}) \quad (13)$$

with parameters defined as in equations (6) and (8) above. Average values across GCMs are shown in Extended Data Fig. 1a. Uncertainty in the growth rate for each future year is calculated as $\sigma_{gt}^2 = \mathrm{var}(g_t^{jsm\kappa})$, that is, the variance in projected growth rates in a given year across all bootstrap–RCP–GCM–SSP estimates. This probably represents a substantial lower bound on the true uncertainty in the growth rate, as it accounts only for uncertainty induced by additional warming and not for uncertainty in the underlying secular rate of growth (for which the SSPs do not provide uncertainty estimates).

Parameter choices and estimates of future growth rates are then used in either equation (11) or (12) to calculate year-specific discount rates r_t. The resulting estimates of Ramsey-based discount rates are shown in Extended Data Fig. 1b. All versions estimate higher interest rates in earlier periods, which is primarily a result of higher estimated baseline (SSP) growth rates in the earlier half of the century. Discount rates by end of century using the Ramsey approach range from 1.2% (Stern) to 4.2% (Weitzman), with the inclusion of the uncertainty term lowering discount rates only slightly.

Given that future baseline growth rates in developing and developed countries could be different, and given that the marginal effect of warming will probably differ between developing and developed countries given their different baseline temperatures, we also run scenarios where discount rates are allowed to differ between rich and poor countries (defined as being below or above the median level of GDP per capita at baseline). Specifically, using SSP1 data we produce separate population-weighted growth series for poor and rich countries (as shown in Extended Data Fig. 1c), and plug these growth projections into the Ramsey equation for each of the three benchmark choices of ρ and η to produce the six time series of discount rates that appear in Extended Data Fig. 1d. These income-specific discount rates, which are higher for poor countries than for rich countries given differences in baseline growth rates, are then applied to the relevant country groupings in the calculations below. As shown in Extended Data Fig. 3, allowing for income-specific discount rates results in higher median estimates of the global benefit of restricting warming to 1.5 °C. This is because global benefits are driven largely by impacts in the largest economies, including the USA and China, and allowing for income-specific discount rates lowers the rates for rich countries relative to the pooled scheme (for example, compare Extended Data Fig. 1b against Extended Data Fig. 1d), which translates to larger cumulative benefits in large economies projected to be harmed by warming (which again includes both the USA and China).

Beyond the Ramsey framework, another approach to specifying the discount rate uses the observed evolution of market interest rates over long periods combined with models of interest rate behaviour to project interest rates. We extract estimates from two of these exercises[35,36], both of which assume an initial interest rate of 4% and then project interest rates to fall by almost half by end of century (Groom and Newell-Pizer; Extended Data Fig. 1b). Unlike for the Ramsey discount rates, we assume these market discount rates are the same across bootstrap–RCP–GCM–SSP combinations, and just vary over time as shown in the plot.

For each bootstrap–RCP–GCM–SSP combination, each of these fourteen discount rates (six Ramsey with global average income, three Ramsey with rich/poor differences, two market-based, and fixed rates of 2.5%, 3% and 5%) are calculated for each and used in equation (10) to calculate the present value (in 2010) of the damages from warming.

Step (6). Calculate percentage or absolute damages at 1.5 °C versus 2 °C. To calculate relative damages at 1.5 °C versus 2 °C for a given bootstrap–RCP–SSP combination, we take estimates of percentage impacts $\Psi_{it}^{jsm\kappa}$ or discounted absolute impacts $\Theta_i^{jsm\kappa}$ across GCMs and fit a linear least-squares regression that relates estimated damages to the amount of global warming projected by the climate model by the end of the projection period (ΔT^{sm}). So for absolute damages in a given country, this regression is:

$$\Theta_i^{jsm\kappa} = \beta_i^{js\kappa}\Delta T^{sm} + \varepsilon_i \quad (14)$$

This relation is shown to be well approximated at the global level by a linear model (Fig. 1e–g). The slope of the linear fit $\beta_i^{js\kappa}$ is that bootstrap's estimate of the per-degree-Celsius impact of global temperature change on GDP per capita in country *i*. Halving this value thus gives us the impact of a half-degree change in global temperature for a given bootstrap, which, given linearity, is the estimated impact of limiting global warming to 1.5 °C relative to 2.0 °C in that country. Equation (14) is then re-estimated for each country and for each bootstrap, generating 1,000 estimates of impacts in each country for each RCP and SSP combination. We also estimate equation (14) at the global level to generate comparable results on percentage and absolute damages to global GDP. Global results are shown in Figs. 1 and 2, and country-level results are shown in Fig. 3a and b.

Step (7). Calculate probability of economic benefits of limiting warming to 1.5 °C versus 2 °C. Finally, we calculate the probability of economic gain under the 1.5 °C versus 2 °C scenarios—that is, the probability that damages from 1.5 °C of global warming will be smaller than damages from 2 °C of global warming—as the fraction of estimates of $\beta^{js\kappa}$ across 1,000 bootstrap runs that are negative. This is calculated for the world as a whole, as well as separately for each country (Fig. 3c and d).

Quantifying impacts of global warming beyond 2 °C. Recent estimates suggest that countries' current mitigation commitments (NDCs) are unlikely to limit global warming to 2 °C and are instead more likely to be consistent with warming in a 2.5–3 °C range[7]. To evaluate the impact of warming under these alternative warming outcomes, as well as for warming that exceeds 3 °C, we recalculate estimates of $\Psi_t^{jsm\kappa}$ and $\Theta^{jsm\kappa}$ across all RCPs *s* and for all SSPs κ. This provides estimates of the global impact of various warming scenarios relative to a no-warming counterfactual.

As shown in Fig. 4 and Extended Data Fig. 6, impacts are larger at higher levels of warming, with estimates suggesting that if current NDCs are achieved, global GDP could be 15%–25% lower by the end of the century as compared to a world that did not warm. Impacts for warming beyond 3 °C are even larger, but decline less steeply at the highest levels of warming (consistent with ref. [4]). This is because for hot countries that are substantially harmed by high levels of warming, GDP levels are bounded below by zero, whereas for cold countries that are substantially benefited by future warming, GDP levels can grow unbounded.

Quantifying sources of uncertainty in overall impacts of global warming. Our impact estimates (for example, on discounted global world product $\Theta^{jsm\kappa}$ from equation (10) above) are derived by combining historical regression results, future climate change projections from climate models, assumptions on baseline future growth rates from SSPs, and discount rates. Each of these has associated uncertainty, which we propagate throughout the analysis. In particular, total uncertainty in the impact of warming on global GDP under a given forcing scenario is a combination of uncertainty in how economies respond to warming (what we term 'historical regression uncertainty'), uncertainty across climate models in the amount and pattern of warming for a given level of forcing ('climate model uncertainty'), uncertainty in baseline future growth rates across SSPs ('SSP uncertainty'), and plausible alternatives for how to specify the discount rate ('discount rate uncertainty'). To quantify the relative contribution of each to overall impact uncertainty under a given level of forcing (RCP), we hold three out of four variables fixed and allow the fourth to vary. Variables are fixed as follows: historical regression uncertainty is fixed at the regression point estimate, discount rates are fixed at 3%, the SSP is fixed at the SSP providing the median impact estimate (typically SSP3), and the climate model projection is fixed at the model giving the median global warming projection for either mid-century or the end of the century.

Results for discounted cumulative global GDP loss due to warming are shown in Fig. 4b–d. For both 2049 (RCP4.5) and 2099 (RCP2.6), historical regression uncertainty—that is, uncertainty in how economies have responded to warming in the recent past—is the dominant source of uncertainty in overall impact projections for a given forcing level, followed by uncertainty due to alternative possible specifications of the discount rate. For instance, holding all other sources of uncertainty fixed for the end of the century, historical regression uncertainty alone leads to a 95% confidence interval of impact estimates of −US$122 trillion to

US$32 trillion, discount rate uncertainty to a 95% confidence interval of −US$375 trillion to −US$25 trillion, and climate model uncertainty to a 95% confidence interval of −US$78 trillion to US$4 trillion. Thus the overall uncertainty in impacts induced by uncertainty in economic parameters is around 2–4 times higher than that resulting from climate model uncertainty.

There are multiple caveats to this analysis, including that historical uncertainty would be larger if regression models with additional lags were also included, and that discount rate uncertainty could be understated if our 14 alternative discounting approaches do not span the range of 'plausible' discount rates.

While further constraining the range of plausible discount rates is perhaps challenging, not least owing to ethical considerations central to the choice of social-welfare-based discount rates[33], reducing uncertainty around how economies will respond to warming could be more tractable. Promising avenues could include detailed empirically based bottom-up assessments of climate impacts at the country level[23], leveraging existing sub-national or firm (company)-level data to estimate impacts[15,17], or using new fine-scale remote-sensing-based estimates of economic output to greatly increase the temporal and spatial specificity of outcome measurements[39,40].

Data availability. All data and code that support the findings of this study are available at https://purl.stanford.edu/vn535jm8926.

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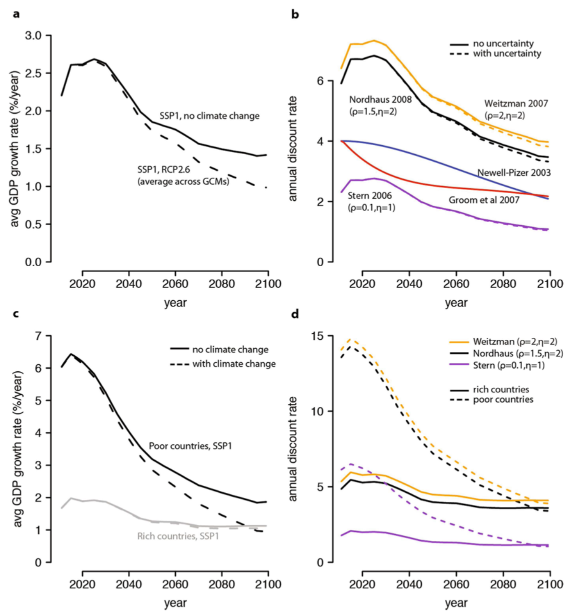
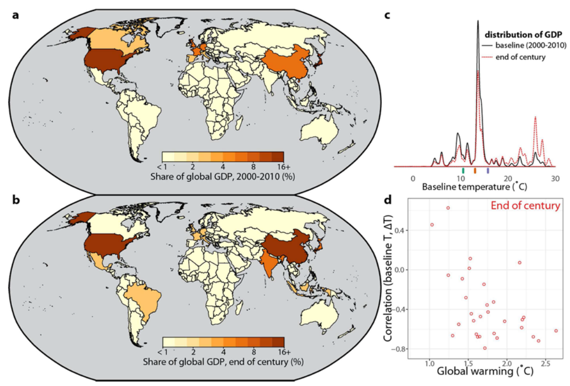
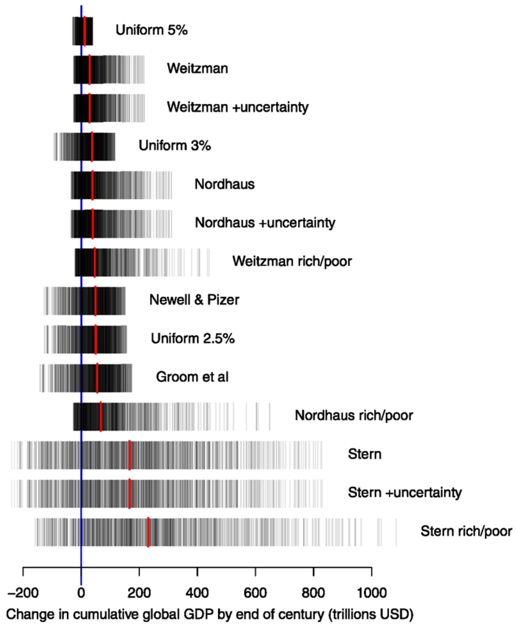


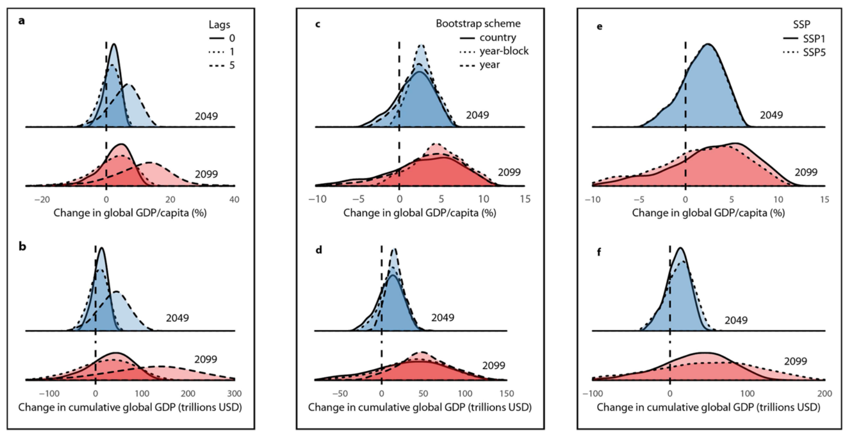
Extended Data Fig. 1 | Discount rate scenarios used in calculation of cumulative discounted impacts of future warming. a, Projected global average annual growth rates under SSP1 with and without climate change; estimates are averaged across bootstraps and climate models. Projected growth rates with climate change are used to define future consumption growth in Ramsey-based discount rates. **b,** Evolution of discount rates under different schemes through 2099. Ramsey-based schemes are Stern[30], Weitzman[31] and Nordhaus[32], with corresponding assumptions about the pure rate of time discount ρ and the elasticity of marginal utility of consumption η shown in parentheses. Dashed lines are versions of these Ramsey-based discounting schemes that account for growth-rate uncertainty. Non-Ramsey schemes are Newell and Pizer[35] and Groom[36]. **c,** Projected average annual growth rates separately for rich and poor countries under SSP1, with and without climate change. **d,** Corresponding Ramsey-based discount rates calculated separately for rich and poor countries, using income-specific growth rates from **c**.



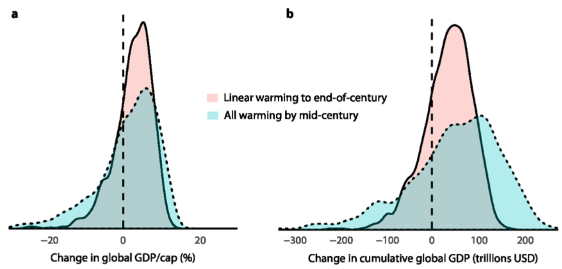
Extended Data Fig. 2 | Global GDP impacts can be negative at +1 °C but positive at +2 °C for some high-temperature-optimum bootstrap runs. a, b, Country share of global GDP at baseline (**a**) and by the end of the century (**b**) under SSP1, assuming no climate change. **c**, Distribution of global GDP by temperature, under baseline (black) and the end of the century SSP1 without climate change (red dashed); absent climate change, a substantial portion of global GDP is projected to be produced in countries with hotter average temperatures. **d**, Climate-model-predicted average global warming under RCP2.6 by the end of the century (*x* axis) versus the correlation between country-level baseline average temperature and country-level predicted warming in each model. In models that warm less at the global scale, countries that are currently warm tend to exhibit relatively larger warming, while in models that warm more at the global scale, countries that are currently cool tend to exhibit relatively larger warming. Future impacts on global GDP are a sum of country-specific impacts, which are a function of where each country is on the temperature response function (Fig. 1a) and the projected amount of future warming in that country; a given percentage impact in a country with a large GDP has a larger effect on global GDP than the same percentage impact in a country with small GDP. For high-temperature-optimum response functions (for example, Fig. 1g), impacts can be negative at +1 °C but positive at +2 °C because (i) absent climate change, a much larger proportion of total global GDP is projected by SSP1 to be produced in countries that are currently warmer than the optimum, and (ii) climate models with lower overall global warming projections under RCP2.6 tend to have higher relative warming in countries that are currently warm. This generates negative impacts at about 1 °C, where impacts are dominated by negative effects in warm countries (largely in the developing world), but positive impacts at about 2 °C, where high-latitude countries instead warm disproportionately and experience benefits that outweigh the damages in tropical countries.



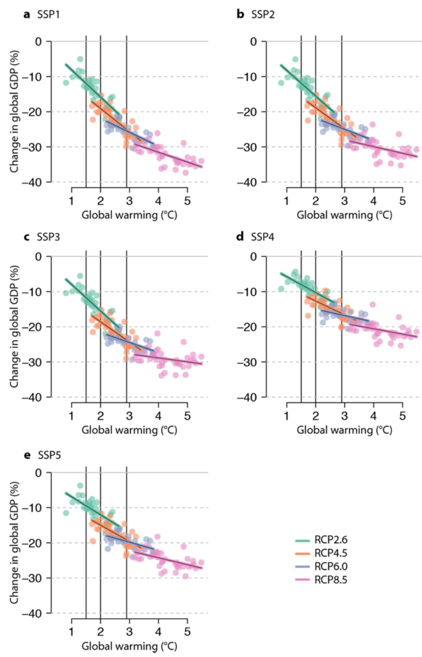
Extended Data Fig. 3 | Change in cumulative global GDP under 1.5 °C versus 2 °C global warming by the end of the century under different discounting schemes. Positive values indicate benefits (reduced losses) at 1.5 °C versus 2 °C. Each vertical line corresponds to a bootstrap estimate of benefits under each discounting scheme[30–32,35,36]. Red lines indicate median across bootstraps for each discounting scheme. Uniform schemes correspond to those in Extended Data Table 1; other schemes are described in Methods.



Extended Data Fig. 4 | Robustness of results to alternative specifications. Change in global GDP per capita in 2049 and 2099 based on regression models that include 0, 1 or 5 lags (**a** and **b**); bootstrap schemes that sample by country, five-year block or single year (**c** and **d**); or alternative SSPs (**e** and **f**). Top panels show percentage changes in global GDP per capita under 1.5 °C versus 2 °C; the bottom panels show change in cumulative global GDP in US$ trillions under a 3% discount rate.



Extended Data Fig. 5 | Robustness under alternative warming paths. Benefit—in terms of per capita GDP (**a**) and cumulative GDP (**b**)—of 1.5 °C versus 2 °C by end of century under the baseline assumption that overall projected warming occurs linearly between the baseline year and 2099 (pink), versus projected benefit assuming that all projected warming occurs by 2049 and temperatures remain constant thereafter (blue). Both scenarios have the same projected global warming by the end of the century. For the same level of overall warming by the end of the century, scenarios with rapid initial warming worsen the overall impacts of climate change and increase the cumulative benefits of limiting warming to 1.5 °C versus 2 °C.



Extended Data Fig. 6 | Projected change in global GDP (%) under global warming by the end of the century, for each SSP. Panels **a–e** show the change in GDP for different climate models under different RCP forcing scenarios, relative to a no-warming baseline (median bootstrap) for SSPs 1–5, respectively. Results are as in Fig. 4a, but for each SSP. Each dot represents an RCP-climate model projected change in global GDP under a given SSP; colours represent the four RCPs. Lines are least-squares fits to the points corresponding to the different RCPs with matching colour scheme. The three vertical black lines denote the 1.5 °C target, the 2 °C target and the median-estimated warming expected under current Paris commitments (2.9 °C)[7]. Warming is relative to pre-industrial levels.

Extended Data Table 1 | Change in cumulative global GDP (in US$ trillions) under 1.5 °C versus 2 °C global warming by the end of the century under different discounting schemes

discount scheme	1%	5%	10%	25%	50%	75%	90%	95%	99%
Uniform 5%	-31	-18	-11	0	11	21	29	33	40
Weitzman	-29	-17	-12	4	28	65	112	144	217
Weitzman +uncertainty	-29	-17	-12	4	28	65	112	144	217
Uniform 3%	-95	-54	-32	3	36	65	88	101	119
Nordhaus	-39	-23	-16	5	39	91	160	206	312
Nordhaus +uncertainty	-39	-23	-16	5	39	91	160	206	313
Weitzman rich/poor	-22	-14	-6	11	46	96	176	244	442
Newell & Pizer	-130	-72	-43	5	49	86	115	132	156
Uniform 2.5%	-129	-73	-43	5	50	87	118	136	161
Groom et al	-145	-81	-48	5	56	98	132	151	179
Nordhaus rich/poor	-28	-17	-7	17	67	140	257	360	657
Stern	-240	-136	-88	24	166	336	515	618	840
Stern +uncertainty	-240	-136	-88	24	166	336	515	619	841
Stern rich/poor	-171	-99	-38	71	231	414	623	740	1091

Values show estimated impacts at different quantiles of the estimated impact distribution for each discounting scheme (uniform schemes[37], Weitzman[31], Nordhaus[32], Newell and Pizer[35], Groom[36] and Stern[30]), and correspond to estimates shown in Extended Data Fig. 3. Positive values indicate benefits (reduced losses) at 1.5 °C versus 2 °C.

Extended Data Table 2 | Probability that limiting global warming to 1.5 °C will generate benefits relative to 2 °C warming

%Δglobal GDP/capita by mid-century		
benefit threshold	RCP4.5	RCP6.0
0%	0.80	0.73
1.25%	0.63	0.53
2.50%	0.42	0.31
3.75%	0.21	0.13
5.00%	0.07	0.03

Cumulative Δglobal GDP by mid-century						
	RCP4.5			RCP6.0		
benefit threshold	2.5%	3.0%	5.0%	2.5%	3.0%	5.0%
0	0.76	0.76	0.75	0.69	0.68	0.68
$10 trillion	0.56	0.53	0.32	0.47	0.43	0.23
$20 trillion	0.33	0.27	0.03	0.24	0.18	0.01
$30 trillion	0.14	0.08	0.00	0.08	0.04	0.00
$40 trillion	0.04	0.01	0.00	0.01	0.00	0.00

%Δglobal GDP/capita by end-of-century	
benefit threshold	RCP2.6
0%	0.76
2%	0.62
4%	0.45
6%	0.27
8%	0.12
10%	0.03

Cumulative Δglobal GDP by end-of-century			
	RCP2.6		
benefit threshold	2.5%	3.0%	5.0%
0	0.78	0.78	0.76
$10 trillion	0.72	0.71	0.53
$20 trillion	0.68	0.63	0.28
$50 trillion	0.50	0.38	0.00
$100 trillion	0.18	0.05	0.00
$150 trillion	0.02	0.00	0.00

Left panels show benefits in terms of percentage change in global GDP per capita by mid-century and the end of the century. For instance, by mid-century under RCP4.5 there is a 42% probability of benefits exceeding 2.5% of global GDP per cap. Right panels show benefits in terms of cumulative change in global GDP by mid-century and the end of the century, under three different discount rates for each relevant RCP. For instance, by the end of the century, there is a 50% probability of benefits exceeding US$50 trillion using a discount rate of 2.5%.

Extended Data Table 3 | Probability that limiting global warming to 1.5 °C will generate different levels of benefits relative to 2.0 °C warming, under different discounting schemes

discount scheme	0	$10 trillion	$20 trillion	$40 trillion	$100 trillion	$200 trillion	$350 trillion
Uniform 5%	0.76	0.53	0.28	0.01	0.00	0.00	0.00
Weitzman	0.79	0.67	0.57	0.40	0.13	0.02	0.00
Weitzman +uncertainty	0.79	0.67	0.57	0.40	0.13	0.02	0.00
Uniform 3%	0.78	0.71	0.63	0.47	0.05	0.00	0.00
Nordhaus	0.80	0.70	0.63	0.50	0.22	0.06	0.01
Nordhaus +uncertainty	0.80	0.70	0.63	0.50	0.22	0.06	0.01
Weitzman rich/poor	0.86	0.76	0.68	0.54	0.24	0.08	0.02
Newell & Pizer	0.78	0.72	0.68	0.55	0.17	0.00	0.00
Uniform 2.5%	0.78	0.72	0.68	0.56	0.18	0.00	0.00
Groom et al	0.78	0.73	0.69	0.59	0.24	0.00	0.00
Nordhaus rich/poor	0.87	0.80	0.73	0.63	0.38	0.17	0.05
Stern	0.80	0.78	0.76	0.72	0.62	0.44	0.23
Stern +uncertainty	0.80	0.78	0.76	0.72	0.62	0.44	0.23
Stern rich/poor	0.86	0.85	0.83	0.80	0.70	0.54	0.32

Benefits are in terms of cumulative change in global GDP by the end of the century (RCP2.6). Discounting schemes are: uniform schemes[37], Weitzman[31], Nordhaus[32], Newell and Pizer[35], Groom[36] and Stern[30]).

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The COVID-19 lockdowns: a window into the Earth System

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Abstract | Restrictions to reduce human interaction have helped to avoid greater suffering and death from the COVID-19 pandemic, but have also created socio-economic hardship. This disruption is unprecedented in the modern era of global observing networks, pervasive sensing and large-scale tracking of human mobility and behaviour, creating a unique test bed for understanding the Earth System. In this Perspective, we hypothesize the immediate and long-term Earth System responses to COVID-19 along two multidisciplinary cascades: energy, emissions, climate and air quality; and poverty, globalization, food and biodiversity. While short-term impacts are dominated by direct effects arising from reduced human activity, longer-lasting impacts are likely to result from cascading effects of the economic recession on global poverty, green investment and human behaviour. These impacts offer the opportunity for novel insight, particularly with the careful deployment of targeted data collection, coordinated model experiments and solution-oriented randomized controlled trials, during and after the pandemic.

COVID-19 is disrupting lives and livelihoods around the world. The most important consequences are the public health crisis and associated economic and humanitarian disasters, which are having historic impacts on human well-being. In addition, after more than four months of widespread sheltering and other restrictions, it is clear that the scale and persistence of socioeconomic disruption represent an unprecedented modification of human interactions with the Earth System, the impacts of which will be long-lasting, widespread and varying across space and time (FIG. 1).

Some obvious and immediate effects are reflected in the worldwide reports of reduced traffic congestion, clearer skies, cleaner waterways and the emergence of wildlife into human settlements. In addition to anecdotal reports, effects are being detected in a variety of long-term physical observations (from improved air quality to reduced seismic noise) and socioeconomic indicators (such as reduced mobility and declining economic growth and greenhouse-gas emissions). While some of these impacts might be considered beneficial to the environment, negative consequences are also emerging, including cascading effects for poverty, food security, mental health, disaster preparedness and biodiversity.

As with previous calamities, such as volcanic eruptions[1–3], electrical blackouts[4] and the short-term reductions in human mobility following the 11 September attacks[5], the current COVID-19 crisis will inevitably present a new test bed for understanding how the Earth System works, including the critical role of humans[6]. This test bed could provide answers to long-standing questions, such as the processes linking heterogeneous local pollutant emissions and regional atmospheric chemistry and air quality, or the relationship between global economic integration and poverty-driven environmental degradation. The uniquely pervasive disruption also has the potential to reveal novel questions about the Earth System that have not previously been asked, and many diverse efforts are already underway to learn from this inadvertent Earth System modulation.

In this Perspective, we examine the impacts of COVID-19-related social disruption on two multidisciplinary pathways: energy, emissions, climate and air quality; and poverty, globalization, food and biodiversity. We first consider hypotheses about how the COVID-19 disruption could influence the Earth System along these pathways and then explore the potential for rapid advances in understanding if we are able to carefully observe, test and characterize Earth System processes during and after the COVID-19 event.

COVID-19 disrupts the Earth System

Under usual daily life, the human footprint on the Earth System is vast. As a result, a very large perturbation is required to cause an observable difference from this 'business-as-usual' baseline: COVID-19 is providing that perturbation. As of July 2020, as much as half the world's population has been under some version of sheltering orders[7] (FIG. 2a). These orders have substantially reduced human mobility and economic activity (FIG. 2b), with ~70% of the global workforce living in countries that have required closures for all non-essential workplaces and ~90% living in countries with at least some required workplace closures[8].

The scale of this socioeconomic disruption is likely to be detected in the Earth System at local to global scales (FIG. 1). Some responses are direct, while others will result from interactions between humans, ecosystems and climate. The impacts of the socioeconomic disruption are, thus, also likely to vary across timescales: although the direct impacts of the reduction in human mobility will be strongest during the sheltering period, many of the most lasting impacts could result from cascading effects

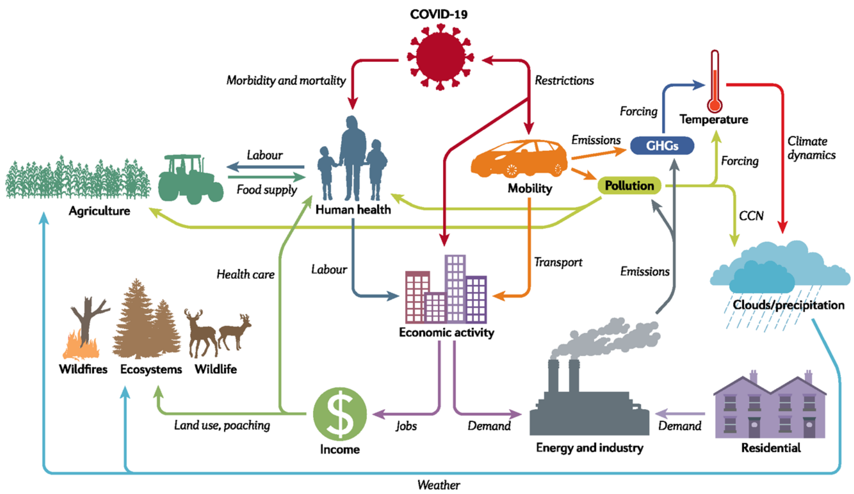

Fig. 1 | **Earth System interactions linked to the COVID-19 socioeconomic disruption.** Two pathways highlight the potential for multi-dimensional Earth System responses: energy, emissions, climate and air quality; and poverty, globalization, food and biodiversity. Interactions will manifest differently in different regions and on different timescales, with the sign of the interaction potentially changing across different phases of the event. Note that these interactions are indicative of primary hypotheses, but not all possible interactions are shown. CCN, cloud condensation nuclei; GHGs, greenhouse gases.

initiated by the economic recession, some of which (such as those induced by changes in public policy, the structure of the economy and/or human behaviour) could persist for decades following the initial economic recovery.

The reduction of human activities, and the efforts to manage their revival, have varied around the world (FIG. 2). Given the variations in the timing, strength and approach to sheltering[7], it may be possible to track effects through the components of the Earth System. Likewise, because the large-scale reduction in human activity will necessarily be temporary, it will be possible to observe whether or how Earth System processes return to their previous states after activity returns to something approaching pre-pandemic levels. The event, therefore, provides a unique test bed for probing hypotheses about Earth System sensitivities, feedbacks, boundaries and cascades[6,9–11], presuming that the observing systems are in place to capture these responses (BOX 1).

Path I: Energy, emissions, climate and air quality. Impacts on energy consumption, and associated emissions of greenhouse gases and air pollutants, are likely to cascade across timescales (FIG. 1). In the near-term, reductions in mobility and economic activity have reduced energy use in the commercial, industrial and transportation sectors, and might have increased energy use in the residential sector[12,13]. These direct impacts will interact with secondary influences from energy markets, such as the severe short-term drop in oil prices in March and April 2020 (REF.[14]). Further, as with past economic recessions[15,16], energy demands — and the mix of energy sources — are likely to evolve over the course of the economic recovery in response to market forces, public preferences and policy interventions[17,18]. This evolution could have long-term effects on the trajectory of decarbonization if, for example, the economic disruption delays the implementation of ambitious climate policy or results in decreased investments in low-carbon energy systems[16]. Alternatively, large government stimulus spending could target green investments that overhaul outdated infrastructure and accelerate decarbonization[18].

Misunderstandings have arisen with regards to declines in carbon dioxide emissions caused by COVID-19-related disruption, with some interpreting short-term reductions to suggest that austerity of energy consumption could be sufficient to curb the pace of global warming. A reduction in fossil CO_2 emissions proportional to the economic decline[15] would be dramatic relative to previous declines. For example, the decline in daily CO_2 emissions peaked at >20% in the largest economies during the period of sheltering[13] (FIG. 2c) and the cumulative reduction in global emissions was ~7% from January through April 2020 (REF.[12]) (FIG. 2d). However, these daily-scale declines are temporary[13] and the rebound in emissions that is already evident[13,19] (FIG. 2c) supports the likelihood of a reduction in annual emissions that is smaller than 7%.

Nevertheless, a 5% drop in annual fossil CO_2 emissions from 37 billion metric tonnes per year[20] would exceed any decline since the end of World War II (REF.[13]). There is a strong basis that such a reduced atmospheric CO_2 growth rate would lead to a reduced ocean carbon sink[21] and, thus, also a temporary reduction in the rate of ocean acidification. On the other hand, a 5% decrease would still leave annual 2020 emissions at ~35 billion metric tonnes, comparable to emissions in 2013 (REF.[20]). Such a decline — and associated changes in the ocean and land carbon sinks — might not be statistically detectable above the year-to-year variations in the natural carbon cycle and, regardless, global atmospheric CO_2 concentrations will inevitably rise in 2020, continuing a long-term trend. Progress in understanding the carbon-cycle responses to COVID-19 will, therefore, be challenging and, at a minimum, will require new methods for tracking the unprecedented short-term perturbation in emissions through the Earth System.

Based on past events and fundamental understanding, there are a number of hypotheses of how sheltering-induced changes in atmospheric emissions could influence the climate system more broadly (FIG. 1). On short timescales, reduced air travel decreases the abundance of contrails, which can be detected in the radiation budget (as occurred during the brief cessation of air travel following the 11 September attacks[5]). The response of atmospheric aerosols to sheltering is likely to vary regionally, with changes in emissions, meteorology and atmospheric chemistry influencing the outcome (BOX 2). While reductions in aerosols have occurred in many locations (FIG. 3), they have also been observed to increase in others[22], highlighting the important role of secondary chemistry in these assessments. Changes in atmospheric aerosols could further influence cloud and precipitation processes[23,24], and might be detectable in the local surface energy budget[25]. A reduction in scattering aerosols will also cause warmer surface temperatures over emitting regions[26] (FIG. 4), potentially manifesting as more frequent and/or intense heatwaves[27,28]. If aerosol reductions persist across the Northern Hemisphere, this could have short-term impacts on the onset, intensity and/or intraseasonal variability of monsoon rainfall[29–31], particularly given that both local and remote aerosol emissions can influence variability within the monsoon season[31].

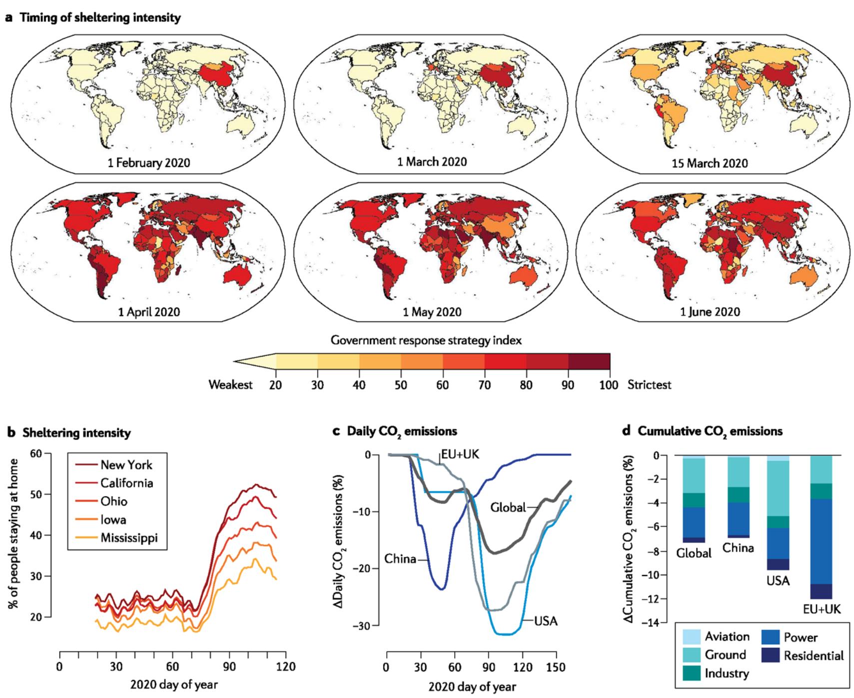

Fig. 2 | **Sheltering orders and changes in mobility and CO_2 emissions.** **a** | The Oxford Government Response Stringency Index[7] on six different dates between 1 February and 1 June. **b** | Percentage of people staying at home, as estimated by mobility data from cell phones[91], for five US states. **c** | Percentage change in carbon dioxide emissions[13,92] for the World, China, the USA and Europe. Each day's value is the percentage departure in 2020 from the respective day-of-year emissions in 2019, accounting for seasonality. **d** | Percentage change in cumulative carbon dioxide emissions[12,93] for January through April 2020 compared with January through April 2019 for the World, China, the USA and Europe. The differences in timing of sheltering and mobility in different areas of the world are a source of information that can be used in understanding causality in the Earth System response. In the case of carbon dioxide emissions, the early onset and subsequent relaxation of sheltering in China is clearly reflected in the timing of reduction and subsequent recovery of emissions in China relative to the USA and Europe.

Box 1 | **Datasets for understanding the Earth System impacts of COVID-19 disruption**

A wide range of data could be leveraged to understand Earth System changes during the COVID-19 pandemic. These include long-term, operationally deployed Earth observations from satellite remote-sensing platforms and atmospheric, oceanic and surface measurement networks. Although long-term socioeconomic data are also operationally available, a 1–2-year processing lag can inhibit real-time analysis. Access to long-term private-sector data could remove some of these barriers. A range of shorter-term and/or intermittent observations are also available. These include stationary and mobile measurements of the atmosphere, ocean and near-surface environment, as well as energy, trade, transportation and other socioeconomic data available at either fine resolution for short periods or coarse resolution for longer periods.

One of the most potent opportunities will be to safely deploy observations in geographic areas or economic sectors where there is already a rich pre-existing data baseline; where Earth System models have generated specific, testable hypotheses; or where initial observations suggest that a strong or unexpected response is already emerging. This strategy could include deployment of stationary and/or mobile sensors, short-term online or phone surveys, and 'citizen-science' opportunities via crowd-sourcing platforms such as the USA National Phenology Network, iNaturalist, PurpleAir and Smoke Sense. There are also abundant opportunities to leverage newer, emerging datasets — such as from cell-phone GPS, social media, e-commerce and the private satellite industry — that, if handled with care to preserve privacy, could help to bridge the gaps in long-term, operational data.

Despite the prevalence of extensive datasets, the current COVID-19 crisis is revealing limitations in the ability to measure critical variables in real time. For example, the event has made clear that the world is ill-equipped to make real-time measurements of economic activity and its immediate consequences. It is also revealing deficiencies in real-time-measurement capacity for emissions of some air pollutants and greenhouse gases, as well as highlighting longer-known issues like a relative inability to assess the vertical structure of pollution in the atmosphere. The crisis is demonstrating the urgent need for improved data, models and analysis to understand and correct those deficiencies.

Many sectors would benefit from a public repository containing the heterogeneous data that are critical to fully understand this unique planetary-scale disruption. Some data sources are public, some are proprietary and some do not yet exist. As has been proven repeatedly in recent years, an open, public repository providing all of these heterogeneous data in a uniform, coordinated format would enable novel, unpredictable insights across multiple research disciplines, long after the event has passed.

On longer timescales, changes in the energy intensity of the economy, the carbon intensity of energy or the pace of deforestation could affect the long-term trajectory of global climate (through the trajectory of greenhouse gas emissions and associated land and ocean carbon-cycle feedbacks). These effects could go in either direction: for example, in the US electricity sector, coal plants will likely shut down at an accelerated pace as a result of the economic slowdown, continuing a long-term decline[32]. However, in the transportation sector, policy intervention to stimulate the economy might loosen emissions standards[33], increasing emissions relative to the pre-pandemic trajectory.

The short-term reductions in pollutant emissions have already resulted in noticeable changes in air quality in some regions (BOX 2). If sustained, improved air quality could yield multiple benefits. These include improved crop health[34], as air pollution can reduce regional harvests by as much as 30% (REF.[35]). In addition, ambient air pollution is a significant cause of premature death and disease worldwide[36], even from short-term exposure[37,38]. Several well-documented historical examples illustrate how decreased ambient air pollution can improve human health[39]. These include effects from short-term reductions in traffic, travel and/or industrial activities associated with events such as the 1996 Atlanta Olympic Games[40] and 2008 Beijing Olympics[41–45]. While associations between air quality and health outcomes are hypothesized in studies of the current pandemic[46,47], understanding the role of air quality as an indicator for the epidemic trajectory is an emerging challenge. Further, any health improvements resulting from improved air quality during the pandemic should not be viewed as a 'benefit' of the pandemic but, rather, as an accidental side effect of the sheltering that was imposed to protect public health from the virus.

Some of the most lasting impacts of the COVID-19 crisis on climate and air quality could occur via insights into the calculation of critical policy parameters. Two of the most important, and controversial, are the value of mortality risk reduction (sometimes termed the value of a statistical life, or VSL) and the pure rate of time preference (or PRTP), which is one component of the social discount rate and measures willingness to trade off well-being over time. The VSL is important to the analysis of all environmental regulation in the United States and can determine whether environmental regulations as mundane as a labelling requirement for toxic chemicals will pass a cost–benefit test. The PRTP is important in evaluating long-term societal trade-offs — most notably, climate-change regulation — and can be important in calculating an economic value of avoiding climate damages[48,49]. With a higher PRTP, aggressive mitigation of greenhouse gases becomes less attractive, while a low rate, which places relatively higher value on the well-being of future generations, suggests that far more aggressive regulation of today's emissions is warranted.

Both the VSL and the PRTP can be difficult to quantify. However, the COVID-19 crisis is making these trade-offs more explicit, as governments, communities and individuals make historic decisions that reflect underlying preferences for current and future consumption and the trade-off between different types of economic activity and individual and collective risk. The diverse responses to the unusual conditions during the pandemic could reveal far more about how different societies manage these trade-offs than has been revealed in the last half-century. As those insights are incorporated into the formal policy-making apparatus, they will have lasting effects on the regulations that impact the long-term trajectory of climate and air quality.

Path II: Poverty, globalization, food and biodiversity. By amplifying underlying inequities in the distribution of resources, the socioeconomic disruption caused by the response to COVID-19 will almost certainly have negative long-term impacts on human health and well-being. In particular, the economic shock is likely to increase the extent and severity of global poverty[50], both from direct impacts on health, employment and incomes and through disruptions of supply chains and global trade[51]. The severe impacts on poverty rates and food security that are already emerging[50] are indicative of these disruptions and are a sign of how tightly many of the world's poorest households are now interwoven into the global economy. The unwinding of these relationships in the wake of restrictions on human mobility and associated economic shocks will provide insight into the role of economic integration in supporting livelihoods around the world. A severe and prolonged deepening of global poverty is also likely to reduce available resources for climate mitigation and adaptation, increasing climate risks and exacerbating climate-related inequities.

The global agriculture sector is a key sentinel for the response of poverty to the pandemic. Primary near-term questions centre around how food security and agriculture-dependent incomes might be affected by unprecedented shocks to local labour supply and global supply chains. A first-order impact has been the income shock associated with widespread sheltering[8]. Loss of wages in both low-income and high-income countries with limited social safety-nets will drive food insecurity and poverty[50].

It is possible that agricultural production in rural areas will proceed largely unaffected, particularly for larger producers of field crops that tend to be heavily mechanized. However, in many locations and for many specialty crops, agriculture still relies heavily on field labour; sufficient labour supply during the key planting and harvest periods is crucial, and there are frequently labour shortages at these critical times. How these pre-existing labour-supply challenges are affected by the scale and scope of sheltering remains to be seen. In the USA, meat-packing plants have become hotbeds of COVID-19, raising the question of whether excessive concentration of this industry might have led to a loss of resilience[52]. Sheltering-induced return migration from urban to rural areas, as has been widely reported in India, could alleviate agricultural labour shortages in some developing countries. However, mandated sheltering could cause reductions in plantings, which, in combination with the prospect of sheltering during the harvest season, could reduce subsequent harvests.

Such supply-side shocks could combine with general disruption of global trade[53] to trigger a cascading series of export bans like those that occurred in 2007–2008 (REF.[54]), which caused a spike in grain prices and contributed to unrest around the world[55]. Initial export restrictions are already emerging[56]. Given that agriculture prices are important for both consumers and producers, such bans tend to hurt rural producers in favour of protecting urban consumers in the exporting countries[57]. They can also lead to food shortages in import-dependent countries and rapid increases in international commodity prices[58], as well as acting to amplify the impacts of climate variability on poverty[59]. However, global grain stocks are much larger today than they were in 2007, which should help buffer some sheltering-related production shortfalls, should they arise.

Deepening of global poverty is likely to have lasting negative environmental impacts (including deforestation, land degradation, poaching, overfishing and loosening of existing environmental policies), as a larger share of the global population is pushed towards subsistence. For example, after decades of efforts to replace environmental degradation with earnings from ecotourism, the collapse of tourism in the wake of COVID-19 is coinciding with a rapid increase in illegal poaching in southern African parks[60]. The rapid response is a potential indicator of the importance of the large African tourism industry for the preservation of endangered species. However, further analysis is needed to distinguish the contributions of income and governance/enforcement. Likewise, deforestation in the Brazilian Amazon surged to >2,000 km^2 in the first five months of 2020, an increase of ~35% compared to the same period in 2019 (REF.[61]). Governance appears to be playing a key role in this initial short-term resurgence during the COVID-19 sheltering. Over the longer term, historical drivers[62,63] suggest that a prolonged poverty shock is likely to increase deforestation and biodiversity loss. These cascading impacts on ecosystems and biodiversity offer a sobering contrast to the reports of wildlife 'rebounds' occurring in response to local sheltering[64].

Changes in human behaviour and decision-making induced by the pandemic are also likely to cascade through the globalized Earth System over the long term. For example, although sheltering orders are reducing personal vehicle use, the long-term impacts are less clear and will be determined, in part, by how human behaviours respond to the pandemic. If, for instance, the pandemic causes people to feel more dependent on cars as 'safe places', that dependence could act to further reinforce the prominence of the automobile at the

Box 2 | **Interpreting energy, emissions, climate and air quality responses**

Changes in atmospheric pollutants have co-occurred with COVID-19 sheltering restrictions[22,78,79], including broadly publicized reductions in satellite-derived tropospheric NO_2 columns[95] (FIG. 3a). The sheltering period can shed light on processes controlling atmospheric constituents on local to global scales. However, accurate attribution requires careful consideration of emissions, meteorology and atmospheric chemistry.

Anthropogenic forcing

The large regional variations in pollutant emissions will create spatial heterogeneity in the response of air quality to sheltering. While some regions show decreases in aerosols (FIG. 3b), post-shutdown increases have been observed in urban regions in China due to secondary chemistry[22]. Sheltering measures were implemented during spring/autumn transitions (FIG. 2), when energy demand, usage and fuel mix fluctuate sharply. Further, observed changes in atmospheric constituents might also be influenced by longer-term emission reductions. These factors must be carefully considered when attributing changes to COVID-19 restrictions. The COVID-19 disruption provides impetus to combine existing energy-consumption data with robust ground-based and space-based atmospheric-chemical measurements to characterize local pollutant emissions and the resulting atmospheric chemistry that drives air quality.

Distinguishing signal from noise

Natural climate variability must be accounted for to quantify the human influence on short-term Earth System changes[96–98]. In the case of quantifying the response of regional air pollution to sheltering, several limitations must be overcome. Irregular sampling frequencies over limited observing periods are a primary barrier. For example, space-based retrievals of air pollutants such as NO_2 are sensitive to physical (such as daily boundary-layer variations) and chemical (such as seasonal lifetime variability) processes. In the Northern Hemisphere, peak sheltering has coincided with the period when NO_2 lifetimes are transitioning from winter maximum to summer minimum, affecting estimation of emissions differences from satellite column density retrievals (FIG. 3a). Further, as NO_2 columns cannot be retrieved under clouds, concentration differences calculated within the period of sheltering, or between 2020 and previous years, could arise due to variable meteorology.

Opportunities for the future

COVID-19 sheltering could help elucidate Earth System processes along the energy–emissions–climate–air quality pathway. For example, observations during this period could yield insights into road-traffic contributions to local air quality, as passenger-car emissions decline but trucking emissions persist. Connections between emissions and climate may be revealed from observations in regions with large aerosol forcing signals, offering much-needed tests for local-to-global responses simulated by Earth System models (FIG. 4). For example, asymmetric hemispheric warming is a robust model response to regional reductions in aerosol emissions[26]; can this signal be distinguished from long-term aerosol trends when accounting for internal variability? These queries sample the rich opportunities to advance understanding of processes governing linkages between energy use, emissions, climate and air quality.

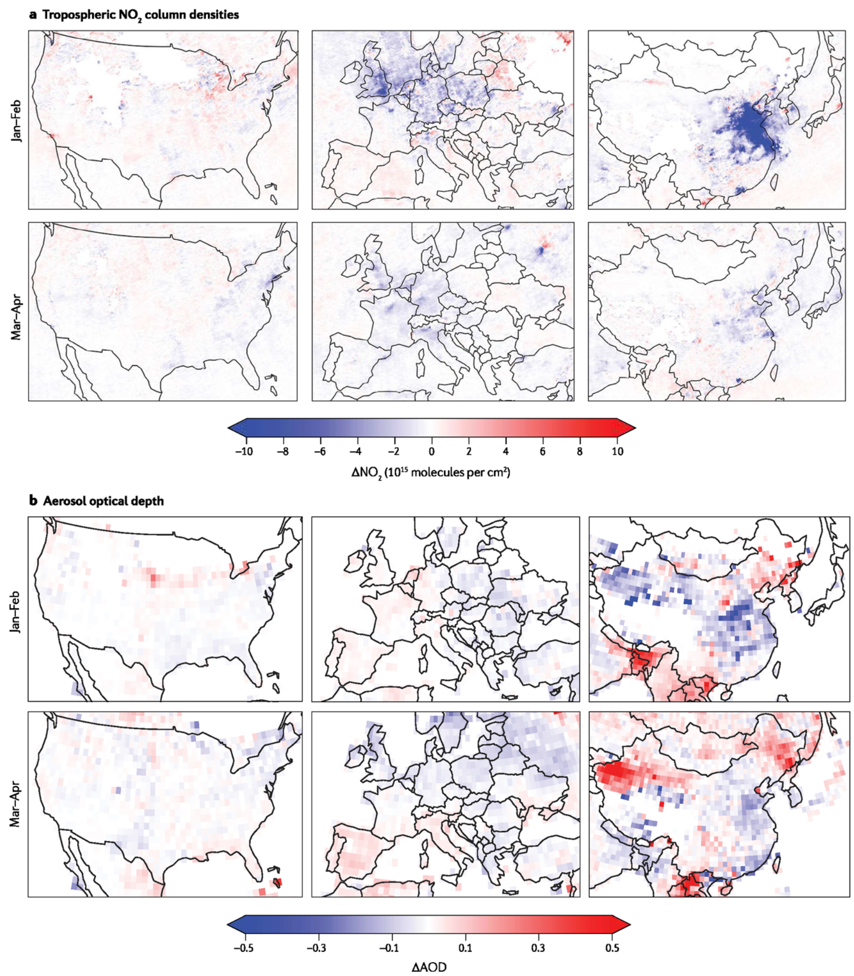

Fig. 3 | **Variability in air-quality indicators during the 2020 winter–spring transition.** Difference in tropospheric NO_2 column density (panel **a**) and aerosol optical depth (panel **b**) for select months between 2020 and 2019. Aerosol optical depth (AOD) data are from the NASA Visible Infrared Imaging Radiometer Suite; NO_2 data are from the NASA Ozone Monitoring Instrument, processed as in REF.[94]. Year-to-year changes in air quality reflect a complex array of processes in addition to COVID-19 restrictions. For example, strong NO_2 decreases over Northeast China coincide with the Wuhan lockdown[95], while those over the UK in January–Febuary predate COVID-19 restrictions. Relative to NO_2, AOD data show less regional coherency. Confident attribution to COVID-19 restrictions highlights a new challenge to explain these observed spatio-temporal differences and to place them in the context of the longer-term satellite and ground-based observations (BOX 2).

expense of public transit. On the other hand, some cities might seek to maintain reductions in traffic by permanently closing some streets and encouraging residents to rely more on walking and bicycles. Another potentially consequential outcome could be a change in the kind of housing and work environments people will prefer in the future. The pandemic favours access to outdoor space and disfavours use of tall buildings with elevators. If these human preferences are sustained for years after the pandemic passes, over the long term, the combination could lead to more sprawling suburbs and fewer residential and office towers, with corresponding consequences for the Earth System.

More broadly, priorities and incentives embedded in government aid and economic stimulus will influence financial investment. For example, rollbacks of environmental restrictions by governments seeking to accelerate economic recovery[33] (including fuel standards, mercury, clean water, and oil and gas production on federal lands) could have consequences that outlast the pandemic. Alternatively, efforts to support economic recovery could be directed towards electrification of transportation, along with green jobs that rebuild public transit, housing and critical infrastructure in an environmentally sensitive way[18]. In the private sector, pandemic-induced changes in perceptions of economic security and human needs could increase investment in technologies or platforms that lower the risk of future pandemics, such as reducing human interactions by introducing more robotics into workplaces. Although the precise trajectory is unknown, the long-term impacts of the pandemic on resource demand and efficiency will be heavily influenced by the response of human behaviour and decision-making, which is likely to vary among and within countries, as has occurred with health practices and policies during the pandemic.

Investigative frameworks

The COVID-19 sheltering has, thus far, been relatively brief, but its impacts are already emerging in the Earth System. Some of these responses, such as those directly connected to mobility and emissions of atmospheric pollutants, might pass when the sheltering passes (FIG. 2c, BOX 2), while others will persist long past the economic recovery (FIG. 1). Given the complexity of Earth System interactions, understanding these short-term, medium-term and long-term responses will require careful deployment of a diverse portfolio of investigative frameworks.

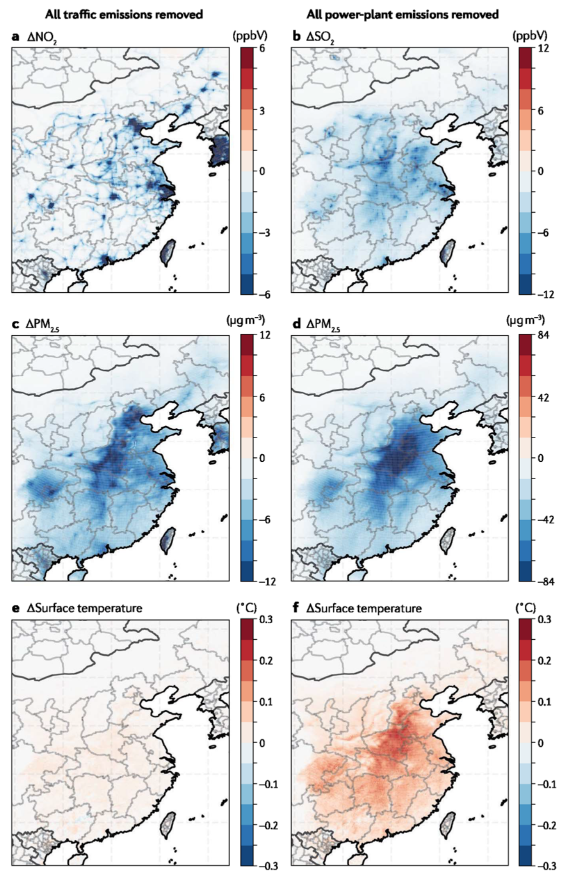

Fig. 4 | **Idealized sensitivity to removal of emissions from traffic and power generation.** NO_2 (panel **a**), SO_2 (panel **b**), $PM_{2.5}$ (panels **c** and **d**) and surface-temperature (panels **e** and **f**) changes for the month of January simulated by the Community Multiscale Air Quality/Weather Research and Forecasting (CMAQ-WRF) model in response to domain-wide removal of traffic (left panels) or power-plant (right panels) emissions. Experiments simulate one month using January 2010 emission factors and January 2013 meteorological fields. They are, thus, idealized illustrations of the potential for Earth System models to pose hypotheses, illuminate and constrain key processes, and identify data-gathering priorities; as these simulations predate the COVID-19 pandemic, they should not be considered an attempt to recreate COVID-19 conditions.

A major challenge will be to test causality when so many important, interacting influences are changing simultaneously. These include potentially confounding effects from large reductions in human activity, government interventions to stem the economic collapse, simultaneous market responses to both the economic shock and government stimulus, and underlying variations such as climate variability and pre-COVID-19 economic conditions. In addition, observational continuity is being affected by sheltering, including atmospheric, oceanic and land surface observations that contribute to the global observing system[65]. Given these challenges, insight must be generated from a combination of ongoing and newly deployed observations, dedicated modelling experiments, solutions-oriented randomized controlled trials (RCTs) and sophisticated quantitative analysis. To maximize effectiveness, these approaches will need to place as much focus on Path II (poverty, globalization, food and biodiversity) as on Path I (energy, emissions, climate and air quality). A key imperative will be to quickly develop and deploy techniques that can bring multiple lines of evidence together to distinguish causality.

A new view to spatial and temporal dynamics of Earth System processes. Because the timing of different government actions is known[7], the spatio-temporal phasing of the socioeconomic disruption can be used to understand regional variations in the Earth System response. In essence, although interventions are occurring around the globe, we are not really experiencing a global shutdown but, rather, a complex patchwork of slowdowns in activity that vary widely in timing, duration, magnitude and baseline starting conditions (FIG. 2a). This variation is increasing as the event moves from the initial global disruption to heterogeneous resumption of activity (FIG. 2a) and extends across the seasonal transition from Northern Hemisphere winter to summer (and potentially beyond). Further, the scale of economic impacts suggest the possibility of sustained recession — or even depression — following the cessation of large-scale sheltering[51,66]. An extended period of substantially reduced economic activity would produce a trajectory of Earth System forcing that remains different from the pre-COVID-19 forcing, well after the COVID-19 restrictions are removed.

These spatial and temporal gradients in human activity are a source of information that becomes even more valuable in the context of observations that are repeated through time[67] or that take advantage of the fact that variations in human interventions are at least partly independent of other co-varying, confounding factors[68]. The magnitude of the socioeconomic disruption is also large enough that it presents the opportunity to design data-gathering campaigns to systematically test hypotheses about both Path I and Path II that would not be observable without the disruption.

For example, the unprecedented reduction in daily fossil CO_2 emissions (FIG. 2c) could lend insight into the processes governing land and ocean carbon sinks, provided that careful testing demonstrates that a signal can be detected amid the noise of natural variability, and that observations can be safely maintained during the event. Rapid declines in emissions can also help to narrow existing uncertainties around anthropogenic sources and their imprint on atmospheric trace gas and aerosol concentrations (BOX 2). Methane emissions from oil and gas fields offer one immediate example: so far during the event, oil and gas companies in the USA still maintained ~11 million barrels of daily crude oil production throughout the spring of 2020, despite a 44% reduction in gasoline sales for the USA in April[14]. Not surprisingly, US inventories continue to climb, reaching their highest levels of the past four decades in June. If oil production slumps this summer, monitoring from satellites, aircraft, towers and on-the-ground sensors will provide an unprecedented opportunity to quantify any change in methane and ethane emissions, including decreases caused by lower production or increases caused by reduced oversight from workers or inspectors. But that will only be possible if the scientific community organizes and there is sufficient operational flexibility to allow for the collection of critical data.

A similar opportunity exists to study the effectiveness of wildfire suppression on air quality. In the USA, federal, state and local fire agencies are adjusting strategies in order to limit use of ground crews and their exposure to COVID-19 (REF.[69]). These strategies could influence aerosol loads from wildfires (which would have potential health consequences[70]). It will, thus, be possible to systematically evaluate the effectiveness of this aggressive fire-suppression approach using existing satellite and ground-based observations.

Earth System models that predict responses and guide observations. Computational models are frequently used to test the response of the Earth System to changes in external forcing, including for quantifying a counterfactual history without human emissions and for generating climate scenarios under future forcing from greenhouse gases or solar geoengineering. In recent decades, Earth System models have become increasingly sophisticated and complex, and have been shown to accurately reproduce[71], and predict[72,73], many aspects of the Earth System[6]. However, limitations to validating the response to large changes in forcing have remained a persistent source of uncertainty, and the models still contain only rudimentary representations of the Path II impacts. The magnitude of the current socioeconomic disruption thus presents a unique setting for systematic Earth System model evaluation and development.

Earth System models could be deployed for a number of benefits. Because the magnitude of COVID-19 socioeconomic disruption is historically unprecedented, it will not be possible to identify all possible Earth System responses based on theory or historical experience alone. Earth System models could be used to create hypotheses that cannot be otherwise foreseen. Generating simulations early in the event — and leveraging pre-existing idealized experiments (FIG. 4) — could inform data collection and preservation, including any new observations that might be needed in order to validate unexpected modelling results (such as predictions of Path I and Path II impacts generated using existing empirical relationships[74,75]). After the event, when the temporal and spatial evolution of specific Earth System forcings is known, coordinated experiments[76] would allow multiple Earth System models to be compared in a unified framework. The fact that the socioeconomic disruption is deliberately temporary will increase the ability to use data collected during and after the event to verify modelling results.

The event could also be used to evaluate the potential efficacy of specific policy interventions for both Path I and Path II impacts. For example, because atmospheric chemistry and pollutant accumulation in the near-surface environment are subject to variable meteorological conditions and highly nonlinear chemical interactions, consideration of policy interventions to improve air quality (such as incentives for electric-vehicle adoption) have relied heavily on theoretical arguments and model simulations. The scale of emissions reductions induced by the socioeconomic disruption opens an opportunity to use observations of primary and secondary pollutants to evaluate the performance of chemical-transport models in simulating a number of complex features of the event (FIG. 4).

For example, comparison of observations over northern China during the 2020 winter lockdown versus the same calendar period in 2019 shows higher ground-level ozone (as expected from theory and modelling, as NOx emissions decline in a high-NOx emission region[77]), which enhances atmospheric oxidizing capacity and subsequent formation of secondary aerosols, such as occurs in extreme-haze events[22,78,79]. In addition, sheltering policies have affected the emission-producing transportation, manufacturing and power-generation sectors[12], though the degree and scope of shutdown in these individual sectors vary considerably[13]. Further, much of this change occurred against the backdrop of the transition from winter to spring, a period when insolation, water vapour and meteorology are changing rapidly. This transition was made even more complex this year by a large-scale dynamical pattern that resulted in a relatively cold spring over much of the central and eastern USA. Together, these challenges present a unique opportunity to evaluate Earth System model simulations of the air-quality response to emissions reductions in specific sectors (BOX 2).

In addition to implications for air quality, the representation of aerosol effects has been one of the key sources of uncertainties in Earth System models[71,80,81]. Should changes in regional aerosol concentrations occur as a result of the COVID-19 sheltering, the event could be used to verify simulated climatic consequences of policies to improve air quality, such as meteorological impacts like short-term increases in heat and precipitation extremes due to 'unmasking' of the effect of greenhouse gases[82]. A key concern is that these short-term, local signals (FIG. 4) need to be evaluated in the longer-term context of both internal climate variability and regulation-induced trends in aerosol emissions (BOX 2). However, the pervasiveness and persistence of the socioeconomic disruption may provide sufficient statistical power to test predictions generated by Earth System models.

Solution-oriented interventions that create randomized research trials. Many of the long-term impacts hypothesized in this Perspective will be determined by the response of human behaviour and decision-making. Systematically testing these human responses can be challenging. However, the scale of government response to the COVID-19 pandemic creates the opportunity to leverage solution-oriented interventions to create randomized research trials that can simultaneously provide assistance and insight about both Path I and Path II impacts.

Similar to the RCTs that are used to test the efficacy of vaccines and therapeutics, RCTs have been deployed to study a variety of other human outcomes, the effectiveness of which was recognized with this year's Nobel Prize in Economics. Although RCTs have been less frequently aimed at environmental outcomes, RCT feasibility has been demonstrated in a number of relevant contexts, including agricultural microcredit[83] and payment for ecosystem services[84–86]. In addition, basic benchmarking studies have been conducted in single locations[87]. Together, these past studies provide the foundational research infrastructure that would be necessary to deploy RCT-based interventions in the COVID-19 context.

RCTs could be used to study vulnerability, resilience and disaster response in the face of extreme events that occur during sheltering[88]. Another prime candidate would be policy interventions designed to prevent the kind of long-term socio-environmental damage that becomes increasingly likely as the disruption becomes more severe and sustained[51]. For example, the emerging poverty shock[50] can be expected to lead to substantial deforestation, land degradation and nutrient loss, even over the next few growing seasons, as smallholder farmers struggle to produce food with fewer inputs and households revert to harvested biomass for cooking. Similar socio-environmental cascades might occur in marine ecosystems. Solution-oriented RCTs would use random assignment (when the trial is of limited scale) or randomized phasing of participation (for comprehensive programmes) to test whether direct payments or other conditional mechanisms, such as payments for protection of ecosystem services, are effective in staving off environmental damages. Studies could compare the efficacy of a given treatment across different locations or domains, and could also benchmark generalized interventions (such as unconditional cash transfers) against more targeted solutions. In addition to helping vulnerable individuals and communities weather the COVID-19-driven poverty shock, such RCTs would provide a much deeper understanding of how and where poverty and environmental degradation are most tightly linked, and what types of interventions are doubly-protective of people and the environment.

A similar opportunity could exist in conjunction with COVID-19 relief and recovery funding. For example, if infrastructure spending is specifically included in recovery measures, that spending would provide an opportunity to systematically study the long-term effectiveness of green investments[18] (including infrastructure and government programmes like jobs and conservation corps) in achieving Path I outcomes such as reduced greenhouse gas emissions and Path II outcomes such as increased resilience to climate extremes[18,89]. Even if federal or state stimulus measures do not explicitly include funding or requirements for these investments, the existing efforts of various states and localities to consider climate and other environmental outcomes in infrastructure investments[89] would create an opening for well-designed, opportunistic research trials built around variations in how government stimulus funding is applied in the context of varying state and local jurisdictional constraints.

Voluntary, solution-oriented actions could create similar opportunities for both Path I and Path II impacts. For example, large fractions of residential developments in the western USA are at the wildland–urban interface. The lack of 'defensible space' around homes substantially increases wildfire risk. It has been proposed that residents who are able to shelter in place could allocate more effort to reducing their fire risk by increasing the defensible space around their homes[90]. With some foresight and investment, this effort could be used to study the effectiveness of defensible space. Other solution-oriented efforts that can be voluntarily undertaken while safely sheltering, such as local food production and preparation, could also be leveraged to study the effectiveness of adaptation and resilience interventions, as well as the effects of changes in consumption patterns on household carbon and environmental footprints.

Summary and future perspectives

The socioeconomic disruption associated with COVID-19 represents a highly unusual alteration of the human interaction with the Earth System. This alteration is likely to generate a series of responses, illuminating the processes connecting energy, emissions, air quality and climate, as well as globalization, food security, poverty and biodiversity (FIG. 1). In many cases, these long-term, indirect Earth System responses could be larger — and of opposite sign — than the short-term environmental effects that have been immediately visible around the world. The potential for long-term impacts via Earth System cascades and feedbacks highlights the opportunity to use this period as an unintended experiment, and to use the knowledge gained to better predict, model and monitor Earth System processes during and after the event.

Given the uncertainty about the length of sheltering orders — and the nature of any interventions that may follow — it is impossible to know how long this inadvertent experiment will last. This uncertainty provides motivation for documenting hypotheses during this initial stage of the global crisis, so that data can be gathered and evaluated within the framework of a priori predictions, rather than post hoc analyses. Some hypotheses are only testable or conclusively verifiable by maintaining and/or deploying data collection during this early stage. Unless prohibited by safety concerns, it is important that these data continue to be collected so that the Earth System response to COVID-19 can be understood. By generating specific hypotheses based on initial observations, existing empirical relationships and process-based models, and then testing those hypotheses with existing and novel data sources, the COVID-19 socioeconomic disruption can provide novel insights into the processes that govern Earth System function and change.

Our primary motivation is to search for insight about the basic functioning of the Earth System that could be helpful in managing and recovering from the event, and in avoiding future impacts. Predicting the impacts of the sheltering on different components of the Earth System can help to aid in environment-related disaster preparedness in different regions. For example, analysis of the Earth System response can enable early detection of hotspots of environmental risk or degradation emerging during the event. Similarly, predicting, monitoring and understanding Earth System processes can help to support a sustainable economic, social and environmental recovery from the event. Although there is uncertainty about the length of the pandemic, the economic effects seem very likely to last for years. The individual, societal and government responses to these economic effects will influence the long-term trajectory of the human footprint on the Earth System.

The current socioeconomic disruption is a singular perturbation of that human footprint. Advancing understanding of this forcing, and the processes by which different components of the Earth System respond, can help to enhance robustness and resilience now and in the future.

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