THE STATE OF CLIMATE SCIENCE AND WHY IT MATTERS

HEARING

BEFORE THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

ONE HUNDRED SIXTEENTH CONGRESS

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Appendix II: Additional Material for the Record

THE STATE OF CLIMATE SCIENCE AND WHY IT MATTERS

WEDNESDAY, FEBRUARY 13, 2019

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

The Committee met, pursuant to notice, at 10:01 a.m., in room 2318, Rayburn House Office Building, Hon. Eddie Bernice Johnson [Chairwoman of the Committee] presiding.

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

HEARING CHARTER

The State of Climate Science and Why it Matters

Wednesday, February 13, 2019
10:00 a.m.
2318 Rayburn House Office Building

PURPOSE

On Tuesday, February 12th, the Committee on Science, Space, and Technology will hold a full Committee hearing entitled "*The State of Climate Science and Why it Matters.*" The purpose of this hearing is to provide a big-picture assessment of the current state of climate science. The Committee will receive expert testimony on recently published significant climate reports and discuss report findings that include the physical mechanisms of climate change, risks to human society at different levels of warming, and the need for adaptation and mitigation.

WITNESSES

- **Dr. Natalie M. Mahowald** - Irving Porter Church Professor of Engineering, Faculty Director for the Environment, Atkinson Center for a Sustainable Future, Cornell University
- **Dr. Robert Kopp** – Director, Rutgers Institute of Earth, Ocean, and Atmospheric Sciences, and Professor, Department of Earth and Planetary Sciences, Rutgers University
- **Dr. Jennifer Francis** – Senior Scientist, Woods Hole Research Center
- **Dr. Joseph Majkut** – Director of Climate Policy, Niskanen Center
- **Dr. Kristie Ebi** - Rohm & Haas Endowed Professor in Public Health Sciences, Director, Center for Health and the Global Environment (CHanGE), University of Washington

BACKGROUND

The State of Climate Science

While the understanding of the basic physical mechanisms of climate change has not changed significantly over the last 20 years, recent research has provided even stronger evidence in support of the scientific consensus that the climate is warming and it is primarily driven by the emissions of greenhouse gases due to human activities. In addition, there is significant literature on the contemporary impacts of climate change to human and ecological systems, as well as extensive analysis of likely future impacts given different levels of warming. Several recent national and international reports, described below, have assessed and synthesized the current state of scientific understanding of climate change and related impacts, as well as the costs and benefits of different mitigation strategies.

Recent Climate Reports

IPCC Special Report on Global Warming of 1.5°C. Released in October 2018, the Intergovernmental Panel on Climate Change (IPCC)[1] Special Report on Global Warming of 1.5°C[2] (IPCC SR1.5) was produced separately from the periodic assessments required under the United Nations Framework Convention on Climate Change (UNFCCC). The IPCC SR1.5 was commissioned by world leaders, including some from small island nations, under the 2015 Paris Agreement.[3] While the final pledges under the Paris Agreement would limit warming to 2°C, some countries requested a study on how the risks of warming of 1.5°C above preindustrial levels would compare to the risks of warming of 2°C. The report's 91 authors and review editors from 40 countries drew its conclusions through a review of over 6,000 studies. Apart from comparing the risks of 1.5°C to 2°C, it provides context for these targets by showing where they fall on the current emissions trajectory.

The report found that limiting warming to 1.5°C rather than 2°C would have wide-ranging benefits. However, doing so "would require rapid, far-reaching and unprecedented changes in all aspects of society," including cutting global carbon emissions to net zero by 2050, and boosting renewable energy to make up over 50 percent of the U.S. energy mix by 2050. It is estimated that achieving this goal would require five times the current investment in low carbon technologies, as well as high prices on carbon emissions. The scientific literature has demonstrated lower risks at 1.5°C compared with 2°C in <u>every</u> category addressed. In fact, one of the biggest differences between this report and past IPCC assessments is that it provides an unprecedented level of granularity in differentiating the risks of a 1.5°C world compared with a 2°C world. Though the IPCC SR1.5 finds it is more difficult to transition global carbon emissions to a level that would limit warming to 1.5°C than to 2°C, it would avoid enormous losses to global Gross Domestic Product (GDP). The U.S. could lose around 1.2 percent of its GDP for every additional 1°C of warming above the current levels. The IPCC SR1.5 concludes that though technology to limit warming to 1.5°C does exist, global political trends make this outcome difficult, even nearly impossible, to achieve.

Fourth National Climate Assessment. The National Climate Assessment is a congressionally mandated report published quadrennially by the U.S. Global Change Research Program (USGCRP), a federal program directed by Congress to coordinate 13 member federal agencies[4]

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[1] The Intergovernmental Panel on Climate Change (IPCC) was created by the United Nations Framework Convention on Climate Change (UNFCCC), a multilateral agreement signed by President George H.W. Bush and ratified by the Senate. It is an international body that develops non-policy-prescriptive reports; these reports do not produce their own science but rather synthesize current climate science to inform decision makers and the public and are usually released every 5 to 6 years. (https://www.ipcc.ch/)

[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 and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp.

[3] A multilateral agreement to limit climate change to 2C signed by 195 countries in 2016. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[4] The 13 agencies are the Departments of Agriculture, Commerce, Defense, Energy, Health and Human Services, the Interior, State, and Transportation, as well as the Environmental Protection Agency, National Aeronautics and Space

that conduct or apply research on global environmental change.[5] *Volume I of the Fourth National Climate Assessment (NCA4 Vol 1): Climate Science Special Report*,[6] released in 2017, examines the latest science on the physical drivers of climate change, climate models and projections, changes in temperature and extreme weather, ocean acidification, and sea level rise. More than 300 scientists in the 13 member agencies wrote this 470-page volume, and its conclusions are based on the evaluation of over 1,500 climate science studies. The final product was then peer reviewed by the National Academies of Science, Engineering and Medicine (NASEM).

The report is consistent with the last twenty years of climate science, which has confirmed that since the turn of the century, climate change is occurring and is caused by carbon pollution released by human industrial activity. More robust evidence now exists showing the correlation between human activities and increases in global temperature, the warming and further acidification of our oceans, rising sea levels, and disappearing arctic ice sheets. The conclusions of the report are scientifically conservative; the authors required a large amount of evidence and a high number of studies supporting a finding before including it in the report's conclusions. Though NCA4 Vol 1 does not provide policy recommendations or assess climate mitigation or adaption strategies, it does note that limiting global warming to 2°C will require major reductions in greenhouse gas emissions.

Volume II of the Fourth National Climate Assessment (NCA4 Vol 2): Impacts, Risks, and Adaptation in the United States,[7] released in November 2018, is a 1,524-page report that exhaustively outlines the effects and risks of climate change in the U.S., which is broken into 10 geographic regions,[8] and 16 national topics.[9] The NCA4 Vol 2 shows how climate change is increasingly impacting our communities, and how mitigation and adaptation strategies can improve the circumstances. Key scientific advances since the Third National Climate Assessment (NCA3) include advances in attribution of human influence on climate and extreme weather events, rapid changes for ice loss globally, as well as increases in ocean acidification, warming and deoxygenation. Following feedback received after the publication of the NCA3, the NCA4 provided its analysis in a more localized format to better describe and communicate specific climate change impacts on different regions across the country. The NCA4 Vol 2 finds that under high emissions scenarios with limited or no adaptation, losses are great: a predicted $141 billion

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Administration, National Science Foundation, Smithsonian Institution, and U.S. Agency for International Development.

[5] It was established by Presidential Initiative in 1989 under George H. W. Bush, and mandated by Congress in the Global Change Research Act of 1990. (https://www.globalchange.gov/about/legal-mandate)

[6] USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp., doi: 10.7930/J0J964J6.

[7] USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018

[8] Regions include Northeast, Southeast, U.S. Caribbean, Midwest, Norther Great Plains, Southern Great Plains, Northwest, Southwest, Alaska, Hawai'i & U.S.-Affiliated Pacific Islands.

[9] National topics include Our Changing Climate, Water, Energy Supply, Delivery & Demand, Land Cover & Land-Use Change, Forests, Ecosystems, Ecosystem Services, & Biodiversity, Coastal Effects, Oceans & Marine Resources, Agriculture & Rural Communities, Built Environment, Urban Systems, & Cities, Transportation, Air Quality, Human Health, Tribes & Indigenous Peoples, Climate Effects on U.S. International Interests, Sectoral Interactions, Multiple Stressors, & Complex Systems.

from heat-related deaths, $118 billion from sea level rise, $32 billion in costs to infrastructure, and $160 billion lost wages from two billion lost labor hours by the end of the century. It is very likely that some impacts are irreversible. However, many impacts can be avoided or substantially reduced if emissions of greenhouse gases are reduced.

Climate Change and Extreme Weather Events. The nascent field of extreme event attribution tries to determine how much of an extreme event can be attributed to climate change versus regular weather patterns. The field is advancing rapidly, and in 2016, the NASEM published *Attribution of Extreme Weather Events in the Context of Climate Change,*[10] which looked at the consensus on to what extent scientists can estimate the influence climate change has on extreme weather events. Extreme event attribution teases out the effects of anthropogenic, or human-caused, climate change from other factors that influence climate, such as changes in solar activity and natural, internal processes of the climate system, such as El Nino.

The NASEM study found that climate change is exacerbating some extreme weather events, with temperature – such as heat waves and long-term warming – being the strongest influence of climate change on extreme events. It finds less certain links between climate change and the occurrence of tornadoes, hurricanes, or wildfires. However, the intensity of hurricanes, such as the extreme precipitation during Hurricane Harvey, has been linked to climate change. [11] Similarly, the Bulletin of the American Meteorological Society released a supplement in December 2018 entitled "Explaining Extreme Events of 2017 From a Climate Perspective"[12] which found that events ranging from the floods in South America to heatwaves in China were made more likely due to anthropogenic climate change. It is important to note that current scientific literature cannot definitively answer whether climate change "caused" an individual weather event to occur; rather that that climate change can alter the intensity or frequency of certain events.[13] Nevertheless, the report marks the "second year that scientists have identified extreme weather events that they said could not have happened without warming of the climate through human-induced climate change."[14]

Climate Change and Health. As scientific evidence of direct and indirect impacts of climate change on human health is becoming clearer, the global health community is actively framing climate change as a public health crisis. In 2018, the *Lancet Countdown Report: Tracking*

[10] National Academies of Sciences, Engineering, and Medicine. 2016. *Attribution of Extreme Weather Events in the Context of Climate Change*. Washington, DC: The National Academies Press. https://doi.org/10.17226/21852.
[11] Vano J, Dettinger M., Cifelli R *et. al*, "Hydroclimatic Extremes as Challenges for the Water Management Community: Lessons From the Oroville Dam and Hurricane Harvey." Special Supplement to the Bulletin of the American Meteorological Society, Vol. 99 No. 12, December 2018. "Explaining Extreme Events of 2017 From a Climate Perspective."
[12] Special Supplement to the *Bulletin of the American Meteorological Society*, Vol. 99 No. 12, December 2018. "Explaining Extreme Events of 2017 From a Climate Perspective."
https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/
[13] National Academies of Sciences, Engineering, and Medicine News. 2016. *New Report Says Science Can Estimate Influence of Climate Change on Some Types of Extreme Events.*
http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=21852
[14] https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/

Progress on Health and Climate Change[15] was released as a collaboration between researchers around the world. The Lancet Countdown tracks the connections between health and climate as well as how climate change solutions can mitigate health impacts. The Lancet Countdown finds that current public health challenges due to climate change will be further exacerbated as global temperatures rise and the nature and scale of our global response to climate change will determine global health for generations.

24th Conference of the Parties (COP24) Special Report: Health and Climate Change.[16] During the Conference of Parties 23 (COP23) held in Bonn, Germany on behalf of the Republic of Fiji, Prime Minister Bainimarama of Fiji requested that the World Health Organization (WHO) prepare a report on health and climate change to be delivered at the COP24 in Katowice, Poland. [17] The COP24 Special Report made many recommendations such as promoting actions to reduce global carbon emissions and other air pollutants, tracking progress in health due to climate change mitigation, and mobilizing subnational leaders to take action on this issue. They also recommended highlighting the health implications of climate adaptation and mitigation strategies.

The IPCC SR1.5 included health implications throughout its findings. Climate change impacts such as increased global temperatures, extreme weather events, and flooding and sea level rise can exacerbate the spread of infectious and vector borne diseases, degrade air quality, and endanger food and water security. Limiting warming to 1.5°C would have many public health benefits.

The key messages from the human health chapter of the NCA4 Volume 2 show that climate change is already affecting the health of all Americans through increased exposure to extreme weather events and infectious or vector-borne diseases, and through changes in air quality and mental health stress. The most vulnerable populations, such as lower-income communities, the elderly, children, and some communities of color, are likely to experience even greater health risks from climate change. However, adaptation measures can help reduce the impacts and risk of climate-related health impacts, and mitigation of greenhouse gas emissions has clear economic and health benefits.[18]

Evidence of Climate Change Impacts

Climate change is already affecting communities in direct and indirect ways. Some scientifically supported evidence of climate change impacts include:

Sea Level Rise. The average global sea level has risen approximately 7-8 inches since 1900, "with almost half this rise occurring since 1993 as oceans have warmed and land-based ice has melted." By 2030, global mean sea level is *very likely* (emphasis theirs) to rise by 0.3-0.6 feet.[19]

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[15] Watts N, Amann M, Ayeb-Karlsson S, *et al.*: The *Lancet* Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. *Lancet.* 2018; **391**(10120): 581–630. https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(18)32594-7/fulltext
[16] COP24 special report: health and climate change. Geneva: World Health Organization; 2018. Licence: CC BY-NC-SA 3.0 IGO. https://apps.who.int/iris/bitstream/handle/10665/276405/9789241514972-eng.pdf?ua=1
[17] https://www.who.int/globalchange/publications/COP24-report-health-climate-change/en/
[18] NCA4 Volume 2
[19] NCA4 Volume 1

Global Temperature Rise. The planet has already warmed about 1°C above preindustrial levels, and at the current trajectory of carbon emissions, the world could reach anthropogenic global warming of 1.5°C as soon as 2030.[20]

Shrinking Arctic Ice Sheets. Annually averaged arctic ice sheet extent has decreased over 3.5 percent every decade from 1979 to 2016, with the "annual arctic sea ice maximum in March 2017… the lowest maximum areal extent on record."[21]

Warming Oceans. Over 90 percent of the heat attributed to anthropogenic emissions to date have been absorbed by the oceans, making them warmer. Global average sea surface temperature could increase by approximately 2.7°C by 2100 in a high emissions scenario. [22]

Extreme Weather Events. Extreme weather events alone have cost the United States over $1 trillion since 1980,[23] with the U.S. experiencing 14 weather and climate disasters totaling $14 billion in 2018 alone.[24]

Additional Reading

IPCC Special Report: Global Warming of 1.5°C: Summary for Policymakers
https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/

The 1.5 Health Report: Synthesis on Health & Climate Science in the IPCC SR1.5
https://www.who.int/globalchange/181008_the_1_5_healthreport.pdf

NCA4 Volume 1 Executive Summary
https://science2017.globalchange.gov/chapter/executive-summary/

NCA4 Volume 2 Summary Findings
https://nca2018.globalchange.gov/downloads/NCA4_Ch01_Summary-Findings.pdf

[20] IPCC SR1.5
[21] NCA4 Volume 1
[22] NCA4 Volume 1
[23] NCA4 Volume 1
[24] NOAA.gov, February 6th, 2018. "2018 was 4th hottest year on record for the globe."
https://www.noaa.gov/news/2018-was-4th-hottest-year-on-record-for-globe

Chairwoman JOHNSON. This hearing will come to order. Without objection, the Chair is authorized to declare a recess at any time.

Good morning, and welcome to today's hearing entitled, "The State of Climate Science and Why it Matters." Let me first welcome everyone to the full Committee hearing of the Committee on Science, Space, and Technology for the 116th Congress. I'm looking forward to a productive and collegial meeting today, one in which rigorous scientific discourse can help enable the creation of a sound public policy.

Every committee is meeting because we've had to alter committee meetings this week because we've had two funerals. And so we will have Members coming and going, and we hope that you'll understand.

I also want to welcome all of our distinguished witnesses and thank them for their flexibility in making themselves available to participate in this rescheduled hearing.

Today's hearing is the first in what will be multiple climate-change-related hearings this Congress. Following the release of the IPCC (Intergovernmental Panel on Climate Change) Special Report on Global Warming of 1.5 °C, and the National Climate Assessment last year, it is clear that we're responsible for our planet warming at an alarming rate, and we already are feeling the impacts of this warming today. Setting the stage with a discussion of the most relevant and up-to-date scientific evidence from these and other reports will allow us to better understand the climate-related impacts we are experiencing in all of our districts. The evidence of continued unmitigated emissions of greenhouse gases is clear. Our coastal communities are dealing with sea-level rise and ocean acidification, and all communities are dealing with more severe weather incidences and the increased exposure to extreme heat and poor air quality.

Today's discussion on climate science is important to deepening our fundamental understanding of why the climate is changing and how this manifests in ways that impact society. It will also help us as we turn our focus to the role of science and innovative technology development to devise adaptation and mitigation strategies, which will have numerous positive benefits for our economy, our safety and security, and our public health. I am glad we have the leading experts in these fields who worked closely on these reports to guide our discussion.

I also want to note that the impacts of climate change are not limited to what is described in these climate science reports. Just last week, NOAA's (National Oceanic and Atmospheric Administration) State of the Climate Report for 2018 found that it was the wettest year for the contiguous United States in the past 35 years. NASA (National Aeronautics and Space Administration) and NOAA also found that last year had the fourth-highest global surface temperature since 1880. It has almost become a given that we can expect record-breaking temperatures every year, especially since the past 5 years have been the warmest in modern record.

Though this Administration has regrettably chosen to ignore the findings of its own scientists in regards to climate change, we as lawmakers have a responsibility to protect the public's interest. I plan to do this by making sure this Committee is informed by the most relevant and up-to-date science as we work to conduct our legislative and oversight responsibilities. The Science Committee oversees much of the Federal climate research, and as well as the development and demonstration of new and innovative technologies, which makes our role as Members of this Committee critical to preparing our country to deal with climate change.

I look forward to kicking off a fruitful and informative discussion that will continue throughout this Congress on why we need to act on climate change now.

[The prepared statement of Chairwoman Johnson follows:]

Opening Statement
Chairwoman Eddie Bernice Johnson
House Committee on Science, Space, and Technology

The State of Climate Science and Why it Matters
February 13, 2019

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I look forward to kicking off a fruitful and informative discussion that will continue throughout this Congress on why we need to act on climate change now.

Thank you, and I will now yield to Ranking Member Lucas for his statement.

Chairwoman JOHNSON. Now I will recognize the Ranking Member's opening statement.

Mr. LUCAS. Thank you, Chairwoman Johnson, and I would like to again thank you for holding this hearing and providing a platform to hold a constructive dialog on the issue of climate change.

I'm proud to be a western Oklahoma farmer and to represent a resilient community of farmers. As any farmer can tell you, we are especially dependent on the weather. Droughts and heat waves come and go naturally, but the changing climate has intensified their impacts.

We know the climate is changing and that global industrial activity has played a role in this phenomenon. But our communities, like the farmers and ranchers in my district, need to know more about the extent to which a changing climate affects short- and long-term weather patterns.

I believe the Federal Government has a responsibility to prioritize research so that we can better understand the complex relationship between climate and weather and increase preparedness in our communities. I also believe it's critical that America leads the world in developing the next-generation technologies to address the effects of climate change.

Fortunately, we have a unique opportunity here on the Science Committee to promote research and technology solutions. American industry, innovators, and researchers at our national labs are pioneering technologies that capture carbon emissions from coal and natural gas, batteries that store energy from intermittent energy sources like wind and solar, and advanced nuclear reactors that can provide cleaner, more affordable power. These technologies have the potential to reduce greenhouse gas emissions around the world and ensure American energy dominance.

America has always led the way in technology advances. In 1919, my great aunt's prized possession was a phonograph, a mechanical device which was then state-of-the-art technology. A hundred years later, we listen to music on our cell phones, and no one could have predicted the incredible leap forward in technology. Americans are always innovating, finding surprising ways to meet new challenges. Energy is no exception. Hydraulic fracking revolutionized energy production, unlocking a vast American energy resource that was unimaginable just a decade ago. Developed by industry in cooperation with the national labs, fracking reduced the environmental footprint of energy production and has brought cleaner, cheaper natural gas to the market around the world.

Through innovation, we can repeat this incredible success. The next technological breakthrough is right around the corner, and if we want to succeed, we must continue to focus on realistic, technology-driven solutions to climate change that can compete in today's economy. We won't succeed in pie-in-the-sky policies that demand 100 percent renewable energy at the expense of reliable power from nuclear and fossil fuels and raise energy prices for businesses and consumers.

Today, we'll hear from Dr. Joseph Majkut, the Director of Climate Policy for the Niskanen Center, who will stress that it's essential that we take a realistic, innovative, and competitive approach to addressing climate change. I share his belief that by investing in research to develop carbon capture, carbon use, advanced nuclear and renewable energy technologies, we can incentivize innovation and growth in these industries and reduce carbon emissions in the process. Innovation is good for the global environment and the American economy.

I take environmental policy very seriously. This dedication comes from being raised by people who lived through the worst prolonged environmental disaster in American history, the great drought and Dust Bowl of the 1930s. We have a responsibility to ensure events like the Dust Bowl never occur again.

While this Committee cannot control the weather, we can prioritize investments in basic science and energy research that will revolutionize the global energy market. America led the world in coal, oil, and gas. Now we must lead again, and partner with industry to develop breakthrough energy technologies and make our existing energy sources cleaner and more affordable.

I thank our witnesses for being here today, and I yield back the balance of my time, Madam Chairman.

[The prepared statement of Mr. Lucas follows:]

Ranking Member Lucas Opening Statement on Climate Change at Full Committee Hearing

Feb 12, 2019 Opening Statement

Chairwoman Johnson, I would like to thank you for holding this hearing and providing a platform to hold a constructive dialogue on the issue of climate change.

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Through innovation, we can repeat this incredible success. The next technology breakthrough is right around the corner – and if we want to succeed, we must continue to focus on realistic, technology-driven solutions to climate change that can compete in today's economy.

We won't succeed with pie-in-the-sky policies that demand 100% renewable energy at the expense of reliable power from nuclear and fossil fuels and raise energy prices for businesses and consumers.

Today we will hear from Dr. Joseph Majkut, the Director of Climate Policy for the Niskanen Center, who will stress that it is essential that we take a realistic, innovative, and competitive approach to addressing climate change.

I share his belief that by investing in research to develop carbon capture, carbon use, advanced nuclear, and renewable energy technologies, we can incentivize innovation and growth in these industries – and reduce global emissions in the process. Innovation is good for the global environment and the American economy.

I take environmental policy very seriously. This dedication comes from being raised by people who lived through the worst prolonged environmental disaster in American history, the drought and dust bowl of the 1930s. We have a responsibility to ensure events like the dust bowl never happen again.

While this Committee cannot control the weather, we can prioritize investments in basic science and energy research that will revolutionize the global energy market.

America led the world in coal, oil, and gas. Now we must lead again, and partner with industry to develop breakthrough energy technologies and make our existing energy sources cleaner and more affordable. I thank our witnesses for being here today and I yield the balance of my time.

Chairwoman JOHNSON. Thank you very much, Mr. Lucas.

If there are Members who wish to submit additional opening statements, your statements will be added to the record at this point.

At this time I'd like to introduce our witnesses. Our first witness is Dr. Natalie Mahowald, the Irving Porter Church Professor of Engineering, and the Faculty Director for the Environment of the Atkinson Center for a Sustainable Future at Cornell University. Due to the weather-related travel delays, she's joining us through a video link from Ithaca, New York. Her research looks at natural feedbacks in the climate system, and Dr. Mahowald was the lead author on the IPCC Special Report on 1.5 °C Global Warming released last year and the IPCC Fifth Assessment from Working Group 1 on the physical science of climate change in 2013.

She received her Ph.D. in meteorology from the Massachusetts Institute of Technology, and we now will recognize—she'll be our first witness.

Our second witness is Dr. Robert Kopp, who is Director of Rutgers Institute of Earth, Ocean, and Atmospheric Sciences, and Professor in the Department of Earth and Planetary Sciences at Rutgers University. He also serves as Co-Director of Rutgers' Coastal Climate Risk and Resilience Initiative. Dr. Kopp's research focuses on past and future sea-level change and the utilization of climate risk information and decisionmaking. He is a lead author of volume 1 of the Fourth National Climate Assessment (NCA 4) released last year and the IPCC's Sixth Assessment Report, which is due out in 2021.

Dr. Kopp received his Ph.D. in geobiology from the California Institute of Technology.

Our third witness, Dr. Jennifer Francis, who is a Senior Scientist at the Woods Hole Research Center. Dr. Francis' research focuses on climate change impacts in the Arctic and how that affects weather around the world, especially how a warming Arctic may lead to a weakened jet stream. Dr. Francis is regularly quoted in media outlets.

Dr. Francis received her Ph.D. in atmospheric sciences from the University of Washington.

Our fourth witness is Dr. Joseph Majkut from the Niskanen Center. He is an expert on climate science policy, and risk and uncertainty analysis for decisionmaking, and is frequently cited by media outlets on climate scientific research.

He received his Ph.D. in atmospheric and oceanic sciences from Princeton University.

Our final witness, Dr. Kristie Ebi, who is the Director of the Center for Health and the Global Environment, or CHanGE program, and the Rohm and Haas Endowed Professor in Public Health Sciences at the University of Washington. Dr. Ebi's research includes estimating current and future health risks of climate change and estimating the health co-benefits of mitigation policies and technologies. Dr. Ebi was the chapter lead on the Human Health Chapter, volume 2, of the Fourth National Climate Assessment released last year. She also co-chairs the National Academies Committee to Advise a U.S. Global Change Research program.

Dr. Ebi received her Ph.D. in epidemiology from the University of Michigan.

As our witnesses shall know, you will each have 5 minutes for your spoken testimony. Your written testimony will be included in the record of the hearing. When all of you have completed your spoken testimony, we will begin a round of questions. Each Member will have 5 minutes to question the panel.

And we will start with a witness that is appearing on the screen, Dr. Mahowald.

[Audio malfunction in hearing room.]

Chairwoman JOHNSON [continuing]. We can't—let's go to Dr. Kopp and then return when we get the technology working.

TESTIMONY OF DR. ROBERT KOPP, DIRECTOR, RUTGERS INSTITUTE OF EARTH, OCEAN, AND ATMOSPHERIC SCIENCES, AND PROFESSOR, DEPARTMENT OF EARTH AND PLANETARY SCIENCES, RUTGERS UNIVERSITY

Dr. KOPP. All right. Well, thank you, Chairwoman Johnson, Ranking Member Lucas, and Committee Members for inviting me to speak today. My name is Robert Kopp. I am the Director of the Rutgers Institute of Earth, Ocean, and Atmospheric Sciences and a Professor at Rutgers University. My research focuses on past and future sea-level change and on the interactions between climate change and the economy.

I served as one of the 29 lead authors of the fourth volume—of the first volume of the Fourth National Climate Assessment, and I was invited here to speak to the fourth assessment. I should note that I'm doing so in my personal capacity, not to represent the U.S. Global Change Research Program or Rutgers.

The Fourth National Climate Assessment provides an up-to-date assessment of the scientific understanding of climate change, its current effects on the United States, and its potential future impacts. It draws out key findings from the massive body of peer-reviewed science to support scientifically informed climate risk management. Its first volume focuses on the physical science; the second on impacts, risks, and adaptation. The report's nearly 2,000 pages are data-driven and extensively referenced. Both volumes underwent detailed transparent review processes, including open reviews by external experts in the general public and thorough reviews by independent experts convened by the National Academies.

The process of drafting the National Climate Assessment was painstaking and complex, but its fundamental findings are simple and urgent. First, climate change is real, it is happening now, and humans are responsible for it. The planet is running a fever. Its average temperature has increased by nearly 2 °F since 1900 with humans responsible for essentially all of the warming since 1950.

Second, climate change isn't an issue for the distant future. It's already affecting Americans in every region of the country. Across the country, heat waves are becoming more frequent, heavy rainfall more intense, and coastal flooding more common as a result of climate change and sea-level rise. Studies show that climate change intensified the dry hot summer of 2011 in Texas and Oklahoma, the recent drought in California, and the rainfall of Hurricane Harvey in 2017.

Third, climate change is not just an environmental challenge. It's an economic challenge, an infrastructure challenge, a public-health challenge, and a national-security challenge. As the report notes, and I quote, "In the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment," particularly in scenarios with limited adaptation.

Fourth, every amount—every additional amount of greenhouse gas emitted makes climate change more severe. In order to stabilize global climate at any level, human—any level of warming, human emissions of carbon dioxide must be brought as close to zero as possible with any continued emission of CO_2 balanced by human removal of carbon dioxide from the atmosphere, whether that's by expanding forests or using new, little-tested technologies. In other words, to stabilize the global climate, net global carbon dioxide emissions must be brought to zero. The faster we reduce our emissions, the less severe the effects and the lower the risk of unwelcome surprises.

Fifth, though the pace is not yet adequate to minimize climate risk, Americans are already starting to respond by reducing emissions and beginning to adapt to climate-change impacts. As the report notes, 110 cities, several States, and an increasing number of companies have adopted emissions-reduction targets. The report highlights adaptation planning efforts by cities and transport systems, the use of innovative farming techniques to deal with wet and dry extremes, and efforts to measure—to manage water scarcity in places like the Colorado River basin and Texas' Edwards Aquifer. These mitigation and adaptation efforts need to grow dramatically and rapidly to effectively manage climate risk.

In conclusion, the National Climate Assessment shows that climate change is real, it's here, and we humans are responsible for it. To stabilize the global climate, we need to bring net global greenhouse gas emissions to zero. The sooner we do this, the smaller the risks to our economy, health, infrastructure, and security that we will have to manage. But even with strong emissions reductions, there will still be major adaptation challenges ahead. It's therefore essential that climate change become a routine and integrated part of decisionmaking at all levels, public and private, Federal, State, and local.

Thank you for holding this important hearing today. It's my hope that, as the Science Committee, you will look closely at how to advance the climate science enterprise in a manner that supports climate risk management.

[The prepared statement of Dr. Kopp follows:]

Statement of

Robert E. Kopp
Professor, Department of Earth and Planetary Sciences
Director, Rutgers Institute of Earth, Ocean, and Atmospheric Sciences
Rutgers University – New Brunswick

before the

Committee on Science, Space, and Technology
U.S. House of Representatives
February 12, 2019

RUTGERS
Institute of Earth, Ocean, and
Atmospheric Sciences

Thank you, Chairwoman Johnson, Ranking Member Lucas, and committee members for inviting me to speak today.

My name is Robert Kopp. I am the Director of the Rutgers Institute of Earth, Ocean, and Atmospheric Sciences[1] and a Professor in the Department of Earth and Planetary Sciences at Rutgers University–New Brunswick. I also serve as co-director of Rutgers' Coastal Climate Risk & Resilience (C2R2) initiative, which trains graduate students to work together across disciplines and with stakeholders to address coastal resilience challenges. I am also one of the directors of the Climate Impact Lab[2], a multi-institutional collaboration applying climate modeling and Big Data approaches to assess the economic risks of climate change. My research focuses on past and future sea-level change, on the interactions between physical climate change and the economy, and on the use of climate risk information in decision making.

I served as one of the twenty-nine lead authors of Volume 1 of the Fourth National Climate Assessment (NCA). I am also currently serving as a lead author of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, which is due out in 2021.

While the bulk of my testimony is focused on presenting the findings of the Fourth NCA, I am speaking on my own behalf. My testimony is not itself a product of the assessment process, nor does it necessarily represent the positions of the US Global Change Research Program or of Rutgers University. I also would like to note that I was not one of the three coordinating lead authors who oversaw Volume 1, nor was I an author of Volume 2. My comments on Volume 2 are based on my technical contributions and my reading of it as a climate scientist who is up to date with in much of the relevant literature.

The National Climate Assessment process

In 1990, President George H. W. Bush signed the Global Warming Response Act of 1990, which established the interagency U.S. Global Change Research Program (USGCRP) under the auspices of the National Science and Technology Council's Subcommittee on Global Change Research. One of the key tasks of the USGCRP was to undertake a quadrennial National Climate Assessment, which "1) integrates, evaluates, and interprets the findings of the Program . . .; 2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and 3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."[3]

The first NCA was released by USGCRP in the year 2000; the second in 2009; and the third in 2014. The Fourth NCA was developed in two volumes: the first volume, published in 2017, focusing on the physical science, and the second volume, in 2018, on Impacts, Risks, and Adaptation. The report is data-driven and transparent, with nearly 2000 extensively referenced pages and key findings backed by detailed traceable accounts.

[1] For more information: eoas.rutgers.edu
[2] For more information: impactlab.org
[3] *Global Change Research Act of 1990*. Pub. L. No. 101-606, 104 Stat. 3096-3104, November 16, 1990. https://go.usa.gov/xE5Js.

Both volumes underwent extensive review processes involving an open review by external experts and the general public, a thorough review by independent experts convened by the National Academies of Sciences, Engineering, and Medicine, and multiple rounds of interagency review. Report authors provided written responses to all the review comments, which are available online for the external and National Academies reviews.

Climate science is a massive enterprise; while at a global scale, the fundamentals are well established, and in many cases have been known for many decades, even over a century, the scientific understanding of the details is rapidly evolving.

As the periodic nature of the NCA reports reflects, the goal of the NCA process is to provide an up-to-date assessment of the scientific understanding of climate change, its current effects on the United States, and its potential future impacts across a broad range of emissions scenarios. It considers a broad range of possible futures, from one in which fossil fuel use and emissions continue to grow to one in which emissions are rapidly reduced and reach zero before the end of the century.

Key messages of the Fourth National Climate Assessment

The National Climate Assessment draws out key findings from the massive body of peer-reviewed science in order to support scientifically informed climate risk management by federal, state, local, and private-sector decision-making. In addition, by identifying key decision-relevant uncertainties, it can also help direct scientific inquiry toward decision-relevant ends.

The most fundamental messages of Volume 1 of the report are simple, and they are not novel:

1) Climate change is real, it is here now, and humans are responsible for it.

2) Every additional amount of greenhouse gas emitted makes climate change more severe.

3) The faster we reduce our emissions, the less severe the effects and the lower the risk of unwelcome surprises.

Volume 2 expands upon the human consequences of climate change and how the US is responding to them. It tells us that:

1) Climate change is not an issue for the distant future – it is already affecting Americans in every region of the country.

2) Climate change is not just an environmental challenge; it is an economic challenge, an infrastructure challenge, a public health challenge and a national security challenge.

3) Though the pace is not yet adequate to minimize climate risk, Americans are already starting to respond by reducing emissions and beginning to adapt to climate change impacts.

Let me expand upon these points.

Climate change is real, it is here now, and humans are responsible for it.

Our planet is running a fever.

To quote the NCA:

> Global climate is changing rapidly compared to the pace of natural variations in climate that have occurred throughout Earth's history. Global average temperature has increased by about 1.8°F from 1901 to 2016, and observational evidence does not support any credible natural explanations for this amount of warming; instead, the evidence consistently points to human activities, especially emissions of greenhouse or heat-trapping gases, as the dominant cause.[4]

Global average carbon dioxide concentration are now about 410 parts per million – nearly 50% higher than they were at the start of the Industrial Revolution, and a level not seen on this planet for at least about three million years. Carbon dioxide's role as a heat-trapping gas has been known since the discoveries of Eunice Foote and John Tyndall in the mid-19th century. Thus, a warming planet should be entirely expected.

In contrast, to quote the NCA,

> Solar output changes and internal natural variability can only contribute marginally to the observed changes in climate over the last century, and there is no convincing evidence for natural cycles in the observational record that could explain the observed changes in climate.[5]

It is *likely* – a term the NCA uses to mean a chance of at least two in three – that the human contribution to global warming over 1951–2010 is between 93 to 123 percent. (Values larger than 100 percent reflect that, in the absence of human emissions, the planet might actually have cooled over this time period.)

Further, "Thousands of studies conducted by researchers around the world have documented changes in surface, atmospheric, and oceanic temperatures; melting glaciers; diminishing snow cover; shrinking sea ice; rising sea levels; ocean acidification; and increasing atmospheric water vapor."[6]

- "Heat waves have become more frequent in the United States since the 1960s, while extreme cold has become less frequent."[7]

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[4] K. Hayhoe et al., *Our Changing Climate*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 72–144, 73 (D. R. Reidmiller et al. eds., 2018), doi:10.7930/NCA4.2018.CH2.
[5] D. J. Wuebbles et al., *Executive summary*, *in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I 10–34, 14 (D. J. Wuebbles et al. eds., 2017), doi: 10.7930/J0DJ5CTG.
[6] *Id.* at 10.
[7] *Id.* at 11.

- "Heavy rainfall is increasing in intensity and frequency across the United States."[8]
- Higher temperatures are making soil drier, contributing to the intensity of droughts.[9]
- Global average sea level has risen by about 8 inches since 1900,[10] and recent work published since Volume 1 of the NCA was completed shows that global average sea level is now rising at more than 1.5 inches per decade – close to three times the average rate over the last century.[11] This has led to an increase in the frequency of coastal flooding: frequencies that, in some cities, have increased by a factor of ten since the middle of the last century.[12]

Every additional amount of greenhouse gas emitted makes climate change more severe.

In the words of the NCA,

> The magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse gases (especially carbon dioxide) emitted globally. Without major reductions in emissions, the increase in annual average global temperature relative to preindustrial times could reach 9°F (5°C) or more by the end of this century. With significant reductions in emissions, the increase in annual average global temperature could be limited to 3.6°F (2°C) or less.[13]

To a first approximation, carbon dioxide warms the planet in proportion to the total amount emitted – every ton of CO_2 emitted increases the planet's temperature a little, every trillion tons by about 0.4°–1.2°F (0.2–0.7°C).[14] As a reference, current global annual CO_2 emissions are about 42 billion tons,[15] so if CO_2 emissions were frozen at the current levels, we would expect global average temperature to increase by about 1°F every 25 years – in fact, somewhat faster due to the effects of greenhouse gases other than CO_2.

The CO_2 warming is extremely long-lived – most of it happens within a decade or two of emission, and most of it persists for well over a millennium.[16]

The consequence of these physical relationships is that, in order to stabilize global climate, human emissions of CO_2 must be balanced by human removal of CO_2 from the atmosphere,

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[8] *Id.* at 11.
[9] M. F. Wehner et al., *Droughts, Floods, and Wildfires*, *in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I 231–256 (D. J. Wuebbles et al. eds., 2017).
[10] William V. Sweet et al., *Sea level rise*, *in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I 333–363 (D. J. Wuebbles et al. eds., 2017).
[11] WCRP Global Sea Level Budget Group, *Global sea-level budget 1993–present*, 10 EARTH SYSTEM SCIENCE DATA 1551–1590 (2018).
[12] Sweet et al., *supra* note 10.
[13] Wuebbles et al., *supra* note 5 at 11.
[14] Matthew Collins, Reto Knutti & others, *Chapter 12: Long-term Climate Change: Projections, Commitments and Irreversibility*, *in* CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS , 12 (Thomas F. Stocker, Dahe Qin, & others eds., 2013), http://www.ipcc.ch/report/ar5/wg1/.
[15] Corinne Le Quéré et al., *Global Carbon Budget 2018*, 10 EARTH SYSTEM SCIENCE DATA 2141–2194 (2018).
[16] F. Joos et al., *Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis*, 13 ATMOSPHERIC CHEMISTRY AND PHYSICS 2793–2825 (2013).

whether by expanding forests or using new, little-tested technologies. In other words, to stabilize global climate, net global CO_2 emissions must be brought to zero.

The faster we reduce our emissions, the less severe the effects and the lower the risk of unwelcome surprises.

For example, rapid emission reductions could limit warming this century over the contiguous United States to about 1-5°F, whereas sustained emissions growth could lead to 6-12°F of warming – with extreme high temperatures rising even faster.[17] Similarly, global average sea level rise this century will very likely be less than 3 feet in a low-emissions future, whereas a high-emissions future raises the odds on extreme Antarctic instability, potentially leading to 6 feet or more of rise over the course of this century.[18]

And the less we push the Earth's climate from the historical conditions that gave birth to modern civilization, the lower the odds that it will surprise us in potentially dangerous ways.[19]

The first volume's final chapter, which I helped lead, offers a perspective on the way the climate system might surprise us, and comes to three key conclusions:

First, one way the climate system might surprise us is through the cumulative effects of multiple, or 'compound' extreme events – for example simultaneous heat and drought, wildfires associated with hot and dry conditions, flooding associated with high precipitation on top of snow or waterlogged ground, or – to take one recent and now sadly familiar example – multiple severe hurricanes in quick succession. The human impacts of these compound extremes can be larger than that of the individual extremes in isolation. This area is an emerging area of research that is just now starting to come into focus; thus the potential for surprises.

Second, both modeling and geological records of past climate changes demonstrate that self-reinforcing cycles "within the climate system have the potential to accelerate human-induced climate change and even shift the Earth's climate system, in part or in whole, into new states that are very different from those experienced in the recent past – for example, ones with greatly diminished ice sheets or different large-scale patterns of atmosphere or ocean circulation."[20] It is such feedbacks that undergird the potential for high-end sea-level rise mentioned earlier.

Third, comparison of the geological record and climate model simulations reveal another insight. Climate models often have difficulty reproducing past warm climates, which we can learn about from the geological record. In the words of the NCA, "The systematic tendency of climate models to underestimate temperature change during warm paleoclimates suggests that climate models are more likely to underestimate than to overestimate the amount of long-term future change."[21] For example, some of the reconstructions of past warm periods from the geological record may be explained if, above some threshold of CO_2 higher than the current level,

[17] R. S. Vose et al., *Temperature changes in the United States, in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I 185–206 (D. J. Wuebbles et al. eds., 2017), doi: 10.7930/J0N29V45.
[18] Sweet et al., *supra* note 10; Robert E. Kopp et al., *Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections*, 5 EARTH'S FUTURE 1217–1233 (2017).
[19] Robert E. Kopp et al., *Potential surprises – compound extremes and tipping elements, in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I 411–429 (D. J. Wuebbles et al. eds., 2017).
[20] *Id.* at 411.
[21] *Id.* at 411.

widespread reductions in cloud cover increases the sensitivity of the climate to greenhouse gases – a possibility pointed to by a few studies.[22]

These large scale, global effects are important, but nobody lives at the global or national average – everyone lives somewhere, and Volume 2 looks at the human effects of these changes.

Climate change is not an issue for the distant future – it is already affecting Americans in every region of the country.

To help with planning at a state and local level, the report details impacts and adaptation measures in ten regions covering the United States and its affiliated islands. For example, as Hurricanes Harvey and Irma reminded us,

> The Southeast's coastal plain and inland low-lying regions support a rapidly growing population, a tourism economy, critical industries, and important cultural resources that are highly vulnerable to climate change impacts. The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century.[23]

Scientists are increasingly able to evaluate the ways in which climate change is making weather more extreme. For example, studies show that climate change intensified the dry, hot summer of 2011 in Texas and Oklahoma and the 2012-2017 drought in California. A warm, moisture-laden atmosphere led to more intense rainfall during Hurricane Harvey in 2017 – as much as 38% more rain, one study estimated, over the entire duration of the storm.[24] And sea-level rise has made every severe coastal flood, including that of Hurricane Sandy in 2012, more intense and damaging.[25] Sensitive assets like roads, hospitals, power plants, and contamination sites are increasingly frequently threatened.[26]

Climate change is not just an environmental challenge; it is an economic challenge, an infrastructure challenge, a public health challenge and a national security challenge.

The National Climate Assessment notes, drawing in part on my work with my collaborators in the Climate Impact Lab, that "in the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment. Under scenarios with high emissions and limited or no adaptation, annual

[22] For example, Rodrigo Caballero & Matthew Huber, *State-dependent climate sensitivity in past warm climates and its implications for future climate projections*, 110 PNAS 14162–14167 (2013).
[23] L. Carter et al., *Southeast*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 743–808, 744 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH19.
[24] Wehner et al., *supra* note 9; Vose et al., *supra* note 17.
[25] Kenneth G. Miller et al., *A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast*, 1 EARTH'S FUTURE 3–18 (2013).
[26] K. Kloesel et al., *Southern Great Plains*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 987–1035 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH23.

losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century."[27]

The report notes that "the health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being."[28]

And it notes that "Climate change, variability, and extreme events, in conjunction with other factors, can exacerbate conflict, which has implications for U.S. national security. Climate impacts already affect U.S. military infrastructure, and the U.S. military is incorporating climate risks in its planning." [29]

This finding about national security impacts is echoed by the US Intelligence Community's most recent Worldwide Threat Assessment, which notes that "Global environmental and ecological degradation, as well as climate change, are likely to fuel competition for resources, economic distress, and social discontent through 2019 and beyond."[30]

Though the pace is not yet adequate to minimize climate risk, Americans are already starting to respond by reducing emissions and beginning to adapt to climate change impacts.

In terms of mitigation, for example, the report notes that 110 cities have adopted emissions reduction targets; several states have mandatory or voluntary targets; and an increasing number of companies are implementing emissions reduction target and internal carbon prices as well.

In terms of adaptation, the report highlights a multitude of examples from around the country. For example, it notes municipal adaptation planning efforts for climate change and/or more frequent flooding in New York City, Boston, Atlanta, and Charleston.[31] Transport systems like the Port Authority of New York and New Jersey and the Metropolitan Atlantic Rapid Transit Authority are building climate resilience into their infrastructure plans.[32] In the Midwest, the report highlights the use of cover crops and water management systems to limit soil erosion in response to more intense rains, as well as the use of green infrastructure to handle stormwater in

[27] J. Martinich et al., *Reducing Risks Through Emissions Mitigation, in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 1346–1386, 1347 (C. W. Avery et al. eds., 2018), doi: 10.7930/NCA4.2018.CH29.
[28] K. L. Ebi et al., *Human Health, in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 572–603, 540 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH14.
[29] J. B. Smith et al., *Climate Effects on U.S. International Interests, in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 604–637, 605 (C. W. Avery et al. eds., 2018), doi: 10.7930/NCA4.2018.CH16.
[30] DANIEL R. COATS, WORLDWIDE THREAT ASSESSMENT OF THE US INTELLIGENCE COMMUNITY 23 (2019), https://www.dni.gov/files/ODNI/documents/2019-ATA-SFR---SSCI.pdf.
[31] L. A. Dupigny-Giroux et al., *Northeast, in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 669–742 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH18; Carter et al., *supra* note 23.
[32] Dupigny-Giroux et al., *supra* note 31; Carter et al., *supra* note 23.

cities like St. Louis and Minneapolis.[33] On the west coast, the report highlights the growing use of dry farming methods in places like Oregon's Willamette Valley, as well as the growing number of Native American nations that have begun to consider relocation as a last resort.[34] In the Southwest, it highlights the multistate, binational efforts to manage Colorado River waters.[35] In Texas, the Edwards Aquifer Recovery Implementation Program Habitat Conservation Program – addressing the aquifer that provides water to San Antonio, San Marcos, and Austin – incorporates advanced water conservation and market-based solutions for dealing with groundwater pumping during droughts. Forty-four public water supply desalination plants in Texas are helping increase water supply in times of drought.[36]

Scientific uncertainty and climate risk management

Uncertainty is integral to science, and one of the main drivers of scientific pursuits. There is a strong tendency among scientists to focus on what is new, tantalizing, and unknown, rather than what is old and well understood.

In the world of scientific assessments, a great deal of effort has gone into formalizing language for evaluating what is known and how well it is known. The National Climate Assessment, like the Intergovernmental Panel on Climate Change, uses a set of specific definitions for terms like '*likely*,' '*very likely*', and '*virtually certain*.' For example, '*likely*' means 'at least two chances in three,' '*very likely*' means 'at least nine chances in ten', and '*virtually certain*' means 'at least ninety-nine changes in one-hundred.' These judgements of likelihood are based upon an expert evaluation that looks across the available scientific literature.

Similarly, these assessments have defined a set of formal language to characterize the strength of the relevant evidence. For example, '*very high confidence*' conclusions have strong evidence, for example based on well-established theory, multiple sources with consistent results, and well accepted methods. '*Medium confidence*' conclusions have suggestive evidence (e.g., a few sources with limited consistency using emerging methods). '*Low confidence*' conclusions are used to highlight areas of inconclusive evidence, inconsistent findings, and limited agreement on methods and conceptual frameworks.

Here are some examples from the first volume of the Fourth NCA:

> Global annual average temperature (as calculated from instrumental records over both land and oceans) has increased by more than 1.2°F (0.65°C) for the period 1986–2016 relative to 1901–1960; the ... change over the entire period from 1901–2016 is 1.8°F (1.0°C) (*very high confidence*[).][37]

> Many lines of evidence demonstrate that it is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century. Over the

[33] J. Angel et al., *Midwest, in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 872–940 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH21.
[34] C. May et al., *Northwest, in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 1036–1100 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH24.
[35] P. Gonzalez et al., *Southwest, in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 1101–1184 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH25.
[36] Kloesel et al., *supra* note 26.
[37] Wuebbles et al., *supra* note 5 at 13.

> last century, there are no convincing alternative explanations supported by the extent of the observational evidence. Solar output changes and internal natural variability can only contribute marginally to the observed changes in climate over the last century, and there is no convincing evidence for natural cycles in the observational record that could explain the observed changes in climate. (*Very high confidence*)[38]
>
> The frequency and intensity of heavy precipitation events in the United States are projected to continue to increase over the 21st century (*high confidence*). There are, however, important regional and seasonal differences in projected changes in total precipitation: the northern United States, including Alaska, is projected to receive more precipitation in the winter and spring, and parts of the southwestern United States are projected to receive less precipitation in the winter and spring (*medium confidence*).[39]
>
> Relative to the year 2000, [global average sea level] is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1.0–4.3 feet (30–130 cm) by 2100 (*very high confidence in lower bounds; medium confidence in upper bounds for 2030 and 2050; low confidence in upper bounds for 2100*).[40]

For effective climate risk management, it's important to consider not only high-confidence conclusions, but also low-confidence ones. Low-confidence conclusions are often associated with areas subject to what is sometimes called 'deep uncertainty': areas where there is little agreement among experts about the relative importance of different processes or likely values of key variables.[41] In many cases, deep uncertainty is associated with what the report also calls 'potential surprises.'

An archetypal example of this, given the current scientific understanding, involves the behavior of the Antarctic ice sheet late in this century and beyond. As the report notes, "Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a [global average sea level] rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed."[42] This deep uncertainty arises in large part from expert disagreement about the importance of different processes that can give rise to self-reinforcing cycles leading to relatively rapid ice-sheet loss.

What does the presence of deep uncertainty mean for risk management?[43]

Consider two dice games, played against the house (in this case, Mother Nature). In both games, there is a large pot on the table, representing assets at risk, and you have no choice but to play the game.

In the first game, if you roll snake-eyes on a pair of dice, you lose the pot; otherwise you keep it. Thus, there is a well-defined, 1-in-36 chance of losing. A risk-neutral player should be willing to

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[38] *Id.* at 14.
[39] *Id.* at 21.
[40] Sweet et al., *supra* note 10 at 333.
[41] Robert J. Lempert, *A new decision sciences for complex systems*, 99 PNAS 7309–7313 (2002).
[42] Sweet et al., *supra* note 10 at 333.
[43] The remainder of this section of my written testimony is based on my own research and experience, not on the Fourth National Climate Assessment.

spend 1/36th of the pot to insure the rest. In the game, this expenditure might be a side bet; with respect to sea-level rise, it might represent investment in protective measures against global mean sea-level rise exceeding 1.2 feet by 2050.

In the second game, Mother Nature has written a number between 2 and 7 on a piece of a paper you cannot see. If you roll above this number, you get to keep the pot; if you do not, you lose it. This game exhibits deep uncertainty: different expert players might have different conceptual models underlying how this number was selected and may not agree on how likely different numbers are.

You definitely would not play this game the same way you would play the first game – deep uncertainty does not justify assuming the most optimistic possible state of the world. Unless you are extremely risk averse, you probably also would not play the game the same way you would if you knew for certain a seven was written down; if you did that, there is a fair chance you would lose a good deal, though not as much as if you were too optimistic.

This second game is roughly analogous to the current state of understanding of the prospect of global average sea-level rise between 4 and 8 feet over this century under a high-emissions future.

Fortunately, we are not playing a one-shot game. Sea-level rise takes place over time, and we will not get 8 feet of sea-level rise tomorrow. Scientific understanding is evolving, and it is quite possible that within thirty years research will reveal what number is written on that sheet of paper. It might also turn out within thirty years that we are on course for a low-emissions future, in which case the uncertainty will be less deep and more closely resemble that of the first game.

Many decisions have a timeframe within the next thirty years and are not affected by this deep uncertainty in sea-level rise. Other decisions may require action now for the long-term. For instance, the existing rail tunnels under the Hudson River are about a century old. In building a new tunnel – a process that is slow and yields a product that may well last for over a century – it may be more cost-effective to build now for high-end sea-level rise rather than trying to retrofit if it turns out in a couple decades that the world is on course for a high-end rise.

Still other decisions permit staged, adaptive management: take action for the next thirty years but know now what follow-on actions you will take depending on what number turns out to be written down. This last approach may be the best for jointly minimizing climate and investment risk when managing complex systems, such as the portfolio of actions required to protect coastal populations from sea-level rise.

This last approach of adaptive management is also known in the literature as a 'flexible adaptation pathways' approach. A key part of such approaches is the inclusion of research investments focused on narrowing key uncertainties as one part of a portfolio of risk management strategies. Another key part is drawing up contingency plans for different possible futures in advance and mapping out which future discoveries will trigger which actions. Managing climate risk in this way requires long-term, sustained investment in research that cuts across the disciplinary boundaries of climate science, social science, engineering, and decision science.

Advancing the climate science enterprise for climate risk management[44]

The recognition of the urgent need for scientific knowledge to inform action has led to the development of what is sometimes called 'transdisciplinary' science.[45] Transdisciplinary science brings researchers from different disciplines together with stakeholders to tackle a common real-world problem. Transdisciplinary science is not necessarily applied research, as it may aim not only to translate existing understanding into practice but also to address some of the fundamental scientific uncertainties relevant to effective risk management. The tie to real-world problems is, however, a core element.

Climate risk management calls out for such transdisciplinary research, as well as for educational initiatives preparing students to conduct such research. At Rutgers, we have a number of such efforts. For example, our Coastal Climate Risk and Resilience program[46] trains graduate students to work with natural scientists, social scientists, engineers, urban planners, and stakeholders to manage coastal risk. The New Jersey Climate Change Alliance[47] is a University-managed network of stakeholders that links scientific experts with local, state, and private decision-makers. And we are a partner in the Climate Impact Lab, which is bringing climate scientists, economists, and data scientists together with stakeholders in state governments and the private sector to better integrate economic assessments of climate risk into regulatory and investment decisions.

But true transdisciplinarity is hard – it requires a considerable investment on the part of researchers or their institutions in maintaining strong, working, trusting relationships with stakeholders. And building such relationships takes time – if it must be done from scratch, it does not fit well with the time pressures faced by pre-tenure faculty or graduate students.

Right now, in the climate risk area, most transdisciplinary collaborations are driven by strong personalities or short-term funding opportunities. But the climate risk problem is not going to go away. Society is not well served if the networks that sustain such collaborations have to be rebuilt when individuals leave an institution or funding temporarily dries up.

Fortunately, there is an example of academic institutions supporting transdisciplinary collaborations that has worked in the United States for over a century, long before the modern jargon of 'transdisciplinarity' was coined.

In 1862, amidst the bloodshed of the Civil War, Abraham Lincoln signed the Morrill Act, establishing the United States' land-grant college system. The Morrill Act and follow-on legislation transformed higher education in the United States. They established a network of universities devoted to training the next generation of farmers and engineers, conducting innovative and useful research to advance agriculture, and engaging with farmers to disseminate the fruits of this research. The Smith-Lever Act of 1914 established cooperative extension

[44] This section of my written testimony is based on my own research and experience, not on the Fourth National Climate Assessment.

[45] Gertrude Hirsch Hadorn et al., *The Emergence of Transdisciplinarity as a Form of Research*, *in* HANDBOOK OF TRANSDISCIPLINARY RESEARCH 19–39 (Gertrude Hirsch Hadorn et al. eds., 2008), https://doi.org/10.1007/978-1-4020-6699-3_2 (last visited Feb 6, 2019).

[46] For more information: c2r2.rutgers.edu

[47] For more information: njadapt.rutgers.edu

services at land-grant institutions with the aim of bringing scientific knowledge about agriculture out of the universities and into the country. The cooperative extension services have placed agents in every US county and built networks of trust that link the land-grant institutions to the (primarily agricultural) community.

It is worth considering an investment analogous to that of cooperative extension in expanding the infrastructure for scientific climate risk management. The unique advantage of land-grant universities is the extension tradition, upon which can be built robust networks to sustain stakeholder engagement in climate risk research and education. This requires support to shift the maintenance of stakeholder networks away from individual investigators and grants and to the institution.

Building upon the extension strength also requires addressing countervailing incentives at the level of the individual scientist. Transdisciplinary research is inherently slower than more ivory-tower research, requiring that researchers invest time in stakeholder engagement. More flexible tenure evaluation processes that recognize the value of this engagement can help advance this mission, and this shift would be assisted by appropriate nudges from funding agencies.

In conclusion:

The National Climate Assessment provides an extensively reviewed evaluation of a vast body of scientific literature. It shows that:

Climate change is real, it is here, and we humans are responsible for it. To stabilize global climate, we need to bring net global greenhouse gas emissions to zero; the sooner we do this, the smaller the risks – to our economy, infrastructure, health, and national security – that we will have to manage. But even with strong emission reductions, there will still be major adaptation challenges ahead. It is therefore essential that climate change become a routine and integrated part of decision-making at all levels – public and private; federal, state, and local.

Thank you for holding this hearing today. It's my hope that, as the Science Committee, you will look closely at both how to advance the climate science enterprise in a manner that supports climate risk management and also at how to support climate risk management that is scientifically informed.

ROBERT E. KOPP is Director of the Rutgers Institute of Earth, Ocean, and Atmospheric Sciences and a Professor in the Department of Earth and Planetary Sciences at Rutgers University–New Brunswick. He also serves as co-director of Rutgers' Coastal Climate Risk & Resilience (C2R2) initiative, which trains graduate students to work together across disciplines and with stakeholders to address coastal resilience challenges, and as a director of the Climate Impact Lab, a multi-institutional collaboration applying climate modeling, econometrics, and Big Data approaches to assess the economic risks of climate change

Professor. Kopp's research focuses on past and future sea-level change, on the interactions between physical climate change and the economy, and on the use of climate risk information in decision making. He is a lead author of *Economic Risks of Climate Change: An American Prospectus* (Columbia University Press, 2015), the Fourth National Climate Assessment, and the Intergovernmental Panel on Climate Change's Sixth Assessment Report. He has authored more than 80 peer-reviewed scientific journal articles, and his work has also appeared in popular venues, including the *New York Times* Sunday Review.

Previously, he was Associate Director of the Rutgers Energy Institute, an AAAS Science & Technology Policy Fellow at the U.S. Department of Energy, and a postdoctoral fellow in geosciences and public policy at Princeton University.

Professor Kopp is a fellow of the American Geophysical Union and a recipient of the American Geophysical Union's James B. Macelwane and William Gilbert Medals and the International Union for Quaternary Research (INQUA)'s Sir Nicholas Shackleton Medal. He has an undergraduate degree in geophysical sciences from the University of Chicago and a Ph.D. in geobiology from the California Institute of Technology.

Chairwoman JOHNSON. Thank you very much, Dr. Kopp. Do we have that ready yet? OK. We'll move to Dr. Francis.

TESTIMONY OF DR. JENNIFER FRANCIS, SENIOR SCIENTIST, WOODS HOLE RESEARCH CENTER

Dr. FRANCIS. Good morning. My name is Jennifer Francis. I'm an atmospheric scientist at the Woods Hole Research Center in Massachusetts, and I study the connections between climate change and extreme weather. Thank you, Chairwoman Johnson and Members of the Committee, for the opportunity to testify here today.

It's not your imagination. Extreme weather events have become more frequent in recent decades. If we could have figure 1.

[Slide.]

Dr. FRANCIS. According to this analysis by Munich Re, one of the foremost reinsurance companies in the world, the occurrence of extreme weather events has nearly tripled since the 1980s. They are shown by the green, blue, and orange bars in this figure.

Images of recent extreme weather events are etched into our memories: Neighborhoods flooded by feet of rain unleashed by Hurricanes Harvey and Florence, docks sitting high and dry in California's reservoirs, and a sunken New Jersey roller coaster in the wake of Superstorm Sandy to name only a few. Yes, extreme weather has always happened, but there's no question that it's more vicious now, and all the signs point to it getting worse as the globe continues to warm under a thickening blanket of greenhouse gases.

Before I go any further, let's clear up a few definitions that sometimes cause confusion. Climate change versus global warming: Climate change means all the ways that the climate system is changing, while global warming is just one of those ways. Climate versus weather: Climate is the average of all the weather that occurs at a particular location, while weather is the day-to-day swings in temperature and precipitation. Think of climate as your personality and weather as your mood on any given day.

The links between climate change and extreme weather are a hot topic of scientific research. Some of the connections are straightforward. For example, global warming is making heat waves more intense and persistent and therefore more deadly. And as the air and oceans warm, evaporation also increases, which fuels an uptick in heavy precipitation events. The warmer oceans are also fueling rapid intensification of tropical storms, and because sea level is higher, storm surges are doing more damage now. On a happier note, though, fewer low-temperature records are being broken. All of these changes are clearly tied to a warming planet.

Other less straightforward connections are emerging as well. The polar vortex has been in the news a lot lately, so let's start with winter extremes. The polar vortex is a frigid pool of air encircled by strong winds that sits up high above the Arctic only during winter. Recent studies suggest it has been weakening and deforming more often lately, and when that happens, extreme cold and hot temperatures strike the northern hemisphere.

If I could at the next figure, please.

[Slide.]

Dr. FRANCIS. This map of temperature departures during the recent Eastern cold snap demonstrates this clearly, so even though cold records are being broken less often, severe cold spells and heat waves will still happen.

Turning southward, global warming appears to be widening the tropics. This may sound like a good thing, but it's causing abnormal heat and drought in temperate regions such as Australia, southern California, and South Africa. We're also learning that earlier spring snow melt is causing high latitude land areas to dry out and warm up faster. This creates land temperature patterns that can trap summer weather systems and make them stagnant. Studies have linked deadly summer heat waves and floods to this change in the climate.

Finally, rapid Arctic warming may be favoring weather regimes that exacerbate drought, heat, and wildfires in our Western States while stacking the deck toward cool and stormy conditions in the East. Remember the parade of bomb cyclones that struck the eastern seaboard last winter? This pattern was responsible.

In a nutshell, we know that our atmosphere is warmer and wetter, which alters every weather event that happens now. It's relatively easy to determine that climate change made Harvey's rainfall more intense, but it's much harder to say whether Harvey would have stalled over Houston in the absence of climate change. There's no doubt that the Arctic has warmed much faster than elsewhere, but whether Arctic air is surging southward more frequently now because of climate change is a cutting-edge research question.

This is just a sampling of the many topics being studied in our universities and research laboratories, the results of which are crucial to understanding climate change impacts, knowledge that will help decisionmakers and each of us prepare for a future with even more destructive weather extremes. Clearly more work is needed to confirm or reject these complex relationships, though many are already coming into sharp focus.

Thank you again for inviting me to be here.

[The prepared statement of Dr. Francis follows:]

WOODS HOLE RESEARCH CENTER

Testimony for Congressional Hearing
House Science, Space, and Technology Committee

10:00 am EST, 12 February 2019

by Jennifer Francis PhD, Senior Scientist at the Woods Hole Research Center, Falmouth, MA
www.whrc.org | JenniferAFrancis.com

My name is Jennifer Francis. I'm an atmospheric scientist at the Woods Hole Research Center in Massachusetts. My research focuses on the connection between climate change and extreme weather events. Thank you, Chairwoman Johnson and members of the committee, for the opportunity to testify here today.

It's not your imagination: extreme weather events have become more frequent in recent decades. According to analysis by Munich Re, one of the foremost reinsurance companies in the world, the occurrence of extreme weather events around the globe has nearly tripled since the 1980s [**Fig. 1**].

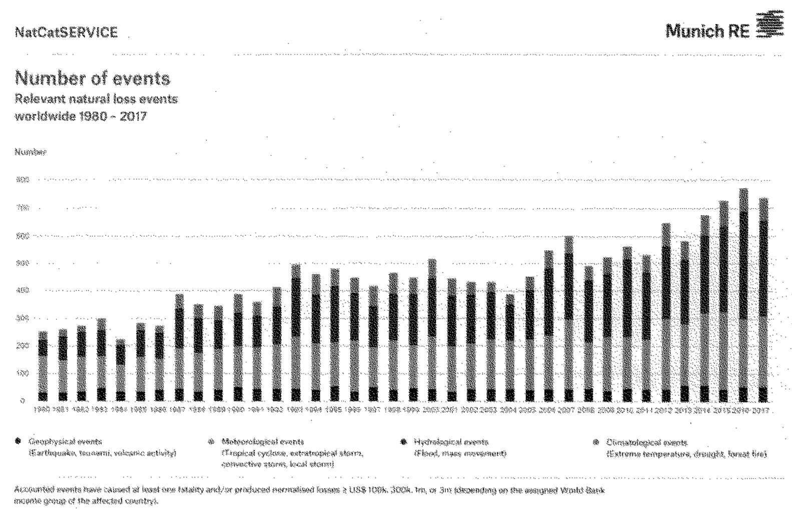

Figure 1: Number of extreme events related to weather (green, blue, and orange) and non-weather (red) events from 1980 to 2017. Compiled by Munich Re, 2018: https://natcatservice.munichre.com

Images of floods caused by feet of rain unleashed by hurricanes Harvey and Florence, docks sitting on dry soil in California's reservoirs, a sunken New Jersey roller coaster in the wake of Superstorm Sandy – to name only a very few – are forever etched in our memories. Yes, extreme weather has always happened, but there's no question that it's more vicious now, and all signs point to it getting worse as the globe continues to warm under a thickening blanket of greenhouse gases.

Before I go any further, let's clear up a few definitions that sometimes cause confusion. Climate change versus global warming: Climate change means all the ways that the climate system is changing, while global warming is just one of those ways. Climate versus weather: Climate is the average of all the weather that occurs at a particular location, while weather is the day-to-day swings in temperature and precipitation. Think of climate as your personality, while weather is your mood on any given day.

The links between climate change and extreme weather are a hot topic of scientific research. Some of the connections are straightforward and undisputed. For example, increasing global temperatures are making heat waves more intense and persistent, and therefore more deadly. As the air and oceans warm, evaporation also increases, which fuels an uptick in heavy precipitation events [**Fig. 2**].

Observed Change in Heavy Precipitation

Observed Change in the Total Annual Precipitation Falling in the Heaviest 1% of Events

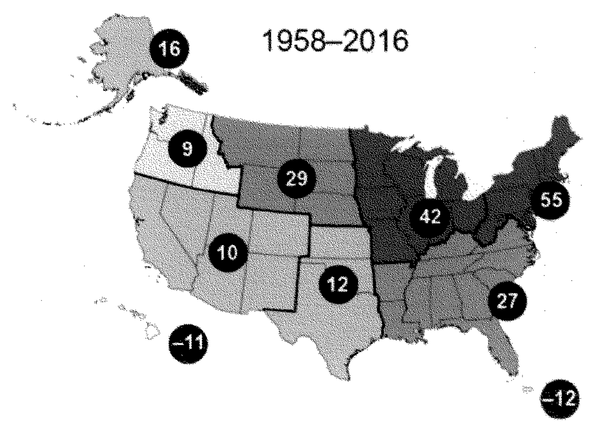

Figure 2: from National Climate Assessment Report 2018: https://nca2018.globalchange.gov/

The extra moisture and warmer oceans are also fueling rapid intensification of tropical storms. Storm surges are doing more damage because sea level is higher. On a happier note, though, fewer low-temperature records are being broken. Evidence of these changes is abundant and clearly tied to a warming planet owing to human influences [**Fig. 3**].

Recent studies are uncovering a myriad of other less straightforward connections, as well. The polar vortex has been in the news a lot lately, so let's start with winter extremes.

The true polar vortex is a pool of frigid air encircled by strong winds that sits about 30 miles above the Arctic during winter. Some evidence suggests it has been weakening and deforming more often lately[1], and when that happens, extreme cold AND hot temperatures strike areas in the northern hemisphere, as is clearly apparent in temperature anomalies during the severe cold snap two weeks ago [**Fig. 4**]. New research suggests that rapid Arctic warming is making these vortex splits more likely[2]. So even though cold records are being broken less often, severe and persistent cold spells will still happen.

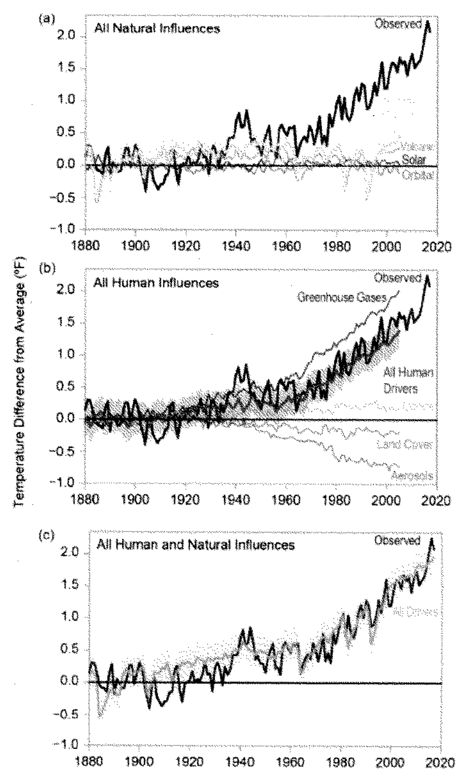

Figure 3: Climate model simulations illustrating the roles of various factors influencing global temperature changes since the late 1800s. Note that natural factors alone (top) would have caused the Earth to be in a gradual cooling cycle. From National Climate Assessment Report 2018.

Turning southward, global warming appears to be widening the tropical zone farther north and south. A symptom of this expansion is abnormal heat and drought in temperate regions such as Australia, southern California, and South Africa.

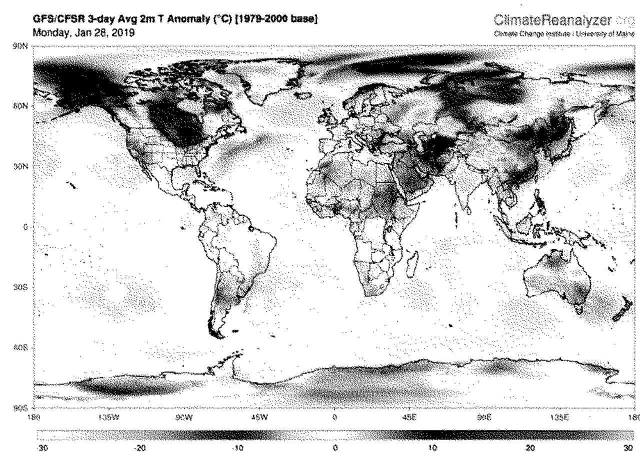

Figure 4: Global near-surface air temperature departures during the late January 2019 extreme cold spell in the Midwest. From the U. of Maine's Climate Reanalyzer http://www.climatereanalyzer.org

Another emerging hypothesis is related to the rapid loss of the spring snowcover over northern parts of continents. This earlier melt is causing high-latitude land areas to dry out and warm up faster, creating land temperature patterns that can trap summer weather systems in slow steering currents, making them stagnant. Studies have linked deadly summer heat waves and floods to this change in the climate[3].

Finally, a complex interplay between shifting ocean temperature patterns and a rapidly warming Arctic may be favoring weather regimes that exacerbate drought, heat, and wildfires in our western states while stacking the deck toward cool and stormy conditions in the east. Remember the parade of "bomb cyclones" that struck the eastern seaboard last winter? This west/east pattern was responsible.

In a nutshell, we know that climate change has made our atmosphere warmer and wetter, which alters every weather event that happens now. But assessing how climate change may affect the track and persistence of a weather system is still a challenge. It's relatively easy to determine that climate change made Hurricane Harvey's rainfall more intense[4], but it's much harder to say whether Harvey would have formed in the absence of climate change, or whether climate change caused it to stall over Houston. There's no doubt that the Arctic has warmed much faster than elsewhere, but whether Arctic air is surging southward more frequently now because of climate change is a cutting-edge research question.

WOODS HOLE RESEARCH CENTER

This is just a sampling of the many topics being studied in our country's universities and research laboratories, the results of which are crucial to understanding climate change impacts that will help decision-makers and each of us prepare for a future with even more intense and destructive weather extremes. Clearly more work is needed to confirm or reject these complex relationships, though many are already coming into sharp focus.

Thank you again for the opportunity to participate in this hearing.

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Dr. Jennifer Francis is an atmospheric scientist at the Woods Hole Research Center.

She is well known for her research on the link between climate change and extreme weather. Dr. Francis' research has focused especially on the connection between the rapidly warming Arctic and disruptions to the jet stream.

She is regularly quoted in major media outlets and appears on television to explain climate change impacts. This year, her research has been featured in the *New York Times*, the *Wall Street Journal*, *USA Today*, the *Chicago Tribune*, on *NPR*, and on *PBS News Hour*. Her writing has appeared in the *Washington Post*.

Before WHRC, Dr. Francis was at the Rutgers University Department of Marine and Coastal Sciences. She received her Ph.D. in Atmospheric Sciences from the University of Washington and her undergraduate degree from San Jose State.

Chairwoman JOHNSON. Thank you, Dr. Francis.
Dr. Majkut?

TESTIMONY OF DR. JOSEPH MAJKUT, DIRECTOR OF CLIMATE POLICY, NISKANEN CENTER

Dr. MAJKUT. Good morning, and thank you for having me, Chairwoman Johnson, Ranking Member Lucas, Members of the Committee.

My name is Joseph Majkut, and I am the Director of Climate Policy at the Niskanen Center, which is a 501(c)(3) located here in Washington. We work to promote public policy to advance an open society and particularly in climate we promote a mainstream understanding of climate science. It's nothing to be afraid of. And we aim to better characterize the risks of climate change. And on the policy side we support market-based policies to reduce greenhouse gas emissions.

The Committee asked that we comment on the recent United Nations' Intergovernmental Panel on Climate Change's Special Report on Global Warming of 1.5 °C, as well as the Fourth National Climate Assessment prepared by the USGRCP (U.S. Global Change Research Program), and I'd like to offer a brief summary of those reports.

Climate change is real, and global emissions of greenhouse gases are driving latter-day global warming. Manifestations of that warming are increasingly observed, as Dr. Francis just told us in great detail, and attributed to global emissions as well. But these are early days, so many of the changes scientists expect to see are either subtle or undetectable at high confidence.

Yet as climate change continues, more severe and perverse effects will manifest themselves causing economic harms and damages to individuals, ecosystems, and other things that we tend to be concerned about. The science tells us also that limiting climate change means ceasing global emissions, and that's a challenging thing to do.

The goals articulated in international agreements, that is limiting warming to 1.5 or 2 °C globally are probably unlikely given that they would require global emissions to fall by 45—or 25 percent by 2030 and further from there. That doesn't mean that the impulse to do that is unjustified given the risks we face. Those emissions reductions, however, sit in stark contrast to what we've seen over the last few decades. To even get close, we'll need significant innovation in low-carbon technology, finance, and market design in order to be able to provide reliable, affordable, and globally accessible low-carbon energy.

Given the present circumstance, how should this Committee respond this Congress? I've got three areas that I think the Committee should point its attention to. First, the time to talk about solving climate change has really passed us. We're managing a chronic condition, and we cannot place the burden on reducing global emissions alone. Rather, we must prioritize reducing social—societal vulnerability and adapting to climate change where we can. While this will largely be an effort for the private sector and local government, those efforts will be bolstered by continued Federal support for research into climate change's effects and the risks that our communities face. This research can be disseminated through social and professional networks, and devices like the National Climate Assessment provide a very good venue for that work.

Second, a world aiming for 2 °C will require a portfolio of low-carbon energy sources, including carbon capture and storage for fossil fuels. In a world aiming for 1.5 °C, processes that remove carbon from the atmosphere will need to be deployed at a scale capturing up to 1/4 of today's emissions, and that is a mind-boggling number for an infant technology. Both of these will be large industries, but the technologies are so infant that they need your support. Faster progress is possible through smart investments in advanced research, which deserve the Committee's continued attention and support.

Third, we have to research alternatives. Last Congress I testified before your Subcommittees on Environment and Energy on a research and governance agenda for so-called geo-engineering technologies, which could sever the link between global emissions and warming. While we had a productive hearing, there's still much that this Committee could do to support early research into these technologies and help establish a set of norms under which that research could be done.

Thank you for inviting me to testify, and I look forward to a robust discussion.

[The prepared statement of Dr. Majkut follows:]

STATEMENT OF JOSEPH MAJKUT
DIRECTOR OF CLIMATE POLICY
NISKANEN CENTER
CONCERNING THE STATE OF CLIMATE SCIENCE
FEBRUARY 13, 2018

Good morning Chairwoman Johnson, Ranking Member Lucas, and members of the Committee. I am grateful for the invitation to join you today, and for the opportunity to share my perspective on the state of climate science, and why it matters.

My name is Joseph Majkut. I am the director of climate policy at the Niskanen Center, located here in Washington, D.C.[1] The Niskanen Center is nonpartisan 501(c)(3) organization that promotes public policy to advance an open society. We reject ideological dogmatism and argue for a balanced consideration of the need for social justice, civil liberties, individual freedom, and community wellbeing. Our work in climate seeks to promote mainstream understanding of climate science, better characterize the risks of climate change, and support market-based policies to reduce greenhouse gas emissions.

The atmosphere, and the climate it maintains, are a public good. No matter your beliefs about the proper size and scope of government, the reality is that government must act to reduce the risks of climate change, and it already is doing so in several areas. But at present, far too many tons of CO2 are emitted here, and abroad, without sufficient regard to the damages they will cause future generations. In the long term, that will make us worse off.

The responses to this problem do not have to be onerous government regulation and mandates, and they don't have to be hasty. It wouldn't be wise to halt emissions tomorrow or prevent future economic growth, but we could be doing much more to reduce emissions here in the United States beyond the already laudable reductions we've seen in the last 10 years. Congress should pursue new solutions to outpace and underspend the mix of regulations and subsidies that we have today. There is no better innovative force than the private sector, but if you really want energy innovation, you need to show innovators there is a market waiting for them.

For this hearing, we were asked to advise the committee on how recent scientific advances have affected our understanding of the risks of climate change and what society can do to respond to those risks. We were asked to specifically comment on the United Nations Intergovernmental

[1] The Niskanen Center's writing and analysis on climate matters can be found here: https://niskanencenter.org/blog/policies/climate/

Panel on Climate Change's Special Report Global Warming of 1.5C[2] and the 4th National Climate Assessment prepared by the U.S. Global Change Research Program.[3]

I think a fair summary of those reports might go as follows. Climate change is real and global emissions of greenhouse gases are a leading driver of latter-day global warming. The manifestations of that warming are being increasingly observed in climate indices and understood as a factor in weather and climate events. But these are early days, so many of the changes scientists expect are still subtle or even undetectable at high confidence. As climate change continues, more severe and pervasive effects will reveal themselves, causing damages to individuals, ecosystems, and economic harm.

However, halting climate change at the levels being targeted in international agreements, either 1.5 or 2 degrees C, would require significant reductions in global emissions rates to start immediately and proceed quickly. To be consistent with continued economic growth, those reductions will require technological innovations to provide reliable, affordable, and globally-accessible low-carbon energy.

Given where we find ourselves, how should this committee respond in this Congress?

First, the time to talk about solving climate change has passed. The warming that has already occurred is evident and will continue with global emissions. We are managing a chronic condition and we cannot place the whole burden on reducing global emissions. Reducing societal vulnerability and adapting to climate change should be a priority, but is also largely an activity done in the private sector and through local governance. Those efforts can be meaningfully informed through federal support for research into how climate change will affect our communities. The products of that work can be disseminated through social and professional networks, as well as through efforts like the repeating National Climate Assessment. Identifying new research needs and new means of understanding climate risks at all levels of government is valuable.

Second, I think it is prudent for the committee to recognize that the emissions reductions necessary to meet any temperature target, but especially anything approaching 2 or 1.5C, will require substantial technological innovations and a portfolio of low-carbon energy sources. In all likelihood, emissions pathways consistent with a 2C warming limit will involve some form of carbon capture and storage for fossil fuels and 1.5C will necessitate carbon removal technology.[4]

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[2] Intergovernmental Panel on Climate Change: https://www.ipcc.ch/sr15/

[3] United States Global Change Research Program: https://nca2018.globalchange.gov

[4] Nature: Negative Emissions Physically Needed To Keep Global Warming Below 2˚C

These, in addition to novel renewable and energy storage solutions, can be aided by smart investments in advanced research and deserve the committee's continued attention and support.

Third, we should be researching alternatives. In the case of stabilizing temperatures at modest levels or warming, the only alternative to massive reductions in global emissions and deployments of carbon removal would be the deployment of geoengineering technologies that would intentionally offset the warming effect of global emissions. I was honored to testify last Congress before the Subcommittees on Environment and Energy on a research and governance agenda for those technologies. While we had a productive hearing, there is still much that this committee could do to both support early research into these technologies and help establish a set of norms under which that research could be done. We do not know if we will use such technologies, just as we can't be sure that future generations will deploy carbon removal, but we can create knowledge for them.

The General Picture of Climate Science

Note: The text in this section is excerpted from a previously published paper available in full by download,[5] which offers my summary of the state of basic science on climate change and its drivers.

The foundations of climate science date back to the early 19th century, when scientists—using their newfound sophistication in chemistry and physics—became aware that heat trapping gases in the atmosphere maintained global temperatures above freezing. Despite continued scientific study, the field was of little public interest until the 1960s, when scientists became increasingly concerned that greenhouse gas emissions might dangerously interfere with the planet's climate. Such concerns have inspired growing volumes of scientific research into the causes and potential effects of climate change ever since.

The contemporary state of knowledge regarding climate science is compiled by the Intergovernmental Panel on Climate Change (IPCC) and other scientific societies, including the National Academies of Sciences.[6] Just as basic chemistry and physics would predict, industrial activity has indeed increased the amount of greenhouse gases in the atmosphere (primarily CO_2), trapped heat, and warmed the climate. Associated changes have been measured in temperatures, rainfall, sea level, and other basic ecological and physical conditions around the world.

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https://www.nature.com/articles/ncomms8958
[5] Climate Science: A Guide to the Debate, Niskanen Center, March 2017:
https://niskanencenter.org/wp-content/uploads/2017/03/NISKANEN-CLIMATE-PRIMER-2017-03-13.pdf
[6] National Academies of Sciences and the Royal Society, Climate Change: Evidence and Causes, 2014:
https://www.nap.edu/catalog/18730/climate-change-evidence-and-causes

According to the IPCC AR5, these effects should be expected to continue with additional emissions, “increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems.”

The 4th National Climate Assessment

The 4th National Climate Assessment presents a detailed evaluation of the available literature on how climate change has affected natural systems and human interests—across different regions, economic sectors, and ecological systems within the United States; how it will continue to do so in the future; and what communities are doing in response. The detailed report released in the fall of 2018 was preceded by a special report on climate science released the previous year.[7]

What, if any, climate change are we seeing in the United States?

The authors of the NCA4 spend a lot of time assessing and identifying how and where weather and climate have changed over the United States in the last century and decades and the relationship. The summary report is itself quite long and detailed, but the topline messages are also pretty clear.

Changes in weather and environmental conditions are evident in the United States, though detecting trends and associating them with global emissions is still an emerging field of study. So while there is pretty high confidence in the connection between global temperatures and emissions, that confidence diminishes as scientists consider more regional and local trends, particular classes of weather events, and individual weather events themselves.

The NCA reports on climate trends in varying phenomena. Some examples from the 3rd chapter on the special report on science show the varying levels of phenomena, and the heterogeneity of regional climate trends. (Bulleted list are quotes)

- Temperature Change: Detectable anthropogenic warming since 1901 has occurred over the western and northern regions of the contiguous United States according to observations and CMIP5 models *(medium confidence)*, although over the southeastern United States there has been no detectable warming trend since 1901.
- Precipitation Change: For the continental United States, there is *high confidence* in the detection of extreme precipitation increases, while there is *low confidence* in attributing the extreme precipitation changes purely to anthropogenic forcing.

[7] US GCRP, National Climate Assessment 4 Volume 1: Climate Science Special Report: https://science2017.globalchange.gov

- Precipitation Change: For the continental United States, there is *high confidence* in the detection of extreme precipitation increases, while there is *low confidence* in attributing the extreme precipitation changes purely to anthropogenic forcing.
- Extreme Storms: There is broad agreement in the literature that human factors (greenhouse gases and aerosols) have had a measurable impact on the observed oceanic and atmospheric variability in the North Atlantic, and there is *medium confidence* that this has contributed to the observed increase in Atlantic hurricane activity since the 1970s. There is no consensus on the relative magnitude of human and natural influences on past changes in hurricane activity.
- Arctic Changes: It is *very likely* that human activities have contributed to observed arctic surface temperature warming, sea ice loss, glacier mass loss, and Northern Hemisphere snow extent decline (*high confidence*).
- Sea Level Rise: Human-caused climate change has made a substantial contribution to global mean sea level rise since 1900 *(high confidence),* contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years *(medium confidence).*

The relationship between specific instances of extreme weather and climate change is also complicated, but connections are emerging both in the physical world, and in scientific understanding in the field of extreme event attribution. The NCA lists a few examples where particular temperature events have been linked to climate change with *medium confidence*, like a 2011 heat wave in Texas.

As the NCA reports, such individual assessments are in their early days and confidence in them increases with the detection and attribution of underlying trends (i.e. temperature trends and heat waves) or an understanding of physical mechanisms (i.e. warming surface waters and tropical cyclone strength and wetness).

What are the drivers of climate risks for the United States?

The predicted severity of climate risks depends strongly on the scenarios that you evaluate or highlight. The NCA reports that for a scenario with low future global emissions (RCP2.5), temperature increases over the continental US will range between 2.8 and 7.3 degrees F by the end of the century. But in a scenario with high future global emissions (RCP8.5), temperature increases range between 8.5-11.9 degrees F. In general, the negative effects of climate change get worse with total warming.

In a bit of good news, the worst case scenarios used in NCA4 are looking unlikely. The RCP8.5 scenario combines assumptions of high population growth, stagnating economic growth, and limited energy efficiency and technological innovation, resulting in high levels of long-term ghg emissions. In reality, there have been substantial advancements made in low and zero carbon technologies[8], and GDP per unit of energy use has been rising steadily since 1990[9]. These promising trends, as well as declining levels of global poverty, indicate that the RCP8.5 scenario can likely be avoided.

In a bit of bad news, the best case scenarios used in NCA4 are looking unlikely. The best case scenario (RCP2.6) would require global emissions cuts to proceed rapidly starting very soon. And as I discuss in the next section, nothing in the recent history of emissions indicates that we will come at all close. Even if you add up all that countries pledged to do as part of the Paris Climate Agreement, fully-achieved emissions reductions would still be too slow to meet stringent temperature targets.

In general, it is appropriate for scientific assessment to consider a range of plausible outcomes and even to push the bounds of plausibility to examine how the climate system works in extreme scenarios. And just because something is unlikely does not mean that it is absurd to consider it. Rather, we should consider climate risk across a broad set of scenarios, calibrate our expectations the best we can, and understand that human agency will make a primary difference between the worse case and the best case over this whole century.

Comments on the UN IPCC Special Report on 1.5C

The IPCC Special Report on 1.5C assessed the state of the scientific literature on the relative impacts of global warming between 1.5 and 2 C and the future greenhouse emissions necessary to meet or otherwise exceed those levels of global warming. This report differs from previous efforts from the IPCC, which analyzed scenarios with average warming between 1 and 4 C at the end of this century.[10]

What motivates the 1.5 C goal?

The study was commissioned after diplomats set the ambitious intention of keeping warming to within 1.5C as part of the Paris Climate Agreement, accelerating ambition beyond the previously-established goal of 2C. By its nature, the 1.5C goal was politically determined (same with 2C) and it was motivated by the desire to spare particularly vulnerable people, places, and things from the impacts of imminent climate change.

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[8] International Renewable Energy Energy Agency, Renewable Power Generation Costs in 2017 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf

[9] World Bank: GDP per Unit of Energy Use https://data.worldbank.org/indicator/EG.GDP.PUSE.KO.PP.KD

[10] Intergovernmental Panel on Climate Change, Assessment Report 5: https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_SPM_FINAL.pdf

The IPCC survey shows that the impacts of climate change are projected to increase with warming, but that there is no particular global calamity that we know will occur at either 1.5C or 2C, or even beyond 2C with certainty. The world does respond to warming in round numbers, so there isn't some level above which everything is lost or below which everything is fine. Instead, the risks go up with the extent of warming. Halting global warming at 3C would mean less damages than 4, 2C less than 3 C, and 1.5C less than 2C.

As we consider global warming between 1.5 and 2C, the IPCC reports that projections reveal significant and notable effects:

- the increase in global sea level at the end of this century could increase by an additional 4 inches (10 cm) against a rise of 15 (40cm).
- doubling of the land area that will experience a transition between native ecosystems (up to 13% of global land area) and a doubling of the number of animal and insect species that will lose a majority of their historical climatological range.

While even the doubling of a particular effect is significant, it also doesn't demonstrate that there is some qualitative shift in climate impacts that might occur between 1.5 and 2C. But the report does show that particular climate effects could fairly be called devastating for some locations or ecosystems, even at such modest warmings. The prevalence of coral reefs provides an example. At 1.5C, coral reefs are projected to decline by 70-90%. But at 2C, the decline is projected to be greater than 99%—an absolute catastrophe for that particular kind of ecosystem and related economies.

Is 1.5C (or 2C) even possible?

The IPCC authors report that maintaining warming below 1.5C will require emissions reductions that imply a significant demand for technical innovations in low carbon energy. Unfortunately, the emissions reductions necessary to keep temperatures below 1.5C are quite rapid and strain credulity.

The IPCC reports the now common scientific understanding that global temperatures have increased about 1 degree centigrade above pre industrial levels (likely range of 0.8 to 1.2 C). That gives us about the 0.5C of warming before 1.5C. Scientific analysis tells us that there is a relatively proportional relationship between the total historical global emissions and the level of global warming that follows. Temperature increase is a function of the cumulative stock of long lived climate pollutants, primarily CO_2, in the atmosphere. This stock effect means that for every year of emissions, the total amount of warming we expect to see goes up a little bit. It also means that we can roughly translate that remaining warming into remaining global emissions.

For the special report, the IPCC did just that. They found that the so-called carbon budget is between 420 GtCO2 and 770 GtCO2. For reference, current global emissions are about 42 GtCO2 per year and US emissions are just over 5 GtCO2 per year.[11] That means that global warming in excess of 1.5C would be likely within 10 to 20 years at today's global emissions levels. After that, there is enough CO2 in the air to warming beyond the stretch goal of Paris.

To avoid such a warming, global emissions would need to fall precipitously in the coming decades. The IPCC reports 45 percent from 2010 levels by 2030 and by nearly 100 percent by 2050 (since emissions have gone up since 2010, even larger cuts to today's emissions are necessary). The more moderate goal of limiting warming to 2C would similarly require emissions rates to fall 25 percent by 2030 and for emissions to be functionally eliminated by around 2070.

Such a dramatic turnaround is inconsistent with the past few decades, which saw steady increases in CO2 emissions from fossil fuel burning (rising from ~ 25 - 37 GtCO2) and relatively stable emissions from deforestation (between 4 - 6 GtCO2).[12] The rise in fossil emissions is largely attributable to increases in economic growth and energy demand, with a relatively flat CO2 intensity of energy supply globally. That increase was moderated, however, by increasing energy efficiency of the economy.

To continue global economic growth, the energy efficiency of the economy should continue to increase and the CO2 intensity of the energy supply must decrease. That means that we need to reduce the price of energy from clean sources relative to emitting sources, so that the transition to a clean economy is a benefit for society.

While the cost of generating energy from renewable resources like wind and solar has fallen in recent years, and the forward outlook is sunnier still, the reality is that the IPCC report should serve as wakeup call for anyone dedicating their efforts to halting warming at 1.5C, 2C, or more. The rate and depth of emissions cuts implied by these targets indicate that we should endeavor to keep all options on the table when addressing climate change. In a recent survey of the available literature of decarbonizing just the U.S. power sector, authors Thernstrom and Jenkins surveyed 30 papers and found a sturdy consensus that "a diversified mix of low-CO2 generation resources offers the best chance of affordably achieving deep decarbonization.[13]" In particular, the ability

[11] US Environmental Protection Agency, 2018 Emissions Inventory: https://www.epa.gov/sites/production/files/2018-04/documents/9509_fastfacts_20180410v2_508.pdf
[12] Global Carbon Project, 2018 Global Carbon Budget: http://www.globalcarbonproject.org/carbonbudget/18/files/GCP_CarbonBudget_2018.pdf
[13] Jenkins and Thernstrom, DEEP DECARBONIZATION OF THE ELECTRIC POWER SECTOR INSIGHTS FROM RECENT LITERATURE, 2017 :

to generate and dispatch electricity from non-renewable sources such as energy storage, nuclear reactors, or fossil-fuels with carbon capture and storage appears to be of great value.

After emissions reach zero, the scenarios examined by the IPCC that limit warming to 1.5C require substantial negative emissions, or carbon dioxide removal. That is the removal of CO2 from the atmosphere through technological processes (like burning cultivated biomass for energy and capturing the resulting CO2 before it escapes to the atmosphere) or growing trees in forests. Carbon dioxide removal is invoked in all scenarios that appear consistent with limiting warming to 1.5C in this century in the IPCC report. The amount of carbon dioxide removal invoked across the different scenarios analyzed by the IPCC is primarily driven by how much is emitted in the next few decades, with slower emissions reductions implying higher burdens for carbon removal. The amount of carbon dioxide that would need to be removed from the atmosphere is gargantuan, between 100-1000 GtCO2, over the course of the century.

Supporting early development of the technologies and processes that will be necessary to remove CO2 at those levels would be a helpful contribution from this committee. The prospective scope of such an operation is enormous and is a real opportunity for industrial innovation. Given the advantages of fossil fuels, it is reasonable to think that they will continue to be a major energy source, creating a market for carbon capture as part of the emissions reductions portfolio. And the industry opportunity is large. A study published last week estimated that a meaningful deployment of carbon capture would be approximate 2-4 times the modern day oil industry, by volume of product.[14] If you add in the potential for a carbon removal industry, then the scale of the opportunity grows.

Climate action is not inconsistent with the continued use of fossil fuels in coming decades. In fact, successfully meeting these proposed targets will probably require their continued use in conjunction with carbon capture.

Conclusion and Recommendations

Thank you for your time today. Climate change is an important topic for public policymakers to which scientific information can make significant inputs. We all know that scientific considerations are not the only factor at play, but it is and remains one of our greatest achievements. In this case, science can help us understand the scope of the problem and the effectiveness of proposed responses. The U.S. research enterprise overseen by this committee is

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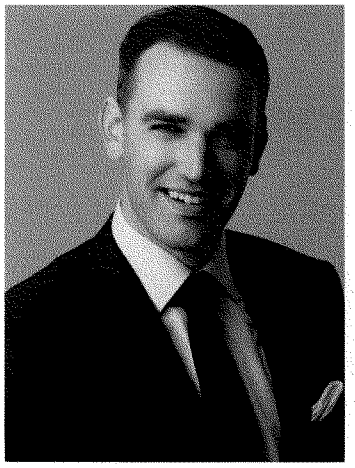
https://www.innovationreform.org/wp-content/uploads/2018/02/EIRP-Deep-Decarb-Lit-Review-Jenkins-Thernstrom-March-2017.pdf

[14] https://www.nature.com/articles/nclimate3231

a valuable resource in either regard. I thank the Committee for its attention to this issue and look forward to an ongoing conversation.



JOSEPH MAJKUT
Director of Climate Policy

Joseph Majkut is director of climate policy at the Niskanen Center. He is an expert in climate science, climate policy, and risk and uncertainty analysis for decision making. He is frequently cited by prominent media outlets; his writing has been featured in scientific journals, public media, and environmental trade press; and he has been invited to testify before Congress on climate and scientific research. Before joining the Niskanen Center, he worked on climate change policy in Congress as a congressional science fellow, supported by the American Association for the Advancement of Science. He holds a PhD from Princeton University in Atmospheric and Oceanic Sciences, a master's degree in Applied Mathematics from the Delft University of Technology, and a bachelor's degree in Mathematics from Harvey Mudd College.

Chairwoman JOHNSON. Thank you very much, Dr. Majkut.
Dr. Ebi?

TESTIMONY OF DR. KRISTIE L. EBI, ROHM AND HAAS ENDOWED PROFESSOR IN PUBLIC HEALTH SCIENCES, AND DIRECTOR, CENTER FOR HEALTH AND THE GLOBAL ENVIRONMENT (CHanGE), UNIVERSITY OF WASHINGTON

Dr. EBI. Thank you, Chairman Johnson, Ranking Member Lucas, distinguished Members of the Committee, for the opportunity to speak with you today. As you know, my name is Kristie Ebi. I've got more than 20 years' experience——

[Audio malfunction in hearing room.]

Dr. EBI. Do you want me to start over? Sorry about that. The evidence is clear. Climate change is adversely affecting the health of Americans. Climate change is heating the land and oceans, melting snow and ice, increasing the frequency and severity of extreme weather events, and raising sea levels. All of these have significant implications for our health and well-being, as well as for our public health and healthcare infrastructure. It is timely and appropriate for Congress to understand this issue of critical national importance so that effective actions can be taken to protect and promote the health of all Americans now and in the future.

Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events by increasing the prevalence of some vector, food, and water-borne infectious diseases; by reducing the quality and safety of our air, food, and water; and by worsening our mental health and well-being. Climate change also can affect health by, for example, undermining economic productivity and reducing labor productivity.

As the Fourth U.S. National Climate Assessment highlights, Americans are already suffering and dying from our changing climate with primarily negative risks projected to increase with each additional unit of warming. The IPCC's Special Report on Global Warming of 1.5 °C, which assessed research in the U.S. and globally, concluded that lower risks are projected at 1.5, than at 2 °C for heat-related morbidity and mortality, for ozone mortality if the precursor emissions remain high. Risks from vector-borne diseases such as malaria, dengue fever, and Lyme disease are projected to increase with warming from 1.5 to 2 °C, including potential shifts in their geographic range to areas previously unexposed to these diseases.

Individuals and communities are differentially exposed to climate-related hazards and disproportionately affected by climate-related health risks. Populations experiencing greater risk include children, older adults, low-income communities, and some communities of color.

The adverse health impacts of climate change have many potential economic and social costs, including medical expenses and caregiving services, as well as costs that are harder to quantify such as those associated with pain, suffering, inconvenience, or reduced enjoyment of leisure activities. Further, our healthcare infrastructure is vulnerable to extreme events with, for example, many hospitals and healthcare clinics located in coastal regions subject to flooding.

The magnitude and pattern of future health risks depend on the rapidity and extent of greenhouse gas emission reductions and on the level of ambition and investment in adaptation. Many projected risks and costs which, in some cases, may be extremely unaffordable, can be reduced by taking immediate action to increase preparedness for effectively managing health and healthcare infrastructure risks. Examples include developing early notification and response plans such as for extreme heat, implementing integrated surveillance of climate-sensitive infectious diseases, and incorporating climate projections into emergency preparedness and disaster risk-management initiatives. These steps can protect health now and provide a basis for more effective adaptation to our future climate.

Nearly all mitigation policies to reduce greenhouse gas emissions have benefits for health for Americans in the near- and in the long-term by reducing premature mortality and by avoiding hospitalizations. By the end of this century, thousands of premature deaths could be avoided and hundreds of millions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.

Finally, on a personal note, I grew up in Senator Dingell's district. He was a very dedicated public servant who helped write most of our major environmental and energy laws that were passed by Congress. My condolences to his family, his friends, and his colleagues. Thank you.

[The prepared statement of Dr. Ebi follows:]

Written Testimony of

Kristie L. Ebi
Rohm and Hass Endowed Professor in Public Health Science
School of Public Health
University of Washington

Full Committee Hearing
on:
The State of Climate Science

before the
United States House Committee on Science, Space, and Technology

February 13, 2019

Good morning, Chairwoman Johnson and Ranking Member Lucas. Thank you for the opportunity to speak with the full committee today about the current understanding of the health risks of climate change. My name is Kristie L. Ebi; I am the Director of the Center for Health and the Global Environment (CHanGE) and the Rohm and Hass Endowed Professor in Public Health Sciences at the University of Washington School of Public Health. Climate change is affecting the health of Americans today and will affect our health and our public health and healthcare infrastructure in the future. This is an issue of critical national importance. Therefore, it is timely and appropriate for Congress to understand these challenges so that effective actions can be taken to protect and promote the health of Americans now and in the future.

In summary, the evidence is clear: climate change is adversely affecting the health of Americans, with the impacts projected to increase with each additional unit of warming, depending on the rapidity and extent of greenhouse gas emission reductions. Climate change has warmed the world by roughly 1.8°F since preindustrial times, with the rate of warming increasing significantly since the 1970s[1]. This warming is heating the land and oceans, melting snow and ice, increasing the frequency and severity of extreme weather events, and raising sea levels. All of these have potential implications for our health and well-being.

There are immediate actions that could increase preparedness for effectively managing these risks, including the risks to our healthcare infrastructure. Further, nearly all mitigation policies to reduce greenhouse gas emissions have benefits for health. The costs associated with those benefits, as measured by reductions in premature mortality and avoided hospitalizations, are about the same as the cost of the policies.

The following sections (1) summarize the health risks of a changing climate in the United States, including the risks for our health care infrastructure, and describe populations at particular risk; (2) show how adaptation can protect and promote population health today and in the future; and

[1] https://science2017.globalchange.gov/

(3) discuss the significant health co-benefits of mitigation policies and technologies. My testimony draws primarily from the 4th U.S. National Climate Assessment (NCA4)[2] and the Lancet Countdown Brief for the United States[3]. Other recent publications and assessments of the health risks of climate change include the Lancet Countdown[4]; the Intergovernmental Panel on Climate Change Special Report on Warming of 1.5°C[5]; and a publication in the New England Journal of Medicine on the imperative for climate action to protect health[6].

Health risks of a changing climate in the United States

There is an increasing body of evidence highlighting the damaging effects of climate change on human health and health care infrastructure. This research was assessed in the NCA4 in the chapter on human health and in the sectoral chapters, and the *Lancet* Countdown Brief for the United States. These reports, and the underlying science on which they are based, concluded that climate change harms health and health care infrastructure. A key message from the NCA4 was:

> *The health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.*

A wide range of health outcomes can be affected by weather, climate variability, and climate change (Figure 1). Scientists have explored the many different pathways linking our changing climate with human health. For example, recent warming has lengthened the pollen season in the Midwest anywhere from 2-4 weeks, exacerbating allergic rhinitis and allergic asthma[7]. Additional warming is likely to further lengthen the season, substantially reducing the quality of life for those with these conditions.

The adverse health effects attributed to climate change have many potential economic and social costs, including medical expenses, caregiving services, lost productivity, as well as costs that are harder to quantify, such as those associated with pain, suffering, inconvenience, or reduced enjoyment of leisure activities[2]. These health burdens are typically borne by the affected individual and by family, friends, employers, communities, and insurance or assistance programs.

A recent research project I conducted with colleagues summarized the 109 published projections of the health risks associated with temperature extremes and occupational heat stress, air quality,

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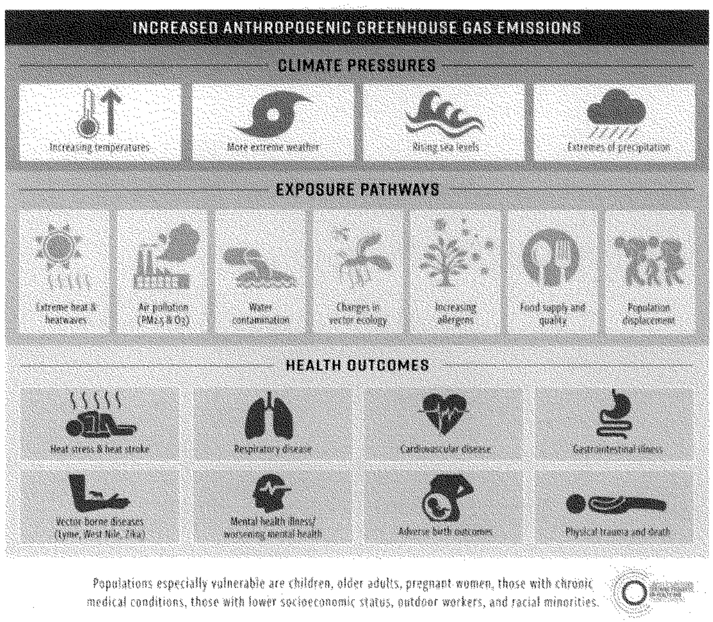
[2] https://nca2018.globalchange.gov/chapter/14/
[3] http://www.lancetcountdown.org/media/1426/2018-lancet-countdown-policy-brief-usa.pdf
[4] http://www.lancetcountdown.org/the-report/
[5] https://www.ipcc.ch/sr15/
[6] Haines A, Ebi K. The imperative for climate action to protect health. *New England Journal of Medicine* 2019;380:263-273.
[7] Ziska L, Knowlton K, Rogers C, et al. Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *Proceedings of the National Academy of Sciences* 2011;108(10): 4248.

undernutrition, and vector-borne diseases to estimate how these risks would differ at increases in warming of 1.5°C, 2°C, and higher[8]. Risks were higher at 2°C for adverse health consequences associated with exposures to high ambient temperatures, ground-level ozone, and undernutrition, with regional variations. Risks for vector-borne diseases could increase or decrease with higher global mean temperatures, depending on regional climate responses and disease ecology. The Intergovernmental Panel on Climate Change Special Report on Warming of 1.5°C concluded that[5]:

> Any increase in global warming is projected to affect human health, with primarily negative consequences (*high confidence*). Lower risks are projected at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*) and for ozone-related mortality if emissions needed for ozone formation remain high (*high confidence*). Urban heat islands often amplify the impacts of heatwaves in cities (*high confidence*). Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5°C to 2°C, including potential shifts in their geographic range (*high confidence*).

Figure 1: Summary of the health risks of climate change in the United States



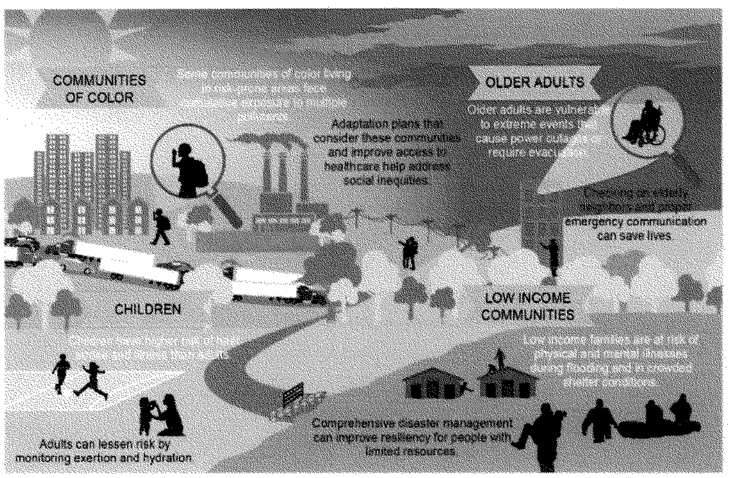
[8] Ebi KL, Hasegawa T, Hayes K, Monaghan A, Paz S, Berry P. Health risks of warming of 1.5° C,. 2° C, and higher, above pre-industrial temperatures. *Environmental Research Letters* 2018;13:063007.

Another key message from the NCA4 was that although everyone is exposed to a changing climate, exposure and resilience capacity vary across the population (Figure 2):

> *People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks. Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color.*

Figure 2 shows examples of populations at higher risk of exposure to adverse climate-related health threats along with adaptation measures that can help address disproportionate impacts. When considering the full range of threats from climate change as well as other environmental exposures, these groups are among the most exposed, most sensitive, and have the least individual and community resources to prepare for and respond to health threats. White text indicates the risks faced by those communities, while dark text indicates actions that can be taken to reduce those risks.

Figure 2: Exposure and resilience vary across populations and communities [2]



Low-income communities and some communities of color are often already overburdened with poor environmental conditions and are disproportionately affected by, and less resilient to, climate-sensitive health outcomes[2]. Climate change is expected to compound existing health issues in Native American and Alaska Native communities, partly due to the loss of traditional foods and practices, the mental stress from permanent community displacement, increased injuries from lack of permafrost, storm damage and flooding, smoke inhalation, damage to water and sanitation systems, decreased food security, and new infectious diseases

Vulnerability is typically higher in communities with less access to information, resources, institutions, and other factors to prepare for and avoid the health risks of climate change. Some of these communities include poor people in high-income regions, minority groups, women, pregnant women, those experiencing discrimination, children under five, persons with physical and mental illness, persons with physical and cognitive disabilities, the homeless, those living alone, Indigenous people, people displaced because of weather and climate, the socially isolated, poorly planned communities, the disenfranchised, those with less access to healthcare, the uninsured and underinsured, those living in inadequate housing, and those with limited financial resources to rebound from disasters[2].

Summary of selected health risks

This section summarizes some of the most well-understood health risks associated with climate change and their effects across the United States.

Extreme heat: Summers are starting earlier, lasting longer, and are on average hotter, with temperature records being broken regularly. The average summer temperature in 2016 was 2.2°F greater than the 1986-2005 average, resulting in 12.3 million more Americans exposed to extreme heat that year[3]. Thus, it should not be surprising that extreme heat is the leading cause of weather-related deaths in the U.S.

Exposure to extreme heat can lead to heat exhaustion, life threatening heat stroke, and exacerbate chronic lung, heart, and kidney diseases. Further, emerging evidence suggests that hotter temperatures can cause pregnancy complications, worsen mental health conditions, and increase suicides, amongst other risks[3]. One estimate projected that by the year 2050, approximately 3,400 more Americans could die annually from heat–related causes[9].

Individuals more sensitive to exposure to extreme heat include children, pregnant women, outdoor workers, older adults, those who are chronically ill, and low-income families. Health risks may be higher earlier in the summer season when people are less accustomed to experiencing higher temperatures. Here are some of the facts:

- At least 729 children died from heatstroke across the country after being left in hot cars between 1990 and 2014[10].
- Studies in the United States have linked extreme heat exposure to preterm births and low birth weights[11].

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[9] U.S. Environmental Protection Agency. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment [Internet]. Washington DC; 2017. Available from: https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=OAP&dirEntryId=335095

[10] Zonfrillo MR, Ramsay ML, Fennell JE, Andreasen A. Unintentional non-traffic injury and fatal events: Threats to children in and around vehicles. Traffic injury prevention 2018;19(2), 184-188.

[11] Kuehn L., McCormick,S. Heat exposure and maternal health in the face of climate change. International journal of environmental research and public health Kuehn, L., & McCormick, S. (2017). Heat exposure and maternal health in the face of climate change. International journal of environmental research and public health, 14(8), 853.2017;14(8), 853.

- Outdoor workers in the agriculture and construction industries are disproportionately vulnerable to heat-related illness. In Maricopa County, Arizona, 115 men in these industries died due to heat-related causes between 2002-2009, comprising 35% of all male deaths from heat-related causes[12].

However, heat-related deaths can be prevented. Strategies to accomplish this include heatwave early warning and response systems, which provide advanced and timely information to individuals about the risks of thermal extremes through television, radio, text messaging, and other forms of communication, empowering individuals and communities to make smart choices to protect themselves. Other options include individual acclimatization (the process of adjusting to higher temperatures) and protective measures, such as air conditioning at home, cooling shelters, green space in the neighborhood, and resilient power grids to avoid power outages during extreme weather events[2].

Communities across the United States should learn from past heat-related tragedies to protect populations from future extreme heat events. The City of Philadelphia, PA provides an example. In July 1993, a devastating heat wave hit the Mid-Atlantic region, resulting in 118 excess deaths in Philadelphia[13]. Since that tragic event, the City of Philadelphia took proactive measures to prevent a repeat occurrence, despite rising summer temperatures. The City developed a system triggered when the National Weather Service issues an Excessive Heat Warning. The Philadelphia Department of Public Health (PDPH) Excessive Heat Public Safety Plan uses a variety of communication tools, including press releases, social media, and the PDPH website to inform the public about heat-related dangers. An emergency phone line staffed with public health nurses is also opened, as are cooling centers to allow individuals without access to cooling to seek relief. This comprehensive heat early warning system provides frequent and consistent messaging to the public, warning of the dangers of extreme temperatures and providing information on how to stay cool. Since 1993, heat-related deaths in Philadelphia have fallen dramatically, with annual deaths now in the low single digits.

Analyses of hospital admissions, emergency room visits, and emergency medical services calls show that hot days also are associated with an increase in heat-related illnesses, including cardiovascular and respiratory complications, renal failure, electrolyte imbalance, kidney stones, negative impacts on fetal health, and preterm birth[2]. Risks vary across regions. The healthcare costs from just one heatwave in California were estimated at $179 million[14].These costs could be reduced substantially with investments in heatwave early warning systems and other preventive measures, saving money and lives.

[12] Petitti DB, Harlan SL, Chowell-Puente G, Ruddell D. Occupation and Environmental Heat-Associated Deaths in Maricopa County, Arizona: A Case-Control Study. PLoS ONE 2013;8(5): e62596. https://doi.org/10.1371/journal.pone.0062596

[13] Kalkstein LS, Sheridan SC, Kalkstein AJ. Heat/Health Warning Systems: Development, Implementation, and Intervention Activities. In: Ebi K.L., Burton I., McGregor G.R. (eds) *Biometeorology for Adaptation to Climate Variability and Change.* Biometeorology, vol 1. 2009. Springer, Dordrecht

[14] Knowlton K, Rotkin-Ellman M, Geballe L, Max W, Solomon GM. Six Climate Change–Related Events In The United States Accounted For About $14 Billion In Lost Lives And Health Costs. *Health Affairs* 2011 Nov 2 [cited 2018 Nov 7];30(11):2167–76. Available from: http://www.healthaffairs.org/doi/10.1377/hlthaff.2011.0229

Heatwave early warning systems established in large cities across America informed the development of the National Integrated Heat Health Information System (NIHHIS) that provides an online portal of information and resources to help communities understand prepare for the health impacts of extreme heat[15]. NIHHIS is an interagency partnership developed by the Centers for Disease Control and Prevention, the National Oceanic and Atmospheric Administration, and domestic and international partners, with the goals of building understanding of the problem of extreme heat; defining demand for climate services that enhance societal resilience; developing science-based products and services from a sustained climate science research program; and improving capacity, communication, and societal understanding of the problem in order to reduce morbidity and mortality due to extreme heat. Communities, particularly in smaller cities and rural areas, generally need human and financial resources to design and implement heatwave early warning systems that take into account local vulnerabilities and capacities.

Extreme Weather and Climate Events: Extreme weather and climate events, such as floods, droughts, and wildfires, are increasing with climate change, threatening health and healthcare facilities. Hurricanes also cause significant damage. The health, well-being, and security of populations are significantly and increasingly affected by extreme weather and climate events. Death, physical injury, and increased risk of disease and mental health impacts can result from climate-related disasters. The indirect consequences can include substantial and long-lasting impacts on health systems, population health, and livelihoods. These events can destroy health care infrastructure, damage medical equipment and supplies, result in fewer health personnel to provide care, and disrupt health-related services (e.g. water and sanitation facilities), leading to a reduced capacity to meet public health needs[2,3]. Loss of livelihoods (e.g. lower crop yields) and population displacement can also adversely affect, for example, nutritional status and mental illness.

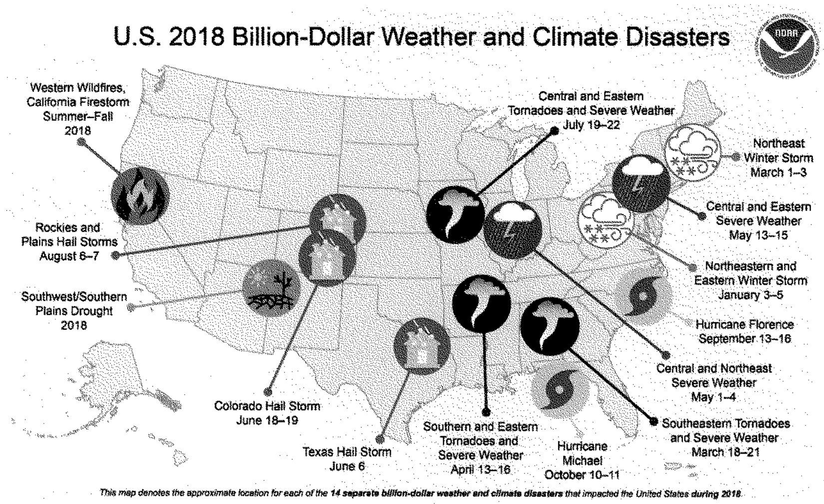
One example is the health impacts of drought and periods of unusually dry weather. In late 2015, California was in the fourth year of its most severe drought since becoming a state, with 63 emergency proclamations declared in cities, counties, tribal governments, and special districts[2]. Households in Tulare and Mariposa counties reported a range of drought-related health impacts, including increased dust leading to allergies, asthma, and other respiratory issues and acute stress and diminished peace of mind. These health impacts were not evenly distributed, with more negative physical and mental health impacts reported when drought negatively affected household property and finances.

Extreme weather and climate events are having an increasingly devastating impact on Americans in terms of lives lost, lives affected, and economic cost. In 2017 alone there were 16 billion-dollar disasters in the U.S. that together cost about $306 billion dollars[16]. The official death toll was estimated at 3,278, although the actual total was likely much higher. During the same year, 23 events (floods, storms, wildfires) affected approximately 866,835 individuals, and the homes of 109,108 individuals were destroyed[3]. The U.S. had 14 billion-dollar disasters in 2018, killing at least 247 people, and costing the nation an estimated $91 million (Figure 3). Most of that

[15] https://toolkit.climate.gov/tool/national-integrated-heat-health-information-system-nihhis
[16] https://www.ncdc.noaa.gov/billions/

damage, about $73 billion, was attributable to three events: Hurricanes Michael and Florence and the collection of wildfires that raged across the West. Since 1980, overall damages from 219 weather and climate billion-dollar disasters in the U.S. exceeded $1.6 trillion., with over 10,000 deaths.

Figure 3: U.S. 2018 billion-dollar weather and climate disasters



The 2018 wildfire season in California was the deadliest and most destructive on record, with 8,527 fires burning an area of nearly 1.9 million acres, the largest amount burned in a fire season, and about 100 fatalities. In addition, large populations were exposed to gases and fine particulates that can harm the heart and lungs; at times, the air quality in parts of California were unhealth for all to breathe. Wildfires are expected to become more common as the climate continues to change, which means more Americans could be exposed and adversely affected.

The impacts of an extreme weather or climate event are often not confined to the directly affected area. For example, wildfire smoke can affect air quality over multiple states. Individuals displaced by hurricanes or floods may move to other regions to seek shelter and access health care.

Children, older adults, low-income communities, some communities of color, and those experiencing discrimination are disproportionately affected by extreme weather and climate events, partially because they are often excluded in planning processes. Other populations that could experience increased sensitivity to extreme weather and climate events include outdoor workers and communities disproportionately burdened by poor environmental quality.

In addition to the direct harms on human health, extreme weather and climate events have the potential to adversely affect the operation of hospitals and other critical healthcare physical infrastructure. During Hurricane Harvey, hospitals in Houston, Texas were challenged to provide essential medical services to their patients. According to Darrel Pile, chief executive of the Southeast Texas Regional Advisory Council, Harvey "challenged every plan we've written, every resource, every piece of inventory…it was just unimaginable[17]." Despite the challenges faced during and after Harvey, the impacts on healthcare could have been far worse, had health systems not had plans in place to deal with an event of this magnitude. Such plans included sealing flood-prone areas and making provisions for extra personnel and supplies. As climate change increases the risks of extreme weather and climate events that can disrupt healthcare operations, additional planning will be needed to ensure continuity of care even during meteorological conditions thought unimaginable a decade ago.

Air quality: Poor air quality causes a host of health complications, including premature mortality, exacerbations of chronic obstructive pulmonary disease, asthma, and allergies. Climate change is decreasing air quality by increasing concentrations of ground-level ozone that harms the lungs and can cause early death. Long-term exposure to ozone is linked to aggravation of asthma and is likely one cause of asthma development. Long-term exposures to higher concentrations of ozone may also be linked to permanent lung damage, such as abnormal lung development in children.

Earlier springs, warmer temperatures, precipitation changes, and higher carbon dioxide concentrations can increase exposure to pollen allergens that can be especially problematic to those with hay fever and asthma. Warmer spring temperatures cause some plants to start producing pollen earlier, while warmer fall temperatures extend the growing season for other plants, such as ragweed[18]. Figure 4 shows changes in the ragweed pollen season from 1995-2015. While air quality across the U.S. improved since 1988, it has been deteriorating in western states because of wildfires.

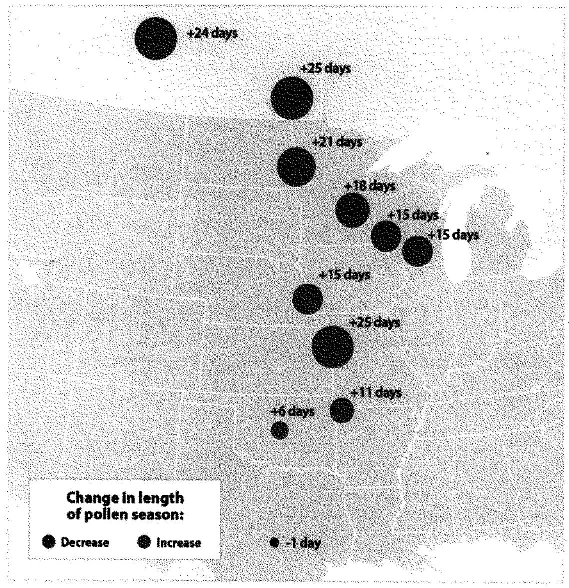
People most at risk from poorer air quality include people with asthma, children, older adults, and people who are active outdoors, especially outdoor workers. In addition, people with certain genetic characteristics, and people with reduced intake of certain nutrients, such as vitamins C and E, are at greater risk from ozone exposure[19].

[17] https://www.washingtonpost.com/national/health-science/some-hospitals-evacuated-but-houstons-vaunted-medical-world-mostly-withstands-harvey/2017/08/30/2e9e5a2c-8d90-11e7-84c0-02cc069f2c37_story.html?utm_term=.2c45181 0a9db

[18] https://www.epa.gov/climate-indicators/climate-change-indicators-ragweed-pollen-season

[19] https://www.epa.gov/arc-x/climate-adaptation-ground-level-ozone-and-health

Figure 4: Changes in the ragweed pollen season, 1995-2015



This figure shows how the length of ragweed pollen season changed at 11 locations in the central United States and Canada between 1995 and 2015. Red circles represent a longer pollen season; the blue circle represents a shorter season. Larger circles indicate larger changes. Source: EPA

Infectious diseases: Multiple infectious diseases are transmitted by mosquitoes, ticks, and fleas (e.g. vectors), including Lyme disease, dengue fever, and West Nile virus. The number of cases of climate-sensitive infectious diseases tripled between 2004-2016, with over 96,000 documented cases in 2016[3]. Areas not accustomed to particular infectious diseases are reporting cases for the first time. For instance, in my home of Western Washington, public health officials identified the first locally-transmitted case of West Nile Virus, a likely harbinger of trends to come as summers continue to warm in the Pacific Northwest.

Climate change is expected to alter the geographic range, seasonal distribution, and abundance of disease vectors, exposing more people in North America to ticks that carry Lyme disease or other bacterial and viral agents, and to mosquitoes that transmit West Nile and other viral diseases[2]. In the absence of adaptation, exposure to the mosquito *Aedes aegypti* that can transmit dengue, Zika, chikungunya, and yellow fever viruses, is projected to increase by the end of the century due to climatic, demographic, and socioeconomic changes, with some of the largest increases projected to occur in North America. Similarly, changes in temperature may influence the distribution and abundance of tick species that transmit common pathogens. At the same time, very high temperatures may reduce transmission risk for some diseases.

Changing weather patterns interact with other factors, including how pathogens adapt and change, changing ecosystems and land use, demographics, human behavior, and the status of public health infrastructure and management. Economic development may substantially reduce transmission risk by reducing contacts with vector populations.

Outbreaks occurring in other countries can impact U.S. populations and military personnel living abroad and can sometimes affect the United States[2]. For example, the 2015–16 El Niño, one of the strongest on record, may have contributed to the 2014–16 Zika epidemic in the Americas. Warmer conditions may have facilitated expansion of the geographic range of mosquito populations and increased their capacity to transmit Zika virus. Zika virus can cause a wide range of symptoms, including fever, rash, and headaches, as well as birth defects. The outbreak began in South America and spread to areas with mosquitoes capable of transmitting the virus, including Puerto Rico, the U.S. Virgin Islands, Florida, and Texas.

Effective public health strategies can reduce the dangers associated with the expansion of the geographic range of climate-sensitive infectious diseases. As diseases move into new areas, public health messaging on appropriate prevention strategies must be adopted in order to prevent uncontrolled outbreaks. Similarly, continuing education for healthcare professionals should emphasize the potential health hazards associated with climate change. Many medical staff may be faced with conditions never encountered heretofore in their careers and must be prepared to treat them appropriately.

Additionally, it is possible to forecast where and when the associated diseases could occur based on understanding the environmental determinants of these vectors and the pathogens they can carry[20]. This vital information can provide up to months lead time for public health practitioners to prepare for and effectively respond to outbreaks.

Water-related illnesses and deaths: The growth rate of several important human pathogens that can contaminate water depend on the temperature of the water. Because there are thresholds for of how many organisms are required for disease to occur, increasing water temperatures associated with climate change are projected to alter the seasonality of growth and the geographic range of harmful algae and coastal pathogens[3]. Further, runoff from more frequent and intense rainfall is projected to increasingly compromise recreational waters and sources of drinking water through increased introductions of pathogens and toxic algal blooms. Projected increases in extreme precipitation and flooding, combined with inadequate water and sewer infrastructure, can contribute to viral and bacterial contamination from combined sewage overflows and a lack of access to potable drinking water, increasing exposure to pathogens that can cause gastrointestinal illnesses.

[20] Morin CW, Semenza JC, Trtanj JM, Glass GE, Boyer C, Ebi KL. Unexplored Opportunities: Use of Climate-and Weather-Driven Early Warning Systems to Reduce the Burden of Infectious Diseases. *Current Environmental Health Reports* 2018: p. 1-9; https://doi.org/10.1007/s40572-018-0221-0

There is robust scientific understanding of the relationship between warmer water temperatures associated with longer summers and the growth of bacteria called *Vibrios* that can cause diarrheal illnesses, food poisoning, and skin infections. In the Northeast U.S., there was a 27% increase in the coastline area suitable for *Vibrios* in the 2010s vs the 1980s[3]. This means more Americans could be at risk through contact with the water or by eating contaminated shellfish. Increases in air temperatures and heatwaves are expected to increase temperature-sensitive marine pathogens such as *Vibrios*. Improving research and communication around the risks posed by *Vibrios* is essential to protecting human health as well as the viability of the shellfish industry that forms a critical component of many coastal and Native American communities.

The relationships between precipitation and temperature-driven transmission of waterborne diseases are complex and site-specific, with, for example, some areas finding increased numbers of cases associated with excessive rainfall and others finding stronger associations with drought. Heavy rainfall, flooding, and high temperatures are associated with increases in diarrheal disease and can increase other bacterial and parasitic infections such as leptospirosis and cryptosporidiosis.

Food security and nutrition: Climate change, including changes in some extreme weather and climate events, can adversely affect U.S. and global food security by, for example, altering exposures to certain pathogens and toxins (for example, *Salmonella* and *Campylobacter*), disrupting food availability, decreasing access to food, and increasing food prices[2]. Food quality also is expected to be affected by rising carbon dioxide concentrations that decrease dietary iron, zinc, protein, and other macro- and micronutrients in key staple crops such as wheat and rice. However, any impact on human health will depend on the many other drivers of global food security and factors such as food chain management, human behavior, and food safety governance.

Projected changes in carbon dioxide concentrations and climate change could diminish expected gains in global nutrition[2].

Mental health: Exposure to short-lived or prolonged weather- or climate-related events can result in mental health consequences, from stress and distress symptoms to clinical disorders, such as anxiety, depression, post-traumatic stress, and suicidality[2]. These mental health impacts can interact with other health, social, and environmental stressors to diminish an individual's well-being. Individuals whose households experienced a flood or risk of flood report higher levels of depression and anxiety, with these impacts possibly persisting for several years. Disasters present a heavy burden on the mental health of children when there is forced displacement from their home or a loss of family and community stability. Increased use of alcohol and tobacco are common following disasters as well as droughts. Higher temperatures can lead to an increase in aggressive behaviors, including homicide.

Groups potentially more vulnerable include the elderly, pregnant women, people with preexisting mental illness, the economically disadvantaged, tribal and Indigenous communities, and first responders. Social cohesion, good coping skills, and preemptive disaster planning are examples of adaptive measures that can help reduce the risk of prolonged psychological impacts.

Adaptation can protect and promote population health today and in the future

Targeted policies and programs are needed to protect vulnerable populations, and healthcare systems must become more resilient. The NCA4 concluded:

> *Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services. Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design.*

Individuals, communities, public health departments, healthcare facilities, organizations, and others are taking action to reduce health and social vulnerabilities to current climate change and to increase resilience to the risks projected in coming decades[2].

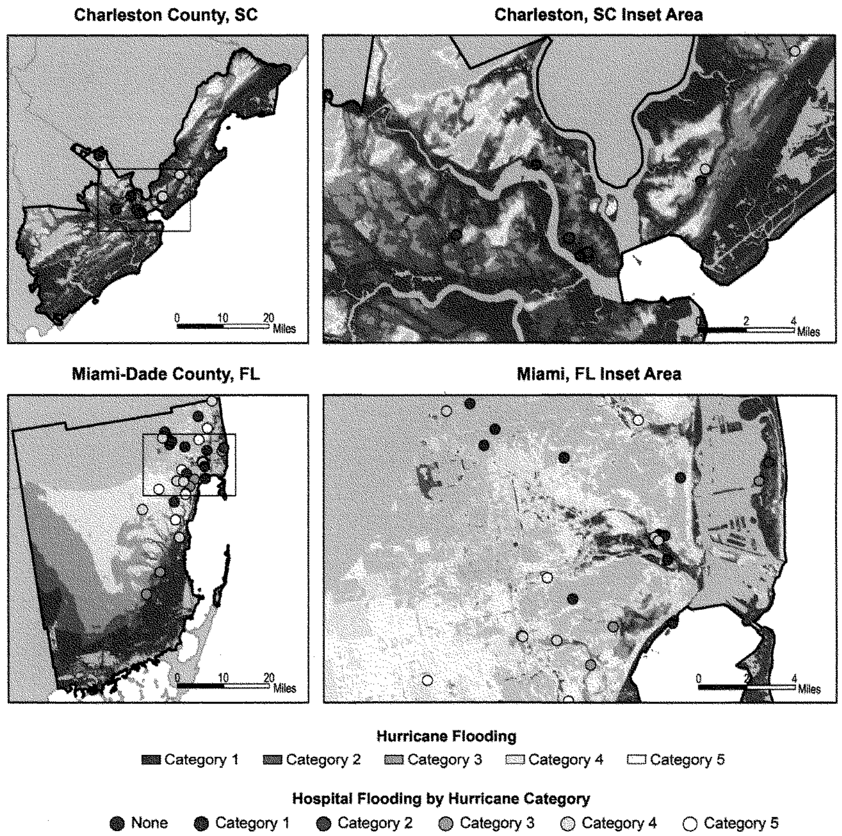
Examples of state-level adaptation actions include conducting vulnerability and adaptation assessments, developing comprehensive response plans (such as for extreme heat), climate-proofing healthcare infrastructure, and implementing integrated surveillance of climate-sensitive infectious disease that can incorporate short-term to seasonal forecasts (such as for Lyme disease or dengue fever)[2]. Incorporating climate projections into emergency preparedness and disaster risk management can increase preparedness for changing weather patterns.

Local efforts include altering urban design (for example, by using cool roofs, tree shades, and green walkways) and improving water management (for example, via desalination plants or watershed protection)[2]. These can provide health and social justice benefits, elicit neighborhood participation, and increase resilience for specific populations, such as outdoor workers.

Early warning and response systems can protect population health now and provide a basis for more effective adaptation to future climate[2]. Improvements in forecasting weather and climate conditions and in environmental observation systems, in combination with social factors, can provide information on when and where changing weather patterns could result in increasing numbers of cases of, for example, heat stress or an infectious disease.

Adaptation is needed for our healthcare infrastructure. For example, in coastal regions, many hospitals and clinics are located in areas subject to flooding, as was witnessed in Houston, Miami, and Puerto Rico following hurricanes in 2017[2]. This also is true in many other coastal communities. Mapping which hospitals may be subject to various levels of inundation is an important step; figure 5 shows the locations of hospitals in Charleston County, South Carolina, and Miami-Dade County, Florida, with respect to storm surge inundation for different categories of hurricanes making landfall at high tide[2]. Colors indicate the lowest category hurricane affecting a given location, with darker blue shading indicating areas with the greatest susceptibility to flooding and darker red dots indicating the most vulnerable hospitals. Four of the 38 (11%) hospitals in Miami-Dade County face possible storm surge inundation following a Category 2 hurricane; this could increase to 26 (68%) following a Category 5 hurricane. Charleston hospitals are more exposed to inundation risks. Seven of the 11 (64%) hospitals in Charleston County face possible storm surge inundation following a Category 2; this could increase to 9 (82%) following a Category 4. The impacts of a storm surge will depend on the effectiveness of resilience measures, such as flood walls, deployed by the facilities.

Figure 5: Hospitals at risk from storm surge by hurricanes in Miami-Dade County, Florida and Charleston County, South Carolina



Data from National Hurricane Center 2018 and the Department of Homeland Security 2018

In addition, healthcare facilities may benefit from modifications to prepare for potential future extreme weather and climate events. For example, Nicklaus Children's Hospital, formerly Miami Children's, invested $11.3 million in a range of technology retrofits, including a hurricane-resistant shell, to withstand Category 4 hurricanes for uninterrupted, specialized medical care services[2]. The hospital was able to operate uninterrupted during Hurricane Irma and provided shelter for spouses and families of storm-duty staff and some storm evacuees.

Adaptation efforts outside the health sector can have health benefits when, for example, infrastructure planning is designed to cool ambient temperatures and attenuate storm water runoff and when interagency planning initiatives involve transportation, ecosystem management, urban planning, and water management[2]. Adaptation measures developed and deployed in other sectors can harm population health if they are developed and implemented without taking health into consideration.

Health co-benefits of mitigation policies and technologies

Most policies to reduce emissions have health benefits for the health of Americans in the near and long term. The NCA4 concluded:

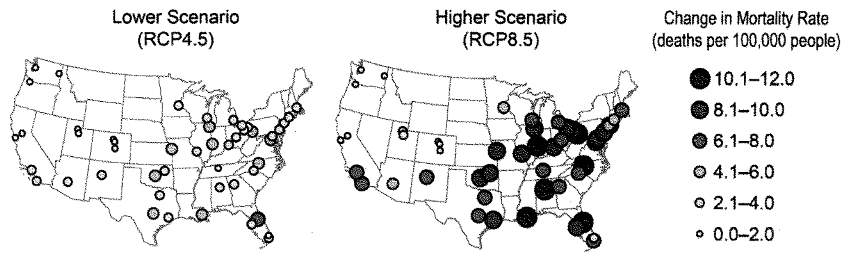
> *Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term. By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.*

Policies to reduce greenhouse-gas emissions in the energy sector, housing, and the built environment more generally (ranging from buildings to parks); transportation; and agriculture and food systems can result in near-term benefits to human health[6]. These benefits can arise from reduced exposure to air pollution, particularly fine particulates (particulate matter with a diameter of ≤2.5 μm (PM2.5), including black carbon) and ground-level ozone (levels of which may increase with climate change).

There is a growing literature in which the health benefits of reductions in air pollution as a result of climate-change mitigation strategies are quantified. For example, under a scenario of lower greenhouse gas emissions (RCP4.5), by the end of this century, thousands of lives could be saved and hundreds of billions of dollars of health-related costs could be avoided compared to a scenario of higher emissions (RCP8.5)[2]. Annual health impacts (including from temperature extremes, poor air quality, and vector-borne diseases) and health-related costs are projected to be approximately 50% less under lower greenhouse gas emissions (RCP4.5) than under higher emissions (RCP8.5). The projected lives saved and economic benefits are likely to underestimate the true value because they do not include benefits of impacts that are difficult to quantify, such as mental health or long-term health impacts.

For example, figure 6 shows estimated changes in annual net mortality due to extremely hot and cold days in 49 U.S. cities for 2080–2099 as compared to 1989–2000[2]. Across these cities, the change in mortality is projected to be an additional 9,300 deaths each year under higher greenhouse gas emissions (RCP8.5) and an additional 3,900 deaths each year under lower emissions (RCP4.5). There is an approximate 50% reduction in these estimates under the assumption that the human health response to extreme temperatures in all 49 cities was equal to that of Dallas today (for example, as a result of availability of air conditioning or physiological adaptation). For example, in Atlanta, an additional 349 people are projected to die from extreme temperatures each year by the end of century under RCP8.5. Assuming residents of Atlanta in 2090 have the adaptive capacity of Dallas residents today, this number is reduced to 128 additional deaths per year.

Figure 6: Projected change in annual extreme temperature-related mortality[2]



Cities without circles should not be interpreted as having no extreme temperature impact. Data were not available for the U.S. Caribbean, Alaska, and Hawaii and the U.S.-Affiliated Pacific Islands regions.

Other examples include:[2]

- Under higher emissions (RCP8.5), almost two billion labor hours are projected to be lost annually by 2090 from the impacts of temperature extremes, costing an estimated $160 billion in lost wages (2015 dollars). States within the Southeast and Southern Great Plains regions are projected to experience higher impacts, with labor productivity in jobs with greater exposure to heat projected to decline by 3%. Some counties in Texas and Florida are projected to experience more than 6% losses in annual labor hours by the end of the century.
- Annual national cases of West Nile neuroinvasive disease are projected to more than double by 2050 due to increasing temperatures, among other factors, resulting in approximately $1 billion per year in hospitalization costs and premature deaths under higher emissions (RCP8.5; 2015 dollars). In this same scenario, an additional 3,300 cases and $3.3 billion in costs (2015 dollars) are projected each year by the end of the century. Approximately half of these cases and costs would be avoided under lower emissions (RCP4.5).
- By the end of the century, warming under a higher scenario (RCP8.5) is projected to increase the length of time recreational waters have concentrations of harmful algal blooms (cyanobacteria) above the recommended public health threshold by one month annually; these bacteria can produce a range of toxins that can cause gastrointestinal illness, neurological disorders, and other illnesses. The increase in the number of days where recreational waters pose this health risk is almost halved under lower emissions (RCP4.5).

Although the health benefits of policies to reduce carbon emissions are potentially large, there may be unintended adverse consequences[6]. An example is the introduction of diesel engines that were sometimes promoted to reduce greenhouse-gas emissions but release more fine particulates and nitrogen oxides than gasoline engines. Poorly designed food and agricultural policies to reduce greenhouse-gas emissions could threaten food security by limiting protein sources and increasing food prices for the poor. In addition, increased exposure to household air pollution could result from improving the energy efficiency of households through the use of insulation and draft proofing without improving ventilation. Mitigation policies must consider and minimize these potential harmful effects.

Conclusion

Climate change is affecting the health of Americans, with the magnitude and pattern of future harms dependent on the urgency and level of ambition in designing and implementing adaptation and mitigation measures that will promote and protect our health and our public health and healthcare infrastructure as the climate continues to change.

Kristie L. Ebi is director of the Center for Health and the Global Environment (CHanGE), and Rohm and Haas Endowed Professor in Public Health Sciences at the University of Washington. She has been conducting research and practice on the health risks of climate variability and change for more than twenty years, including on extreme events, thermal stress, foodborne safety and security, and vectorborne diseases. She focuses on understanding sources of vulnerability; estimating current and future health risks of climate change; designing and implementing adaptation policies and measures to reduce the risks of climate change in multi-stressor environments; and on estimating the health co-benefits of mitigation policies and technologies. She has supported multiple countries in Central America, Europe, Africa, Asia, and the Pacific in assessing their vulnerability and implementing adaptation measures. She co-chairs the International Committee On New Integrated Climate change assessment Scenarios (ICONICS), facilitating development of new climate change scenarios; chairs the National Academies Board on Environmental Change and Society; and co-chairs the National Academies Committee to Advise the U.S. Global Change Research Program. Dr. Ebi's scientific training includes an M.S. in toxicology and a Ph.D. and a Masters of Public Health in epidemiology, and two years of postgraduate research at the London School of Hygiene and Tropical Medicine. She has edited five books on aspects of climate change and has more than 200 publications.

Chairwoman JOHNSON. Thank you very much.

We're going to return now to our first witness. No? She's not quite ready.

Let me thank all of the witnesses. We now will go to our first round of questions. I will go through a few questions I have at the beginning.

Last month's government shutdown lasted for 35 days. During that time, many Federal science activities were put on hold. While some essential activities continued like the National Weather Service forecast, many other activities stopped entirely like updates to NOAA's climate and hurricane models. There were also staffing issues like the National Center for Environmental Protection, which had just one person out of 200 on staff during the shutdown.

These questions are for any or all of you that would like to respond. First question, what are the short- and long-term impacts of a government shutdown on Federal climate science? And with the United States currently a global leader in climate science, how do government shutdowns risk the U.S. leadership in producing top climate science? And what impact does it have on the rest of the world? We are heading to another potential shutdown, but hopefully it won't occur. But what are the top risks of our climate science enterprise when or if another shutdown is a reality?

You can start, Dr. Kopp.

Dr. KOPP. Sure. I'll just give a couple quick examples. So during the last shutdown, I was at an IPCC lead author meeting in Vancouver, and there were several of our co-authors who couldn't make it there because of the shutdown. And then of course, if you're looking at a large collaboration, having people who not only can't be there but also can't even be there remotely sort of makes you an unreliable partner, right? And so if you ask, how does this affect U.S. leadership, well, if we are an unreliable partner in international collaborations, that does make it harder for us to be a leader.

Another example, one of my co-authors at NOAA, we're working on a paper together, he didn't have access to his computer or data during the shutdown, and so all of the analyses that might've happened during that time were stalled. It's one thing if this is a couple of weeks, but if it's a chronic condition, this really accumulates.

Dr. FRANCIS. I would just add to what Dr. Kopp has mentioned. There were several major scientific conferences that occurred during the shutdown, and a large number of government employees were just unable to attend and present the research that they'd been working on for literally years, which is a huge detriment to their careers. Also, several field programs that were supposed to occur could not, so in some cases those field programs maybe won't happen ever or at least they'll be delayed for a year or more because there's a lot of planning and logistics that have to be lined up to make those field programs work. There was also a big delay in processing proposals for more research or processing reports on that research, and all of that just delays the progress of science.

Chairwoman JOHNSON. Thank you.

Dr. EBI. To add to the other comments, everything you heard so far this morning about climate change is driven by data, and those data need to be collected. Equipment is not perfect, as we saw so far this morning, and someone needs to go out and fix equipment. There are various things that need to take place to make sure that you continue those data series. You can't make up data that you can't go back and regenerate what you didn't collect, and so having these gaps where we don't have our critical Federal employees taking care of collecting the data that we need so critically to provide the science you need to make informed decisions.

Chairwoman JOHNSON. Thank you very much. Now, according to the IPCC's special report, limiting global warming to 1.5 centigrade over the long-term would, compared to 2, provide clear benefits to people and natural ecosystems. However, it would also require rapid far-reaching and unprecedented changes in all aspects of society to achieve decarbonization of our economy.

So for each panelist, if you would just comment, what are the potential costs of failing to limit warming to 1.5 centigrade? The witnesses can speak to their own areas of expertise in societal, economic, and environmental impacts.

Dr. KOPP. Well, I mean, there are a number of risks that accumulate the more carbon dioxide we put in. More heat waves lead to more mortality, as we've heard from our other speakers. Sea-level rise will be somewhat higher under 2 degrees versus 1.5 degrees, and so that leads to more coastal flooding.

Both of those goals are heavy lifts, and so, the most important thing to keep in mind, I would argue, is that to stabilize climate at any level we need to get net global greenhouse gas emissions to zero. And I think it's important we recognize the more warming we let happen, the more the risks accumulate, but we've got to keep that goal as our centerpiece, net global—net-zero global greenhouse gas emissions.

Dr. FRANCIS. And I would just reiterate the fact that we are already seeing a large increase in the occurrence of extreme weather events and the intensity of many of those types of events, and that's only going to get worse as the globe continues to warm.

And I just wanted to add also that it may seem arbitrary to pick 1.5 or 2.0-degree warming of the earth, but that's actually a very useful thing to do because we can use these very sophisticated climate models that have been developed by many groups over many years to simulate the kinds of extreme events and the kinds of changes in the physical climate system that would occur under both of those scenarios. They're very useful for helping us visualize what the world would look like under those two different kinds of conditions, and by doing that, we can see we really don't want a world with a 2-degree warming, and we certainly don't want to go past that, so it's a very useful exercise to go through visualizing these endpoints.

Dr. MAJKUT. Yes, I would echo my colleagues that the way I think about climate risk as we progress through these various temperature levels is the planet doesn't really care about it being 1.5 °C or 2 °C, but the risks accumulate as we go higher and higher up through warming levels.

The thing that jumped out to me as I was preparing for the hearing was the effect on coral reefs, funny enough. At 1.5 °C scientists are projecting that up to 90 percent of coral reefs globally will be substantially diminished by warming events, and at 2 °C that number goes to over 99 percent, which would be utterly devastating. So when we think about these global targets, we could really interpret it—interpret those low-temperature targets as being hedges, right, looking to avoid catastrophic impacts on particular systems.

Chairwoman JOHNSON. Dr. Ebi?

Dr. EBI. Another critical conclusion of the Special Report on Global Warming of 1.5 is that it is possible to stay below 1.5 °C, and we can do that with current technologies. We have to increase our level of ambition. We have to be more proactive, but it's not impossible. So there is both the message that it's critical that we do so and that it's possible to make that commitment to stay below 1.5.

And as the other speakers mentioned, as we increase from today, which is 1 °C above preindustrial to 1.5 to 2 degrees, that each unit of warming is associated with adverse consequences for our health, our livelihoods, our ecosystems, and for our economies.

Chairwoman JOHNSON. Thank you very much. Before we proceed, I think we might have Dr. Mahowald ready for testimony. You may proceed.

TESTIMONY OF DR. NATALIE M. MAHOWALD, IRVING PORTER CHURCH PROFESSOR OF ENGINEERING, FACULTY DIRECTOR FOR THE ENVIRONMENT, ATKINSON CENTER FOR A SUSTAINABLE FUTURE, CORNELL UNIVERSITY

Dr. MAHOWALD. Chairwoman Johnson, Ranking Member Lucas, and distinguished Members of the Committee, thank you for the opportunity to testify at today's hearing on the state of climate science and why it matters. I'd also like to thank the technical staff in the House and here at Cornell for making this happen.

My name is Natalie Mahowald. I'm a Professor of Atmospheric Sciences at Cornell University with over 20 years' research expertise in climate science. I'm here today because—to explain why climate science matters and to put simply, it matters because the health and well-being of Americans matter, the U.S. economy matters, national security matters, and ensuring that the next generation of citizens can enjoy a better lifestyle than we do matters.

Over the past year, we've witnessed record-breaking storms, precipitation, heat waves, fires, and flooding, all of which show the power of weather and the potential for changes in climate to harm human lives and livelihoods. At the same time, we're witnessing a global revolution in the development of innovative new technologies that hold the promise of delivering a low-carbon-emitting future. China and Europe in particular are investing heavily in these new technologies. The United States can take a leadership role in business, science, and technology to bring both clean energy and new jobs to thousands of Americans.

These topics—climate change, its impacts, and the technologies to mitigate and adapt its effects—were the subject of the IPCC's special report on limiting warming to 1.5 °C, on which I was a lead author. This report comes at a critical time when we are rejecting the old-fashioned view that either we protect the environment or we promote business. The goal of the report is to identify solutions to reach low-climate targets while promoting economic growth and eradicating poverty.

Scientific evidence is clear that human activities have caused warming of 1.0 °C since the late 1800s. If we keep warming at the same rate, we will pass 1.5 °C around 2040. Past emissions alone, however, are unlikely to cause 1.5 degrees warming. In other words, if we can cut emissions quickly enough, we can arrest the Earth's warming trends, keep temperatures below 1.5 degrees. This would require extremely ambitious emission cuts, 45 percent reduction in global emissions by 2030, which is much more ambitious than agreed to by the Paris Agreement and the voluntary reduction. In fact, the voluntary reductions agreed to through the Paris Agreement are likely to result in a warming of perhaps 3 °C. While this falls short of the stated goals of the Paris Agreement where governments agreed to keep warming below 2 degrees, it is much lower than the business-as-usual scenarios of up to a 5-degree increase in warming by 2100.

The climate impacts will be lower at lower temperatures. Adaptation to climate change is easier at lower temperatures, but it's still going to be required. Whatever temperature target policymakers set as a goal, the 1.5 report provides a menu of policy options from which they can choose. This report also suggests an array of technologies and techniques across many sectors that may be deployed to strengthen the response to climate change. Combined, these policies, technologies, and techniques can help reduce climate change impacts either through mitigation or adaptation and are appropriate for any climate target. For example, reducing subsidies for fossil fuels or removing regulatory barriers for new energy-producing technology and promoting a stable business environment to low-carbon technologies and techniques can create jobs, save money, improve health, and mitigate climate change.

Promoting policies at the local, State, and Federal levels that move existing financing into new areas of research development and deployment for the energy industry, transportation, agriculture, and building sectors can create new business opportunities and technologies while mitigating for climate.

Finally, an important new area of research will be carbon dioxide removal and utilization technology. The world is very different today than it was 50 years ago in terms of how we live, how we interact with each other, virtually and in person, and globally. The world in 50 years will again be different, and the challenge of climate change will be one of the key ways that define our future in terms of mitigation and adaptation to climate change. Keeping America in a business and technological leadership role requires thoughtful investment in research development and deployment and innovative technologies and techniques that our international competitors are already investing in and will result in a more prosperous, healthier, safer America and world.

Thank you for the opportunity to testify. I look forward to your questions.

[The prepared statement of Dr. Mahowald follows:]

Statement to the
Committee on Science, Space and Technology
Of the United States House of Representatives

Hearing on
"The State of Climate Science and Why it Matters"

February 12, 2019

Natalie Mahowald

Irving Porter Church Professor of Engineering
Department of Earth and Atmospheric Sciences
and
Faculty Director,
Atkinson Center for a Sustainable Future

Cornell University

Chairwoman Johnson, Ranking Member Lucas and distinguished members of the committee: thank you for the opportunity to testify at today's hearing on the State of Climate Science and Why it Matters.

My name is Natalie Mahowald. I am the Faculty Director for the Atkinson Center for a Sustainable Future at Cornell University, as well as the Irving Porter Church Professor of Engineering in the area of Atmospheric Sciences in the Department of Earth and Atmospheric Sciences. I have research expertise in climate change science for over 20 years.

I have been asked to present to the Committee results from the Intergovernmental Panel on Climate Change's *Special Report on Limiting Warming to 1.5C* (the "1.5 report"), on which I was a lead author. As an attachment to my written testimony, I would like to submit for the record a copy of the summary for policy makers from the Special Report on 1.5C.

The Intergovernmental Panel on Climate Change is overseen by the United Nations Environment Programme and the World Meteorological Organization. The purpose of the IPCC is to assess scientific and socioeconomic information for policymakers to help them make informed decisions. The IPCC organizes the scoping, writing and approval of assessment reports, which undergo strict review and scrutiny by the scientific community before also being approved by the government approval session of the IPCC [1]. Assessment reports do not report new research, nor do they contain the scientific opinions of a few scientists, but rather they are a consensus view of the scientific literature. All of the results included in the summary for policymakers represent those in which the scientific community has medium or high confidence, meaning that multiple scientific papers, with different authors and using different approaches, came to the same conclusion. Thus, these reports are meant to be as helpful as possible for policymakers by providing them only with information representing the consensus view of current scientific literature.

There were 91 authors from 44 countries (including several from the United States) who wrote the 1.5 report. Another 133 scientists contributed elements to the report. The report was reviewed three times by experts, which included over 42,000 comments from more than 1,000 reviewers. Each comment was considered and responded to by the authors. The Summary for Policymakers for the report was approved line-by-line by all the governments participating in the IPCC as representing both the underlying report and the peer reviewed scientific literature. Each of the previous IPCC reports have all undergone a similarly robust review to ensure that they represent the consensus view of the scientific literature.

The 1.5C report was unique in several ways. First, this was the first IPCC report to be specifically requested by governments. Second, the mandate for the report was extremely broad: not only was the goal to access the impacts of limiting warming to 1.5C but to also examine how efforts to limit warming to 1.5C might strengthen the global response to the

[1] https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/

threat of climate change, promote sustainable development and increase efforts to eradicate poverty[2]. Finally, this particular report comes at a critical time when we are rejecting the old-fashioned view that either we protect the environment OR we promote businesses and eradication of poverty. The goal of the 1.5C report was to identify solutions that will protect the environment WHILE promoting economic growth and eradicating poverty. In other words, this report focuses on identifying ways to create sustainable development and mitigation strategies to reach low climate targets, while also protecting us against the climate change that we cannot avoid.

For many years, the scientific consensus on climate change has been clear, with over 97% of climate scientists agreeing that human-caused climate change is a problem we need to address[3]. This has been seen in IPCC reports, National Assessment Reports, including the 4th assessment released this year, [4] as well as review documents from the United States' most esteemed scientists in the National Academies.[5]

The consensus of the scientific evidence clearly demonstrates that human activities have caused 1.0C of global warming since the late 1800s. Current trends suggest that if we keep warming at the same rate, we will pass 1.5C around 2040. Without concerted climate action, some estimates suggest warming of 4-5C by 2100.

Past emissions alone, however, are unlikely to cause 1.5C of warming. In other words, if we can cut net emissions quickly enough, we can arrest the earth's warming trends and keep temperatures below 1.5C. This would require extremely ambitious emission cuts—a 45% reduction in global emissions by 2030, much more ambitious than agreed to by the Paris Agreement. For example, the emission reductions voluntarily agreed to by different countries as part of the Paris Agreement are likely to result in warming of about 3.0C by 2100 [6]. While this falls short of the stated goals of the Paris agreement, where governments agreed to try to keep warming below 2.0C, it is much lower than the business-as-usual scenarios of perhaps 5C warming at 2100, assuming only technological innovation.[7]

We are already seeing the impact of climate change on extreme events, for example an increase in the intensity of precipitation, increased heat waves and droughts. A new set of research completed in time for the 1.5C report looked at the importance of only 0.5C warming on extreme events. These studies focused on, for example, the difference between a warming of 0.5C and the 1.0C of today using historical data, or between 1.0 and 1.5C in future climate projections, and they suggest that even small changes, such as 0.5C warming, can have significant impacts on humans and ecosystems. In addition, the climate impacts from 1.5 C

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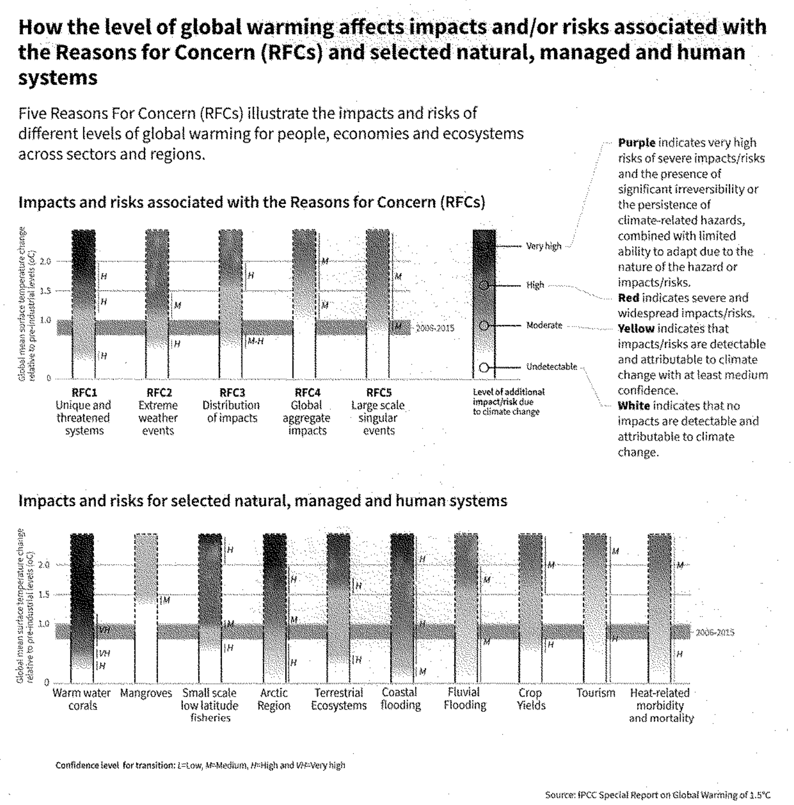
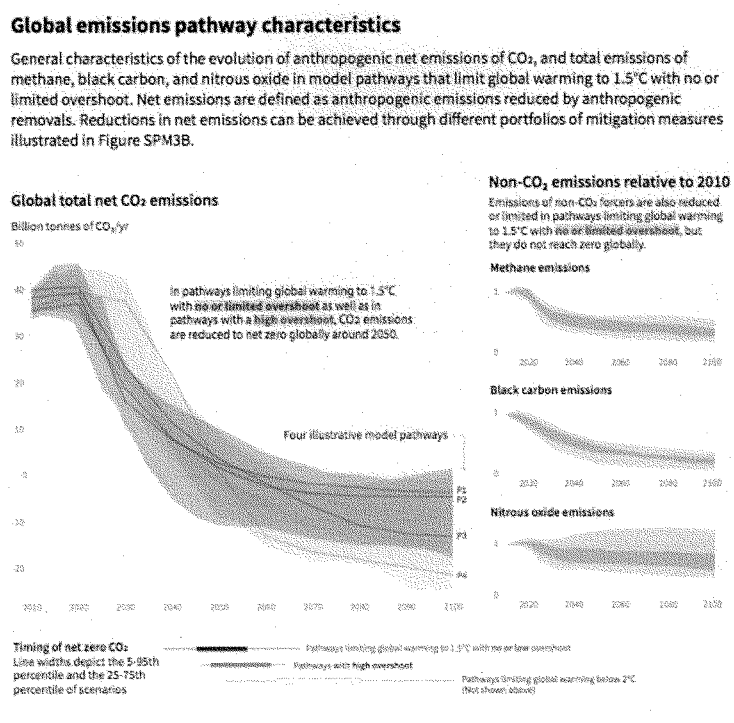
[2] https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/
[3] https://climate.nasa.gov/scientific-consensus/
[4] https://nca2018.globalchange.gov/
[5] https://www.nap.edu/catalog/18730/climate-change-evidence-and-causes
[6] https://report.ipcc.ch/sr15/index.html (Summary for Policy Makers,D1.1, page 20)
[7] https://www.ipcc.ch/report/ar5/syr/ (Summary for Policy Makers: SPM2.2, page 10)

global warming are less than that from 2.0C or higher temperatures. Overall, the lower we can keep the global warming, the less climate impacts there will be (Figure 2 from the report).



Adaptation to climate change at the current 1.0C or at a potential future at 1.5C is much easier than at higher temperatures, but will still be required in agricultural lands and cities, and especially in low-lying regions. The poor and vulnerable will be much more able to adapt if the level of global warming is lower. In other words, the lower the anthropogenic temperature changes are kept, the easier it will be for both ecosystems and people to adapt. Making sure that new infrastructure investments are consistent with future climate projections is vital to both mitigation and adaptation efforts.

Ambitious mitigation will be required to keep climate change below 1.5C. This includes strategies such as conversion to sustainable energy – wind or solar, for example – and adoption of sustainable agricultural practices as quickly as possible. Changes in individual behaviors such as energy conservation or shifts in diet can also make a huge difference in cutting emissions. In addition, development of new technologies or methods to remove carbon dioxide from the atmosphere are likely to be required to keep global warming below 1.5C. Scenarios that keep warming below 1.5C are shown in Figure 3a from the 1.5C report below



While limiting warming to 1.5C may not be the pathway chosen by policymakers, the 1.5 C report provides a menu of policy choices from which policymakers – who hail from different regions and face different challenges – may choose. The 1.5C report also suggests an array of technologies and techniques across many sectors that could be deployed to help strengthen the response to the threat of global warming. Combined, these policies and technologies can help reduce climate change impacts either through mitigation or adaptation and they are appropriate for any climate target. For example, reducing subsidies or regulatory environments that make fossil fuel energy sources less attractive, while incentivizing stable business investment and public-private partnerships in low carbon energies and industry can create jobs, save money and mitigate climate change. Promoting policies at the local, state and federal level that shift private and public financing into new areas of research, development and deployment for the energy, industry, transportation, agriculture and building sectors can create new business opportunities and technologies while also mitigating the effects of climate change. The 1.5C report found that an important new area of research will be carbon dioxide removal and utilization technologies. Recent reports from the National Academies also show the promise of a well-organized research agenda in this area[8].

Ambitious cuts in emissions can be consistent with ensuring people around the world are healthy, prosperous and supplied with ample food, clean air and water. New energy production technologies such as solar and wind can be actually cheaper than older, dirtier fossil-fuel based technologies, and may in some cases require much less infrastructure. Development and deployment of similar low carbon technologies in other sectors remains an important area that needs addressing. The 1.5C report shows that the goals of reaching low climate targets and other goals, such as prosperity and environmental protections, are not mutually exclusive. Indeed, limiting warming can go hand in hand with increasing economic prosperity. While much more action needs to be undertaken, the good news is momentum is beginning in the areas of research, development and deployment of innovative technologies and techniques. This Congress has an opportunity to build on that momentum to help the United States lead in the development of these new technologies and result in a more prosperous, healthier and safer world.

Thank you again for the invitation to testify. I am happy to elaborate on any of these points or answer any questions the Committee may have.

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[8] Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. http://nap.edu/25259 and Gaseous Carbon Waste Streams Utilization: Status and Research Needs: http://nap.edu/25232

Attachment A

Short Narrative Biography

February 12, 2019

Natalie Mahowald

Natalie Mahowald is the Irving Porter Church Professor of Engineering, in the area of Atmospheric Sciences at Cornell University in the Department of Earth and Atmospheric Sciences. She is also a Faculty Director for the Atkinson Center for a Sustainable Future. She earned her undergraduate degrees in Physics and German at Washington University in St. Louis in 1988, her M.S. in Natural Resource Policy at the University of Michigan, and her Ph.D. in Meteorology at MIT in 1996. She also worked in air pollution consulting and studied in Germany before her Ph.D. She did her postdoctoral work at Stockholm University, before moving to a faculty position at University of California, Santa Barbara. She then moved to the National Center of Atmospheric Research before starting as a faculty member at Cornell in 2007.

She has numerous scientific awards to her name, including being named a Fellow of both the American Meteorological Society (2011) and the American Geophysical Union (2013), and being awarded a Guggenheim Fellowship (2013). She was named by Thompson ISI as a highly cited research for 2002-2012, and for each of the years since. She was the Henry G. Houghton Awardee from the Aemrican Meteorological Society (for best young atmospheric chemistry or physical meteorologist in 2006). She has over 170 peer reviewed publications, and a Web of Science H-factor of 68.

She was a lead author on the Special Report on 1.5C from the Intergovernmental Panel on Climate Change just approved last October, as well as on the 5rh Assessment from the,Working Group 1 on the Physical science of Climate Change in 2013.

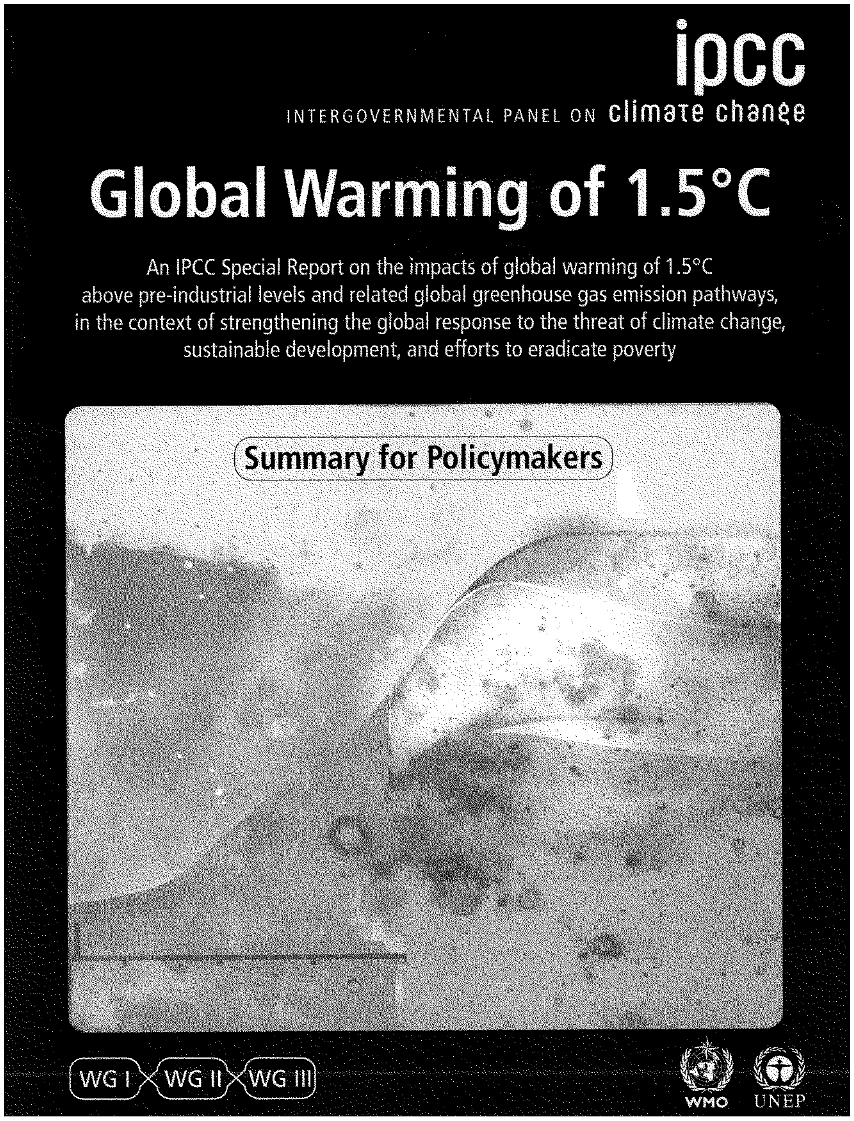
The focus of Natalie's work is on natural feedbacks in the climate system, and how they responded in the past to natural climate forcings, and how they are likely to respond in the future. Much of her work focused on mineral aerosols, which are an excellent example of an earth system process: they both respond to climate, as well as force climate to change. She has also worked on fire, the carbon cycle, and more recently on understanding natural emissions of methane and nitrous oxide.

Attachment B

IPCC Special Report: Summary for Policymakers

February 12, 2019

Natalie Mahowald


ipcc
INTERGOVERNMENTAL PANEL ON climate change
Global Warming of 1.5°C
An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty
Summary for Policymakers
WG I
WG II
WG III
WMO
UNEP

Global warming of 1.5°C

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Summary for Policymakers

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Summary for Policymakers

SPM

Summary for Policymakers

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SPM

Introduction

This Report responds to the invitation for IPCC '... to provide a Special Report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways' contained in the Decision of the 21st Conference of Parties of the United Nations Framework Convention on Climate Change to adopt the Paris Agreement.[1]

The IPCC accepted the invitation in April 2016, deciding to prepare this Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

This Summary for Policymakers (SPM) presents the key findings of the Special Report, based on the assessment of the available scientific, technical and socio-economic literature[2] relevant to global warming of 1.5°C and for the comparison between global warming of 1.5°C and 2°C above pre-industrial levels. The level of confidence associated with each key finding is reported using the IPCC calibrated language.[3] The underlying scientific basis of each key finding is indicated by references provided to chapter elements. In the SPM, knowledge gaps are identified associated with the underlying chapters of the Report.

A. Understanding Global Warming of 1.5°C[4]

A.1 Human activities are estimated to have caused approximately 1.0°C of global warming[5] above pre-industrial levels, with a *likely* range of 0.8°C to 1.2°C. Global warming is *likely* to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*) (Figure SPM.1) {1.2}

A.1.1 Reflecting the long-term warming trend since pre-industrial times, observed global mean surface temperature (GMST) for the decade 2006–2015 was 0.87°C (*likely* between 0.75°C and 0.99°C)[6] higher than the average over the 1850–1900 period (*very high confidence*). Estimated anthropogenic global warming matches the level of observed warming to within ±20% (*likely range*). Estimated anthropogenic global warming is currently increasing at 0.2°C (*likely* between 0.1°C and 0.3°C) per decade due to past and ongoing emissions (*high confidence*). {1.2.1, Table 1.1, 1.2.4}

A.1.2 Warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic. Warming is generally higher over land than over the ocean. (*high confidence*) {1.2.1, 1.2.2, Figure 1.1, Figure 1.3, 3.3.1, 3.3.2}

A.1.3 Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5°C of global warming occurred (*medium confidence*). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950. {3.3.1, 3.3.2, 3.3.3}

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1 Decision 1/CP.21, paragraph 21.

2 The assessment covers literature accepted for publication by 15 May 2018.

3 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5.

4 See also Box SPM.1: Core Concepts Central to this Special Report.

5 Present level of global warming is defined as the average of a 30-year period centred on 2017 assuming the recent rate of warming continues.

6 This range spans the four available peer-reviewed estimates of the observed GMST change and also accounts for additional uncertainty due to possible short-term natural variability. {1.2.1, Table 1.1}

A.2 Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are *unlikely* to cause global warming of 1.5°C (*medium confidence*). (Figure SPM.1) {1.2, 3.3, Figure 1.5}

A.2.1 Anthropogenic emissions (including greenhouse gases, aerosols and their precursors) up to the present are *unlikely* to cause further warming of more than 0.5°C over the next two to three decades (*high confidence*) or on a century time scale (*medium confidence*). {1.2.4, Figure 1.5}

A.2.2 Reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal time scales (*high confidence*). The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (*high confidence*) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (*medium confidence*). On longer time scales, sustained net negative global anthropogenic CO_2 emissions and/or further reductions in non-CO_2 radiative forcing may still be required to prevent further warming due to Earth system feedbacks and to reverse ocean acidification (*medium confidence*) and will be required to minimize sea level rise (*high confidence*). {Cross-Chapter Box 2 in Chapter 1, 1.2.3, 1.2.4, Figure 1.4, 2.2.1, 2.2.2, 3.4.4.8, 3.4.5.1, 3.6.3.2}

A.3 Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C (*high confidence*). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (*high confidence*). (Figure SPM.2) {1.3, 3.3, 3.4, 5.6}

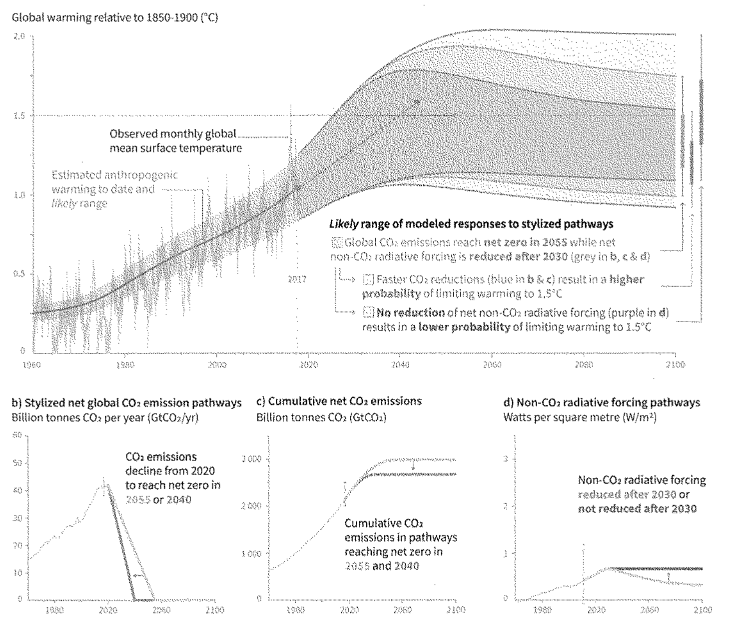
A.3.1 Impacts on natural and human systems from global warming have already been observed (*high confidence*). Many land and ocean ecosystems and some of the services they provide have already changed due to global warming (*high confidence*). (Figure SPM.2) {1.4, 3.4, 3.5}

A.3.2 Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate, they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (*high confidence*). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (*high confidence*). {3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8 in Chapter 3}

A.3.3 Adaptation and mitigation are already occurring (*high confidence*). Future climate-related risks would be reduced by the upscaling and acceleration of far-reaching, multilevel and cross-sectoral climate mitigation and by both incremental and transformational adaptation (*high confidence*). {1.2, 1.3, Table 3.5, 4.2.2, Cross-Chapter Box 9 in Chapter 4, Box 4.2, Box 4.3, Box 4.6, 4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.5, 4.4.1, 4.4.4, 4.4.5, 4.5.3}

Cumulative emissions of CO_2 and future non-CO_2 radiative forcing determine the probability of limiting warming to 1.5°C

a) Observed global temperature change and modeled responses to stylized anthropogenic emission and forcing pathways



Faster immediate CO_2 emission reductions limit cumulative CO_2 emissions shown in panel **(c)**.

Maximum temperature rise is determined by cumulative net CO_2 emissions and net non-CO_2 radiative forcing due to methane, nitrous oxide, aerosols and other anthropogenic forcing agents.

Figure SPM.1 | Panel a: Observed monthly global mean surface temperature (GMST, grey line up to 2017, from the HadCRUT4, GISTEMP, Cowtan–Way, and NOAA datasets) change and estimated anthropogenic global warming (solid orange line up to 2017, with orange shading indicating assessed *likely* range). Orange dashed arrow and horizontal orange error bar show respectively the central estimate and *likely* range of the time at which 1.5°C is reached if the current rate of warming continues. The grey plume on the right of panel a shows the *likely* range of warming responses, computed with a simple climate model, to a stylized pathway (hypothetical future) in which net CO_2 emissions (grey line in panels b and c) decline in a straight line from 2020 to reach net zero in 2055 and net non-CO_2 radiative forcing (grey line in panel d) increases to 2030 and then declines. The blue plume in panel a) shows the response to faster CO_2 emissions reductions (blue line in panel b), reaching net zero in 2040, reducing cumulative CO_2 emissions (panel c). The purple plume shows the response to net CO_2 emissions declining to zero in 2055, with net non-CO_2 forcing remaining constant after 2030. The vertical error bars on right of panel a) show the *likely* ranges (thin lines) and central terciles (33rd – 66th percentiles, thick lines) of the estimated distribution of warming in 2100 under these three stylized pathways. Vertical dotted error bars in panels b, c and d show the *likely* range of historical annual and cumulative global net CO_2 emissions in 2017 (data from the Global Carbon Project) and of net non-CO_2 radiative forcing in 2011 from AR5, respectively. Vertical axes in panels c and d are scaled to represent approximately equal effects on GMST. {1.2.1, 1.2.3, 1.2.4, 2.3, Figure 1.2 and Chapter 1 Supplementary Material, Cross-Chapter Box 2 in Chapter 1}

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B. Projected Climate Change, Potential Impacts and Associated Risks

B.1 Climate models project robust[7] differences in regional climate characteristics between present-day and global warming of 1.5°C,[8] and between 1.5°C and 2°C.[8] These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions (*medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*). {3.3}

B.1.1 Evidence from attributed changes in some climate and weather extremes for a global warming of about 0.5°C supports the assessment that an additional 0.5°C of warming compared to present is associated with further detectable changes in these extremes (*medium confidence*). Several regional changes in climate are assessed to occur with global warming up to 1.5°C compared to pre-industrial levels, including warming of extreme temperatures in many regions (*high confidence*), increases in frequency, intensity, and/or amount of heavy precipitation in several regions (*high confidence*), and an increase in intensity or frequency of droughts in some regions (*medium confidence*). {3.2, 3.3.1, 3.3.2, 3.3.3, 3.3.4, Table 3.2}

B.1.2 Temperature extremes on land are projected to warm more than GMST (*high confidence*): extreme hot days in mid-latitudes warm by up to about 3°C at global warming of 1.5°C and about 4°C at 2°C, and extreme cold nights in high latitudes warm by up to about 4.5°C at 1.5°C and about 6°C at 2°C (*high confidence*). The number of hot days is projected to increase in most land regions, with highest increases in the tropics (*high confidence*). {3.3.1, 3.3.2, Cross-Chapter Box 8 in Chapter 3}

B.1.3 Risks from droughts and precipitation deficits are projected to be higher at 2°C compared to 1.5°C of global warming in some regions (*medium confidence*). Risks from heavy precipitation events are projected to be higher at 2°C compared to 1.5°C of global warming in several northern hemisphere high-latitude and/or high-elevation regions, eastern Asia and eastern North America (*medium confidence*). Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (*medium confidence*). There is generally *low confidence* in projected changes in heavy precipitation at 2°C compared to 1.5°C in other regions. Heavy precipitation when aggregated at global scale is projected to be higher at 2°C than at 1.5°C of global warming (*medium confidence*). As a consequence of heavy precipitation, the fraction of the global land area affected by flood hazards is projected to be larger at 2°C compared to 1.5°C of global warming (*medium confidence*). {3.3.1, 3.3.3, 3.3.4, 3.3.5, 3.3.6}

B.2 By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depend on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*). {3.3, 3.4, 3.6}

B.2.1 Model-based projections of global mean sea level rise (relative to 1986–2005) suggest an indicative range of 0.26 to 0.77 m by 2100 for 1.5°C of global warming, 0.1 m (0.04–0.16 m) less than for a global warming of 2°C (*medium confidence*). A reduction of 0.1 m in global sea level rise implies that up to 10 million fewer people would be exposed to related risks, based on population in the year 2010 and assuming no adaptation (*medium confidence*). {3.4.4, 3.4.5, 4.3.2}

B.2.2 Sea level rise will continue beyond 2100 even if global warming is limited to 1.5°C in the 21st century (*high confidence*). Marine ice sheet instability in Antarctica and/or irreversible loss of the Greenland ice sheet could result in multi-metre rise in sea level over hundreds to thousands of years. These instabilities could be triggered at around 1.5°C to 2°C of global warming (*medium confidence*). (Figure SPM.2) {3.3.9, 3.4.5, 3.5.2, 3.6.3, Box 3.3}

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7 Robust is here used to mean that at least two thirds of climate models show the same sign of changes at the grid point scale, and that differences in large regions are statistically significant.

8 Projected changes in impacts between different levels of global warming are determined with respect to changes in global mean surface air temperature.

B.2.3 Increasing warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure (*high confidence*). Risks associated with sea level rise are higher at 2°C compared to 1.5°C. The slower rate of sea level rise at global warming of 1.5°C reduces these risks, enabling greater opportunities for adaptation including managing and restoring natural coastal ecosystems and infrastructure reinforcement (*medium confidence*). (Figure SPM.2) {3.4.5, Box 3.5}

B.3 On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5°C of global warming compared to 2°C. Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater and coastal ecosystems and to retain more of their services to humans (*high confidence*). (Figure SPM.2) {3.4, 3.5, Box 3.4, Box 4.2, Cross-Chapter Box 8 in Chapter 3}

B.3.1 Of 105,000 species studied,[9] 6% of insects, 8% of plants and 4% of vertebrates are projected to lose over half of their climatically determined geographic range for global warming of 1.5°C, compared with 18% of insects, 16% of plants and 8% of vertebrates for global warming of 2°C (*medium confidence*). Impacts associated with other biodiversity-related risks such as forest fires and the spread of invasive species are lower at 1.5°C compared to 2°C of global warming (*high confidence*). {3.4.3, 3.5.2}

B.3.2 Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1°C of global warming, compared with 13% (interquartile range 8–20%) at 2°C (*medium confidence*). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (*medium confidence*). {3.4.3.1, 3.4.3.5}

B.3.3 High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (*high confidence*) and this will proceed with further warming. Limiting global warming to 1.5°C rather than 2°C is projected to prevent the thawing over centuries of a permafrost area in the range of 1.5 to 2.5 million km^2 (*medium confidence*). {3.3.2, 3.4.3, 3.5.5}

B.4 Limiting global warming to 1.5°C compared to 2°C is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm-water coral reef ecosystems (*high confidence*). {3.3, 3.4, 3.5, Box 3.4, Box 3.5}

B.4.1 There is *high confidence* that the probability of a sea ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5°C when compared to 2°C. With 1.5°C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2°C global warming. Effects of a temperature overshoot are reversible for Arctic sea ice cover on decadal time scales (*high confidence*). {3.3.8, 3.4.4.7}

B.4.2 Global warming of 1.5°C is projected to shift the ranges of many marine species to higher latitudes as well as increase the amount of damage to many ecosystems. It is also expected to drive the loss of coastal resources and reduce the productivity of fisheries and aquaculture (especially at low latitudes). The risks of climate-induced impacts are projected to be higher at 2°C than those at global warming of 1.5°C (*high confidence*). Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (*high confidence*) with larger losses (>99%) at 2°C (*very high confidence*). The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (*high confidence*). {3.4.4, Box 3.4}

9 Consistent with earlier studies, illustrative numbers were adopted from one recent meta-study.

B.4.3 The level of ocean acidification due to increasing CO_2 concentrations associated with global warming of 1.5°C is projected to amplify the adverse effects of warming, and even further at 2°C, impacting the growth, development, calcification, survival, and thus abundance of a broad range of species, for example, from algae to fish (*high confidence*). {3.3.10, 3.4.4}

B.4.4 Impacts of climate change in the ocean are increasing risks to fisheries and aquaculture via impacts on the physiology, survivorship, habitat, reproduction, disease incidence, and risk of invasive species (*medium confidence*) but are projected to be less at 1.5°C of global warming than at 2°C. One global fishery model, for example, projected a decrease in global annual catch for marine fisheries of about 1.5 million tonnes for 1.5°C of global warming compared to a loss of more than 3 million tonnes for 2°C of global warming (*medium confidence*). {3.4.4, Box 3.4}

B.5 Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C. (Figure SPM.2) {3.4, 3.5, 5.2, Box 3.2, Box 3.3, Box 3.5, Box 3.6, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 5.2}

B.5.1 Populations at disproportionately higher risk of adverse consequences with global warming of 1.5°C and beyond include disadvantaged and vulnerable populations, some indigenous peoples, and local communities dependent on agricultural or coastal livelihoods (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island developing states, and Least Developed Countries (*high confidence*). Poverty and disadvantage are expected to increase in some populations as global warming increases; limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050 (*medium confidence*). {3.4.10, 3.4.11, Box 3.5, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 4.2.2.2, 5.2.1, 5.2.2, 5.2.3, 5.6.3}

B.5.2 Any increase in global warming is projected to affect human health, with primarily negative consequences (*high confidence*). Lower risks are projected at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*) and for ozone-related mortality if emissions needed for ozone formation remain high (*high confidence*). Urban heat islands often amplify the impacts of heatwaves in cities (*high confidence*). Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5°C to 2°C, including potential shifts in their geographic range (*high confidence*). {3.4.7, 3.4.8, 3.5.5.8}

B.5.3 Limiting warming to 1.5°C compared with 2°C is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America, and in the CO_2-dependent nutritional quality of rice and wheat (*high confidence*). Reductions in projected food availability are larger at 2°C than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon (*medium confidence*). Livestock are projected to be adversely affected with rising temperatures, depending on the extent of changes in feed quality, spread of diseases, and water resource availability (*high confidence*). {3.4.6, 3.5.4, 3.5.5, Box 3.1, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4}

B.5.4 Depending on future socio-economic conditions, limiting global warming to 1.5°C compared to 2°C may reduce the proportion of the world population exposed to a climate change-induced increase in water stress by up to 50%, although there is considerable variability between regions (*medium confidence*). Many small island developing states could experience lower water stress as a result of projected changes in aridity when global warming is limited to 1.5°C, as compared to 2°C (*medium confidence*). {3.3.5, 3.4.2, 3.4.8, 3.5.5, Box 3.2, Box 3.5, Cross-Chapter Box 9 in Chapter 4}

B.5.5 Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century[10] (*medium confidence*). This excludes the costs of mitigation, adaptation investments and the benefits of adaptation. Countries in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth due to climate change should global warming increase from 1.5°C to 2°C (*medium confidence*). {3.5.2, 3.5.3}

10 Here, impacts on economic growth refer to changes in gross domestic product (GDP). Many impacts, such as loss of human lives, cultural heritage and ecosystem services, are difficult to value and monetize.

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B.5.6 Exposure to multiple and compound climate-related risks increases between 1.5°C and 2°C of global warming, with greater proportions of people both so exposed and susceptible to poverty in Africa and Asia (*high confidence*). For global warming from 1.5°C to 2°C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (*medium confidence*). {Box 3.5, 3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9}

B.5.7 There are multiple lines of evidence that since AR5 the assessed levels of risk increased for four of the five Reasons for Concern (RFCs) for global warming to 2°C (*high confidence*). The risk transitions by degrees of global warming are now: from high to very high risk between 1.5°C and 2°C for RFC1 (Unique and threatened systems) (*high confidence*); from moderate to high risk between 1°C and 1.5°C for RFC2 (Extreme weather events) (*medium confidence*); from moderate to high risk between 1.5°C and 2°C for RFC3 (Distribution of impacts) (*high confidence*); from moderate to high risk between 1.5°C and 2.5°C for RFC4 (Global aggregate impacts) (*medium confidence*); and from moderate to high risk between 1°C and 2.5°C for RFC5 (Large-scale singular events) (*medium confidence*). (Figure SPM.2) {3.4.13; 3.5, 3.5.2}

B.6 Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C (*high confidence*). There are a wide range of adaptation options that can reduce the risks of climate change (*high confidence*). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses (*medium confidence*). The number and availability of adaptation options vary by sector (*medium confidence*). {Table 3.5, 4.3, 4.5, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5}

B.6.1 A wide range of adaptation options are available to reduce the risks to natural and managed ecosystems (e.g., ecosystem-based adaptation, ecosystem restoration and avoided degradation and deforestation, biodiversity management, sustainable aquaculture, and local knowledge and indigenous knowledge), the risks of sea level rise (e.g., coastal defence and hardening), and the risks to health, livelihoods, food, water, and economic growth, especially in rural landscapes (e.g., efficient irrigation, social safety nets, disaster risk management, risk spreading and sharing, and community-based adaptation) and urban areas (e.g., green infrastructure, sustainable land use and planning, and sustainable water management) (*medium confidence*). {4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.5.3, 4.5.4, 5.3.2, Box 4.2, Box 4.3, Box 4.6, Cross-Chapter Box 9 in Chapter 4}.

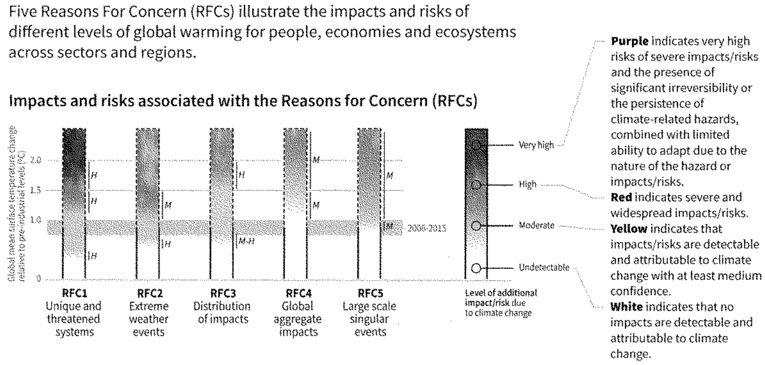
B.6.2 Adaptation is expected to be more challenging for ecosystems, food and health systems at 2°C of global warming than for 1.5°C (*medium confidence*). Some vulnerable regions, including small islands and Least Developed Countries, are projected to experience high multiple interrelated climate risks even at global warming of 1.5°C (*high confidence*). {3.3.1, 3.4.5, Box 3.5, Table 3.5, Cross-Chapter Box 9 in Chapter 4, 5.6, Cross-Chapter Box 12 in Chapter 5, Box 5.3}

B.6.3 Limits to adaptive capacity exist at 1.5°C of global warming, become more pronounced at higher levels of warming and vary by sector, with site-specific implications for vulnerable regions, ecosystems and human health (*medium confidence*). {Cross-Chapter Box 12 in Chapter 5, Box 3.5, Table 3.5}

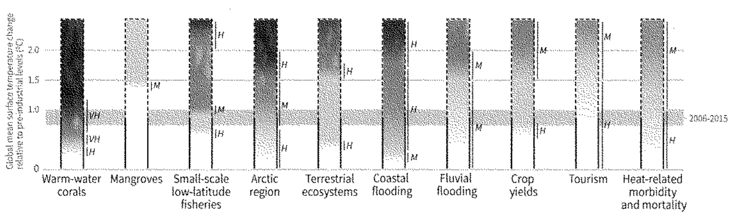
How the level of global warming affects impacts and/or risks associated with the Reasons for Concern (RFCs) and selected natural, managed and human systems

Five Reasons For Concern (RFCs) illustrate the impacts and risks of different levels of global warming for people, economies and ecosystems across sectors and regions.

Impacts and risks associated with the Reasons for Concern (RFCs)



Impacts and risks for selected natural, managed and human systems



Confidence level for transition: *L*=Low, *M*=Medium, *H*=High and *VH*=Very high

Figure SPM.2 | Five integrative reasons for concern (RFCs) provide a framework for summarizing key impacts and risks across sectors and regions, and were introduced in the IPCC Third Assessment Report. RFCs illustrate the implications of global warming for people, economies and ecosystems. Impacts and/or risks for each RFC are based on assessment of the new literature that has appeared. As in AR5, this literature was used to make expert judgments to assess the levels of global warming at which levels of impact and/or risk are undetectable, moderate, high or very high. The selection of impacts and risks to natural, managed and human systems in the lower panel is illustrative and is not intended to be fully comprehensive. {3.4, 3.5, 3.5.2.1, 3.5.2.2, 3.5.2.3, 3.5.2.4, 3.5.2.5, 5.4.1, 5.5.3, 5.6.1, Box 3.4}

RFC1 Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots.

RFC2 Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding.

RFC3 Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability.

RFC4 Global aggregate impacts: global monetary damage, global-scale degradation and loss of ecosystems and biodiversity.

RFC5 Large-scale singular events: are relatively large, abrupt and sometimes irreversible changes in systems that are caused by global warming. Examples include disintegration of the Greenland and Antarctic ice sheets.

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C. Emission Pathways and System Transitions Consistent with 1.5°C Global Warming

C.1 In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C[11] CO_2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range). Non-CO_2 emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C. (*high confidence*) (Figure SPM.3a) {2.1, 2.3, Table 2.4}

C.1.1 CO_2 emissions reductions that limit global warming to 1.5°C with no or limited overshoot can involve different portfolios of mitigation measures, striking different balances between lowering energy and resource intensity, rate of decarbonization, and the reliance on carbon dioxide removal. Different portfolios face different implementation challenges and potential synergies and trade-offs with sustainable development. (*high confidence*) (Figure SPM.3b) {2.3.2, 2.3.4, 2.4, 2.5.3}

C.1.2 Modelled pathways that limit global warming to 1.5°C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010). These pathways also reduce most of the cooling aerosols, which partially offsets mitigation effects for two to three decades. Non-CO_2 emissions[12] can be reduced as a result of broad mitigation measures in the energy sector. In addition, targeted non-CO_2 mitigation measures can reduce nitrous oxide and methane from agriculture, methane from the waste sector, some sources of black carbon, and hydrofluorocarbons. High bioenergy demand can increase emissions of nitrous oxide in some 1.5°C pathways, highlighting the importance of appropriate management approaches. Improved air quality resulting from projected reductions in many non-CO_2 emissions provide direct and immediate population health benefits in all 1.5°C model pathways. (*high confidence*) (Figure SPM.3a) {2.2.1, 2.3.3, 2.4.4, 2.5.3, 4.3.6, 5.4.2}

C.1.3 Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the pre-industrial period, that is, staying within a total carbon budget (*high confidence*).[13] By the end of 2017, anthropogenic CO_2 emissions since the pre-industrial period are estimated to have reduced the total carbon budget for 1.5°C by approximately 2200 ± 320 $GtCO_2$ (*medium confidence*). The associated remaining budget is being depleted by current emissions of 42 ± 3 $GtCO_2$ per year (*high confidence*). The choice of the measure of global temperature affects the estimated remaining carbon budget. Using global mean surface air temperature, as in AR5, gives an estimate of the remaining carbon budget of 580 $GtCO_2$ for a 50% probability of limiting warming to 1.5°C, and 420 $GtCO_2$ for a 66% probability (*medium confidence*).[14] Alternatively, using GMST gives estimates of 770 and 570 $GtCO_2$, for 50% and 66% probabilities,[15] respectively (*medium confidence*). Uncertainties in the size of these estimated remaining carbon budgets are substantial and depend on several factors. Uncertainties in the climate response to CO_2 and non-CO_2 emissions contribute ±400 $GtCO_2$ and the level of historic warming contributes ±250 $GtCO_2$ (*medium confidence*). Potential additional carbon release from future permafrost thawing and methane release from wetlands would reduce budgets by up to 100 $GtCO_2$ over the course of this century and more thereafter (*medium confidence*). In addition, the level of non-CO_2 mitigation in the future could alter the remaining carbon budget by 250 $GtCO_2$ in either direction (*medium confidence*). {1.2.4, 2.2.2, 2.6.1, Table 2.2, Chapter 2 Supplementary Material}

C.1.4 Solar radiation modification (SRM) measures are not included in any of the available assessed pathways. Although some SRM measures may be theoretically effective in reducing an overshoot, they face large uncertainties and knowledge gaps

11 References to pathways limiting global warming to 2°C are based on a 66% probability of staying below 2°C.

12 Non-CO_2 emissions included in this Report are all anthropogenic emissions other than CO_2 that result in radiative forcing. These include short-lived climate forcers, such as methane, some fluorinated gases, ozone precursors, aerosols or aerosol precursors, such as black carbon and sulphur dioxide, respectively, as well as long-lived greenhouse gases, such as nitrous oxide or some fluorinated gases. The radiative forcing associated with non-CO_2 emissions and changes in surface albedo is referred to as non-CO_2 radiative forcing. {2.2.1}

13 There is a clear scientific basis for a total carbon budget consistent with limiting global warming to 1.5°C. However, neither this total carbon budget nor the fraction of this budget taken up by past emissions were assessed in this Report.

14 Irrespective of the measure of global temperature used, updated understanding and further advances in methods have led to an increase in the estimated remaining carbon budget of about 300 $GtCO_2$ compared to AR5. (*medium confidence*) {2.2.2}

15 These estimates use observed GMST to 2006–2015 and estimate future temperature changes using near surface air temperatures.

as well as substantial risks and institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development. They also do not mitigate ocean acidification. (*medium confidence*) {4.3.8, Cross-Chapter Box 10 in Chapter 4}

Global emissions pathway characteristics

General characteristics of the evolution of anthropogenic net emissions of CO_2, and total emissions of methane, black carbon, and nitrous oxide in model pathways that limit global warming to 1.5°C with no or limited overshoot. Net emissions are defined as anthropogenic emissions reduced by anthropogenic removals. Reductions in net emissions can be achieved through different portfolios of mitigation measures illustrated in Figure SPM.3b.

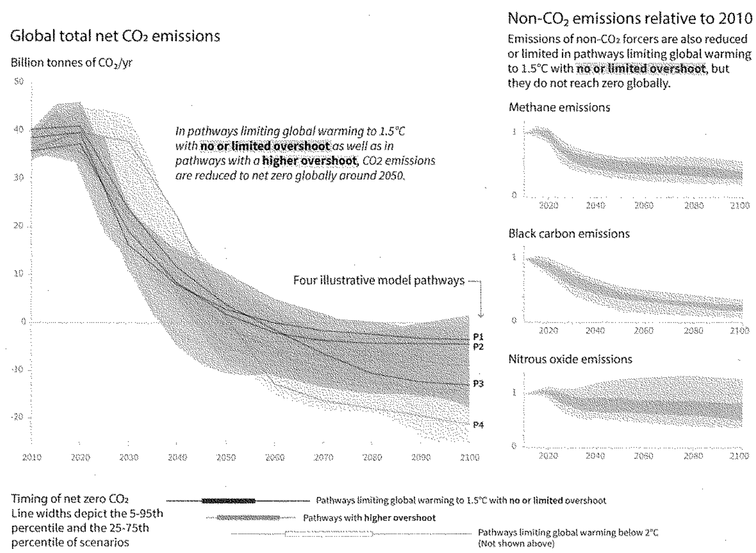
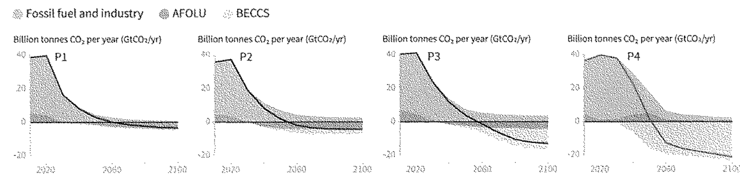


Figure SPM.3a | Global emissions pathway characteristics. The main panel shows global net anthropogenic CO_2 emissions in pathways limiting global warming to 1.5°C with no or limited (less than 0.1°C) overshoot and pathways with higher overshoot. The shaded area shows the full range for pathways analysed in this Report. The panels on the right show non-CO_2 emissions ranges for three compounds with large historical forcing and a substantial portion of emissions coming from sources distinct from those central to CO_2 mitigation. Shaded areas in these panels show the 5–95% (light shading) and interquartile (dark shading) ranges of pathways limiting global warming to 1.5°C with no or limited overshoot. Box and whiskers at the bottom of the figure show the timing of pathways reaching global net zero CO_2 emission levels, and a comparison with pathways limiting global warming to 2°C with at least 66% probability. Four illustrative model pathways are highlighted in the main panel and are labelled P1, P2, P3 and P4, corresponding to the LED, S1, S2, and S5 pathways assessed in Chapter 2. Descriptions and characteristics of these pathways are available in Figure SPM.3b. {2.1, 2.2, 2.3, Figure 2.5, Figure 2.10, Figure 2.11}

Characteristics of four illustrative model pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limits global warming to 1.5°C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for emissions and several other pathway characteristics.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Global indicators	P1	P2	P3	P4	**Interquartile range**
Pathway classification	No or limited overshoot	No or limited overshoot	No or limited overshoot	Higher overshoot	No or limited overshoot
CO_2 emission change in 2030 (% rel to 2010)	-58	-47	-41	4	(-58,-40)
in 2050 (% rel to 2010)	-93	-95	-91	-97	(-107,-94)
Kyoto-GHG emissions in 2030 (% rel to 2010)*	-50	-49	-35	-2	(-51,-39)
in 2050 (% rel to 2010)	-82	-89	-78	-80	(-93,-81)
*Final energy demand** in 2030 (% rel to 2010)*	-15	-5	17	39	(-12,7)
in 2050 (% rel to 2010)	-32	2	21	44	(-11,22)
Renewable share in electricity in 2030 (%)	60	58	48	25	(47,65)
in 2050 (%)	77	81	63	70	(69,86)
Primary energy from coal in 2030 (% rel to 2010)	-78	-61	-75	-59	(-78, -59)
in 2050 (% rel to 2010)	-97	-77	-73	-97	(-95, -74)
from oil in 2030 (% rel to 2010)	-37	-13	-3	86	(-34,3)
in 2050 (% rel to 2010)	-87	-50	-81	-32	(-78,-31)
from gas in 2030 (% rel to 2010)	-25	-20	33	37	(-26,21)
in 2050 (% rel to 2010)	-74	-53	21	-48	(-56,6)
from nuclear in 2030 (% rel to 2010)	59	83	98	106	(44,102)
in 2050 (% rel to 2010)	150	98	501	468	(91,190)
from biomass in 2030 (% rel to 2010)	-11	0	36	-1	(29,80)
in 2050 (% rel to 2010)	-16	49	121	418	(123,261)
from non-biomass renewables in 2030 (% rel to 2010)	430	470	315	110	(245,436)
in 2050 (% rel to 2010)	833	1327	878	1137	(576,1299)
Cumulative CCS until 2100 ($GtCO_2$)	0	348	687	1218	(550,1017)
of which BECCS ($GtCO_2$)	0	151	414	1191	(364,662)
Land area of bioenergy crops in 2050 (million km^2)	0.2	0.9	2.8	7.2	(1.5,3.2)
Agricultural CH_4 emissions in 2030 (% rel to 2010)	-24	-48	1	14	(-30,-11)
in 2050 (% rel to 2010)	-33	-69	-23	2	(-47,-24)
Agricultural N_2O emissions in 2030 (% rel to 2010)	5	-26	15	3	(-21,3)
in 2050 (% rel to 2010)	6	-26	0	39	(-26,1)

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment. National and sectoral characteristics can differ substantially from the global trends shown above.

** Kyoto-gas emissions are based on IPCC Second Assessment Report GWP-100*
*** Changes in energy demand are associated with improvements in energy efficiency and behaviour change*

Figure SPM.3b | Characteristics of four illustrative model pathways in relation to global warming of 1.5°C introduced in Figure SPM.3a. These pathways were selected to show a range of potential mitigation approaches and vary widely in their projected energy and land use, as well as their assumptions about future socio-economic developments, including economic and population growth, equity and sustainability. A breakdown of the global net anthropogenic CO_2 emissions into the contributions in terms of CO_2 emissions from fossil fuel and industry; agriculture, forestry and other land use (AFOLU); and bioenergy with carbon capture and storage (BECCS) is shown. AFOLU estimates reported here are not necessarily comparable with countries' estimates. Further characteristics for each of these pathways are listed below each pathway. These pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements. For comparison, the right-most column shows the interquartile ranges across pathways with no or limited overshoot of 1.5°C. Pathways P1, P2, P3 and P4 correspond to the LED, S1, S2 and S5 pathways assessed in Chapter 2 (Figure SPM.3a). {2.2.1, 2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.4.1, 2.4.2, 2.4.4, 2.5.3, Figure 2.5, Figure 2.6, Figure 2.9, Figure 2.10, Figure 2.11, Figure 2.14, Figure 2.15, Figure 2.16, Figure 2.17, Figure 2.24, Figure 2.25, Table 2.4, Table 2.6, Table 2.7, Table 2.9, Table 4.1}

C.2 Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (*medium confidence*). {2.3, 2.4, 2.5, 4.2, 4.3, 4.4, 4.5}

C.2.1 Pathways that limit global warming to 1.5°C with no or limited overshoot show system changes that are more rapid and pronounced over the next two decades than in 2°C pathways (*high confidence*). The rates of system changes associated with limiting global warming to 1.5°C with no or limited overshoot have occurred in the past within specific sectors, technologies and spatial contexts, but there is no documented historic precedent for their scale (*medium confidence*). {2.3.3, 2.3.4, 2.4, 2.5, 4.2.1, 4.2.2, Cross-Chapter Box 11 in Chapter 4}

C.2.2 In energy systems, modelled global pathways (considered in the literature) limiting global warming to 1.5°C with no or limited overshoot (for more details see Figure SPM.3b) generally meet energy service demand with lower energy use, including through enhanced energy efficiency, and show faster electrification of energy end use compared to 2°C (*high confidence*). In 1.5°C pathways with no or limited overshoot, low-emission energy sources are projected to have a higher share, compared with 2°C pathways, particularly before 2050 (*high confidence*). In 1.5°C pathways with no or limited overshoot, renewables are projected to supply 70–85% (interquartile range) of electricity in 2050 (*high confidence*). In electricity generation, shares of nuclear and fossil fuels with carbon dioxide capture and storage (CCS) are modelled to increase in most 1.5°C pathways with no or limited overshoot. In modelled 1.5°C pathways with limited or no overshoot, the use of CCS would allow the electricity generation share of gas to be approximately 8% (3–11% interquartile range) of global electricity in 2050, while the use of coal shows a steep reduction in all pathways and would be reduced to close to 0% (0–2% interquartile range) of electricity (*high confidence*). While acknowledging the challenges, and differences between the options and national circumstances, political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies have substantially improved over the past few years (*high confidence*). These improvements signal a potential system transition in electricity generation. (Figure SPM.3b) {2.4.1, 2.4.2, Figure 2.1, Table 2.6, Table 2.7, Cross-Chapter Box 6 in Chapter 3, 4.2.1, 4.3.1, 4.3.3, 4.5.2}

C.2.3 CO_2 emissions from industry in pathways limiting global warming to 1.5°C with no or limited overshoot are projected to be about 65–90% (interquartile range) lower in 2050 relative to 2010, as compared to 50–80% for global warming of 2°C (*medium confidence*). Such reductions can be achieved through combinations of new and existing technologies and practices, including electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization and storage (CCUS). These options are technically proven at various scales but their large-scale deployment may be limited by economic, financial, human capacity and institutional constraints in specific contexts, and specific characteristics of large-scale industrial installations. In industry, emissions reductions by energy and process efficiency by themselves are insufficient for limiting warming to 1.5°C with no or limited overshoot (*high confidence*). {2.4.3, 4.2.1, Table 4.1, Table 4.3, 4.3.3, 4.3.4, 4.5.2}

C.2.4 The urban and infrastructure system transition consistent with limiting global warming to 1.5°C with no or limited overshoot would imply, for example, changes in land and urban planning practices, as well as deeper emissions reductions in transport and buildings compared to pathways that limit global warming below 2°C (*medium confidence*). Technical measures and practices enabling deep emissions reductions include various energy efficiency options. In pathways limiting global warming to 1.5°C with no or limited overshoot, the electricity share of energy demand in buildings would be about 55–75% in 2050 compared to 50–70% in 2050 for 2°C global warming (*medium confidence*). In the transport sector, the share of low-emission final energy would rise from less than 5% in 2020 to about 35–65% in 2050 compared to 25–45% for 2°C of global warming (*medium confidence*). Economic, institutional and socio-cultural barriers may inhibit these urban and infrastructure system transitions, depending on national, regional and local circumstances, capabilities and the availability of capital (*high confidence*). {2.3.4, 2.4.3, 4.2.1, Table 4.1, 4.3.3, 4.5.2}

C.2.5 Transitions in global and regional land use are found in all pathways limiting global warming to 1.5°C with no or limited overshoot, but their scale depends on the pursued mitigation portfolio. Model pathways that limit global warming to 1.5°C with no or limited overshoot project a 4 million km² reduction to a 2.5 million km² increase of non-pasture agricultural land for food and feed crops and a 0.5–11 million km² reduction of pasture land, to be converted into a 0–6 million km² increase of agricultural land for energy crops and a 2 million km² reduction to 9.5 million km² increase in forests by 2050 relative to 2010 (*medium confidence*).[16] Land-use transitions of similar magnitude can be observed in modelled 2°C pathways (*medium confidence*). Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (*high confidence*). Mitigation options limiting the demand for land include sustainable intensification of land-use practices, ecosystem restoration and changes towards less resource-intensive diets (*high confidence*). The implementation of land-based mitigation options would require overcoming socio-economic, institutional, technological, financing and environmental barriers that differ across regions (*high confidence*). {2.4.4, Figure 2.24, 4.3.2, 4.3.7, 4.5.2, Cross-Chapter Box 7 in Chapter 3}

C.2.6 Additional annual average energy-related investments for the period 2016 to 2050 in pathways limiting warming to 1.5°C compared to pathways without new climate policies beyond those in place today are estimated to be around 830 billion USD2010 (range of 150 billion to 1700 billion USD2010 across six models[17]). This compares to total annual average energy supply investments in 1.5°C pathways of 1460 to 3510 billion USD2010 and total annual average energy demand investments of 640 to 910 billion USD2010 for the period 2016 to 2050. Total energy-related investments increase by about 12% (range of 3% to 24%) in 1.5°C pathways relative to 2°C pathways. Annual investments in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of six (range of factor of 4 to 10) by 2050 compared to 2015 (*medium confidence*). {2.5.2, Box 4.8, Figure 2.27}

C.2.7 Modelled pathways limiting global warming to 1.5°C with no or limited overshoot project a wide range of global average discounted marginal abatement costs over the 21st century. They are roughly 3-4 times higher than in pathways limiting global warming to below 2°C (*high confidence*). The economic literature distinguishes marginal abatement costs from total mitigation costs in the economy. The literature on total mitigation costs of 1.5°C mitigation pathways is limited and was not assessed in this Report. Knowledge gaps remain in the integrated assessment of the economy-wide costs and benefits of mitigation in line with pathways limiting warming to 1.5°C. {2.5.2; 2.6; Figure 2.26}

16 The projected land-use changes presented are not deployed to their upper limits simultaneously in a single pathway.

17 Including two pathways limiting warming to 1.5°C with no or limited overshoot and four pathways with higher overshoot.

C.3 All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). CDR deployment of several hundreds of $GtCO_2$ is subject to multiple feasibility and sustainability constraints (*high confidence*). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred $GtCO_2$ without reliance on bioenergy with carbon capture and storage (BECCS) (*high confidence*). {2.3, 2.4, 3.6.2, 4.3, 5.4}

C.3.1 Existing and potential CDR measures include afforestation and reforestation, land restoration and soil carbon sequestration, BECCS, direct air carbon capture and storage (DACCS), enhanced weathering and ocean alkalinization. These differ widely in terms of maturity, potentials, costs, risks, co-benefits and trade-offs (*high confidence*). To date, only a few published pathways include CDR measures other than afforestation and BECCS. {2.3.4, 3.6.2, 4.3.2, 4.3.7}

C.3.2 In pathways limiting global warming to 1.5°C with limited or no overshoot, BECCS deployment is projected to range from 0–1, 0–8, and 0–16 $GtCO_2\ yr^{-1}$ in 2030, 2050, and 2100, respectively, while agriculture, forestry and land-use (AFOLU) related CDR measures are projected to remove 0–5, 1–11, and 1–5 $GtCO_2\ yr^{-1}$ in these years (*medium confidence*). The upper end of these deployment ranges by mid-century exceeds the BECCS potential of up to 5 $GtCO_2\ yr^{-1}$ and afforestation potential of up to 3.6 $GtCO_2\ yr^{-1}$ assessed based on recent literature (*medium confidence*). Some pathways avoid BECCS deployment completely through demand-side measures and greater reliance on AFOLU-related CDR measures (*medium confidence*). The use of bioenergy can be as high or even higher when BECCS is excluded compared to when it is included due to its potential for replacing fossil fuels across sectors (*high confidence*). (Figure SPM.3b) {2.3.3, 2.3.4, 2.4.2, 3.6.2, 4.3.1, 4.2.3, 4.3.2, 4.3.7, 4.4.3, Table 2.4}

C.3.3 Pathways that overshoot 1.5°C of global warming rely on CDR exceeding residual CO_2 emissions later in the century to return to below 1.5°C by 2100, with larger overshoots requiring greater amounts of CDR (Figure SPM.3b) (*high confidence*). Limitations on the speed, scale, and societal acceptability of CDR deployment hence determine the ability to return global warming to below 1.5°C following an overshoot. Carbon cycle and climate system understanding is still limited about the effectiveness of net negative emissions to reduce temperatures after they peak (*high confidence*). {2.2, 2.3.4, 2.3.5, 2.6, 4.3.7, 4.5.2, Table 4.11}

C.3.4 Most current and potential CDR measures could have significant impacts on land, energy, water or nutrients if deployed at large scale (*high confidence*). Afforestation and bioenergy may compete with other land uses and may have significant impacts on agricultural and food systems, biodiversity, and other ecosystem functions and services (*high confidence*). Effective governance is needed to limit such trade-offs and ensure permanence of carbon removal in terrestrial, geological and ocean reservoirs (*high confidence*). Feasibility and sustainability of CDR use could be enhanced by a portfolio of options deployed at substantial, but lesser scales, rather than a single option at very large scale (*high confidence*). (Figure SPM.3b) {2.3.4, 2.4.4, 2.5.3, 2.6, 3.6.2, 4.3.2, 4.3.7, 4.5.2, 5.4.1, 5.4.2; Cross-Chapter Boxes 7 and 8 in Chapter 3, Table 4.11, Table 5.3, Figure 5.3}

C.3.5 Some AFOLU-related CDR measures such as restoration of natural ecosystems and soil carbon sequestration could provide co-benefits such as improved biodiversity, soil quality, and local food security. If deployed at large scale, they would require governance systems enabling sustainable land management to conserve and protect land carbon stocks and other ecosystem functions and services (*medium confidence*). (Figure SPM.4) {2.3.3, 2.3.4, 2.4.2, 2.4.4, 3.6.2, 5.4.1, Cross-Chapter Boxes 3 in Chapter 1 and 7 in Chapter 3, 4.3.2, 4.3.7, 4.4.1, 4.5.2, Table 2.4}

SPM

D. Strengthening the Global Response in the Context of Sustainable Development and Efforts to Eradicate Poverty

D.1 Estimates of the global emissions outcome of current nationally stated mitigation ambitions as submitted under the Paris Agreement would lead to global greenhouse gas emissions[18] in 2030 of 52–58 $GtCO_2eq\ yr^{-1}$ (*medium confidence*). Pathways reflecting these ambitions would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (*high confidence*). Avoiding overshoot and reliance on future large-scale deployment of carbon dioxide removal (CDR) can only be achieved if global CO_2 emissions start to decline well before 2030 (*high confidence*). {1.2, 2.3, 3.3, 3.4, 4.2, 4.4, Cross-Chapter Box 11 in Chapter 4}

D.1.1 Pathways that limit global warming to 1.5°C with no or limited overshoot show clear emission reductions by 2030 (*high confidence*). All but one show a decline in global greenhouse gas emissions to below 35 $GtCO_2eq\ yr^{-1}$ in 2030, and half of available pathways fall within the 25–30 $GtCO_2eq\ yr^{-1}$ range (interquartile range), a 40–50% reduction from 2010 levels (*high confidence*). Pathways reflecting current nationally stated mitigation ambition until 2030 are broadly consistent with cost-effective pathways that result in a global warming of about 3°C by 2100, with warming continuing afterwards (*medium confidence*). {2.3.3, 2.3.5, Cross-Chapter Box 11 in Chapter 4, 5.5.3.2}

D.1.2 Overshoot trajectories result in higher impacts and associated challenges compared to pathways that limit global warming to 1.5°C with no or limited overshoot (*high confidence*). Reversing warming after an overshoot of 0.2°C or larger during this century would require upscaling and deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges (*medium confidence*). {1.3.3, 2.3.4, 2.3.5, 2.5.1, 3.3, 4.3.7, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4}

D.1.3 The lower the emissions in 2030, the lower the challenge in limiting global warming to 1.5°C after 2030 with no or limited overshoot (*high confidence*). The challenges from delayed actions to reduce greenhouse gas emissions include the risk of cost escalation, lock-in in carbon-emitting infrastructure, stranded assets, and reduced flexibility in future response options in the medium to long term (*high confidence*). These may increase uneven distributional impacts between countries at different stages of development (*medium confidence*). {2.3.5, 4.4.5, 5.4.2}

D.2 The avoided climate change impacts on sustainable development, eradication of poverty and reducing inequalities would be greater if global warming were limited to 1.5°C rather than 2°C, if mitigation and adaptation synergies are maximized while trade-offs are minimized (*high confidence*). {1.1, 1.4, 2.5, 3.3, 3.4, 5.2, Table 5.1}

D.2.1 Climate change impacts and responses are closely linked to sustainable development which balances social well-being, economic prosperity and environmental protection. The United Nations Sustainable Development Goals (SDGs), adopted in 2015, provide an established framework for assessing the links between global warming of 1.5°C or 2°C and development goals that include poverty eradication, reducing inequalities, and climate action. (*high confidence*) {Cross-Chapter Box 4 in Chapter 1, 1.4, 5.1}

D.2.2 The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5°C and higher levels of global warming, as well as those from mitigation and adaptation, particularly for poor and disadvantaged populations, in all societies (*high confidence*). {1.1.1, 1.1.2, 1.4.3, 2.5.3, 3.4.10, 5.1, 5.2, 5.3. 5.4, Cross-Chapter Box 4 in Chapter 1, Cross-Chapter Boxes 6 and 8 in Chapter 3, and Cross-Chapter Box 12 in Chapter 5}

D.2.3 Mitigation and adaptation consistent with limiting global warming to 1.5°C are underpinned by enabling conditions, assessed in this Report across the geophysical, environmental-ecological, technological, economic, socio-cultural and institutional

18 GHG emissions have been aggregated with 100-year GWP values as introduced in the IPCC Second Assessment Report.

dimensions of feasibility. Strengthened multilevel governance, institutional capacity, policy instruments, technological innovation and transfer and mobilization of finance, and changes in human behaviour and lifestyles are enabling conditions that enhance the feasibility of mitigation and adaptation options for 1.5°C-consistent systems transitions. (*high confidence*) {1.4, Cross-Chapter Box 3 in Chapter 1, 2.5.1, 4.4, 4.5, 5.6}

D.3 Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5°C, although trade-offs are possible (*high confidence*). {1.4, 4.3, 4.5}

D.3.1 Adaptation options that reduce the vulnerability of human and natural systems have many synergies with sustainable development, if well managed, such as ensuring food and water security, reducing disaster risks, improving health conditions, maintaining ecosystem services and reducing poverty and inequality (*high confidence*). Increasing investment in physical and social infrastructure is a key enabling condition to enhance the resilience and the adaptive capacities of societies. These benefits can occur in most regions with adaptation to 1.5°C of global warming (*high confidence*). {1.4.3, 4.2.2, 4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.4.1, 4.4.3, 4.5.3, 5.3.1, 5.3.2}

D.3.2 Adaptation to 1.5°C global warming can also result in trade-offs or maladaptations with adverse impacts for sustainable development. For example, if poorly designed or implemented, adaptation projects in a range of sectors can increase greenhouse gas emissions and water use, increase gender and social inequality, undermine health conditions, and encroach on natural ecosystems (*high confidence*). These trade-offs can be reduced by adaptations that include attention to poverty and sustainable development (*high confidence*). {4.3.2, 4.3.3, 4.5.4, 5.3.2; Cross-Chapter Boxes 6 and 7 in Chapter 3}

D.3.3 A mix of adaptation and mitigation options to limit global warming to 1.5°C, implemented in a participatory and integrated manner, can enable rapid, systemic transitions in urban and rural areas (*high confidence*). These are most effective when aligned with economic and sustainable development, and when local and regional governments and decision makers are supported by national governments (*medium confidence*). {4.3.2, 4.3.3, 4.4.1, 4.4.2}

D.3.4 Adaptation options that also mitigate emissions can provide synergies and cost savings in most sectors and system transitions, such as when land management reduces emissions and disaster risk, or when low-carbon buildings are also designed for efficient cooling. Trade-offs between mitigation and adaptation, when limiting global warming to 1.5°C, such as when bioenergy crops, reforestation or afforestation encroach on land needed for agricultural adaptation, can undermine food security, livelihoods, ecosystem functions and services and other aspects of sustainable development. (*high confidence*) {3.4.3, 4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4}

D.4 Mitigation options consistent with 1.5°C pathways are associated with multiple synergies and trade-offs across the Sustainable Development Goals (SDGs). While the total number of possible synergies exceeds the number of trade-offs, their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition. (*high confidence*) (Figure SPM.4) {2.5, 4.5, 5.4}

D.4.1 1.5°C pathways have robust synergies particularly for the SDGs 3 (health), 7 (clean energy), 11 (cities and communities), 12 (responsible consumption and production) and 14 (oceans) (*very high confidence*). Some 1.5°C pathways show potential trade-offs with mitigation for SDGs 1 (poverty), 2 (hunger), 6 (water) and 7 (energy access), if not managed carefully (*high confidence*). (Figure SPM.4) {5.4.2; Figure 5.4, Cross-Chapter Boxes 7 and 8 in Chapter 3}

D.4.2 1.5°C pathways that include low energy demand (e.g., see P1 in Figure SPM.3a and SPM.3b), low material consumption, and low GHG-intensive food consumption have the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (*high confidence*). Such pathways would reduce dependence on CDR. In modelled pathways, sustainable development, eradicating poverty and reducing inequality can support limiting warming to 1.5°C (*high confidence*). (Figure SPM.3b, Figure SPM.4) {2.4.3, 2.5.1, 2.5.3, Figure 2.4, Figure 2.28, 5.4.1, 5.4.2, Figure 5.4}

Indicative linkages between mitigation options and sustainable development using SDGs (The linkages do not show costs and benefits)

Mitigation options deployed in each sector can be associated with potential positive effects (synergies) or negative effects (trade-offs) with the Sustainable Development Goals (SDGs). The degree to which this potential is realized will depend on the selected portfolio of mitigation options, mitigation policy design, and local circumstances and context. Particularly in the energy-demand sector, the potential for synergies is larger than for trade-offs. The bars group individually assessed options by level of confidence and take into account the relative strength of the assessed mitigation-SDG connections.

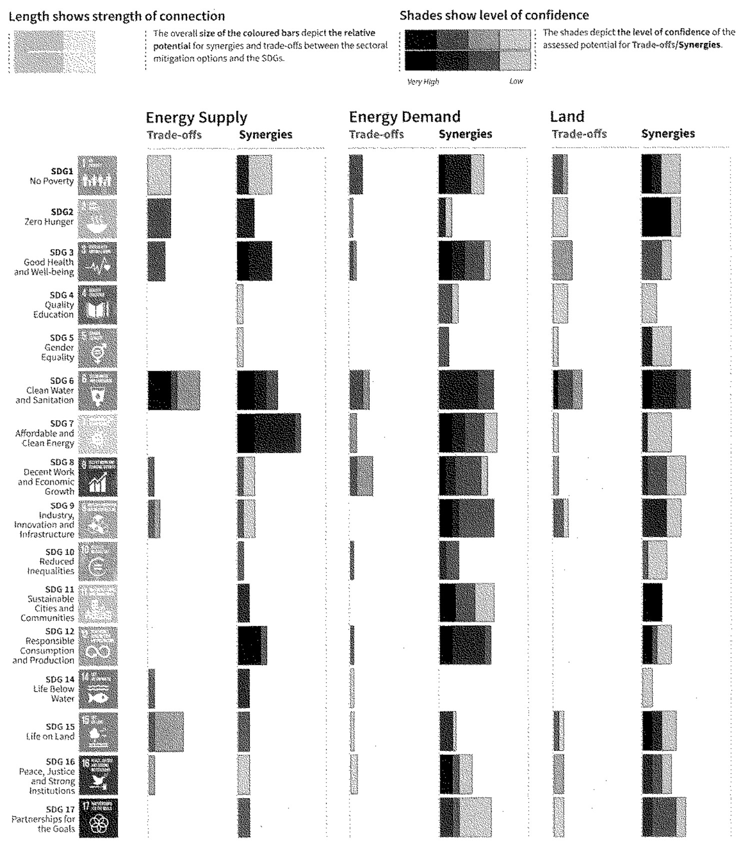


Figure SPM.4 | Potential synergies and trade-offs between the sectoral portfolio of climate change mitigation options and the Sustainable Development Goals (SDGs). The SDGs serve as an analytical framework for the assessment of the different sustainable development dimensions, which extend beyond the time frame of the 2030 SDG targets. The assessment is based on literature on mitigation options that are considered relevant for 1.5°C. The assessed strength of the SDG interactions is based on the qualitative and quantitative assessment of individual mitigation options listed in Table 5.2. For each mitigation option, the strength of the SDG-connection as well as the associated confidence of the underlying literature (shades of green and red) was assessed. The strength of positive connections (synergies) and negative connections (trade-offs) across all individual options within a sector (see Table 5.2) are aggregated into sectoral potentials for the whole mitigation portfolio. The (white) areas outside the bars, which indicate no interactions, have *low confidence* due to the uncertainty and limited number of studies exploring indirect effects. The strength of the connection considers only the effect of mitigation and does not include benefits of avoided impacts. SDG 13 (climate action) is not listed because mitigation is being considered in terms of interactions with SDGs and not vice versa. The bars denote the strength of the connection, and do not consider the strength of the impact on the SDGs. The energy demand sector comprises behavioural responses, fuel switching and efficiency options in the transport, industry and building sector as well as carbon capture options in the industry sector. Options assessed in the energy supply sector comprise biomass and non-biomass renewables, nuclear, carbon capture and storage (CCS) with bioenergy, and CCS with fossil fuels. Options in the land sector comprise agricultural and forest options, sustainable diets and reduced food waste, soil sequestration, livestock and manure management, reduced deforestation, afforestation and reforestation, and responsible sourcing. In addition to this figure, options in the ocean sector are discussed in the underlying report. {5.4, Table 5.2, Figure 5.2}

Information about the net impacts of mitigation on sustainable development in 1.5°C pathways is available only for a limited number of SDGs and mitigation options. Only a limited number of studies have assessed the benefits of avoided climate change impacts of 1.5°C pathways for the SDGs, and the co-effects of adaptation for mitigation and the SDGs. The assessment of the indicative mitigation potentials in Figure SPM.4 is a step further from AR5 towards a more comprehensive and integrated assessment in the future.

D.4.3 1.5°C and 2°C modelled pathways often rely on the deployment of large-scale land-related measures like afforestation and bioenergy supply, which, if poorly managed, can compete with food production and hence raise food security concerns (*high confidence*). The impacts of carbon dioxide removal (CDR) options on SDGs depend on the type of options and the scale of deployment (*high confidence*). If poorly implemented, CDR options such as BECCS and AFOLU options would lead to trade-offs. Context-relevant design and implementation requires considering people's needs, biodiversity, and other sustainable development dimensions (*very high confidence*). (Figure SPM.4) {5.4.1.3, Cross-Chapter Box 7 in Chapter 3}

D.4.4 Mitigation consistent with 1.5°C pathways creates risks for sustainable development in regions with high dependency on fossil fuels for revenue and employment generation (*high confidence*). Policies that promote diversification of the economy and the energy sector can address the associated challenges (*high confidence*). {5.4.1.2, Box 5.2}

D.4.5 Redistributive policies across sectors and populations that shield the poor and vulnerable can resolve trade-offs for a range of SDGs, particularly hunger, poverty and energy access. Investment needs for such complementary policies are only a small fraction of the overall mitigation investments in 1.5°C pathways. (*high confidence*) {2.4.3, 5.4.2, Figure 5.5}

D.5 Limiting the risks from global warming of 1.5°C in the context of sustainable development and poverty eradication implies system transitions that can be enabled by an increase of adaptation and mitigation investments, policy instruments, the acceleration of technological innovation and behaviour changes (*high confidence*). {2.3, 2.4, 2.5, 3.2, 4.2, 4.4, 4.5, 5.2, 5.5, 5.6}

D.5.1 Directing finance towards investment in infrastructure for mitigation and adaptation could provide additional resources. This could involve the mobilization of private funds by institutional investors, asset managers and development or investment banks, as well as the provision of public funds. Government policies that lower the risk of low-emission and adaptation investments can facilitate the mobilization of private funds and enhance the effectiveness of other public policies. Studies indicate a number of challenges, including access to finance and mobilization of funds. (*high confidence*) {2.5.1, 2.5.2, 4.4.5}

D.5.2 Adaptation finance consistent with global warming of 1.5°C is difficult to quantify and compare with 2°C. Knowledge gaps include insufficient data to calculate specific climate resilience-enhancing investments from the provision of currently underinvested basic infrastructure. Estimates of the costs of adaptation might be lower at global warming of 1.5°C than for 2°C. Adaptation needs have typically been supported by public sector sources such as national and subnational government budgets, and in developing countries together with support from development assistance, multilateral development banks, and United Nations Framework Convention on Climate Change channels (*medium confidence*). More recently there is a growing understanding of the scale and increase in non-governmental organizations and private funding in some regions (*medium confidence*). Barriers include the scale of adaptation financing, limited capacity and access to adaptation finance (*medium confidence*). {4.4.5, 4.6}

D.5.3 Global model pathways limiting global warming to 1.5°C are projected to involve the annual average investment needs in the energy system of around 2.4 trillion USD2010 between 2016 and 2035, representing about 2.5% of the world GDP (*medium confidence*). {4.4.5, Box 4.8}

D.5.4 Policy tools can help mobilize incremental resources, including through shifting global investments and savings and through market and non-market based instruments as well as accompanying measures to secure the equity of the transition, acknowledging the challenges related with implementation, including those of energy costs, depreciation of assets and impacts on international competition, and utilizing the opportunities to maximize co-benefits (*high confidence*). {1.3.3, 2.3.4, 2.3.5, 2.5.1, 2.5.2, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4, 4.4.5, 5.5.2}

D.5.5 The systems transitions consistent with adapting to and limiting global warming to 1.5°C include the widespread adoption of new and possibly disruptive technologies and practices and enhanced climate-driven innovation. These imply enhanced technological innovation capabilities, including in industry and finance. Both national innovation policies and international cooperation can contribute to the development, commercialization and widespread adoption of mitigation and adaptation technologies. Innovation policies may be more effective when they combine public support for research and development with policy mixes that provide incentives for technology diffusion. (*high confidence*) {4.4.4, 4.4.5}.

D.5.6 Education, information, and community approaches, including those that are informed by indigenous knowledge and local knowledge, can accelerate the wide-scale behaviour changes consistent with adapting to and limiting global warming to 1.5°C. These approaches are more effective when combined with other policies and tailored to the motivations, capabilities and resources of specific actors and contexts (*high confidence*). Public acceptability can enable or inhibit the implementation of policies and measures to limit global warming to 1.5°C and to adapt to the consequences. Public acceptability depends on the individual's evaluation of expected policy consequences, the perceived fairness of the distribution of these consequences, and perceived fairness of decision procedures (*high confidence*). {1.1, 1.5, 4.3.5, 4.4.1, 4.4.3, Box 4.3, 5.5.3, 5.6.5}

D.6 Sustainable development supports, and often enables, the fundamental societal and systems transitions and transformations that help limit global warming to 1.5°C. Such changes facilitate the pursuit of climate-resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities (*high confidence*). {Box 1.1, 1.4.3, Figure 5.1, 5.5.3, Box 5.3}

D.6.1 Social justice and equity are core aspects of climate-resilient development pathways that aim to limit global warming to 1.5°C as they address challenges and inevitable trade-offs, widen opportunities, and ensure that options, visions, and values are deliberated, between and within countries and communities, without making the poor and disadvantaged worse off (*high confidence*). {5.5.2, 5.5.3, Box 5.3, Figure 5.1, Figure 5.6, Cross-Chapter Boxes 12 and 13 in Chapter 5}

D.6.2 The potential for climate-resilient development pathways differs between and within regions and nations, due to different development contexts and systemic vulnerabilities (*very high confidence*). Efforts along such pathways to date have been limited (*medium confidence*) and enhanced efforts would involve strengthened and timely action from all countries and non-state actors (*high confidence*). {5.5.1, 5.5.3, Figure 5.1}

D.6.3 Pathways that are consistent with sustainable development show fewer mitigation and adaptation challenges and are associated with lower mitigation costs. The large majority of modelling studies could not construct pathways characterized by lack of international cooperation, inequality and poverty that were able to limit global warming to 1.5°C. (*high confidence*) {2.3.1, 2.5.1, 2.5.3, 5.5.2}

SPM

D.7 Strengthening the capacities for climate action of national and sub-national authorities, civil society, the private sector, indigenous peoples and local communities can support the implementation of ambitious actions implied by limiting global warming to 1.5°C (*high confidence*). International cooperation can provide an enabling environment for this to be achieved in all countries and for all people, in the context of sustainable development. International cooperation is a critical enabler for developing countries and vulnerable regions (*high confidence*). {1.4, 2.3, 2.5, 4.2, 4.4, 4.5, 5.3, 5.4, 5.5, 5.6, 5, Box 4.1, Box 4.2, Box 4.7, Box 5.3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 13 in Chapter 5}

D.7.1 Partnerships involving non-state public and private actors, institutional investors, the banking system, civil society and scientific institutions would facilitate actions and responses consistent with limiting global warming to 1.5°C (*very high confidence*). {1.4, 4.4.1, 4.2.2, 4.4.3, 4.4.5, 4.5.3, 5.4.1, 5.6.2, Box 5.3}.

D.7.2 Cooperation on strengthened accountable multilevel governance that includes non-state actors such as industry, civil society and scientific institutions, coordinated sectoral and cross-sectoral policies at various governance levels, gender-sensitive policies, finance including innovative financing, and cooperation on technology development and transfer can ensure participation, transparency, capacity building and learning among different players (*high confidence*). {2.5.1, 2.5.2, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, Cross-Chapter Box 9 in Chapter 4, 5.3.1, 5.5.3, Cross-Chapter Box 13 in Chapter 5, 5.6.1, 5.6.3}

D.7.3 International cooperation is a critical enabler for developing countries and vulnerable regions to strengthen their action for the implementation of 1.5°C-consistent climate responses, including through enhancing access to finance and technology and enhancing domestic capacities, taking into account national and local circumstances and needs (*high confidence*). {2.3.1, 2.5.1, 4.4.1, 4.4.2, 4.4.4, 4.4.5, 5.4.1 5.5.3, 5.6.1, Box 4.1, Box 4.2, Box 4.7}.

D.7.4 Collective efforts at all levels, in ways that reflect different circumstances and capabilities, in the pursuit of limiting global warming to 1.5°C, taking into account equity as well as effectiveness, can facilitate strengthening the global response to climate change, achieving sustainable development and eradicating poverty (*high confidence*). {1.4.2, 2.3.1, 2.5.1, 2.5.2, 2.5.3, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, 5.3.1, 5.4.1, 5.5.3, 5.6.1, 5.6.2, 5.6.3}

Box SPM.1: Core Concepts Central to this Special Report

Global mean surface temperature (GMST): Estimated global average of near-surface air temperatures over land and sea ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period. When estimating changes in GMST, near-surface air temperature over both land and oceans are also used.[19] {1.2.1.1}

Pre-industrial: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial GMST. {1.2.1.2}

Global warming: The estimated increase in GMST averaged over a 30-year period, or the 30-year period centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue. {1.2.1}

Net zero CO_2 emissions: Net zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period.

Carbon dioxide removal (CDR): Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

Total carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from the pre-industrial period to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Remaining carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from a given start date to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Temperature overshoot: The temporary exceedance of a specified level of global warming.

Emission pathways: In this Summary for Policymakers, the modelled trajectories of global anthropogenic emissions over the 21st century are termed emission pathways. Emission pathways are classified by their temperature trajectory over the 21st century: pathways giving at least 50% probability based on current knowledge of limiting global warming to below 1.5°C are classified as 'no overshoot'; those limiting warming to below 1.6°C and returning to 1.5°C by 2100 are classified as '1.5°C limited-overshoot'; while those exceeding 1.6°C but still returning to 1.5°C by 2100 are classified as 'higher-overshoot'.

Impacts: Effects of climate change on human and natural systems. Impacts can have beneficial or adverse outcomes for livelihoods, health and well-being, ecosystems and species, services, infrastructure, and economic, social and cultural assets.

Risk: The potential for adverse consequences from a climate-related hazard for human and natural systems, resulting from the interactions between the hazard and the vulnerability and exposure of the affected system. Risk integrates the likelihood of exposure to a hazard and the magnitude of its impact. Risk also can describe the potential for adverse consequences of adaptation or mitigation responses to climate change.

Climate-resilient development pathways (CRDPs): Trajectories that strengthen sustainable development at multiple scales and efforts to eradicate poverty through equitable societal and systems transitions and transformations while reducing the threat of climate change through ambitious mitigation, adaptation and climate resilience.

19 Past IPCC reports, reflecting the literature, have used a variety of approximately equivalent metrics of GMST change.

Chairwoman JOHNSON. Thank you very much.

Now, the Chair recognizes Mr. Lucas.

Mr. LUCAS. Thank you, Chairwoman. I appreciate that.

As I said in my opening statement, I represent a rural district where weather trends and predictions are extremely important to the agricultural community. Dr. Majkut, what are some of the things that we're doing well, and what are some of the things we could do better to increase preparedness for weather events and other effects associated with climate change?

Dr. MAJKUT. Thank you for the question. I actually think we're doing fairly well. You look at the National Climate Assessment, and it shows a real effort on the part of the scientific community to start understanding what the medium- and long-term effects of climate change are going to be for communities like your own. And just one of the things—and that activity should definitely continue.

One of the things we might think about doing better in the Science Committee and the Science Committee generally can think about doing is getting decisionmakers information that's relevant on the timescales over which they make decisions, right? So you mentioned you represent a farming community and you're a farmer yourself. You understand that what you think about the weather is a question for the next few days and the stuff you're going to do over the next few days. It's not necessarily clear that a 30-year projection is a helpful thing for what you're deciding to do this year or next year. But if you're designing a water system or a stormwater system or something like that, something you want to have around for a long time, then you really do want to have information around what the next 30 or 50 or 100 years are possibly going to look like.

So where I think the scientific community can fairly say is learning how to do that, how to transfer that information and how to make the—kind of that whole range of timeframes from decade to decades to centuries available to people who need to think in that regard.

Mr. LUCAS. My fear from this increased demand for immediate action is pushed down from the top, perhaps unrealistic proposals that aren't practical. The last thing we want to do is dramatically raise energy prices for America. Dr. Majkut, with the growing demand for fossil fuels worldwide, what can we do to ensure that we are leading the way with low-carbon energy solutions?

Dr. MAJKUT. Well, in particular, I think the Committee should continue to focus on and continue to be supportive of advanced research efforts for the things we think we're going to need in the future, and that means reliable, affordable low-carbon energy. And in particular low carbon is the key thing that the climate is worried about, so it doesn't particularly matter whether that's energy that's going to come from a windmill or a fancy kind of battery or is going to come from fossil fuels with carbon capture and storage, or advanced nuclear. Instead, the target should be having a broad array of energy sources that can be used here and abroad at affordable levels and putting in place a research enterprise that is pursuing them with real vigor.

Mr. LUCAS. We make lots of investment in research in the Federal Government, and that's an important thing. How does the private sector advance what the government has started?

Dr. MAJKUT. Well, the private sector is going to be the thing that actually scales those early run projects that received justifiable governmental support into use, right? That's the thing that's going to matter in sub-Saharan Africa, is going to matter in Southeast Asia, is going to matter in Oklahoma, how do those things compete in the marketplace. And so making sure that those innovations diffuse out is a matter of transitional policies and market design.

Mr. LUCAS. From the back door of my house on the farm in western Oklahoma I can see windmills, electric windmills from one horizon to the other. Dr. Majkut, you have referred to the goals set by the Intergovernmental Panel on Climate Change as ambitious. Is there a scenario in which those ambitious goals can be reached by transitioning to 100 percent renewable? By the way, those windmills don't always turn. They turn most of the time. We're a great source, but not all the time. Is there a scenario of how we could get to 100 percent renewable?

Dr. MAJKUT. You could probably write one out on paper where it's physically possible, but I don't know that that's a necessary thing to do. And in particular if, like me and a lot of my colleagues and a lot of folks out in the—and your constituents are concerned about climate and you want to reduce greenhouse gas emissions, having a broad portfolio of options seems like the best choice, and there is a raft of literature showing you that if you want a reliable, low-cost energy system that has a lot less carbon emissions than we have today, you want a wide variety of technologies available.

Mr. LUCAS. Thank you, Doc. I yield back the balance of my time, Madam Chairman.

Chairwoman JOHNSON. Thank you very much, Mr. Lucas. Ms. Stevens?

Ms. STEVENS. Thank you all so much for bringing your expertise and time to today's hearing. We're privileged to be able to engage with you.

Certainly on this topic we have two choices. We can either embrace the need for climate change action and the embracing of climate science through fear or we can embrace it through opportunity. And I am so grateful that Dr. Mahowald was able to bring her testimony to us through video. And my questions are for you if we're able to ask questions of her. Are we able to do that? OK. Fabulous. So how are we as a country measuring up globally in terms of the actions that we are taking around Federal investments to develop innovative technologies and solutions to address the impacts of climate change?

Dr. MAHOWALD. Thank you very much for the question. You're hearing me? Good.

Ms. STEVENS. Yes.

Dr. MAHOWALD. The United States is starting to get the momentum to deal with climate change mitigation and adaptation. Much of the adaptation efforts of course have started at the local level, but they need to be moving across local, State, and Federal levels. We need to be dealing more with the adaptation efforts for climate change, as well as mitigation across the board. At this point the

Federal efforts have not been consistent with what needs to happen for the ambitious targets for climate change. And some of the States have been reacting much more ambitiously than others, and there's several studies suggesting that Federal-level coordination of the States' efforts is much more efficient for the whole system in terms of transitioning to lower-carbon mitigation targets. Thank you.

Ms. STEVENS. Thank you. Well, I happen to represent suburban metro Detroit, the home of the Nation's automotive sector, and our automotive industry is in the race for the future, particularly around energy efficiency. And they see where China and Europe is moving, and they're sort of waiting on the United States. And so I was wondering if you could shed a little bit more light in terms of any projections that you might have that our country could capture in terms of return on investment. Should we be making the right strategic investments to lay the foundation for our industrial sector to be making the investments in carbon neutrality?

Dr. MAHOWALD. Well, the transportation sector is an important sector, and of course Detroit is the home of that in the United States. Our competitors are investing heavily in low-carbon options. China is trying to get rid of internal combustion engines. India also has efforts in this area. The United States has the technological and the business innovation advantage. If we can use this, we can maintain our advantage in the automobile industry and other industries as well. But more coordination across the—at the Federal level, across the Federal, State, and local levels will really help in this effort. Thank you.

Ms. STEVENS. Thank you. I think it's fair to say that there's the "if not but for" role the government can play. Certainly industry is making their investments, but they're waiting on the Federal Government to lay the foundation, set the table, as we have in many ways where we created the highways and we plowed fields, but we need to set the table.

And I want to get Dr. Kopp in just quickly with my remaining time available because you also mentioned this in your testimony saying that climate change is not just an environmental challenge, it's an economic challenge. It's an infrastructure challenge, a public health challenge, and a national security challenge. And while we have your great expertise in the room, I was wondering if you could maybe give us a few points around how the United States can continue to be a leader in addressing the impacts of climate change while also maintaining our global economic power.

Dr. KOPP. Well, I want to come back to the thing I said at the very end of my remarks, which is that we need to make climate change a routine and integrated part of decisionmaking, public and private sector, Federal, State, and local, right? We make lots of decisions, particularly when we think about, say, infrastructure investments or particularly when we think about national security that play out over decades. And any time we're thinking about changes over decades, we're thinking about a world where the climate is changing in ways that we can project. And so we have to move beyond using the past as a guide to what we do and, when we're building a new rail tunnel under the Hudson, say, or we're building new water infrastructure, right, those need to be planned with all the range of possible futures that we might project in mind.

Ms. STEVENS. Yes, thank you. I yield back the remainder of my time.

Chairwoman JOHNSON. Thank you very much. Mr. Brooks?

Mr. BROOKS. Thank you, Madam Chairman.

Dr. Kopp, I'm looking at your written testimony as opposed to your oral testimony. On page three you state, quote, "Climate change is real, it is here now, and humans are responsible for it," end quote. Is that an accurate statement of your quote?

Dr. KOPP. Yes, it is.

Mr. BROOKS. And on page five of your written testimony you state, quote, "Global average sea level has risen by about 8 inches since 1900," end quote, citing the Climate Science Special Report, Earth National Climate Assessment. Is that an accurate reading of that quote?

Dr. KOPP. Yes, it is.

Mr. BROOKS. Are you familiar with the Earth's last glacial maximum roughly 21,000 years ago?

Dr. KOPP. Yes, I am.

Mr. BROOKS. And is it fair to say that sea levels during the last glacial maximum were roughly 400 feet lower than they are today?

Dr. KOPP. Yes, it is.

Mr. BROOKS. And would it also be fair to say, then, the sea levels over the last 21,000 years, 400 divided by 21,000 or 210 centuries, sea levels have risen on average over that 21,000-year period of time at roughly 2 feet per century?

Dr. KOPP. Well, it was concentrated in the first half of that time, but yes.

Mr. BROOKS. From the 21,000- to the 7,000-year-ago period is the concentration, then it still increased—sea levels did—but at a much lower rate during the last 7,000 years?

Dr. KOPP. When they stopped rising is a scientific uncertainty, but certainly that by 7,000 years ago the giant ice sheet that was sitting on North America was gone, and so the contribution to sea level that came from that ice sheet ended.

Mr. BROOKS. So apparently, somewhere between 21,000 and 7,000 years ago we had a very significant rise in sea levels, much more than the 2-feet-per-century average of the overall 21,000-year period. Did humans cause that?

Dr. KOPP. No, they did not.

Mr. BROOKS. They did not. So there are other causes to sea-level rises other than humans, and at least in this instance over the last 21,000 years we're looking at an average sea-level rise of 2 feet per century on average, 210 centuries, a little over 400 feet total. What was the cause of that?

Dr. KOPP. Well, if you go back 21,000 years ago, my home State was sitting in its northern edge is under about a mile of ice, and that ice sheet, which we call the Lorne Tide, had a whole lot of water locked up in it. And so as that ice melted, sea level rose. We're now in a very different world where there's—the ice on the planet is largely in—almost exclusively in Antarctica and Greenland, and so what we're concerned about now——

Mr. BROOKS. OK. I'm not asking what we're concerned about now. I'm asking what caused the 400 feet in sea-level rise over the last 21,000 years? Would it be fair to say that it was global warming?

Dr. KOPP. Yes, it would be.

Mr. BROOKS. And what is it that caused that global warming that began roughly 18 to 21,000 years ago?

Dr. KOPP. So that—we were in an Ice Age roughly 18,000 years ago, and the differences between the Ice Ages and the periods like we're in now, which are called interglacials because we're not in a glacial period, are paced by changes in Earth's orbit, amplified by changes in carbon dioxide.

Mr. BROOKS. OK. So there have been fluctuations in orbit, perhaps changes in carbon dioxide, and perhaps also some change in the actual tilt?

Dr. KOPP. Yes, well, when I talk about changes in orbit on that frequency you're talking about where Earth is pointing, what we call a precession.

Mr. BROOKS. OK. And during the last glacial maximum, is it fair to say that almost all of Canada was uninhabitable, along with New England, New York, everything north of the Ohio River was in effect uninhabitable?

Dr. KOPP. Certainly on the east side of the country, yes.

Mr. BROOKS. And would it also be fair to say that certainly at least in that instance, global warming was a desirable thing if you're a Canadian?

Dr. KOPP. Well, there weren't many Canadians, but yes.

Mr. BROOKS. Well, there weren't any back then.

Dr. KOPP. Over in the West there were, but yes.

Mr. BROOKS. OK. Now, let's talk about the remedy for a second. You may recall that in 2008 Dr. Steven Chu, who later became President Obama's Secretary of Energy, stated that, to combat climate change, quote, "Somehow, we have to figure out how to boost the price of gasoline to the levels in Europe," end quote, which was about $8.70 per gallon. Do you agree with Steven Chu that that is a remedy that the United States should implement?

Dr. KOPP. Well, there's lots of policy solutions. My job is——

Mr. BROOKS. I'm just asking about this one. Yes or no?

Dr. KOPP. We are dumping CO_2 into the atmosphere. One way of dealing with the problem would be to put a price on carbon that reflected the cost of that carbon dioxide is imposing on the world.

Mr. BROOKS. Is that a yes or a no?

Dr. KOPP. I'm going to give you the scientific answer and say it depends. It's one of the solutions that would work.

Mr. BROOKS. All right. Thank you, Madam Chairman. I appreciate the time.

Mrs. FLETCHER [presiding]. Thank you. I'll now recognize Mr. Tonko.

Mr. TONKO. Thank you, Madam Chairman. And I thank Chairwoman Johnson for holding what I think is a very important hearing today and for our witnesses for joining us.

I am beyond excited that, as a Committee, we are committing to seriously examining and addressing the urgent threat of climate change. I'm glad that this majority is focused on climate change and that we have stepped up to face the task at hand. And in particular, as a Member of the Science Committee, I am proud that after so many years of inaction, we are moving forward and giving this critical issue the time and focus it deserves and requires. Inaction is expensive.

As we address climate change, our planning must be science-based and evidence-based. The overwhelming majority of the scientific community knows that climate change is happening and that we are already feeling the impacts. The scientific evidence on climate change clearly tells us that we need to take action. Taking action means there will be challenges but also opportunities. We have a real opportunity to transform our economy to one that is cleaner, safer, and more just. We have the chance to advance clean-energy technologies, design the infrastructure of the future that will help communities endure and rethink every industry we have ever known. Investing in solutions and resilience today will help manage and limit those risks and serve as a foundation for job creation, healthier communities, and economic opportunity.

It has been a decade since the House last seriously attempted to address climate change, and with that, Dr. Mahowald—and I will address you as a fellow upstate New Yorker. And I know what weather can mean at this time of year, so we're sorry that you're not with us, but thank you for joining us via technology. So, Doctor, how has our understanding of climate science and its impacts developed over the past 10 years?

Dr. MAHOWALD. Thank you very much for the question and for your understanding of upstate New York's weather.

Our understanding of climate science over the last 10 years has really benefited from the leaps in technology in terms of computer simulation, high—some of the big data analysis methods that we now have. And some of what that has allowed us to do is to really see the impacts of small changes in temperature on humans and ecosystems. And this was highlighted in the 1.5 report.

Often what scientists do is we simply look at the big changes, but for this particular report we were asked to look at the difference between 1.5 and 2 degrees, and we focused on that. Almost 6,000 new studies were assessed in that report and really focused on what small changes in temperature can do in terms of impacts on humans. And that report highlights that small temperature changes, for example, can have a big impact. Thank you.

Mr. TONKO. Thank you very much. And when many talk about climate change, they associate the tone of urgency. Do you think there's more or less urgency than we faced a decade ago?

Dr. MAHOWALD. Thank you for the question. I think there's more urgency. Every day there's more people on this planet asking for more energy, and we're building more facilities. And right now, the technologies that people use, just by default, are technologies that emit a lot of carbon dioxide. The faster we can start using research, developing and deploying technologies that don't emit as much CO_2, this can snowball into making it more and more economically feasible and politically feasible. All the infrastructure will be there to have lower-carbon technologies deployed. So the urgency is twofold. It's both because we're accumulating this CO_2 in the atmosphere, and in addition, we're accumulating infrastructure and technology that emits a lot of CO_2. So there's a lot of urgency on the technology side, and then of course we're seeing more and more impacts on people. Thank you.

Mr. TONKO. Thank you very much for your input and that of Cornell routinely on these issues.

Dr. Ebi, according to both the IPCC's special report and the NCA 4, climate change takes a toll on mental health. Those who survive extreme weather events and see their communities damaged can suffer from depression, anxiety, suicidal thoughts, and posttraumatic stress disorder (PTSD). A report notes that droughts have led to an increase in alcohol and drug use and higher temperatures are associated with more aggressive behaviors. How does climate change affect mental health, and what steps can the medical community take to ease the psychological burden?

Dr. EBI. Thank you. That's an excellent summary of how climate change can affect mental health through exposure to extreme events. There needs to be increased awareness about this across the health professions so that there are greater actions when we have these extreme events, that we do have mental healthcare professionals available to help people after an event. And we need a lot greater preparedness for these events. If the United States was as prepared as it should be, we wouldn't have seen the impacts we've seen over the last couple of years. So investing in adaptation, investing in making sure we understand what future risks could look like, we're better able then to handle all of the challenges, including the mental health ones. Thank you.

Mr. TONKO. Thank you very much.

With that, I yield back, Madam Chair.

Mrs. FLETCHER. Thank you. I will now recognize Mr. Weber for 5 minutes.

Mr. WEBER. I thank the gentlelady from Texas. Dr. Majkut, you mentioned that there is, quote, "No better incentive for us than the private sector, but if you really want energy innovation, you need to show the innovators there's a market waiting for them," end quote. Dr. Majkut, I ran an air-conditioning company for 35 years, built it from the ground up, and I know that when the weather got hot, my business on the Gulf Coast of Texas was in great demand. I will tell you this: The more the Department of Energy raised energy ratings and required that manufacturers build higher-efficient equipment, the more that those units cost. And the more they cost—air conditioning went up—the more the demand for that high-efficient equipment went down because people were already hard-pressed in living their lives and they couldn't afford higher prices. And on the Gulf Coast of Texas you don't want to be without air conditioning. Now, I don't know how many of you all live in the southern part of the country, but it's extremely important to us.

Applying this same developing concept to clean-energy technologies, Dr. Majkut, how do we show innovators that there is a demand and a market waiting for them?

Dr. MAJKUT. Well, it depends on the area in which you're working, right?

Mr. WEBER. Did I mention I live on the Gulf Coast of Texas?

Dr. MAJKUT. Sure did, sir.

Mr. WEBER. Yes.

Dr. MAJKUT. There's a lot of things government can do to create markets for innovation. A lot of them fall into other committees' jurisdiction, right? You can use tax policy, you could use incentive policies. I can't speak to the air-conditioning example largely because it's not my area of expertise, but I do know that we can look at cost-cutting measures, we can look at technological innovation to make more efficient air conditioners as an example, less costly at the front. We can look at financing mechanisms that amortize a more efficient air conditioner costs less to use over time, so how do you find ways to help people make an upfront capital investment, et cetera.

Mr. WEBER. OK. I'm going to move along a little bit. That's a great thought. As Ranking Member Lucas said, the push down from the top was the last thing we want to do because it would dramatically raise energy prices. And then there was some discussion between the witnesses with one of the Members about raising those energy prices. Do we raise those energy prices to whatever it takes? I know, Dr. Kopp, you didn't have an exact price, but do we just commit to raising them to whatever it takes? Dr. Kopp?

Dr. KOPP. I would say a number of the policy solutions you're talking about would raise the per-unit energy price, but the idea behind trying to get the markets to work is that you wouldn't necessarily be raising the amount that people are spending on energy because, to take the air-conditioning example that Dr. Majkut was talking about, right, it costs a little bit more up front just like solar costs a little bit more than a coal-powered plant upfront——

Mr. WEBER. But the——

Dr. KOPP. But you spend less over time——

Mr. WEBER. OK. I——

Dr. KOPP [continuing]. And so not—a lot of these policies wouldn't necessarily——

Mr. WEBER. So——

Dr. KOPP [continuing]. Increase——

Mr. WEBER. Let me move down. So, Dr. Francis, whatever price it takes to get to that point, is that kind of the philosophy here? Does it matter if we raise energy prices?

Dr. FRANCIS. I don't think it's fair to say that whatever cost it takes, but I think we need to have a strategic plan for——

Mr. WEBER. Would you put a percentage on that? Raise them 10 percent, 20 percent, 15 percent?

Dr. FRANCIS. Energy policy is not my area of expertise——

Mr. WEBER. OK.

Dr. FRANCIS [continuing]. And economics is not in my field of expertise——

Mr. WEBER. Fair enough.

Dr. FRANCIS [continuing]. But I feel that putting a higher price on energy——

Mr. WEBER. Let me jump——

Dr. FRANCIS [continuing]. Would do what we want it to do.

Mr. WEBER. Let me jump over to Dr. Ebi here. Any price, 10 percent more, 15 percent more?

Dr. EBI. The question is partially what's the price but also how do you manage that. And is some of that price turned back——

Mr. WEBER. Well, that's a growing technology, and we want America to be in the lead, American business and enterprise, right, to be in the lead for this, but I think there is a price where you make it so untenable for Americans that all of a sudden they kind of get turned off to the idea, and we don't want to do that. That's my point.

Let me move on. Mr. Lucas said that in his State, he's got lots of windmills. And I think you said you could see them from one horizon to the next. Have you ever noticed that on the hottest day of the year the windmills aren't turning, and that's why it's the hottest day of the year? I mean, it's unbelievable that—we can't rely on those.

When it comes to national security—and you mentioned this, Dr. Kopp, actually in your comments—we're going to need a backup that our country can depend on, and it's going to have to be fossil fuel. I can tell you about requirements for energy. I'm working on nuclear energy capability. It needs to be at the table. It needs to be a major part of our portfolio. So we've got to take these things into account. And I appreciate you all being here today. And I'm out of time, Ms. Fletcher.

Mrs. FLETCHER. Thank you. I'll now recognize Mr. Foster for 5 minutes.

Mr. FOSTER. Thank you, Madam Chair. And first, I'd like to thank Chairwoman Johnson for convening this important hearing. The climate challenges facing humanity are large, and unfortunately, serious debate on the best paths forward has often been stifled by the politization of this issue, at least in this Committee.

For years, too often we found ourselves wasting time arguing with non-technical witnesses about, for example, whether or not it's a matter of scientific debate, whether or not it would be a good thing if the Greenland ice sheet melted. But—and so I was really thrilled to see some of the changes that appear to be occurring in this Committee.

Over the last several years I have to say on a personal note I have grown truly tired of introducing myself as the only Ph.D. natural scientist in the U.S. Congress. And to that end, I am thrilled to welcome onto the Committee and into Congress Dr. Jim Baird as the second Ph.D. national—natural scientist in the U.S. Congress. And I would also like to congratulate my Republican colleagues on their wisdom in appointing him as the Ranking Member of the Research Subcommittee.

More to that point, I'd also like to thank Ranking Member Lucas and my Republican colleagues for selecting Dr. Majkut as their witness for this hearing. He's someone with a Ph.D. in relevant science and someone with views who are—which are inside the scientific mainstream, and that's refreshing. He is also someone obviously who understands that the question here is not whether or not this problem is real but rather what is the most cost-effective way of solving it, and that is a refreshing change because on this Committee, we have to look deeply at the balance of research and policy spending to solve this problem.

In terms of that, the best way forward, particularly the newer Members on the Committee will be faced with just a mountain of things that have been written on this, and what I consider the best synthesis that I've seen was actually presented by former Energy Secretary Moniz in his testimony to the Senate last week. In a report that he highlighted by the Energy Futures Initiative, which he's one of the leaders on, entitled, "Advancing the Landscape of Clean Energy Innovation" really to my mind touches the main points of what knobs we should be operating in our government both in terms of technological research, private–sector efforts, and public-private partnerships to solve this problem.

And so with that, I would at this point like to ask unanimous consent to enter into the record the report of the Energy Futures Initiative entitled, "Advancing the Landscape of the Clean Energy Innovation."

Mrs. FLETCHER. Without objection.

Mr. FOSTER. And so now I actually have one technical question for the entire panel. It seems to me that one of the changes in the last several years in the thinking on climate, is the rising of the profile of methane as a significant greenhouse gas, that if you look at the impressive progress, apparent progress in the decarbonization of the United States, a big part of that is by converting coal to natural gas use. And it now appears true that a significant—a large single-digit percentage of the methane that we burn actually gets vented, wasted, vented directly to the atmosphere without—before combustion. And so if that is true, the fact that it's such a potent greenhouse gas really negates a lot of the progress in converting coal to natural gas. And apparently the technology to detect the thousands of small methane leaks is tough, and it's not going to be cheap. So I wonder if you had any thinking on what we do about the methane problem and where the research that could really make a difference there would be. We can just go down the line if you want.

Dr. KOPP. Yes, I mean, I think we're sort of throwing money away and hurting the environment when you have natural gas leaks and there has been a lot of discussion about how much—how large those leaks are. All the incentives are there to try to solve those problems, and if it's not happening, that might be a good area for this Committee to figure out how to push it along.

Mr. FOSTER. Yes, I think one of the difficulties I've heard pronounced is that it's simply finding a very large number of small leaks is not cost-effective in terms of the savings in natural gas, and that's one of the things that makes it tough at least with current technology.

Dr. FRANCIS. So I would just like to bring up another issue related to methane, and that is the fact that the permafrost areas in the high Arctic are warming dramatically. We expect to see a lot more thawing happen. And when permafrost thaws, the biological material that's frozen in those soils can decompose then and become either methane or carbon dioxide. And we're seeing the warming happening much faster up there in general and in the Arctic overall. And the loss of sea ice, which is a clear symptom of global warming, is contributing to the acceleration of that thawing of the permafrost. So this is another issue that I think we need to take very seriously, especially in the methane discussion.

Mr. FOSTER. Thank you. And it appears my——

Mrs. FLETCHER. Mr. Foster, your time has expired.

I'd now like to recognize Mr. Babin.

Mr. BABIN. Thank you, Madam Chair. I appreciate it. Thank you all for being here as expert witnesses.

And we heard a little history a while ago. I had to leave the room for a minute, but I did catch the end of it, very interesting because I love history. Are you familiar, Dr. Kopp, with the Norse settlements in Iceland and Greenland but—in and around the year 1000 and that there was farming and animal husbandry in Greenland for nearly 300 years, which lasted up until about 1300 and then we had what we call the Little Ice Age, which lasted up until about 1700, and then the Greenland colony disappeared. But it's archaeologically sound evidence that told us that it did last that long. What could have possibly caused the climate to change so much that we would have farming and animal husbandry in Greenland for a period of 2-1/2, 3 centuries? Could you have blamed that on human emissions or can you give me an answer to that question?

Dr. KOPP. So there are fluctuations that we see in circulation in the North Atlantic. There's something called the North Atlantic oscillation. That might have had a role to play there. The Little Ice Age, which was then triggered, may have had something to do with volcanic emissions. The details of that are still an area of research. A lot of that is more of a localized phenomenon in the North Atlantic. There's some global temperature change, but that global temperature cooling actually starts around 1000 just so you——

Mr. BABIN. What you're saying is we don't really know, but in the opinion of everybody sitting at the table up there, was it more advantageous to have a little warming going on around the globe or was it more advantageous to have a little cooling going around the globe? Because during the Little Ice Age we lost lots and lots of humans to various causes that are in response and as a direct result of dropping temperatures. How would you answer it?

Dr. KOPP. Well, it's a——

Mr. BABIN. I would say that it would be more advantageous to have lived in a climate that was a little bit warmer.

Dr. KOPP. Yes, so I would say that over that period we're talking about a very small change in global temperature, roughly .3 °F, so it's worth keeping that in context when we're talking about the 2 °F, so almost 10 times as much than we've seen over the last century.

Mr. BABIN. Anybody else want to answer that?

Dr. MAJKUT. Yes, Mr. Babin, I think the way I think about it is not that there is an ideal temperature that we know for certain that human flourishing will be maximal. Science can't really tell us that in a meaningful way. What we do know is we've built our society around the temperatures that we've encountered over the last 200, 300 years. And as Dr. Kopp says, we're fixing to change those temperatures quite a bit. And that rapid transition is the cause for concern.

Mr. BABIN. But we do know that when Canada and the eastern part—upper part of the United States was uninhabitable during the Ice Age, that it certainly wouldn't have been conducive to economic development. I just feel like, you know, there's no question that our climate is changing, no question whatsoever, but to blame everything on human activity and expect the United States of America, the taxpayers in our country, to pick up the tab to pay carbon taxes and for carbon footprints and lower their quality of life and standard of living and increase the cost of living while our biggest polluters around the world absolutely go scot-free and continue. So it's hard for me to justify how we could be expected to pay that kind of a price.

And I want to ask one more question, too. Do you support a transparent and full accounting of cost, benefits, and projected impacts to the global climate of individual climate policy proposals? I'm going to ask Dr. Ebi. Is it the way you pronounce your name? I'm sorry.

Dr. EBI. That's fine. It's a difficult name. But thank you for the question.

Mr. BABIN. OK.

Dr. EBI. We do need a full accounting, and that does happen under the United Nations' Framework Convention on Climate Change at least in terms of emissions. And we know the United States alone is responsible for 25 percent of all emissions. There are efforts to try and understand better how much the cost of those emissions are in terms of impacts on our health, impacts on our ecosystems, our livelihoods, on our economies. And there's a growing amount of work looking at what the benefits of action would be.

Just from the health sector we know that the health benefits of many mitigation policies are of the same order of magnitude as the cost of mitigation, that if we get more people to ride their bicycles, to walk to work, to change their diets, to have less exposure to particulates, the avoided premature deaths, the avoided hospitalizations are a very large amount of money that would offset the cost of emission reductions. So we do need to look much more broadly at the cost and the benefits, taking into account who bears the cost and who reaps the benefits and how to make sure that this is done in a way that's as fair as possible.

Mr. BABIN. But if we are responsible for 25 percent of the emissions, as you say, then why should we pay nearly 100 percent of the cost? Because it sounds like that's the direction that you folks would have us go. And I think my time is over and expired, so——

Mrs. FLETCHER. Yes, sir, I believe your time is expired.

Mr. BABIN. Thank you.

Mrs. FLETCHER. Now, I actually am going to recognize myself for 5 minutes for questions.

And I represent the western side of Houston and the greater Houston area along the Texas Gulf Coast along with some of my colleagues on the panel. It is also the heart of the energy industry. And Dr. Francis mentioned hurricane Harvey in her remarks this morning. Harvey, as we all know, was one of the most devastating disasters in our history. It was also our third 500-year storm in a span of less than 3 years, so we are seeing increased frequency and intensity of weather events. We are also seeing the risks of sea-level rise and concern about storm surge in our community.

And in our district, we understand that climate change is real, and we believe working together in a collaborative way is the best approach for us to tackle this challenge. That means collaboration between research institutions, industry, and governments at the Federal, State, and local levels. So we believe that everyone has to be a part of the solution and a part of addressing this challenge.

And with that in mind, I have a few questions relating to these topics, first for Dr. Francis. Can you tell us briefly what the science tells us now about the intensity of the extreme weather events that we've experienced and how that might or will change in the future?

Dr. FRANCIS. Yes, thank you for the question. As I mentioned in my oral testimony, there are certain things that we know for sure are happening in the climate system. And Houston is probably in the crosshairs of a lot of those. You have seen, as you said, increased flooding. We know that heavy precipitation events are increasing dramatically. You've seen heat waves increasing. You've even seen drought increasing. And we also expect to see tropical storms intensifying more rapidly, and potentially we expect to see more of the very strongest tropical storms. A lot of those things are very clear, and what is a little less clear relates back to Harvey and some of the extreme events that you all have witnessed and experienced, and that is we're also seeing an increase in the persistence of weather regimes. So it could be dry, it could be hot, it could be cold, it could be wet, but we're seeing an increased persistence, and we believe that that is also related to climate change.

Mrs. FLETCHER. Thank you very much. And, more broadly for the panel, we do believe it's important to include everyone in working together on these solutions, so, in particular, do any of you have experience with or suggestions on how the energy industry can work together with your institutions and with those of us who are making policy to be part of the solution toward climate mitigation? And I should also add I believe that they already are, and certainly in my district most of the industries have acknowledged and are working to combat climate change, but any specific ideas you have of policies or programs you think would be helpful for this Committee to know?

Dr. KOPP. Well, so there's sort of a style of doing science that I think very much gets at this, and that's science that is sort of stakeholder-engaging and the jargon is transdisciplinary, but basically the idea is start with a problem, right? The problem is the resilience of the energy system off of Houston. And then you're going to get together the different disciplines that you need to address it, you're going to get together stakeholders, and you're going to do the research together in a partnership. And that's a very different style of doing research than what's traditionally happened in universities. And I think we need to be rethinking a little bit of that part of the climate science enterprise to sort of make this more of a problem-focused thing.

Mrs. FLETCHER. Thank you. Dr. Ebi?

Dr. EBI. Thank you. It's a very good question, and I want to echo that working with stakeholders is critically important in this process. And to step back more broadly and say that companies want to have healthy workers and healthy communities. They don't want to see their workers flooded, they don't want to see the impacts on their workers and on their families. And so there are ways that one can work together to try and ensure the resilience of the community while the companies work to ensure their own resilience to make sure that, as these extreme events occur, they are not affected, that their facilities are not affected, so facilitating those partnerships at the Federal, State, and local levels is critically important.

Mrs. FLETCHER. Thank you very much. My time has expired, so I will yield back the remainder and now recognize Mr. Baird for 5 minutes.

Mr. BAIRD. Thank you, Madam Chair. And this is my first congressional Committee hearing, so I hope you'll excuse me if I make any procedural errors. And I'd prefer you not express those to me. I'll just take that. I'm honored to be here in that capacity and to be able to have the discussion that we're having today about climate change. I do appreciate my colleague Dr. Foster for those kind words.

But as a farmer and an animal scientist, I know the importance of leaving the land healthier than how we found it for our next generation. I've got grandchildren, but I think it's important to those children and grandchildren. And so the health of the land has always been a concern for agriculture people, and that is important to our ability to feed ourselves.

But in that vein, I also recognize that the natural evolution process over time, the tremendous ability of mammalian tissue or mammals and plant tissue to adapt to their environment, I don't see much discussion about that in some of the presentations. But I do find your presentations extremely interesting and very insightful.

I would like to just point out a couple things. Dr. Ebi, not picking on you in any particular reason, but, for example, we mention 729 children died from heatstroke from 1990 to 2014, so I guess my question there is, is that because the automobiles were better, or the children are less exposed to their environment than we have in previous centuries and so on? So I think we need to take those kind of factors in when we make those predictions about the impact of the climate on some of the issues we're concerned about.

For example, the elderly, are we older as a generation, so we're becoming more susceptible as we age and so compared to 50 years ago we're living a lot longer. And so those are just things that if you want to respond to that, you're welcome to. It was really more of a comment than anything, but I'll give you that option.

Dr. EBI. Well, thank you. And thank you for those comments, and I do have a couple of short responses. On the evolution, the climate now is changing faster than it's been in 10,000 years, and so it is a challenge for many of our plants and other species to try and evolve fast enough in the face of this rapid rate of change.

In terms of the children dying in cars, the data were only collected over a certain period, so we don't have data from before then. But the point is as temperatures are going up and we're seeing more heat waves, we're seeing higher temperatures in summer, people don't realize how quickly cars heat up. And so it's terribly unfortunate how many infants are dying in cars because people don't realize, as they say I'm only going to be gone for a minute, that that minute may be too much for an infant in the higher temperatures we're experiencing now.

Mr. BAIRD. I really understand that and can appreciate that, and I think that's a tremendous mistake that parents make. But my question comes back to, is that because the cars are tighter, the windshields are better, the glass heats up more, and so on? No excuse for leaving those children, and I don't want to comment about that. That's OK. We're OK there.

But I do have some questions for Dr. Majkut. In the developing field of technology, the United States, I think we ought to be a leader in that because we have the ability and the talent to do it. We have the research capability. So my question to you is, are we behind other countries in our developing a cleaner environment, cleaner energy sources?

Dr. MAJKUT. It's a tough question to answer. I think the answer probably varies on exactly where you answer. I think in bulk, no. The U.S. research enterprise is really strong. We provide a lot of resources to that enterprise. And if you look at environmental performance not just on climate but on other issues over the last decades, we're doing pretty well.

Mr. BAIRD. So would it be fair to say that our country makes a lot more investments in cleaner energy sources than another country around the world in terms of reducing our pollution even though we use a lot of the fossil fuels?

Dr. MAJKUT. I don't know. I don't know the relative spending, sorry.

Mr. BAIRD. OK. Agriculture is extremely important, as I expressed. It's extremely important to my district, and so we have Purdue University in the area, and Dr. Dukes has also provided some assessment of what the climate change has on agriculture, but it can impact growing season, plant growth, animals, and some of the things that's already been discussed. So what do you think we ought to be doing right now to correct these areas? What are some of the things you think you might be able to do relatively rapidly?

Dr. MAJKUT. On farming specifically?

Mrs. FLETCHER. The gentleman's time has expired.

Mr. BAIRD. All these procedures, I tell you. Thank you very much.

Mrs. FLETCHER. I now recognize Mr. Bera—Dr. Bera.

Mr. BERA. Thank you, Chairwoman Fletcher. You look good in that chair, by the way.

First off, it is glad that we're kicking off this Congress and this Committee with a hearing on climate science, on climate change and really taking a look at what we can do to try to mitigate this. And you will hear aspirational goals. You can call them whatever you want, if it's a Green New Deal or something, but aspirational goals are not things that we should shy away from as the United States.

If we look at our own legacy and our own history going back to the—throughout our history but, recent history in the 1960s when President Kennedy challenged us to go to the moon, we had no idea how we were going to do it. It was an aspirational goal, but we put all of our intellect, industry into that, and we accomplished it. And we accomplished it faster than the President challenged us, so let's not be afraid of setting these aspirational goals. And we know from going to the moon and the whole Apollo program, it was economically sound as well because we can think about all the industries and innovation and discovery that came from that.

I'm proud to be a Californian. I'm a lifelong Californian. And in our State we did pass legislation recently that moves us to the goal of 100 percent clean energy by 2045. That is an aspirational goal. But we also know we're the fifth-largest economy in the world. It hasn't stifled our economy. In fact, there's over 500,000 clean and renewable energy jobs in California, and that's growing. So, again, we don't have to be afraid of setting those goals.

Dr. Kopp, I think you mentioned getting to that goal of net-zero global greenhouse gas emissions. I think that's an aspirational goal, but let's set that goal out there and then let's work toward it and use our innovation and intellect to get there.

I've got from a science perspective and a question—and I'll let all the witnesses comment on this—there's also the issue of the carbon that is already sequestered in our atmosphere. And from the scientific perspective, what are the things we're not talking about mitigating future emissions, but are there ideas out there for us to degrade the carbon that already is up there that is trapped?

Dr. KOPP. I don't know if Dr. Mahowald wants to take first crack at that.

Mr. BERA. Sure, whoever wants—go ahead.

Dr. MAHOWALD. I'm happy to speak if I'm able.

Mr. BERA. Yes, please.

Dr. MAHOWALD. The removal of carbon dioxide from the atmosphere is—innovative new technologies are moving in this direction, and we do need more investment in this type of research development and deployment of these technologies. There are some sectors that are going to be very difficult to cut the CO_2 emissions from, and removing carbon dioxide from the atmosphere is a very good method of reducing climate risk at the same time as we are working to mitigate as well as adapt in other areas. So, for example, if you want to sequester more carbon in agricultural soil, this not only reduces the carbon dioxide in the atmosphere, it also makes the agricultural soil more resilient to climate change as an example. But there's two recent National Academies reports on how to look at carbon dioxide removal, and I think it's an area that the United States should invest more research and set up the business environment to allow companies to invest more in. Thank you.

Mr. BERA. Great, thank you. Dr. Kopp?

Dr. KOPP. Yes, just to add onto that, there's a wide range of approaches you can take from expanding forests, which is slow but we know works, to a variety of technological approaches. As I said in my opening remarks, they're sort of new and untested. I think one thing to keep in mind is that the amount of warming we have is roughly proportional to the—all the CO_2 we've emitted, so if we want to reverse warming by removing CO_2 from the atmosphere, we're going to have to talk about building infrastructure that's of a scale comparable to that that we're currently using to put CO_2 into the atmosphere, right? So the first use of these technologies is going to be, as Dr. Mahowald mentioned, for areas where it's hard to get the CO_2 out. But if we want to talk about reversing climate change, you're talking about a huge growth of this area using technologies that are still really to be developed.

Mr. BERA. Right. Any last comments, please?

Dr. EBI. One last comment to go to what you said at the beginning, I'm at a very large State university, and students are so excited about the possibilities of working in this area. Students want to contribute to the solutions. They want the training so that they can be part of this transition that we're going to undergo.

Mr. BERA. So it's a lot like those of us who were growing up in the 1960s during the space race. It's inspiring. And let's not be afraid of setting those aspirational goals.

I'll yield back.

Mrs. FLETCHER. Thank you. And before we move on to our next questions, I would like to enter into the record without objection a consensus letter to Congress from 31 nonpartisan scientific societies that acknowledge and affirm human contributions to climate change and notes the severity of climate change impacts is increasing and is expected to increase substantially in the coming decades.

And with that, I recognize Mr. Waltz for 5 minutes.

Mr. WALTZ. Thank you, Madam Chairman.

So my district's in northeast Florida. I grew up on Florida beaches. The seas are rising. Anyone who's grown up there knows that the beach is smaller than when I was a child. I just don't see how that's disputable. But I do want America to lead this effort. We've led the world in coal, oil, and gas development. Now we need to do it with rapidly growing clean-energy markets. I think to succeed we need a very broad portfolio of—emphasis here—low-cost technologies to speed the transition to renewable cleaner energy. I think that includes nuclear undeniably.

I would caution my colleagues, we have seen a lot of aspirational goals lately. I think we need to be very careful about crossing the line from aspirational to outlandish goals that could harm our economy and frankly give the edge to our global competitors in doing so and frankly take us backward in this effort.

So I'm very concerned as a veteran as well about the national security implications of global warming. I have first-hand seen and unfortunately could not count the amount of soldiers that have died carrying diesel fuel back and forth to outposts that we could have sustained through clean technologies. I've seen—not to mention our global supply chains and not to mention I've spent a lot of time in Africa, Lake Chad basin where we're dealing with the destabilizing effects in Nigeria, Niger, what have you.

So my question for each of the panelists is what R&D—I mean, Dr.—did I say this right—Majkut?

Dr. MAJKUT. Majkut.

Mr. WALTZ. Majkut, excuse me. You said we're doing pretty well in our investments, particularly relative to the rest of the world, and my question for each of you is, where are we not—across the menu of clean-energy technologies, where do we need to do more? And again, keeping this in the context of our broader economic base that I think we need to sustain all of these efforts. So where could we do more? Geothermal—and I'd ask you to choose. The answer can't be yes, all of the above.

Dr. MAJKUT. Let me say first we could be doing more, right? Like the scale of the challenge and a lot of the concerns that your colleagues point out about increasing costs with present-day technologies to reduce greenhouse gas emissions, those are real and valid concerns. And in particular, you can't expect these things to scale unless the prices at which they're trading are competitive. So on the whole, doing more is not necessarily a bad thing, and then doing more smartly is probably the thing that the Committee should really pay attention to.

When I read these IPCC reports or the National Climate Assessment or these other documents, the places where it seems like the technology hasn't caught up with the need, carbon capture and storage is one, right? This allows us to use fossil fuels without—for power generation and take advantage of all of their desirable characteristics without emitting——

Mr. WALTZ. To make it more cost-effective or just to do it?

Dr. MAJKUT. In large part simply to do it. There are very few facilities——

Mr. WALTZ. OK.

Dr. MAJKUT [continuing]. At which this is happening.

Mr. WALTZ. But just in the interest of time, my understanding is the majority of our dams in the United States do not generate electricity. Nuclear accounts for about 1/5 of the United States' electrical generation right now. And then of course, we're seeing just a boom in natural gas and where we can go with it. Would you agree that those are all areas where we can make greater investments that would make a difference on this issue?

Dr. MAJKUT. Yes.

Mr. WALTZ. Would any of the other panelists want to weigh in on either of those questions?

Dr. FRANCIS. Thank you. So I'm from Massachusetts, and in Massachusetts we've had incentives for solar energy for about a decade now, and many roofs have solar panels on them. To put a solar array on your roof now, the payback period is about 6 years before you start basically making money on your investment. It saddens me to fly over your State frankly because I look down and I see almost no roofs with solar panels on them, and you're just missing a huge opportunity. And yes, it took some incentives to get the ball rolling down the hill, but now, the incentives in Massachusetts are disappearing and still people are putting solar on their roofs.

Mr. WALTZ. I would point out to that in Samsula, Florida, Florida Power & Light has a 1,200 solar facility, and it's estimated to provide electricity to 14,000 homes, 30 million solar panels by 2030, but I'm sure we could all collectively do more. Those are State incentives to be clear——

Dr. FRANCIS. That's—yes.

Mr. WALTZ [continuing]. At the State level or local level.

Dr. FRANCIS. Yes.

Mr. WALTZ. Thank you so much. I yield my time.

Mrs. FLETCHER. Thank you. I now recognize Ms. Bonamici for 5 minutes.

Ms. BONAMICI. Thank you very much, Madam Chairwoman.

I want to thank Chairwoman Johnson and Ranking Member Lucas for holding this hearing, and I also wanted to take just a moment to say congratulations to the environmental—Environment

Subcommittee Chair Representative Fletcher and wish her a very happy birthday. Thank you.

Mrs. FLETCHER. Thank you.

Ms. BONAMICI. So thank you to the witnesses for being here today. The science is clear. I've been on this Committee the entire time I've been in Congress. We've had this conversation many times. This—consequences of inaction on climate change will be serious and swift. The findings of the recent report from the International Panel on Climate Change, the IPCC, and the Fourth National Climate Assessment are not just a wake-up call; they are an alarm. At the time when the world is facing record heat waves, droughts, more acidic oceans, rising sea levels, and a surge of—in extreme weather patterns, we must fight for comprehensive policies to protect the health of our oceans and our planet.

I was concerned when the Trump Administration appeared to be burying the Fourth National Climate Assessment. They released it late on a—like late on a holiday weekend, so I shared findings from the assessment on Twitter every day for 6 weeks to call attention to the assessment when the President dismissed the findings in a Washington Post interview last year. I worked with my colleague on this Committee, Mr. Beyer. We led 96 of our colleagues in urging the President to heed the dire warning of the assessment and work with us to protect the health of our planet.

The assessment is the most comprehensive science-based evaluation of the consequences of climate change, the risks of inaction and potential adaptation strategies for the United States to date. We cannot and should not dismiss its findings.

Dr. Ebi, according to the air quality chapter, volume 2, of the assessment, more than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Climate change will increase the risk of unhealthy air quality. How are children, older adults, low-income individuals, communities of color, and those experiencing discrimination disproportionately affected by climate change, and what could we do to mitigate the health consequences of climate change for these vulnerable populations?

Dr. EBI. Thank you for the question. And this is a very serious concern that there are people who are differentially exposed to poor air quality. It's from particulate matter, it's from ozone, and it's also from things like pollen. And so people in the groups that you mentioned often live in communities that have much higher exposure, and it's an opportunity, going back to the question we had a few minutes ago, of looking at issues like energy efficiency to make sure that we reduce how much comes out of our tailpipes so that people don't have so much exposure.

I will note that the United States cannot sell cars in China because we cannot meet their emissions standards. So there's lots of opportunities to reduce emissions. Reduced emissions also from coal-fired power plants is incredibly important to protect people's health.

Ms. BONAMICI. Thank you. We also save healthcare costs, and we want to do that obviously.

Dr. Kopp, I noticed in your written testimony there's a sentence that you have in there about in 1990 President George H.W. Bush signed the Global Warming Response Act of 1990. I just want to note that that was a long time ago, and we still need to respond.

The coastal effects chapter of volume 2 of the Fourth National Climate Assessment states that 13.1 million people are potentially at risk of needing to migrate because of sea-level rise by the year 2100, creating drastic consequences for socially and economically marginalized and low-income groups. In your testimony, you discuss how climate change is an infrastructure challenge. We're having a lot of infrastructure conversations here on the Hill. What infrastructure investments and strategies should Congress address now to prepare for rising sea levels and avoid catastrophic damage?

Dr. KOPP. Well, of course, that's a complicated question because infrastructure is fundamentally local, and so the answer is going to differ depending on where you are. The fundamental thing is if you're building infrastructure that's going to be around for 80 years like—it is foolish not to take into account changing climate conditions and changing sea-level rise for that period and know when you build that what you're going to do if it turns out we're on a relatively, say, low sea-level rise course and what we're going to do if it turns out we're on a relatively high sea-level rise course. We aren't—we don't know yet because it depends both on ice sheet physics that are still being studied and on greenhouse gas emissions that we haven't admitted yet whether we're going to see 2 feet of sea-level rise over the course of this century or more than 6 feet. And those have very different implications, and so we need to be thinking about we can build flexibility into our designs and coupling the infrastructure designs and deployment to the science that will tell us that information as soon as it can.

Ms. BONAMICI. Thank you very much, Madam Chairwoman, and I am just about out of time, so I yield back.

Mrs. FLETCHER. Thank you. I'll now recognize Mr. Norman for 5 minutes.

Mr. NORMAN. I want to thank the panel for taking the time.

Mr. Majkut, I think what's been said here—and I'll ask all the panel—this country's—and I'm from South Carolina. I'm a real estate developer. Is the figure right? We contribute 20 percent to emissions as opposed to other countries?

Dr. MAJKUT. If I'm correct, it's slightly less than like, maybe 15, 16, but ballpark it's right.

Mr. NORMAN. OK. And I've heard the other comments that everybody needs to pay. How do we—if we're 16 percent—pick your figure—how will we make the other 82 percent pay their fair share?

Dr. MAJKUT. So like, first of all, we can generate a lot of innovative technologies here in the United States using our research enterprises that are exportable. We can share that knowledge through formal arrangements or informal ones or simply through exports. We can also demonstrate using a variety of policy instruments that it is possible to have a thriving economy and a healthy society with lower greenhouse gas emissions, and we can export those models as well.

Mr. NORMAN. OK. Anybody—any of the other panelists have any comments on that?

Dr. MAHOWALD. I'd be happy to comment.

Mr. NORMAN. Yes, ma'am.

Dr. MAHOWALD. The other thing to recognize with this very good question is that under the Paris Agreement, countries have voluntarily agreed to cut emissions, and people have evaluated the cost of these and the relative cost to gross domestic product (GDP). And actually the United States' voluntary contribution is actually quite low compared to its GDP. So other countries are volunteering to do more than their fair share. Thank you.

Mr. NORMAN. If that's the case, then it's really apparent now we need to put a price tag on—prioritize or put a price tag, is that right, on what this is going to cost like the green energy deal that—we're probably going to vote on. It's a nonbinding resolution. But before we go doing away with flatulent cows, airplanes, we need to put a price on it, don't we?

Dr. MAJKUT. Yes, from a public policy perspective we should always be cognizant of the costs and benefits of the choices we're making and try to be judicious in moving forward, seeking low-cost options.

Mr. NORMAN. Yes. And in my world, you find your goal, put a price tag on it, and then move from there. And I think everyone would agree this is going to cost dollars. It's going to cost and I think Mr. Kopp—Dr. Kopp, you wouldn't put a figure on how much we're going to have to pay for gas, but it's going to be more expensive than what we've been paying, is that right?

Dr. KOPP. Yes, so I think certainly the upfront cost of energy will go up, but average costs may go down. And I think it's really important that when we look at the costs, we're looking at the costs of climate change in comparison; there's a lot of economic work going on to try to evaluate those two, and these have to be balanced against one another.

Mr. NORMAN. They have to be balanced. And would it not be fair with increased costs, whatever figure we end up with, you're going to rule out some of our most vulnerable communities that are not going to have access to energy, as an example. What kind of cost would that be to them and their health through PTSD, through their mental health? How would we put a number on that?

Dr. MAJKUT. Well, I mean, I think the intent is not to like overly punish any particular class of people or any particular technology. It's to put in place a system that we all are going to benefit from in the long-term. And that means that for day-to-day activities that people are going about, that they're able to do that in a low-carbon way. Great. What we need to do as a society is find ways that that doesn't end up being too costly. And frankly, I don't know that it is going to be too costly. It's just a matter of making smart investments, leading the way to innovation, and then scaling those up through the private sector.

Mr. NORMAN. Dr. Majkut, if, as an example, this Green New Deal were implemented immediately, wouldn't you agree it's going to devastate our economy, and other countries are going to take up the practices that we are eliminating as in the cows that they grow, the other areas that we are going to have to—they will make the difference up in this even though we don't?

Dr. MAJKUT. Yes, in fact, the Green New Deal is a moving target, not sure what it is, but based on my understanding from the resolution that's been introduced, as well as the things that have been said by its primary backers, the decarbonization, that is reducing the CO_2 associated with economic activity, is one of the cheapest elements of the Green New Deal.

Mr. NORMAN. Thank you so much. I'm out of time. I yield back.

Mrs. FLETCHER. Thank you. The Chair will now recognize Mr. McNerney for 5 minutes.

Mr. MCNERNEY. I thank the Chair and I thank the witnesses this morning.

Natural gas sounds great compared to coal, but the more effectiveness of natural gas and reflecting infrared radiation compared to carbon dioxide means that if just 2 percent of the produced gas escapes into the atmosphere, the efficiency benefit over coal is lost. Does anyone on the panel disagree with that? No? Does anyone want to make a remark about that? OK. Thank you.

Dr. MAHOWALD. If I could say something?

Mr. MCNERNEY. Sure, go ahead.

Dr. MAHOWALD. Well, thank you for the question. One of the differences between methane and carbon dioxide is how long they reside in the atmosphere, so in the short-term methane can be very bad for the climate, as well as for air quality, but most of the impacts of methane are actually on air quality. But methane only lasts about 10 years in the atmosphere whereas carbon dioxide, 20 to 30 percent of it is going to last centuries to thousands of years.

So in terms of trying to solve the really big climate problem, we should focus on CO_2. Methane is a big problem for air quality, especially and a little bit for climate, but we should try to mitigate the methane as much as possible. But it is actually lucrative to capture, so it's a much easier target.

Mr. MCNERNEY. That's a good point. We need to capture it——

Dr. MAHOWALD. Studies show that it's economic—that it's actually economically feasible——

Mr. MCNERNEY. OK.

Dr. MAHOWALD [continuing]. To capture much more methane if people were careful about it.

Mr. MCNERNEY. Thank you. Dr. Kopp, how can positive feedback loops accelerate climate change?

Dr. KOPP. Well, there—positive feedback loops are sort of a core part of how the climate system works, so to take one example, if we put more CO_2 into the atmosphere, that causes some amount of the warming. It causes melting of ice in the Arctic. It makes the Arctic less reflective, so that causes more warming. When we talk about, say, tipping points in the climate system, which is language I don't love but is used, there—all of those tipping points are driven by positive feedbacks having to do with things like, for instance, ice sheet ocean interactions leading to rapid loss of the Antarctic ice sheet.

Mr. MCNERNEY. OK. Dr. Ebi, briefly, would you identify some research that the Federal Government should be engaged in on climate change it's not doing right now?

Dr. EBI. Thank you for the question. There are so many opportunities to increase the research enterprise in this area. I'll speak specifically for health. There is almost no Federal research dollars going into research on the health impacts of a changing climate and how we can adapt more effectively to that, so any kind of investment would be very beneficial for the health of Americans and for our healthcare infrastructure.

Mr. MCNERNEY. Thank you. Dr. Kopp, I understand that most or all climate models underestimate or even grossly underestimate the rate of climate change. Do you agree with that?

Dr. KOPP. So I think what you're referring to is the statement in the climate assessment looking at the ability of climate models to reproduce past warm periods, and there's definitely a systematic tendency of climate models if we compared them to the geological record, not to produce as much warming as we see evidenced in the geological record.

Mr. MCNERNEY. Well, given the state that we're in that the climate effects we're seeing now are due to carbon dioxide that was introduced into the atmosphere decades ago, do you think we can avoid a 1.5 °C increase by just reducing carbon emissions alone?

Dr. KOPP. As I think the 1.5 °C report tells us it is possible physically but it may be challenging. If we—we have to get greenhouse gas emissions to net zero very quickly if we want to do that.

Mr. MCNERNEY. Well, I think because of that, we need to expand our research into climate intervention, and not that I want to go there, but given that 1.5-degree change is almost inevitable and 2-degree change is likely in my opinion, we need to understand the tools that would be available to avoid catastrophic change if it comes to that. Would you comment on that?

Dr. KOPP. Yes, so I think it's very clear it would be very helpful to have more effective technologies for removing carbon dioxide from the atmosphere, so that's one category of climate intervention. There's another category that has to do with putting—sorry, pollution in the stratosphere to make the planet more reflective, and I think that needs a lot of careful analysis to see what the risks are and whether that would be feasible from both a technological and policy perspective.

Mr. MCNERNEY. Right. So we need to do research in order to understand what the risks and what the potential benefits of that would be?

Dr. KOPP. Yes.

Mr. MCNERNEY. Thank you. I yield back.

Mrs. FLETCHER. Thank you. The Chair will now recognize Mr. Gonzalez for 5 minutes.

Mr. GONZALEZ. Thank you, Madam Chair. Thank you to everybody for being here.

As a newly elected Member of Congress, I just want to mention first how excited I am to serve with everyone on this Committee and look forward to working on bipartisan solutions that will make the American people proud.

So I believe that climate change is real, and global industrial development is a contributing factor. I also believe that my first responsibility and my unyielding loyalty is to the hardworking men and women of Ohio's 16th District and the economy that allows us to heat our homes, fuel our vehicles, and build our businesses. As I look at the most recent proposal, the Green New Deal, I cannot help but believe that this would put a tremendous burden on my community.

My community is proud of our blue-collar roots. We are proud of the products we make, the crops we farm, and the jobs that we hold. Simply put, the Green New Deal would threaten all of that.

And we only really need to look to Germany and their what I'll call "Green New Deal Lite," for an example. Since 2000, Germany has spent an estimated €189 billion or about $220 billion in renewable energy projects while emissions have been stuck at roughly 2009 levels and even rose recently. According to the Wall Street Journal, taxes and rising power generation costs have made Germany's electric rates the highest in Europe. In sum, they've spent a lot of money, raised taxes and energy prices, and nothing really happened.

The proponents of the Green New Deal are proud to admit that their plan represents a fundamental remaking of America's economy. They believe in a system that relies on a near full government takeover of some of our most important industries to solve our most pressing problems. With Germany's example and common sense as our guide, we simply know that this will not work.

But it's not enough to point fingers. As I said, this is real. We do have a problem, and the government can play a role in helping solve it. What I believe is the most reasonable path forward is a path that does not focus on a Federal takeover of our economy but rather a path that fosters a diverse set of energy sources and seeks to make alternative energy as affordable and reliable as the traditional sources we use today. And for that I do not wish to rely on government takeovers of our biggest industries but rather I want to focus on empowering the American people and unleashing the most powerful economic force in human history. If we do this, then we will be able to reduce carbon emissions at home but also abroad as we are able to commercialize these to-be-developed technologies and sell them around the world. And best of all, we will do that without having to ask my communities to pay a very steep price.

With that, Dr. Majkut, could you comment briefly on the extent to which this is a global issue versus one we can solve on our own? And based on your understanding of global development patterns specifically in China, India, and Africa, how feasible and realistic is it to exclude fossil fuels from all sources of energy globally?

Dr. MAJKUT. Thank you for the question. I think you've really hit the nail on the head, right? The science tells you this is a global issue. Atmosphere doesn't care where carbon dioxide molecules come from. They have the same warming affect no matter where their source was combusted if it's a fossil fuel source.

What the United States can do is work to innovate the technologies we believe we'll need to have not just an economy similar to today's but one that is much larger globally and finding smart ways to make sure those technologies make it to market. And that's an advanced research agenda, that's industrial policies, and it's market and finance design questions.

Mr. GONZALEZ. OK. And then cost is obviously very important, and I think we focus a lot on that, which is right. But when I speak to our manufacturers, one of the issues that they talk about a lot is reliability of the grid. So if we were to switch to these technologies, the renewable technologies today exclusively, we turned the Green New Deal on today, would we even be able to manufacture? Would our manufacturers be able to rely on the grid as it's currently constructed?

Dr. MAJKUT. I don't think so, no. It seems like the lights would go off. But that doesn't mean that you couldn't change over the course of a few decades, which is what we're trying to do.

Mr. GONZALEZ. Right. And then my last question and I hate these up or down ones, so I apologize, but when you think about the Green New Deal as you've seen it—and I know the details need to be fleshed out—do you believe that is a realistic path forward?

Dr. MAJKUT. No, sir. I think——

Mr. GONZALEZ. Thank you.

Dr. MAJKUT [continuing]. It's a broad progressive agenda greenwashed by some climate details.

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

Mrs. FLETCHER. Thank you. The Chair will now recognize Mr. Cohen for 5 minutes.

Mr. COHEN. Thank you, Madam Chair. First, I believe the New Green Deal is aspirational, and I think it's important that it puts attention on the dangers to our planet at this time and the urgency of our actions. Some of the specifics certainly aren't going to happen any time soon. Some of them will probably never happen at all. But the concept of putting people's minds and attentions to climate change is very important. Does anybody disagree that it's not an important matter to inform the public of the urgency of the changes that will occur to our planet? Thank you.

That's why I'm a sponsor of the bill because it brings attention to the issue. It's getting warmer and warmer, hotter and hotter, more violent weather, hurricanes because of the warming oceans and currents, and rising levels—the sea level, endangering what we've known. I've read that Miami Beach could very easily be underwater and it oftentimes has water on Collins Avenue that they have to pump. I think where we ought to concentrate on is Mar-a-Lago and what are the climate consequences to Mar-a-Lago if we don't act? Can anybody give me an idea about how long it might be before the oceans rise to a level to where Mar-a-Lago might be underwater?

Dr. KOPP. So I don't recall exactly how high Mar-a-Lago is.

Mr. COHEN. It depends on the night and who's sponsoring the party I understand.

Dr. KOPP. But we could be looking at sea-level rise anywhere between 2 and 6 feet, and I think under—in this century, depending partially, as I said, on ice sheet physics and partially on how much CO_2 we put into the atmosphere. And my suspicion—because I have actually looked at this before; I just don't recall the details—is that certainly under those higher scenarios you might be looking at permanent flooding to some of that property. [1]

[1] Based on Climate Central's Surging Seas Risk Zone Map (sealevel.climatecentral.org), much of the golf course at Mar-a-Lago floods at a water level about 3 feet above the current high-tide line, and the swimming pool floods at a water level of about 5 feet above the current high-tide line. Currently, the water level reaches about 1 foot above the high-tide line about once a year. Thus, the Mar-a-Lago golf course would be expected to flood annually with about 2 feet of sea-level rise, a level that will most likely be exceeded in south Florida in the 2060s or 2070s under a high-emissions scenario and around the end of the century in a low-emissions scenario.

Continued

Mr. COHEN. What if the—if this happened, your 2 to 6 feet—and I know it's decades and whatever, but they're going to be——

Dr. KOPP. Oh, yes.

Mr. COHEN [continuing]. Generations of people to be Mar-a-Lagites. Do they—what if they built a big seawall, a big beautiful seawall at Mar-a-Lago? Would that do any good against the ocean?

Dr. KOPP. So the challenge in south Florida is that a lot of it is limestone that has—is porous, and so that means that the ocean water isn't just coming from the side, it's coming from underneath. So it's sort of hard to protect south Florida only with seawalls.

Mr. COHEN. That's kind of like El Chapo. He came from underneath, he came from over, so the walls wouldn't do any good there either.

People have talked—the gentleman from South Carolina talked about the cost of all this and there are costs to doing things with industry, but there are tremendous costs if we don't do anything. The air-conditioning bill at Mar-a-Lago would have to go up as it gets hotter and hotter and hotter. Has anybody done a study on the dollar cost, the fiscal cost to business if we don't take action?

Dr. KOPP. So we're part of a collaboration called the Climate Impact Lab together with the University of Chicago, Berkeley, and Rhodium Group, and those are exactly the sort of questions we are working on. We're still working toward some of that, but the approach we use is sort of to look at things like, for instance, how different years in the past have led to different air-conditioning expenditures, take the energy sector as an example, and how that varies based on how hot it is usually and how wealthy people are and use that to project forward. So this is a really cutting-edge area in climate research we're sort of working toward using big data approaches to do—answer those sorts of questions.

Mr. COHEN. So a lot of the issues that will arise like the use of more air conditioning really militates against poor people because they won't have air conditioning at all often or can't afford the utilities, and so they bear the brunt of climate change in a larger, greater way than wealthy people in a climate change burden.

Dr. KOPP. Yes, and so generally what you find is that the poor suffer and the rich can spend to adapt, so they both bear costs, but in some cases it's more personal costs, suffering, and the other is more monetary.

Mr. COHEN. And somebody mentioned—which I pretty much understand, if we correct certain issues here and improve our—reduce our reduction—production of CO_2, that you—if it doesn't happen in the rest of the world, we've still got problems, but isn't the best way to do that the Paris climate accords or some climate accords? Does anybody disagree with the fact that we ought to a climate treaty where we come together and have an accord? We're all in agreement on that? Kumbaya. Thank you, and I yield back.

Mrs. FLETCHER. Thank you. The Chair will now recognize Mr. Cloud for 5 minutes.

The swimming pool would be expected to flood annually with about 4 feet of sea-level rise. Under a high-emissions scenario, we would estimate that the 4-foot threshold has between a 15 and 83 percent chance of being exceeded by the end of the century, depending on the approach used to estimate how fast Antarctica will melt.

Mr. CLOUD. Thank you, Madam Chair. And may I again wish you happy birthday. Thank you all for being here. Mr. Majkut, at the beginning of your written testimony, you say that "There's no better innovative force than the private sector, but if you really want energy innovation, you need to show innovators that there's a market waiting for them." Can you speak to what recommendations you would encourage for energy innovation in the market?

Dr. MAJKUT. Sure. I think a lot of things are already in place showing energy innovators that there is market access for them. The Paris climate agreement is a great example, right? A lot of countries are saying they want to reduce greenhouse gas emissions, and that incentivizes people to innovate ways of doing it.

Speaking of more at a U.S. national level, I think there's a lot of things that could be done on the fiscal side, whether that's a carbon price or smarter regulations than we have today to create a competitive marketplace. There are intermediate steps that can be taken when things aren't quite ready to scale into the market. A good example of that would be the 45Q tax credits that are presently offered for producers—or people who capture carbon and sequester it or use it in some manner at new facilities. That gets you your first few. And then on the backend there is the scientific and engineering enterprise, which reduces the cost of doing all of this.

Mr. CLOUD. Thank you. I hail from Texas, specifically the 27th District of Texas. It's Gulf Coast. My district includes nuclear power. We had the number-one energy-exporting port in the Nation. We have wind energy. We have LNG, crude exports, very diverse as far as an energy portfolio is concerned. Texas is a leader in that, also a leader in wind energy and just having generally speaking a diverse portfolio. The Green New Deal, however, seeks to limit that to specifically noncarbon-produced energy in the next 10 years. Is that feasible without crippling innovation and economy, or do you think that with new technologies, fossil fuels could play a part going forward?

Dr. MAJKUT. Two things. One, I'm not a big fan of timetables generally. I think we know enough that we should be trying to bring low-carbon technology to market. Setting super ambitious goals—I understand the impulse. I totally agree, but I think you can get in your own way. And where we find ourselves today, that's a very ambitious goal for where we've been.

I think the climate doesn't particularly care where energy comes from so long as it's not emitting CO_2, and that means that there are a lot of reasons why you'd want to pursue a diverse innovation portfolio.

Mr. CLOUD. You say that climate doesn't necessarily care where emissions come from. In a sense, too, the market doesn't care where the energy source comes from, and the appetite globally for energy is growing. And it seems like one can make the case in a sense that we've now become the leading exporter of energy to the world, which is in essence creating stability in the world. People are able to buy energy from us instead of countries that hate us. U.S. companies generally also are more likely to care about being good stewards of creation so to speak than other energy-producing nations. Could the case be made that this continued progress in this sort of realm would actually have more of a beneficial environmental effect going down the line?

Dr. MAJKUT. Yes, if I interpret you correctly, I think so. Generally, U.S. practices are at the higher end on lots of environmental compliance issues. It also means freely available low-carbon energy is the thing that's going to power the 21st century and make everybody better off.

Mr. CLOUD. And could you also speak to how important a thriving economy is to creating innovative solutions?

Dr. MAJKUT. It's totally essential. What we seek in the Niskanen Center, what I think is best for this issue is an economy that's flexible to new information, that provides routes for people to finance new projects and find profits where they can make them and then generally we want those—as long as those are low-carbon options, everybody is better off. That's exactly what we're looking to achieve.

Mr. CLOUD. Thank you. I yield my 4 seconds back.

Mrs. FLETCHER. Thank you. The Chair will now recognize Mr. Casten for 5 minutes.

Mr. CASTEN. Thank you. Look, there is—there is no greater threat to our economic well-being, our national security, and even our survival as a species than climate change, and I want to thank Chair Bernice Johnson for taking it seriously, making it a priority of this Committee meeting, and I want to thank all of our guests today for your implicit acknowledgment that while we have the authority in this room to debate and ultimately change the laws of the United States, we have no such authority when it comes to the laws of thermodynamics, so thank you.

I'd like to address my first question to Dr. Francis. We—I represent the 6th District of Illinois. We recently experienced a rather extreme cold snap. And as I think you know and we appreciate, these extreme low temperatures have in fact been attributed counterintuitively to warming in the Arctic that disrupts the jet stream. And yet we have a President who seems to think that a cold snap in one location disproves global warming. Could you please educate us on how global warming in aggregate can lead to periodic polar vortex events in the United States?

Dr. FRANCIS. Yes, thank you very much. It's not a simple story, and it's an emerging science research question, although the science has been progressing very rapidly in this particular connection between what's happening in the far north with weather patterns more generally and particularly with these extreme cold events in the winter. And what we're learning is that there's a region in the Arctic just north of western Russia where sea ice has been disappearing probably faster than anywhere else. And that particular location is special in the sense that when we lose ice in that area, it absorbs a lot of extra heat from the sun, which then gets returned to the atmosphere, and tends to create a pattern in the jet stream that can then influence the true polar vortex, which is much higher up in the atmosphere.

When these conditions all align, it can topple if you will the polar vortex, which is a spinning river of air around this pool of cold air that sits over the Arctic in the wintertime. And when it's a powerful enough punch to that polar vortex, it can cause it to deform or even split into different circulations, and that's exactly what happened this past winter that brought you a new record cold temperature for Illinois. One of these pools of cold air from the Arctic drifted down over North America and reinforced the cold air that's already there during the wintertime. So this connection back to sea ice loss is the climate-change connection because that sea ice is disappearing because of global warming.

Mr. CASTEN. Thank you. While Illinois has seen an increase in extremely cold weather, we're also seeing an increase in extreme heat events. We saw it back in 1995 with the great heat wave in Chicago. A lot of the focus has been on urban impacts. There was a recent 2017 study in Environmental Health that analyzed heat waves in Illinois and found that there were actually significantly higher increases in hospitalizations per capita in rural areas.

And with the consent of the Chair, I'd like to ask unanimous consent to enter this study into the record.

Mrs. FLETCHER. Without objection.

Mr. CASTEN. Thank you. The—my next question is for Dr. Mahowald. The cost of climate—of inaction on climate change is high, but over the last two decades we've seen cost of renewable technologies fall, lots more opportunities for energy efficiency, and at least some initial decoupling of economic growth from CO_2 emissions. This is frankly not that surprising to me. I don't think—nor to the business community because I think we all recognize that when we buy less fossil fuel, we actually save money and we have a little bit more money in our pocket, notwithstanding some earlier conversations about air-conditioner economics. If you invest a little bit more capital today to save a lot of money later, that's a good thing.

Dr. Mahowald, you had mentioned in your testimony that limiting warming can in fact go hand-in-hand with increasing economic prosperity, which I hope means that you agree with the points that I just made. I would welcome your thoughts on some of the policy changes you would encourage us to take up that would both lower CO_2 emissions and incentivize more investment in the United States and economic growth.

Dr. MAHOWALD. Well, thank you for the question. I want to be honest here. I'm actually a physical science expert, but I will talk a little bit about what the special report 1.5 has to say on the issue. The important thing that we looked at in this report is where one can cut emissions in the most economic way that also has benefits locally, for example, on air quality or ways that you can change people's behavior that makes them healthier, as well as address this climate change. For example, if Americans and Europeans actually ate the amount of meat and dairy that their doctors recommended they do, they would be healthier. In addition, this would cut emissions of greenhouse gases. So there are a lot of ways that you would save money because you're healthier, humans would be better off, Americans and Europeans would be better off and always, less hospital visits, feel healthier, and at the same time we're trying to address climate change. So there's quite a bit in the report where there's benefits from climate mitigation that we can feel right now.

In addition, the—just the switch in some policies would make it easier for businesses in these innovative new sectors to have a stable business environment. And what's happening in the United States now is the fragmentation a little bit. Some States are more aggressive than others. And so at the Federal level it would help trade within the United States if there was a little more leveling of the terrain.

But overall, there are a multitude of policies and techniques and technologies that are proposed in this special report 1.5 that each individual State and local government, as well as the Federal Government, should evaluate that can make it so that it's economically beneficial to address climate change. Thank you.

Mr. CASTEN. Thank you. And I yield back my negative 1 minute, 30 seconds of time.

Mrs. FLETCHER. Thank you. The Chair will now recognize Mr. McAdams for 5 minutes. Oh, I'm sorry.

Mr. MCADAMS. Thank you.

Mrs. FLETCHER. I'm sorry, Mr. McAdams.

Mr. MCADAMS. Yes.

Mrs. FLETCHER. I didn't see you, Mr. Marshall.

Mr. MCADAMS. OK.

Mrs. FLETCHER. I didn't see that you were sitting—hadn't gone. I'm sorry. The Chair will now recognize Mr. Marshall for 5 minutes and then Mr. McAdams.

Mr. MARSHALL. OK. Thank you, Madam Chairwoman. Let me make my first official words as Ranking Member to wish you a happy birthday as well. And I'm looking beside me here—I was going to ask all the Members to join me in singing happy birthday so the people in the audience are going to have to help me here, Lizzie, OK? Happy birthday to you, happy birthday to you, happy birthday, dear Lizzie, happy birthday to you.

Mrs. FLETCHER. Thank you very much.

Mr. MARSHALL. You're welcome.

Mrs. FLETCHER. Your 5 minutes can begin now.

Mr. MARSHALL. OK. All right. Well, I want to just take a second and focus on innovation. I'm a physician. I think innovation has done more to improve healthcare probably than anything I can think of. It has the potential to drive the cost of healthcare down more than any legislation that we can write up here. And I think of some of the great learning institutions, research institutions in Kansas, Kansas State University, Kansas University, Wichita State University.

So, Dr. Majkut, let me ask you. If I'm going to go back, I'm going to be visiting with my leaders in those universities, what would you be telling them to think about for innovation, for research, and where do you see us going? Just give you some free rope here and chat a little bit.

Dr. MAJKUT. I'm sure I would have a lot of ideas to share with them. I think we have a good grapple on the nature of this issue, and we have a good sense of what it is that we still need, right? Renewable energy is—we talked a little bit about today. It's doing well. It's market-competitive in a lot of cases, but it's intermittent, right, not just because like the sun doesn't shine at night, but sometimes, over the space of months or years, you're going to get different weather patterns, and that's going to affect things.

So really what we need to think about are what are the characteristics in energy sources that we want going forward that we don't already have? So that might be easily dispatchable, very resilient, low-carbon energy sources, for example. Identify those, understand where you can find the most scale, both here in the United States and internationally, and pursue them with speed and vigor.

Mr. MARSHALL. OK. I think about innovation across the country, fracking, some of those types of things are opportunities, carbon capture. Would you suggest us developing innovation here to help other countries? Do you think we should just send money to other countries to help them do things?

Dr. MAJKUT. I think we should focus on innovation. All of our policies should be—at least as a side benefit, incentivize people to innovate new ways of doing things because what we really want is for people to do a lot more globally while emitting a lot less, and that's an innovation challenge primarily.

Mr. MARSHALL. OK. What's the coolest innovation thing out there that we haven't talked about today?

Dr. MAJKUT. Oh, that's interesting. Energy storage, the idea that we can find lots of interesting ways either through mechanical or chemical means to store a lot of energy is a very, I think, an interesting thing. My favorite example is very large flywheels like you have in the clutch of your car. You can, when you have excess energy, spin them up and when you need to take energy out of the storage system, you generate it from this massive spinning wheel.

Mr. MARSHALL. OK.

Dr. MAJKUT. I don't know that that's being deployed, but it's a great idea.

Mr. MARSHALL. OK. Thank you so much. I yield back.

Mrs. FLETCHER. Thank you. I'll now recognize Mr. McAdams for 5 minutes.

Mr. MCADAMS. I was going to sing happy birthday to you. You beat me to it.

Mr. MARSHALL. Oh.

Mr. MCADAMS. Thank you, Madam Chair, and I'm happy to be here for this hearing and for putting climate science at the top of our Committee's priorities for this Congress. I think it's an important issue for the entire Congress and happy to see us taking it up here on the Science Committee as well.

Thank you to our witnesses for your—providing your expert testimony and really enlightening this conversation.

I'm excited to join this Committee and to have an opportunity to understand the latest in climate research and highlight its importance in shaping our policies that will result in clean air, better environmental health, and a clean-energy economy.

As the former Mayor of Salt Lake County, a county in Utah that often sees schoolkids kept inside for recess because the air's not safe to breathe. I have four kids myself and was shocked to learn that part of their common vocabulary is "it's an air day," meaning they have—they don't play outside at recess. They come home bouncing off the walls because they've been kept inside all day.

I know how important it is that we address our winter inversions in Utah, our summer ozone pollution, but while climate change is certainly real and important to us as a—to our global—to us as a planet, it's also very important locally and the impacts that we feel locally vary from place to place, but we see it locally even in Utah. I know how important and imperative it is for Utah families to apply sound science to the solutions that we seek.

Utah remains the youngest State in the country, and numerous studies document the risk to pregnant mothers, to their newborns, and to those with respiratory problems such as asthma when they're exposed to dirty air. We've long been aware of the harm to older adults with heart and lung ailments as well, even the likelihood of premature death.

Utah is keenly aware of the economic costs of climate change as well. When the Wasatch Mountains are not visible due to smog, our ability to sell our region to—we're a region where tourism is an important part of our economy. The ability to sell our region to a new lifestyle-oriented businesses, it's greatly diminished.

Utah has had its share of environmental issues as well, devastating environmental issues from last summer's catastrophic wildfires to extended drought to the shortening of a ski season, first-world problems I recognize, but it does have an impact on us when snow melt comes late and melts early. We also—in a desert area, much of our watershed is captured and stored in the form of snowfall, and then as snow melts, we have reservoirs, but as we have less snowfall and more rainfall, the ways in which over the last couple of centuries we've adapted to living in a desert, will not be adequate as climate patterns change and will be expensive for us. We can adapt fortunately. Unlike some places, we can adapt, but it will be expensive to us locally.

So I think Utahns support efforts to protect our air, to protect our water, to protect our quality of life that we experience in our Rocky Mountains, and in fact our early pioneer settlers in Utah understood that in an arid landscape water is life itself, and anything that threatens the climate threatens our ability to sustain life over the long-term.

As elected leaders, we have the capacity and the responsibility to have fact-based discussions about the issues of climate and environmental protection, and it is critical to our Nation's goals for environmental sustainability, for economic prosperity, and our national security.

So I believe that hearings such as the one today shows that we are serious about protecting health and spurring innovation to address the challenges that we face to transition to a clean-energy economy, and I'm proud to be here and to be part of the solution.

I'm looking forward to working with this Committee to advance solutions to our climate crisis and to jumpstart, as I've said, a clean-energy economy.

So my questions—I guess I'm almost out of time, so my first question and it may be my only question is to Dr. Ebi. The Fourth National Climate Assessment explains how the health of vulnerable populations such as older adults and children will be disproportionately affected by climate change. What are investments in research, not only technology research but also research to the health and other areas of research should we make to further identify, to mitigate, and maybe even remedy these risks?

Dr. EBI. Thank you for the question. It is such an important issue. As I mentioned before, the total Federal investment in this area is really incredibly small. A review by the Office of Management and Budget several years ago said that the NIH (National Institutes of Health) budget in this area is less than 0.02 percent of the budget, and it's likely fallen since then. CDC (Centers for Disease Control and Prevention) gets a little bit of money to work with communities. So what we're seeing are communities who are disadvantaged and don't have access to those who can help them. They don't have access to the research. Very few Departments of Health have access to the kinds of tools that they need. And we've got enormous opportunities to build on the research enterprise to improve the health of Americans right now. And it would be excellent if that investment would take place so that that could start soon.

Mr. MCADAMS. Thank you. Thank you, Madam Chair.

Mrs. FLETCHER. Thank you. Next, we'll hear from Ms. Hill for 5 minutes.

Ms. HILL. Thank you, Madam Chair. So to our guests I want to thank you so much for your testimony, and I apologize for jumping between hearings this morning. But I—based on what I've heard so far, my impression is that in this Congress we should focus on setting the stage and laying the groundwork for the next 20 to 30 years of addressing this issue. I'm hearing that we should focus on research, on infrastructure, on regulation, on public and private partnerships, and on global partnerships and leadership. And I'm wondering from you if you can talk—this question is to all of you—about in each of those areas, what are just the biggest gaps in research where we need to prioritize, the highest priority when it comes to infrastructure as we're working on an infrastructure package, the biggest concern or need when it comes to regulation, the most significant impact we can have in terms of corporate incentives related to the public-private partnerships, and when it comes to the role of foreign policy on global partnerships and leadership. I realize those are a lot of questions, but pick the area you want to focus on and then just give it to me.

Dr. KOPP. So quickly to give everyone—everybody have some time, I agree with all of the things you raised. One thing I think we need to think about is that this is a multigenerational challenge, so as we make the investments today—and I'm going to talk about the research enterprise—we need to think about, well, how are we building the research enterprise to help us deal with the fact that this is a problem that's not going away; it's a chronic problem? And so I would argue we need to be investing in something comparable to the agricultural extension program in our country where we have networks of researchers deployed throughout the country who serve as bridges from the research community to the people on the ground and help build those partnerships and sustain them so that they're not dependent upon a grant here or there or personality here or there but we're really building the sustainable research infrastructure to build a link between science and people making adaptation and mitigation decisions on the ground.

Dr. FRANCIS. And maybe just a little more specifically more related to my field would be some research priorities perhaps that this country has fallen behind in my opinion in terms of model development for climate modeling, and I think this is one of our primary tools for understanding what our future holds based on different scenarios for the future. And also seasonal forecast models, so understanding how the climate change is going to affect weather patterns, so not so much what the weather's going to be tomorrow but getting a bigger lead time in weather patterns that will affect agriculture, which we talked about earlier, and other aspects to infrastructure, that sort of thing.

Dr. MAJKUT. I think on the advanced research side focusing on having a portfolio of options available. This problem looks a lot different today than it did 10 years ago. I think we can reasonably expect it'll look pretty different 10 years from now. And we want to leave our future policymakers or when you're all much senior—more senior, a lot of options on the table. I think that's a really important thing because the scale of the change that will be needed to meet the goals in these reports is substantial, not impossible, but it's substantial.

Ms. HILL. Well, and I think for you in particular, Doctor, I was curious about your thoughts on the public-private partnerships and the corporate incentives that we might be able to put into place.

Dr. MAJKUT. I personally—and as an institution we see a fairly limited role for public-private partnerships. Largely, I think we should be focusing more on market design and particularly we support carbon tax in lieu of regulatory approaches——

Ms. HILL. OK.

Dr. MAJKUT [continuing]. Which we presently have.

Ms. HILL. OK.

Dr. EBI. I'll add an issue that hasn't been raised is multidisciplinary. We've talked about a whole range of risks of a changing climate. Those all interact. They don't happen at once. They happen together. We're seeing heat waves and wildfires. And so making sure that we have the partnerships not only with our stakeholders but across the scientific community, which requires different thinking about how we conduct our research and frankly then how universities are organized to do that research. And so there does need to be significant incentives to move from a disciplinary-based focus to a much broader focus of how we can collectively put together our wisdom, working with the knowledge from our stakeholders, to come up with the innovative solutions that we need.

Ms. HILL. Thank you.

Dr. MAHOWALD. If I can speak?

Ms. HILL. OK. I can't quite hear. Yes. I'm looking at the TV. I have no idea if you know that I'm talking to you.

Dr. MAHOWALD. So I did see you, but thank you for the question. I just want to mention also the area of carbon dioxide removal, we not only need to be working on mitigation and adaptation but a new area of carbon dioxide removal, there's a lot of potential in this area, and there's very little research money being put into this so far from the Federal Government, for example, or from companies.

So this is a new area that could also be very beneficial for reducing climate risk in the future. Thank you.

Ms. HILL. Thank you so much. Do any of you have anything to add in the last 30 seconds? Great. Thank you so much. I yield back.

Mrs. FLETCHER. Thank you. The Chair will now recognize Mr. Lipinski for 5 minutes.

Mr. LIPINSKI. Thank you, Madam Chair. I was just speaking at an Introduce a Girl to Engineering Day event, and I was saying we need everyone that we can get on board to work on the solutions to the big problems that we face. And I mentioned specifically climate change being one of these major problems that—where we're going to need all of the work that—all the best minds and brightest to figure out how we move to a clean-energy economy. One thing I think that we can do a good job at is from the government side is putting more funding into ARPA-E (Advanced Research Projects Agency - Energy) to help move some of these—get some of these innovations developed, moved forward.

But another thing that I have been supportive of—and 10 years ago I actually introduced the first bipartisan carbon fee bill that was introduced where all the money would go back to the public, a fully refunded carbon fee. So I want to ask Dr. Majkut, you just briefly mentioned it. Why do you think that that would be an especially good way to approach this issue?

Dr. MAJKUT. Three reasons. The first is when you take a direct run at the problem, which is greenhouse gas emissions, you are hopefully finding the lowest-cost option. That way you're not playing favorites, renewables versus carbon capture versus nuclear, and you're not pre-committing to things. Rather, decisionmakers throughout the country, whether they are engineers at Exxon Mobil or utility executives, are making decisions to favor low-carbon options. And all their efforts add up relatively quickly. So there's a strong cost-effectiveness and a strong efficacy argument there.

The other reason is—or the second reason is that insofar as this is a question of how do we get affordable, reliable, low-carbon energy out at scale, mechanisms like carbon pricing are the easiest way to achieve scale incentives for all those decisionmakers I just mentioned.

And the third is I think importantly the signal that comes from there being congressional intent on climate change for problems of these timescales, decades, is very important. It provides a lot of certainty for economic firms out in the world both here and abroad that the United States is moving in a particular direction. In the environment we have now, we don't have that.

Mr. LIPINSKI. Thank you. Some of the questions have focused on, well, what are going to be the negative economic consequences from doing something on climate change. I want to focus from a scientific standpoint on what are the consequences to the U.S. economy that—if we fail to address this and slow the rise of greenhouse gases. What do you think—what would you worry about the most? So who wants to start? Mr. Kopp?

Dr. KOPP. Sure. Thank you. So we actually had a paper out on that a couple years ago, and we looked at several different types of impacts. The two that floated to the top were both public health impacts, so the effects on mortality and the effects on the ability of people to work outdoors. Both have quite large economic impacts. We also see economic impacts associated with the stresses that warmer temperatures put on the energy system. We see economic impacts from the damages that storms cause to the coast. We see economic impacts from the effects of warmer temperatures on agriculture. And those are just the sort of sectors where we can sort of look at past behavior and say something about the future. We also have a fair bit of concern about the things that we haven't observed yet in the past that might cause risk. So when we start having more extreme events happening simultaneously, that's a potentially large impact that's harder to assess.

Mr. LIPINSKI. Thank you. Who—anyone else want to add anything? Dr. Francis?

Dr. FRANCIS. So just to follow up with—on that a little bit, we know that in 2018 the losses due to extreme weather were roughly $160 billion just to the United States, and the year before, 2017, they were up around $300 billion, so we're not talking about small numbers here.

But I think what keeps me up at night is thinking about my own daughter and the world that she's going to face if we do nothing, and it—for me the scariest thing is thinking about the security issues overseas and how people are going to be more miserable and therefore more unhappy, and we're going to be dealing with a lot more migration and wars that are the result of people just being very unhappy in their situation.

Mr. LIPINSKI. That's very sobering, but I think it's a good way to end on that concern as we work on moving forward to solve this. And I yield back. Thank you.

Mrs. FLETCHER. Thank you.

Before we bring the hearing to a close, I want to thank our witnesses for being here today and testifying before the Committee.

The record will remain open for 2 weeks for additional statements for the Members and for any additional questions the Committee may want to ask of the witnesses.

The witnesses are excused, and the hearing is now adjourned.

[Whereupon, at 12:48 p.m., the Committee was adjourned.]

Appendix I

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Robert Kopp

Response to Questions for the Record

Robert E. Kopp
Professor, Department of Earth and Planetary Sciences
Director, Rutgers Institute of Earth, Ocean, and Atmospheric Sciences
Rutgers University – New Brunswick

Questions submitted by Rep. Mikie Sherrill, NJ-11

1. Dr. Kopp, your prepared remarks indicated that climate change is not just an environmental challenge, but also an infrastructure challenge. After natural disasters, the immediate response is short term solutions to restore existing infrastructure rather than implementing measures to make our country more resilient to climate change.

   I just met with thirteen members of local government in my district on how to address flooding that exceeds historical norms and the capacity of local communities to respond.

   Given the work Rutgers is doing in this space, can you elaborate on the needs and economic benefits of sustainable infrastructure? How can we better allocate federal funding to address these threats?

Infrastructure built today will last for decades to come – in some cases, quite possibly over a century. For example, the existing rail tunnels under the Hudson River are about a century old; it is thus quite plausible that the new rail tunnel planned to be built will last well into the next century. Over such time scales, climatic conditions may change dramatically, particularly if net greenhouse gas emissions are not expeditiously brought to zero. It's therefore crucial that planning for major infrastructure investments consider the broad range of possible futures to which they might be exposed, and that they are designed in a manner that allows them to be resilient across that broad range. In some cases, that may mean designing for high-end climate change futures; in other cases, that may mean designing in contingency plans for high-end futures (an approach sometimes called 'adaptive management' or 'flexible adaptation pathways').

I would argue that we should expect the design process for major infrastructure investments receiving federal funds to include a rigorous exploration of design resilience to the range of possible futures. That is to say, if new infrastructure will still be around in 2080, the design should include contingency plans that will be followed if we learn in a decade or two that global average sea-level rise by 2080 will approach four feet (the very high end of projections for that time); if like, the Hudson River tunnels, the new infrastructure will still be around in a hundred years, the design plans should including contingencies for sea-level rise approaching ten feet. Similarly, the full range of projections regarding intense rainfall need to be taken into account when building infrastructure that is vulnerable to it. Such flexible adaptation pathways are already encouraged by some states and cities, such as California and New York City.[1]

The 2014 report of the President's State, Local, and Tribal Leaders Task Force on Climate Preparedness and Resilience made a variety of recommendations regarding infrastructure that are worthy of consideration.[2] These include:

- Requiring consideration of climate-related risks and vulnerabilities as part of all Federal investments;
- Maximizing opportunities to take actions that have dual-benefits of increasing community resilience and reducing greenhouse gas emissions;
- Promoting and prioritizing the use of green and natural infrastructure ;
- Supporting and incentivizing climate resilient water resource planning and management; and
- Assisting transportation officials in better understanding the vulnerabilities and risks to transportation networks and facilities and integrate climate resilience planning and preparedness criteria throughout existing Federal transportation funding programs.

More generally, as we assess the state of our nation's infrastructure, it's important that we evaluate not just whether it is in good repair, but whether it is in a state of good resilience. Repairing infrastructure to a state designed for climate conditions of the past is an inadequate approach, given that those conditions are now behind us.

In addition, it is important that climate-related infrastructure decisions take into account the benefits of avoided greenhouse gas emissions. Under the Obama Administration, interagency estimates of the social cost of greenhouse gases provided a uniform, scientifically grounded approach to incorporating the costs of greenhouse gas emissions (and the benefits of their reductions) into regulatory decision-making. Toward the end of the Obama Administration, their use was being broadened to a variety of other planning and investment decisions. Reinstating and expanding their consistent use – and investing in the underlying scientific and economic research – can help ensure that such decisions are based upon an economically sound approach.[3]

2. I appreciated that you discussed national security as a major area under threat of climate change, Dr. Kopp. Can you elaborate on the impact that climate change will

[1] NEW YORK CITY MAYOR'S OFFICE OF RECOVERY AND RESILIENCE, CLIMATE RESILIENCY DESIGN GUIDELINES (2018), https://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v2-0.pdf; CALIFORNIA OCEAN PROTECTION COUNCIL & CALIFORNIA NATURAL RESOURCES AGENCY, STATE OF CALIFORNIA SEA-LEVEL RISE GUIDANCE: 2018 UPDATE (2018), http://www.opc.ca.gov/climate-change/updating-californias-sea-level-rise-guidance/.
[2] PRESIDENT'S STATE, LOCAL AND TRIBAL LEADERS TASK FORCE ON CLIMATE PREPAREDNESS AND RESILIENCE, RECOMMENDATIONS TO THE PRESIDENT (2014), https://obamawhitehouse.archives.gov/sites/default/files/docs/task_force_report_0.pdf.
[3] See NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE, VALUING CLIMATE DAMAGES: UPDATING ESTIMATION OF THE SOCIAL COST OF CARBON DIOXIDE (2017) for an in-depth discussion.

> have on our nation's warfighters and its contribution to increased national security threats?

The Fourth National Climate Assessment[4] identifies several ways in which climate change will impact U.S. security interests.

Climate change has already led to increases in extreme weather, and these increases will continue with further change. For example, sea-level rise is already enhancing the flooding associated with hurricanes, and climate change is projected to increase their wind intensity. Climate change is also already increasing the amount of rain falling in intense events, and thus the associated rain-driven flooding. Climate change is also increasing drought risk in some regions.

As the National Climate Assessment notes, "Developing countries are often highly vulnerable to climate extremes, which can set back development and increase the need for disaster response and recovery assistance."[5] The Department of Defense is often a key participant in post-disaster response efforts around the globe.

While the direct effect of climate extremes on conflict risk remains a contested topic of research, it is clear that the effects of chronic development reversals can increase the risk of civil conflicts, which may affect US security interests.[6] Climate change is also a potential driver of increased migration. As the NCA notes:

> Extreme weather events can in some cases result in population displacement... [T]ropical cyclones are projected to increase in intensity, which would increase the risk of forced migration. Slower changes, including sea level rise and reduced agricultural productivity related to changes in temperature and precipitation patterns, could also affect migration patterns. However, whether migration in response to climate change will generally cause or exacerbate violent conflict is still uncertain.[7]

Department of Defense assets are also exposed to the effects of climate change; as the National Climate Assessment notes, "Climate change is already affecting U.S. Department of Defense (DoD) assets by, among other impacts, damaging roads, runways, and waterfront infrastructure."[8] US Coast Guard assets are similarly exposed.

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[4] J. B. Smith et al., *Climate Effects on U.S. International Interests*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 604–637 (C. W. Avery et al. eds., 2018), doi: 10.7930/NCA4.2018.CH16.

[5] *Id.* at 610.

[6] SOLOMON M. HSIANG & AMIR S. JINA, THE CAUSAL EFFECT OF ENVIRONMENTAL CATASTROPHE ON LONG-RUN ECONOMIC GROWTH: EVIDENCE FROM 6,700 CYCLONES (2014), http://www.nber.org/papers/w20352 (last visited Apr 30, 2018); Solomon M. Hsiang, Marshall Burke & Edward Miguel, *Quantifying the influence of climate on human conflict*, 341 SCIENCE (2013), http://science.sciencemag.org/sci/341/6151/1235367.full.pdf; Håvard Hegre et al., *Forecasting civil conflict along the shared socioeconomic pathways*, 11 ENVIRON. RES. LETT. 054002 (2016).

[7] Smith et al., *supra* note 4 at 613.

[8] *Id.* at 613.

Domestic DoD bases are not isolated from their surrounding communities. Thus, it is important that DoD consider climate impacts not only directly on its own facilities, but also on the communities surrounding their installations that support base functioning. My colleagues at Rutgers have been involved in one such integrated study, the Joint Land Use Study for Naval Weapons Station Earle.[9]

3. New Jersey has set a state standard to reach one hundred percent clean energy by 2050. Yet, we to address climate change through achievable goals and by setting national standards.

   Dr. Kopp, you and your team at Rutgers, the State University of New Jersey, including Jennifer Francis, also on the panel, are doing excellent work on climate science given the resources the federal government has made available for this science. What sort of investments in the climate science enterprise could help make climate science more actionable and bridge the gap between the research and implementing a national energy plan?

An actionable climate science enterprise requires a significant focus on what is sometimes called 'transdisciplinary' science.[10] Transdisciplinary science brings researchers from different disciplines together with stakeholders to tackle a common real-world problem. Transdisciplinary science is not necessarily applied research, as it may aim not only to translate existing understanding into practice but also to address some of the fundamental scientific uncertainties relevant to effective risk management. The tie to real-world problems is, however, a core element.

Climate risk management – both on the mitigation and adaptation sides – calls out for such transdisciplinary research, as well as for educational initiatives preparing students to conduct such research. At Rutgers, we have a number of such efforts. For example, our Coastal Climate Risk and Resilience program[11] trains graduate students to work with natural scientists, social scientists, engineers, urban planners, and stakeholders to manage coastal risk. The New Jersey Climate Change Alliance[12] is a University-managed network of stakeholders that links scientific experts with local, state, and private decision-makers. We are a partner in the Climate Impact Lab, which is bringing climate scientists, economists, and data scientists together with stakeholders in state governments and the private sector to better integrate economic assessments of climate risk into regulatory and investment decisions. And we are working with the state to help build a New Jersey Wind Institute, which should bring a transdisciplinary approach to science and engineering related to off-shore wind energy.

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[9] See https://www.visitmonmouth.com/page.aspx?ID=4782.

[10] Gertrude Hirsch Hadorn et al., *The Emergence of Transdisciplinarity as a Form of Research*, *in* HANDBOOK OF TRANSDISCIPLINARY RESEARCH 19–39 (Gertrude Hirsch Hadorn et al. eds., 2008).

[11] For more information: c2r2.rutgers.edu

[12] For more information: njadapt.rutgers.edu

But true transdisciplinarity is hard – it requires a considerable investment on the part of researchers or their institutions in maintaining strong, working, trusting relationships with stakeholders. And building such relationships takes time – if it must be done from scratch, it does not fit well with the time pressures faced by pre-tenure faculty or graduate students.

Right now, in the climate risk area, most transdisciplinary collaborations are driven by strong personalities or short-term funding opportunities. But the climate risk problem is not going to go away. Society is not well served if the networks that sustain such collaborations have to be rebuilt when individuals leave an institution or funding temporarily dries up.

Fortunately, there is an example of academic institutions supporting transdisciplinary collaborations that has worked in the United States for over a century, long before the modern jargon of 'transdisciplinarity' was coined.

In 1862, amidst the bloodshed of the Civil War, Abraham Lincoln signed the Morrill Act, establishing the United States' land-grant college system. The Morrill Act and follow-on legislation transformed higher education in the United States. They established a network of universities devoted to training the next generation of farmers and engineers, conducting innovative and useful research to advance agriculture, and engaging with farmers to disseminate the fruits of this research. The Smith-Lever Act of 1914 established cooperative extension services at land-grant institutions with the aim of bringing scientific knowledge about agriculture out of the universities and into the country. The cooperative extension services have placed agents in every US county and built networks of trust that link the land-grant institutions to the (primarily agricultural) community.

It is worth considering an investment analogous to that of cooperative extension in expanding the infrastructure for scientific climate risk management. The unique advantage of land-grant universities is the extension tradition, upon which can be built robust networks to sustain stakeholder engagement in climate risk research and education. This requires support to shift the maintenance of stakeholder networks away from individual investigators and grants and to the institution.

Building upon the extension strength also requires addressing countervailing incentives at the level of the individual scientist. Transdisciplinary research is inherently slower than more ivory-tower research, requiring that researchers invest time in stakeholder engagement. More flexible tenure evaluation processes that recognize the value of this engagement can help advance this mission, and this shift would be assisted by appropriate nudges from funding agencies.

Responses by Dr. Jennifer Francis

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Dr. Francis Responses to additional Questions for the Record

1) You state in your testimony how extreme weather events have nearly tripled globally since the 1980s. You discuss the research that underlies this phenomenon, such as how global temperature rise is making heat waves more intense, and warmer oceans and air increases evaporation and thus heavy precipitation. In addition to the processes that we understand with high certainty, you pinpoint some of the emerging frontiers in this research such as uncovering complex interactions between the warming Arctic and the rest of the ocean and atmospheric system.

a. Given that there are a number of frontiers in climate science that need more research to understand how the climate system is changing and will continue to change, which additional research needs related to climate science should be prioritized by federal funding?

In my opinion, the following areas of research related to climate science should be prioritized for federal funding:

- Identification and characterization of critical thresholds and tipping points in the climate system, beyond which reversal is most likely impossible. Policies should be designed to avoid crossing them. Thresholds may exist in both the physical climate system (e.g., amount of ice-sheet loss tolerable before runaway melting occurs, weakening of the capping surface layer in the Arctic Ocean that prevents warm Atlantic water from coming into contact with sea ice) and in ecosystems (e.g., minimum population of a species before extinction). The National Academies of Sciences report *Abrupt Impacts of Climate Change* (2013) is an excellent resource for this topic: https://www.nap.edu/catalog/18373/abrupt-impacts-of-climate-change-anticipating-surprises
- Proactive and reactive adaptation to climate-change impacts. As the climate changes, we will be forced to adapt one way or another. We have a choice:
    - Research to inform proactive responses – Based on climate projections at local/state levels, develop strategies to prepare for gradual change (e.g., sea-level rise, overall warming) and increasingly disruptive extreme events. Strategies should include making infrastructure more resilient (move or reinforce it), designing disaster plans to address future (not past) event likelihoods, reviewing building permit criteria to disallow construction in vulnerable locations, and promoting public education programs to alert residents to dangers and emergency plans. Proactive adaptation will save lives and money.

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- Research to inform reactive response – Smart adaptation strategies will not be able to prepare society for all extreme events, so more efficient and thoughtful emergency response plans – guided by up-to-date impact projections – are required. Reactive approaches alone will result in higher casualties, greater property and infrastructure damage, and longer societal disruption. Research is needed to refine projections of extreme events, economic impacts, evacuation plans, and rebuild-versus-retreat strategies.

- Attribution science – assessing contribution of climate change to exacerbating extreme weather events. Research should be supported that addresses these questions:
    - Is climate change making this type of extreme event more likely? If so, where and under what conditions?
    - What role did climate change play in making a particular extreme event more or less severe?
    - How should federal/state/local policies adapt to prepare for expected increases in extreme events? (proactive approach)
    - How should federal/state/local policies be revised to guide recovery efforts after extreme events that occur repetitively in an area? Should neighborhoods, businesses, and public infrastructure be rebuilt, or should alternative locations be sought (retreat)? When does it become unfair to taxpayers to have federal relief aid spent on rebuilding homes/businesses/infrastructure in disaster-prone areas, particularly private residences?
- Observations – weather, ocean, ecosystems. Sustained measurements are critical to preparedness.
    - Maintain and expand satellite observation network. This is absolutely critical for weather prediction, climate science, and basic geophysical science.
    - Conventional observations systems (e.g., weather stations, ocean buoys, long-term ecosystem monitoring instruments) must be maintained because satellite-based measurements need to be calibrated and remote sensing cannot observe all needed variables.
    - Observations are key to change detection, early warning, and understanding complex interactions within the climate system.
- Social science – turning the tide on anti-science and promulgation of fake news. Research is needed to:

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- Understand why Americans have become more anti-science and how to reverse this trend.
- Target education that will equip citizens with tools to detect misinformation and malicious/manipulative information sources

b. What are the largest uncertainties in projecting future climate change and its impacts?

Regarding projections for the future climate, the largest sources of uncertainty are:

- the pace of ice-sheet melt: affects speed of sea-level rise
- changes in cloud properties: affects sensitivity of global warming to increasing greenhouse gases. Current research suggests that cloud changes are likely to exacerbate global warming
- complex responses of marine and terrestrial ecosystems: affects food security and health of natural systems
- technological breakthroughs: types and pace of advances in technology affect carbon emissions, adaptation strategies, and disaster recovery
- human behavior: responses to extreme events, food shortages, and lack of access to fresh water will affect stability of governments and our own national security. Acceptance of mitigation strategies will determine future carbon emissions and pace of climate change. Adoption of proactive adaption strategies will lessen impacts of climate change.

2) During the hearing, many Members brought up the importance of research and development for climate change mitigation and adaptation.

a. In addition to technological methods, are there other ways that carbon can be removed from the atmosphere? How can the research enterprise better support the development of these methods?

A variety of natural solutions exist that have many additional benefits beyond carbon sequestration:

- planting more trees
- eliminate forest clear-cutting

- improving soil quality in farming areas
- reducing greenhouse gas emissions by the agricultural sector (e.g., less wasteful use of fertilizers, alternative animal feed that reduces methane production, improved animal waste management, more efficient irrigation, smarter matching of crops to local climate).

b. Which approaches to adaptation should be prioritized by federal funding?

There is no single approach to adaptation that will solve the problem. In my view, the suggestions highlighted above are the highest priority approaches that should be supported with federal funding. Many others are also worthy of funding.

c. Which economic tools can be brought to bear to reduce carbon emissions?

- Discontinuing subsidies for fossil-fuel-related enterprises (such as exploration, drilling, pipelines, power plants, and distribution systems) while increasing incentives for the development of renewable energy sources could spur the development of low carbon electricity generation.
    - From 1950-2010, fossil fuels received $594B in subsidies (80%), nuclear $73B (10%), and renewables $74B (10%)[1].
- Recent implementation of carbon fee systems has shown that well-designed policies can reduce carbon emissions and have positive economic influences in the short term. The Tuft University's Climate Policy Lab[4] is systematically studying real word climate policies -- how well they work, and their economic consequences.
    - British Columbia has had a carbon fee program since 2008. Carbon fees are added to fossil fuels burned for transportation, home heating, and electricity, while personal income taxes and corporate taxes are reduced by a roughly equal amount. The fee is collected at the point of retail consumption. During the first five years of the program, fossil fuel consumption dropped 17.4% per capita and the tax shift enabled BC to have one of Canada's lowest income tax rates[2]. In October 2018, Canada as a whole adopted a similar program[3].
    - Revenue from carbon fee could be invested in proactive adaptation.

1. http://www.misi-net.com/publications/NEI-1011.pdf
2. https://en.wikipedia.org/wiki/British_Columbia_carbon_tax

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3. https://www.theguardian.com/environment/climate-consensus-97-per-cent/2018/oct/26/canada-passed-a-carbon-tax-that-will-give-most-canadians-more-money
https://sites.tufts.edu/cierp/research/climate-policy-lab/

Thank-you again for the opportunity to testify at your hearing. If I can be of any further assistance to your committee, please don't hesitate to ask.

Sincerely,

Jennifer Francis, PhD
Senior Scientist
Woods Hole Research Center

Responses by Dr. Joseph Majkut

Joseph Majkut - QFR - *The State of Climate Science and Why it Matters*

Responses to Mr. Posey

Q1: We make adjustments to solutions and objectives as we learn - all of the time being guided by a balancing of the benefits and costs. We have limited resources and money, so we must apply the best alternatives. Is that a reasonable strategy for dealing with climate challenges considering uncertainty and limited resources?

Yes. We should keep our policy approaches to climate and reducing emissions open to new information and be willing to make adjustments along the way.[1] Although this problem is urgent, it will take decades to change the energy system to reduce greenhouse gas emissions and forestall the worst case warmings.

Even over the next decade, we will likely learn a lot. We may learn that the hazards posed by global warming are more severe or less severe than scientists presently expect. We may learn that it is easier to cut greenhouse gas emissions than we had thought. We may also learn that it is harder. We may learn that it is easier to do so with one technology over another, or we may invent something altogether new.

In any of these cases, we want to be in a position to keep learning, updating our expectations, and adjusting our plans. As such, I would recommend maintaining a robust earth science enterprise to monitor the changing climate, an advanced research enterprise to keep pushing the boundaries on low-carbon technology, and a healthy and transparent market in energy services, so that consumers, businesses, and the public can find the lowest cost—or highest benefit—options.

Q2: Do we know the timing and future intensity of climate phenomena like temperature and more importantly, can we accurately predict how a policy change will affect the outcome? Can we really predict how the future climate will change if we, for example, reduce emissions by a given amount or are we just guessing/taking a stab in the dark?

I wouldn't say that we are completely guessing, but I would say that climate predictions are uncertain. What that means is that we cannot say what the global temperature will be in 30, 50, or 100 years with absolute precision. However, we are not shooting in the dark, especially when comparing different future scenarios. If we reduce global emissions quickly, then the climate at the end of the century will look fairly similar to the one we have now, with maybe another degree of warming. If global emissions continue to grow rapidly, then the climate in 2100 will look quite different, with several more degrees of warming.

As I discussed in my testimony–and as highlighted in the reports from the IPCC and US GCRP–the extent of climate change is related to the total amount of CO_2 emitted. So every ton

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[1] For a good description learning in the policy response to climate change, see The National Academies Report *America's Climate Choices*, Chapter 4: A Framework for Making America's Climate Choices, available online at https://www.nap.edu/read/12781/chapter/6

of CO2 emitted can be assigned an increment of warming. Similarly, every non-emission of CO2 will prevent an increment of warming. The timescales, however, are long because the earth system is a little slow to respond to changes in emissions, and changes in policy do not immediately change emissions. So the benefits of changing policy and reducing emissions play out over time.

The science indicates that policy changes which would reduce global emissions would prevent noticeable temperature increases on timescales of a few decades. Meaning that when scientists compare scenarios with high emissions to scenarios with low emissions, the global temperatures are noticeably different in the latter part of the 21st century–even though the emissions rates are quite different within a decade from now.

The table below is from the Intergovernmental Panel on Climate Change's 5th Assessment report.[2] Each row depicts the average warming and likely range of warming for a different scenario (the total human perturbation increases from RCP2.6 to RCP8.5). In observing the table, you see that the average warming between these scenarios starts to diverge in the mid-century, and strongly diverges by the end of the century.

Table SPM.2 | Projected change in global mean surface air temperature and global mean sea level rise for the mid- and late 21st century relative to the reference period of 1986–2005. {12.4; Table 12.2, Table 13.5}

		2046–2065		2081–2100	
	Scenario	**Mean**	***Likely* range[c]**	**Mean**	***Likely* range[c]**
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	**Mean**	***Likely* range[d]**	**Mean**	***Likely* range[d]**
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Q3: [On Solar Radiation Management or Geoengineering] Can you please elaborate on [geoengineering] in your testimony and share with the committee your recommendations for legislation in this regard, as well as the potential role for geoengineering?

In November 2018, the Niskanen Center included immediate policy recommendations for supporting geoengineering research, which is an presently only obliquely supported by the

[2] IPCC Fifth Assessment Report https://www.ipcc.ch/assessment-report/ar5/

federal government, in a report on emerging technologies.[3] I include here an excerpt from that report (italicized).

Geoengineering technologies are one prospective means of addressing climate change. As a class of technologies, they could potentially allow people to intervene in the Earth system at a large enough scale to deliberately alter the climate and decouple the total amount of warming from total emissions of greenhouse gases due to burning fossil fuels. Technological interventions to reduce the human influence on climate fall into two categories: Carbon dioxide (CO2) removal and solar radiation management (SRM).

CO2 removal, or negative emissions, describes technologies that would artificially remove CO2 from the atmosphere and thereby limit the warming and chemical effects of excess CO2. These are interesting technologies for research that are already aligned with much of what is done at the Department of Energy (DOE) and other agencies. SRM refers to interventions that would decrease the amount of solar radiation that reaches the surface of the Earth by increasing the planet's reflectivity. While there are technical nuances and regional variances, the amount of cooling we could expect to see is roughly proportional to the decrease in radiation. These technologies could therefore be tuned to partially or fully offset the warming effects of increased CO2 with a large enough intervention, while very small experiments would have no globally detectable signal.

For SRM, the research agenda is more novel, and governance requirements more pressing, than CO2 removal. Not all of the considerations that will govern decisions to use or refrain from using SRM technologies are scientific. However, numerous scientific and engineering gaps prevent an informed understanding of the costs and benefits of potential unintended consequences. Reducing uncertainties and better characterizing those risks presents the scientific enterprise with the opportunity to add value for future policymakers. The potential scale of climate risks and the costs associated with transitioning to a low-carbon economy mean that the potential value of SRM could register in the trillions of dollars.

Supporting this research, and a reasonable governance agenda, may not require a lot of authorizing legislation. Yet Congress could exercise its oversight role, and the power of the purse, to dedicate federal resources to a safe and well-managed research program.

To that end, our policy recommendations are as follows:

1. *Affirm the Office of Science and Technology Policy's role and authority in overseeing climate engineering research efforts;*

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[3] Joseph Majkut, Ryan Hagemann, Adam Wong *Geoengineering Responses to Climate Change Require Enhanced Research, COnsideration of Societal Impacts, and Policy Development* https://niskanencenter.org/wp-content/uploads/2017/10/Niskanen-Center-Comments-Climate-Engineering-AGU-2.pdf

2. *Convene an ongoing multistakeholder process under the purview of USGCRP that will prioritize the creation of voluntary, consensus-based policy guidelines and recommendations for future research priorities; and*
3. *Apportion dedicated federal funding for climate engineering research and development.*

Responses to Mr. Olsen

Q1: Are you familiar with the Parish Plant? What advances have we seen in CCS in recent years?

The Parish Plant is notable because it is, to my knowledge, the only functioning power plant in the United States that has been modified to use carbon capture and storage (CCS). With about 190 million dollars[4] in financial support from the DOE, the plant's operators installed a unit to capture 90 percent of the CO2 in the exhaust of one of the coal units.That captured CO2 is subsequently being used to increase production in a nearby oil field.

CCS has been piloted or demonstrated at a few plants like the Parish Plant, but it is not in wide use–nor is it regularly deployed on new natural gas or coal plants. The technology is still in its infancy. A 2018 report from the Global CCS Institute[5] found that there are 23 large-scale CCS facilities in operation or under construction around the world, capturing almost 40 Mt of CO2 per year, with an additional 28 pilot and demonstration scale facilities in operation or under construction. Although further deployment of CCS technology will probably help to bring down costs, as of now they remain too expensive to scale into today's commercial markets.

Q2: [In reference to carbon removal technology] Could you talk about some of the technologies you have seen on this front?

There are a number of different carbon removal strategies, each in different stages of development. Land management practices that store CO2 in agricultural soils and forests have proven to work, and are ready to be deployed today. The strategies that rely more on technology—such as direct air capture, which removes CO2 from the atmosphere and stores it—are either at the demonstration or pilot stages. There are additional technologies that are on the horizon, including enhanced weathering of rocks and the genetic modification of phytoplankton to increase their ability to sequester carbon.

As the IPCC SR1.5 report makes plain, in order to limit warming to 1.5 C, processes that remove carbon from the atmosphere will need to be deployed at a scale removing up to ¼ of today's global emissions per year. This is quite a staggering number, given that the technology

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[4] Peter Folger *Carbon Capture and Sequestration (CCS) In the United States*
https://fas.org/sgp/crs/misc/R44902.pdf
[5] Global CCS Institute *2018 Global Status Report*
https://www.globalccsinstitute.com/resources/global-status-report/

is still in its infancy. Direct air capture could cost as much as $400-1000 per ton.[6] These costs render this technology still too expensive to commercialize on the scale required to mitigate dangerous global warming.

Q3: What is the best way to target investments in this kind of technology?

There has to be value associated with removing CO2 from the atmosphere and using it to do something-keep it out of the air, or in a durable and useful product. Advanced research can look for new ways to make CO2 useful. If you want to consider just the task of keeping it out of the air, then Congress might consider increasing the incentives for businesses to innovate these technologies.

This can be done through financial support mechanisms and tax credits, such as the recently-reformed 45Q tax credit for the deployment of carbon capture and storage projects in the U.S. That program will credit companies that capture and store CO2. But given the cost of direct capture (see previous response), it is not clear that those credits will actually lead to deployment of CO2 removal facilities. It might be reasonable for Congress to look at prize models that would reward companies that are able to capture CO2 at lower prices.

Another policy incentive for expanding CCS and CDR technology would be to set a nation-wide price for carbon emissions. Carbon pricing, either through a carbon tax or a national cap-and-trade program, incentivizes emissions reductions and can be designed to credit carbon removal.

Response to Mr. Baird

Q1: [Referring to climate impacts on Indiana agriculture] What can we do right now to mitigate these effects, and what do we need to do for the future?

The Fourth National Climate Assessment[7] predicts that increases in temperatures during the growing season in the Midwest are projected to be the largest contributing factor to declines in the productivity of U.S. agriculture. Mitigating these effects requires that we reduce greenhouse gas emissions across the United States. Economy-wide emissions reductions would require national, regional, state, and/or local policy to reduce the dangerous impacts of climate change.

However, as mentioned in the testimony, climate change is a chronic condition and we must prioritize reducing societal vulnerability through adaptation. In the agricultural sector, producers can adapt to climate change through changing planting decisions, farming practices, and the use of specific technology that can reduce its negative impact on production. Making sure that

[6] National Research Council, Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration. https://www.nap.edu/read/18805/chapter/4#38

[7] U.S. Global Change Research Program *Fourth National Climate Assessment* https://nca2018.globalchange.gov/

farmers, their suppliers and insurers, and our research enterprise can work together easily and smoothly to share information and best practices will be helpful.

Further research into making crops and farming practices will also be helpful. This could involve more research and investment in genetically modified organisms that produce crops that are tolerant to heat, drought, pests and diseases. Current assessments[8] of genetically engineered crops have demonstrated economic benefits for producers, with no substantial evidence that these technologies harm human or animal health. Expanding this and other adaptation measures requires investment in research and development of these technologies, so that future generations can readily adopt these techniques.

[8] National Academy of Sciences *Genetically Engineered Crops: Experiences and Prospects* https://www.nap.edu/catalog/23395/genetically-engineered-crops-experiences-and-prospects

Responses by Dr. Kristie L. Ebi

Responses to questions from Committee Members

1) **In your testimony, you discuss how most policies to mitigate emissions of greenhouse gases have associated health benefits such as reduced air pollution, reduced temperature-related morbidity and mortality, fewer harmful algal blooms, and reduced insect-borne disease.**

   a. ***Can you please expand upon what the current research tells us about the health co-benefits of climate mitigation scenarios?***

   b. ***What is the state of research science modeling the co-benefits of mitigation policies?***

   c. ***Can you expand on how research on health co-benefits can serve policymakers that aim to implement climate mitigation policies?***

   d. ***How can policymakers better communicate this information?***

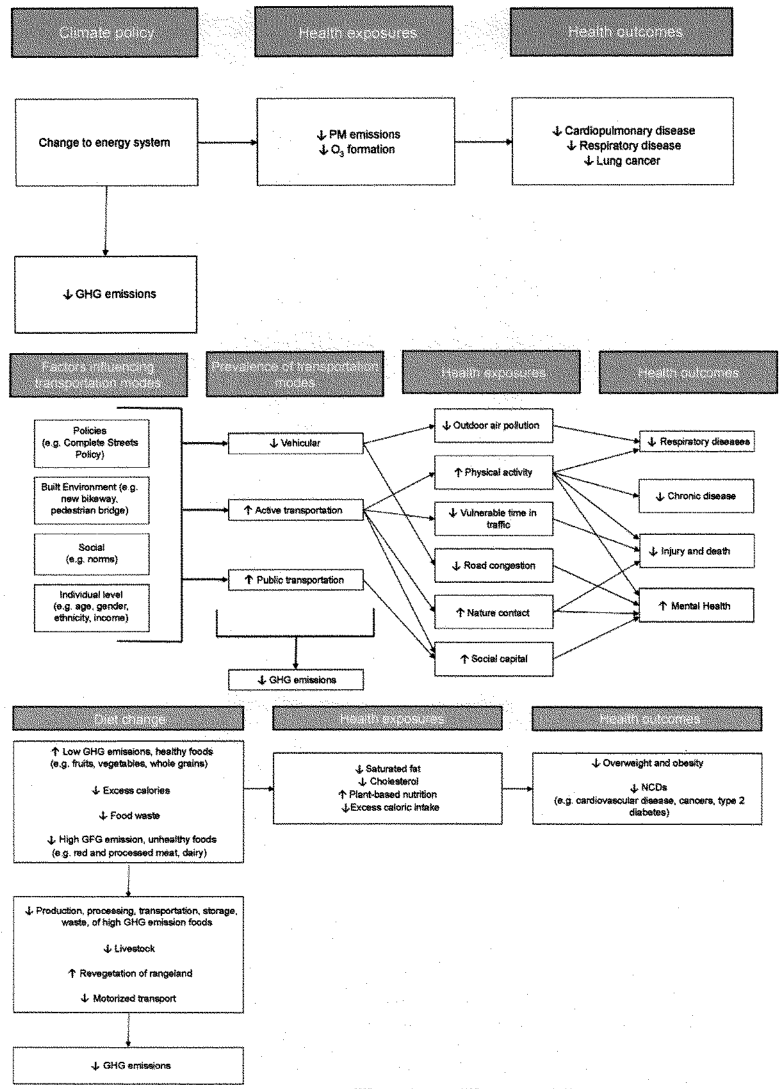
Thank you for the opportunity to clarify the health co-benefits of mitigation policies and technologies.

a) Co-benefits represent selected near-term, positive impacts of mitigation policies that can offset some portion of mitigation costs. Co-benefits arise from policy actions and are distinct from the avoided negative impacts of climate change that the policy action would forestall. Co-benefits are common in the health sector because many prominent sources of greenhouse gas emissions are linked with environmental exposures harmful to people's health. In general, the current research on health co-benefits of climate change mitigation shows that mitigation comes close to paying for itself if health co-benefits are included in cost-benefit analyses.

Health co-benefits are rarely estimated in economic assessments of the cost of implementing mitigation policies, such as those that could achieve greenhouse gas emissions reductions agreed to in the Paris Agreement. This is despite the fact that mitigation policies and technologies can benefit health by, for example, modifying exposures to air pollutants, changing physical activity patterns, and affecting dietary choices. *Ignoring cost savings due to health impacts provides an unbalanced underestimate of the net impacts of mitigation activities and the associated net costs and benefits.*

The figure below summarizes the pathways for health co-benefits. The three panels show the conceptual framework linking climate mitigation and health outcomes via air quality (top panel), transport (middle panel), and diet (bottom panel) from Chang et al. 2017[1].

[1] Chang et al. 2017. *Environmental Research Letters* 12:113001.



GHG = green house gas, NCDs = non-communicable diseases, PM = particulate matter, O_3 = ozone

Two recent evaluations of health co-benefits studies reviewed the health co-benefits of mitigation policy scenarios targeted at multiple sectors and domains, including air quality, transportation, diet, agriculture, housing, industry, and economy.[1,2] The review authors

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[2] Gao et al. 2018. *Science of the Total Environment* 627:388-402.

concluded that implementing a range of mitigation policies results in significant local health benefits that can occur within a few years of policy implementation. In nearly all cases, the economic value of avoided premature deaths and hospitalizations offset a significant proportion of the costs of implementation of the mitigation policies; in some cases, the health co-benefits nearly covered the cost of implementation. The health gains could be further multiplied by comprehensive measures that include more than one sector. In many instances, implementing mitigation policies makes sense because of improvements to population health even without considering the benefits for achieving climate policy. Both of these publications are attached.

Further, the US EPA led an extensive effort to estimate the health impacts and health-related costs by 2100 under Representative Concentration Pathway 4.5 and Representative Concentration Pathway 8.5 (different greenhouse gas emissions trajectories). The results are summarized in the Traceable Account for the Human Health chapter of the 4th U.S. National Climate Assessment; a copy is attached. This literature supported the Key Message:

> *Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term (high confidence). By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions (likely, medium confidence).*

b) There is a growing body of research estimating the health co-benefits of mitigation policies. A challenge with the literature is that most studies are more suited to describing the interaction of climate policy and health than providing specific, accurate estimates of health co-benefits. Greater consistency in modeling choices across studies would facilitate evaluation of mitigation options and promote the aggregate benefits.

To facilitate this, a workshop convened 5-7 March 2019 by the Wellcome Trust, the University of Washington, and the World Health Organization developed a consensus among health co-benefits experts on modeling approaches and inputs such that study outputs can be compared and assessed. A guidance document is being developed to increase the consistency of health co-benefits models such that results are more comparable. The University of Washington Center for Health and the Global Environment also is updating the recent reviews of the health co-benefits of mitigation policies, focusing on air pollution, transport, and diet.

As will be discussed in response to question 2 below, the lack of funding of health co-benefits modeling is limiting rapid advances in estimating health co-benefits at local to national scales. As opposed to other sectors, there are no centers of excellence with long-term funding to develop models across the range of possible health co-benefits.

Overall, methods are available for estimating health co-benefits, but the lack of sustained funding has limited the field's growth and ability to provide estimates of health co-benefits of specific policy proposals that might be under consideration at local to national scales.

c) As mentioned in response to question 1a, research on health co-benefits can provide policymakers with more holistic and realistic information on the costs and benefits of climate mitigation policies. The financial costs of climate mitigation activities do not reflect any beneficial benefits for human health. Mitigation health co-benefits studies can help identify the policies with the greatest benefit to health and to climate mitigation.

Case study research can also complement modeling efforts to provide policy-makers with localized evidence of health co-benefits, as well as compelling narratives and examples of replicable actions. Further, research can provide insights into whether mitigation policies could have adverse health consequences (dysbenefits or harms) and identify. measures that could be taken to reduce those harms.

d) There are several things that policy makers could do to leverage information on health co-benefits. First, they can consistently include health co-benefits in discussions of climate change mitigation. Second, they can work with health co-benefits modelers to explore estimates with particular policy relevance. Third, they can encourage funding for health co-benefits research so more information is available to inform policy debates.

Lessons from research on communication around mitigation action on climate change include that it is (1) important to frame policy solutions in terms of what can be gained from immediate action; (2) aspirational climate policy initiatives can tap into American's deeply held motivation for building a better tomorrow[3]; and (3) Americans find information about the potential health co-benefits of mitigation policy actions compelling[4]. Including information on health co-benefits can help the American public evaluate the value of mitigation policies under consideration.

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[3] Van der Linden 2015. *Perspectives on Psychological Science* DOI:10.1177/1745691615598516

[4] Maibach et al. 2010. *BMC Public Health* 10:299.

2) Your work has touched on the need for a more robust climate change and health research enterprise.

a. What are the most pressing global research priorities related to public health impacts of climate change?

The research priorities for the health risks of climate change can be categorized as (1) increasing understanding of the associations between weather / climate and health; (2) modeling how the burden of climate-sensitive health outcomes could change with additional climate change; (3) developing, implementing, and evaluating policies and measures to promote and protect population health today and in the future; and (4) estimating the health co-benefits of mitigation policies and technologies, to ensure mitigation strategies maximize environmental and health benefits. It is important to build resilience to multiple simultaneous stressors and to mounting damages from climate change across the country.

The Future Earth Knowledge Action Network developed recommendations to the Belmont Forum on critical research areas at the nexus of climate change, environment, and health. The recommendations were identified through scoping meetings, consultative discussions, and an online global survey. Key research priorities are summarized below.

1. *Support is needed for implementation science; models and scenarios to describe future vulnerabilities under a range of climate and development futures; and research and monitoring of global environmental change and health.*

Implementation science is needed to bridge from science to policy, including explicitly incorporating future risks of climate change into policymaking, understanding the process of promoting stakeholder engagement, making science relevant at the spatial, temporal, and administrative scales of interest, and improving monitoring and evaluation of decisions.

Models and scenarios to described future vulnerabilities to inform modeling of risks are needed under a range of climate change and development projections by extending the Shared Socioeconomic Pathways (SSPs) to strengthen the representation of drivers of health. Results will help inform modeling of future risks of climate change, to inform policy decisions at the country level.

2. *More effective disease control strategies require better understanding of the relative importance for health of land use change, biodiversity loss, and other environmental drivers and their interactions.*

Significant investments in the weather, water, and climate research enterprise have resulted in greater skill in seasonal and sub-seasonal forecasting of weather and climate events of relevance for human health. These forecasts, coupled with knowledge of exposure-response relationships, can identify conditions conducive to disease outbreaks weeks to months in advance of outbreaks. This information could then be used by public health professionals to improve surveillance in the most likely areas for threats (Morin et al. 2018)[5]. Early warning systems are well established for drought and famine. And while weather- and climate-driven early warning systems for certain diseases, such as dengue fever and cholera, are employed in some regions, this area of research is underdeveloped. Developing and deploying early warning systems based on temperature, precipitation, and other environmental data provide an opportunity for early detection leading to early action and response to potential pathogen threats, thereby reducing the burden of infectious diseases today and as some diseases change their geographic range, seasonality, and intensity of transmission with climate change.

In general, declining biodiversity is associated with increased disease risks, although the associations are complex and variable across settings, and mechanisms and pathways are often not fully understood. Climate change can accelerate biodiversity loss and lead to changes in the distribution and incidence of a range of infectious diseases including vector-borne, food- and water-related diseases. Also, environmentally-friendly public policies can result in health benefits through mechanisms such as reduced air pollution, clean water, reduced vector borne disease risk, and improving mental health, but the reported benefits need better quantification in a range of settings.

3. *Understanding the effects of multiple interacting social and environmental changes on the quality and quantity of food will help develop solutions to improve nutrition and health.*

Feeding the world's population remains a pressing challenge. Human populations are growing, while globalization is spurring a nutrition transition in many low- and middle-income countries to diets high in fat and sugar, with major effects on global health by increasing the risks of non-communicable diseases. The growing demand for food is placing pressure on the world's food systems and the ecosystems that support them. Additionally, climate change and changes in water availability will impact the quality and quantity of food, with the most negative effects in tropical and sub-tropical regions. There are important health implications, directly via nutritional pathways, such as increased risks of stunting, and indirectly, for example by increasing the impoverishment of subsistence farmers. Increased exposure to heat stress will also threaten the livelihood of subsistence farmers and other outdoor workers in sub-tropical and tropical regions.

Rising concentrations of carbon dioxide (CO_2) from the burning of fossil fuels and deforestation will also adversely affect nutritional outcomes through plant physiology mechanisms. Plants obtain the carbon necessary for their growth primarily from atmospheric CO_2 and draw other required chemicals from the soil. CO_2 concentrations are rising in the atmosphere, increasing from about 280 ppm during preindustrial times to 410 ppm today. Higher concentrations of CO_2 are generally acknowledged to stimulate plant photosynthesis and growth, with potential benefits for the productivity of the cereal crops that remain the world's most important sources of food. However, concentrations of minerals critical for human health, particularly iron and zinc, do not change in unison with CO_2 concentrations. The result is that major cereal crops, particularly rice and wheat, respond to higher CO_2 by increasing synthesis of carbohydrates (e.g. starches and sugars) to the detriment of protein and by reducing the quantity of micronutrients

[5] Morin et al 2018 *Current Environmental Health Reports* doi.org/10.1007/s40572-018-0221-0

and B-vitamins critical for human health (e.g. Zhu et al. 2018)[6]. This reduction in nutritional quality could affect hundreds of millions of people.

Research is needed to analyze environmental and health consequences of the current and projected agri-food systems; develop innovative foods or production methods that optimize health and environment outcomes; identify and evaluate dietary changes that are culturally acceptable, economically feasible, healthy, and environmentally sustainable; and assess combinations of strategies that will enable effective behavioral change. A particular emphasis is needed on the vulnerability of subsistence agriculture to environmental change.

4. *Models and scenarios are needed to assess future health risks from climate change, and the potential losses and damages to critical health infrastructure from extreme weather and climate events, including economic and societal costs of disaster preparedness and response.*

Research in this area will contribute to our understanding of the limits to adaptation. Research outputs, such as software tools for scenario analysis, can be used by local authorities, disaster management organizations, departments of health, private sector, NGOs and other civil society partners involved in efforts to increase resilience and reduce vulnerability. In particular, vulnerability considerations should identify and address gender, socio-economic status, and other determinants of health that may contribute to inequity.

Global change is increasing the risks of a range of disasters at local to regional scales - some rapid and "kinetic" such as intense storms and floods; others such as heat waves and landscape fires; and still others that may persist over months and even multiple years, such as droughts and pandemics. Disasters cause acute injuries and deaths, and follow-on impacts, including infectious diseases, mental illness, hunger, conflict, and population migration. Often these effects are complex and inter-related. Research could help advance the science of disaster (impact based) event forecasting, the understanding of disaster impacts on disease dynamics, mental health, food systems, etc. as well as the practice of disaster preparedness and response, and the promotion of disaster resilience. This work could include evaluating the effectiveness of ecosystem-based strategies such as the protection of wetlands, coral reefs and mangroves, and the effectiveness of social safety nets, and preparedness efforts, particularly in urban contexts. Climate change is expected to accentuate vulnerability to a wide range of extreme weather and climate-related disasters and increase population exposure to harm.

5. *Research should utilize complex systems approaches and innovative tools such as in situ sensors and smartphone-based geocoded personal data collection to understand vulnerabilities and building resilience in urban areas.*

The majority of the global human population now lives in urban centers. Cities are responsible for 85% of global economic activities and about 75% of greenhouse gas emissions. The effects of urban lifestyles on health and wellbeing vary widely, and are affected by wealth, social status, and specific features of the urban environment. In high and middle-income countries, urban health threats include air pollution, noise, barriers to physical activity, absence of green space, and in some cases social exclusion and poverty. Cities in low income countries confront all these

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[6] Zhu et al. 2018 DOI: 10.1126/sciadv.aaq1012

problems, compounded by critical shortages of physical infrastructure (potable water supplies, sanitation, electricity, waste management, transport), uncertain land tenure, poor governance, and other challenges. Cities are subject to the urban heat island effect, resulting in higher temperatures (and associated elevated health risks). Green space can reduce the heat island effect and passive and active cooling of buildings may reduce the health effects of heat extremes, as well as have positive impacts on mental health and wellbeing. Many cities are susceptible to sudden climate disruptions; reasons range from being situated in coastal locations subject to storm surges and sea level rise to having poor quality and vulnerable infrastructure.

6. *Research at the interface of energy, climate change, air quality, and health could support analyses of the health, socio-economic and environmental effects of different energy sources (e.g. biomass, manufactured fossil fuels, and renewables); emerging technologies (e.g. hydraulic fracturing); and strategies to promote clean energy use.*

Energy production and use has brought enormous benefits for health and has created a host of negative health outcomes from indoor and ambient air pollution and other exposures; pollution causes about 7 million deaths annually. Eighty-five per cent of fine particulate air pollution is related to energy use. At the same time, many people in low- and middle-income countries lack sufficient energy, and available energy sources such as biomass (particularly when burned indoors in close quarters) bring many ill effects. Innovative energy strategies and technologies offer promise for health, equity, and sustainable development; well-crafted policies can reduce greenhouse gas emissions and short-lived climate pollutant emissions whilst yielding health benefits.

7. *Health impact assessment should be integrated into evaluations of technologies and policies to support progress towards the circular economy.*

Current patterns of economic development are inefficient and produce large amounts of waste including pollutants that can affect human health. Efficient use of natural resources and energy together with more effective regulation of the use and disposal of potentially toxic chemicals can result in substantial benefits to health and natural systems. However, the effects of widespread population exposure to many chemicals in the environment are still poorly understood. For example, electronic and other waste is exported to low income countries where regulations are lax and millions of people work in or live in close proximity to waste dumps. Contamination of freshwater from agricultural runoff and industrial chemicals is a serious threat to health in some parts of the world. The circular economy aims to promote greater resource productivity to reduce waste and avoid pollution including through reuse, recycling and increased durability of products, but little is known about the implications for health. Health benefits could accrue from reduced exposure to toxic pollutants but there are also risks to health for example from poorly regulated recycling and trade in waste products.

b. Can you also discuss the state of the research enterprise on climate change and health in the United States, and what specific investments should be prioritized?

The research enterprise on climate change and health in the United States is quite small, ad hoc, and leveraged on investments in other areas of environmental health research, particularly the study of air pollution. Because funding is limited, research has focused most intently on exposures that are relatively easy to measure, such as ambient temperature. Other issues with more substantial health burdens, such as Lyme disease and wildfire impacts, have been relatively neglected. No funding agency has identified climate change and health as part of its portfolio, and the field's growth has been constrained by lack of investment in training, development of senior research mentors, and sustained funding upon which interested investigators might build their careers.

A 2009 review estimated the extent of Federal funding to research on the health risks of climate change was less than $3 million annually; this was funding across the National Institutes of Health (NIH), the Centers for Disease Control and Prevention; and the Environmental Protection Agency[7]. The review recommended funding of greater than $200 million annually to help the US prepare for, manage, and recover from the health risks posed by climate change. A separate review of the 2008 budget appropriations found that of the nearly 53,000 awards by NIH that year, approximately 0.17% were focused on or related to climate[8]. The National Institute of Environmental Health Sciences (NIEHS), an institute within the National Institutes of Health, announced in 2011 that it would launch a research program in climate change and health. Its Strategic Plan 2012-2017 mentioned climate change twice; one mentioned climate change as a driver of changes in environmental exposures that could contribute to the worldwide increase in chronic, non-communicable diseases[9]. The second mention was as an example of research to help inform policy responses. The annual budget reported by NIH to the US Global Change Research Program on climate change in 2015-2017 was $8 million per year, or about 0.025% of the overall NIH budget of US$32 billion in 2016 and 0.3% of the research budget of the US Global Change Research Program that coordinates federal research across agencies conducting research on climate change. A search of the NIEHS website in 2016 listed 13 ongoing projects that focused on some aspect of climate change and health. The NIH Research Portfolio Online Reporting Tools lists projects under the category "Climate-related exposures and conditions"; all were awarded in 2015 or 2016. A listing for the category "Climate change" identifies 30 projects funded in 2017, including funding for conferences. In comparison, research on antibiotic resistant bacteria received $774 million in 2016.

Climate change is altering all aspects of life, with risks projected to increase substantially over this century even with proactive adaptation. Significant investments in research and technology development are needed that prioritize the needs of particularly vulnerable communities and locations. The methods and tools are available, as is a growing base of researchers and

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[7] Ebi et al. 2009. *Environmental Health Perspectives* 117:857-862
[8] Jessup et al. 2013. *Environmental Health Perspectives* 121:399-404
[9] Ebi et al. 2016. Environmental Health 15:108

practitioners. Federal funding agencies need to acknowledge and fund the research and development that will help individuals and communities to prepare for a future that will differ in many aspects from today. Failure to do so will harm the health and well-being of Americans.

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Review

Public health co-benefits of greenhouse gas emissions reduction: A systematic review

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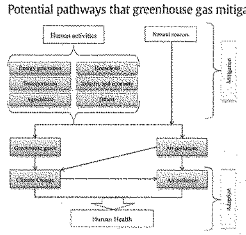
HIGHLIGHTS

- Public health co-benefits of GHG mitigation was primarily observed in five economic sectors.
- Comprehensive GHG mitigation measures across various sectors tend to provide greater ancillary health gains.
- Health co-benefits assessments of GHG reductions are based almost entirely on descriptive or modeling studies.
- Overestimation or underestimates may arise during the health co-benefits assessment of GHG mitigation strategies.
- Voluntary engagements in the use of standard methods to estimate the co-benefits of GHG abatement are needed.

GRAPHICAL ABSTRACT

Potential pathways that greenhouse gas mitigation measures result in public health co-benefits.



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ABSTRACT

Background and objectives: Public health co-benefits from curbing climate change can make greenhouse gas (GHG) mitigation strategies more attractive and increase their implementation. The purpose of this systematic review is to summarize the evidence of these health co-benefits to improve our understanding of the mitigation measures involved, potential mechanisms, and relevant uncertainties.
Methods: A comprehensive search for peer-reviewed studies published in English was conducted using the primary electronic databases. Reference lists from these articles were reviewed and manual searches were

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Keywords:
Air pollution
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Greenhouse gas emissions
Health co-benefits
Mitigation
Uncertainty

performed to supplement relevant studies. The identified records were screened based on inclusion criteria. We extracted data from the final retrieved papers using a pre-designed data extraction form and a quality assessment was conducted. The studies were heterogeneities, so meta-analysis was not possible and instead evidence was synthesized using narrative summaries.

Results: Thirty-six studies were identified. We identified GHG mitigation strategies in five domains – energy generation, transportation, food and agriculture, households, and industry and economy – which usually, although not always, bring co-benefits for public health. These health gains are likely to be multiplied by comprehensive measures that include more than one sectors.

Conclusions: GHG mitigation strategies can bring about substantial and possibly cost-effective public health co-benefits. These findings are highly relevant to policy makers and other stakeholders since they point to the compounding value of taking concerted action against climate change and air pollution.

Contents

1. Introduction

There is robust evidence that climate change is well underway and that anthropogenic greenhouse gas (GHG) emissions, primarily from the burning of fossil fuels, are the main drivers (Solomon, 2007; Stocker et al., 2013). According to the Intergovernmental Panel on Climate Change (IPCC), the average global surface temperature rose by about 0.85 °C from 1880 to 2012, and high-end emissions projection scenarios have shown that if no further mitigation actions are taken, the globe will warm by 2.6–4.8 by the end of the century (Stocker et al., 2013; Watts et al., 2015). Even if carbon dioxide (CO_2) emissions abruptly ceased, climate change would continue for hundreds of years due to the inertia in the global climate system (Matthews and Caldeira, 2008; Solomon et al., 2009).

There are clear signs that climate change already threatens human health, directly and indirectly, and is expected to cause increasingly adverse impacts in the future (Ebi et al., 2017; Field et al., 2014; Forzieri et al., 2017; Gasparrini et al., 2017; Pachauri et al., 2014a; Smith et al., 2014; Woodward et al., 2014). Climate change can affect public health by various pathways (Fig. 1) (Field et al., 2014; McMichael et al., 2006; Seal and Vasudevan, 2011; Shannon et al., 2007). It is estimated that there were 125 million additional vulnerable adults exposed to heatwaves between 2000 and 2016, due to the increasing exposure to more frequent and intense heatwaves (Watts et al., 2017a; Watts et al., 2017b). Increasing ambient temperatures during this peroid have reduced 5.3% outdoor manual labour productivity worldwide (Watts et al., 2017b). In 2016, the value of economic losses resulting from climate-related events were reach totally US$129 billion (Watts et al., 2017a). According to the report from World Health Organization (WHO), considering only the well understood impacts of climate change, and assuming continued progress in economic development and public health protection, that climate warming is still likely to cause about 250,000 additional deaths annually worldwide between 2030 and 2050 (Hales et al., 2014). Climate change has been described as the biggest global threat confronting public health in the 21st century (Costello et al., 2009; Watts et al., 2015).

In light of the broad evidence that climate change is occurring with potentially expensive and far-reaching health consequences, urgent and substantial actions are needed, to limit disruption of the global climate. We have the means to mitigate climate change (Cheng and Berry, 2013; Pachauri et al., 2014a; Smith et al., 2014; Watts, 2009; Xia et al., 2015), but many countries are reluctant to make decisive changes (Edenhofer et al., 2014; Haines, 2012). In general, the focus lies on developing economies, reducing poverty, and improving living standards, and climate change is often perceived as a distant threat and a lower priority on the political agenda (Aunan et al., 2004; Li and Crawford-Brown, 2011). Additionally, developing countries often insist that the "common but shared responsibility" principle of the 1992 United Nations Framework Convention on Climate Change (UNFCCC) should be applied, meaning they should not have the same GHG emissions reduction obligations as developed countries until a certain level of development is achieved

(Baer et al., 2008; Costa et al., 2011). Low- and middle-income countries point out that they are only retracing the same development path taken in the past by present-day high-income countries. This highlights the worldwide challenge to find equitable low-carbon routes to achieve better health and prosperity.

Studies published in *The Lancet* have shown that appropriate climate change mitigation strategies can have additional, independent, and largely beneficial effects on public health (Haines, 2012; Watts, 2009). For instance, GHG mitigation actions aimed at reducing fossil-fuel combustion can produce health benefits by decreasing local air pollution because, GHGs and air pollutants are, to a large extent, emitted from the same sources (Fig. 2) (Aunan et al., 2006; Chae and Park, 2011; Cifuentes et al., 2001b; Watts et al., 2017b). Win-win opportunities of this kind may make GHG mitigation strategies more attractive and encourage their implementation (Edenhofer et al., 2014; Field et al., 2014; Shindell et al., 2012; Watts et al., 2017b). At the very least, co-benefits can reduce or exceed the costs of taking actions against climate change and therefore, can strengthen the case for climate change mitigation policies in the face of scientific uncertainty (Kelly et al., 2017; Nemet et al., 2010).

Although the scientific literature has focused on the "health co-benefits" of GHG mitigation in recent years, to date, no comprehensive review has been conducted specifically assessing the relationship between GHG emissions reduction and ancillary health benefits. Summarizing and understanding these co-benefits on health can provide helpful information for policy makers in their decision-making processes to prioritize the development and implementation of win-win GHG mitigation measures that can help protect people from the impacts of climate change (Cheng and Berry, 2013; Pachauri et al., 2014a; Watts et al., 2015). Accordingly, the purpose of this review is to synthesize the current evidence of public health co-benefits of GHG emissions reduction in different economic sectors. We aim to summarize what is presently known about the pathways by which GHG reductions can bring ancillary health benefits and the relevant uncertainties associated with process of the health co-benefits assessment.

2. Methods

2.1. Relevant definitions

According to the Fifth Assessment Report of the IPCC, the term "co-benefits," also known as ancillary benefits, refers to the positive effects that a policy or measure aimed at a particular objective has on other objectives, irrespective of the net effects on overall social welfare (Pachauri et al., 2014a; Smith et al., 2014). We define public health co-benefits as measures to reduce the emissions of climate-warming pollutants (mainly GHGs), which also hold the potential

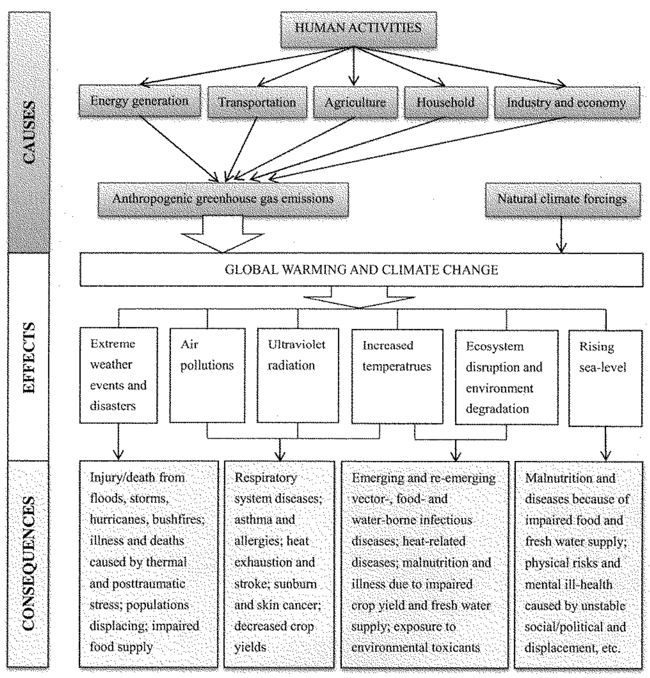

Fig. 1. Schematic summary of climate change determinants and potential pathways through which climate change affects human health.

to improve human health, independent of the effects on climate change.

GHGs, defined under the Kyoto protocol, include CO_2, methane (CH_4), nitrous oxide (N_2O), and three halocarbons, and the effects of GHG mixtures are commonly reported in terms of CO_2 equivalents (CO_2-eqs) (Breidenich et al., 1998). In order to limit mean global warming to 2 °C, it is necessary to reduce the emissions of not only the official GHGs but all climate-active pollutants with high positive radiative forcing (RF). These include, black carbon (BC) and O_3 (Kopp and Mauzerall, 2010; Shindell et al., 2012; Smith et al., 2009). Thus, in the present study, we include O_3 and BC as CO_2-eqs (greenhouse pollutants).

2.2. Data sources and search strategy

A comprehensive literature search for peer-reviewed studies published up to March 2015 was conducted using the electronic databases PubMed, Embase, Web of Science and ScienceDirect (Elsevier). We subscribed to the email alert service of each selected database so that we could receive (follow-up) uptodate information on related studies. In addition, relevant websites and materials from the WHO, the IPCC, the International Energy Agency (IEA), Global Change (http://www.globalchange.gov/), and the World Bank were also searched for further information. References in the retrieved articles were examined and then manual searches were conducted to recover relevant papers that were not included in the major databases. Only English-language articles were included in the initial search.

Our primary search used the following Medical Subject Headings (MeSH terms) from the US National Library of Medicine and key words: "greenhouse gas," "GHG," "carbon," "CO_2," "black carbon," "methane," "ozone," "capture," "cut," "low," "limit," "mitigation," "reduce," "sequestration," "benefit," "co-benefit," "effect," "impact," "cost," "disease burden," and "health." The search terms were adapted to the different databases in order to facilitate a comprehensive search, and the general search strategy is presented in Table 1.

2.3. Inclusion criteria

Our inclusion criteria were based on the primary searches related to GHG emissions reduction and public health co-benefits.

- Types of studies: only original, peer-reviewed journal articles were included. Reviews, reports, conference abstracts, books, and meta-analyses were excluded.
- Research factors: GHG emissions reduction was one of the exposure indicators of interest.
- Target outcomes: at least one public health co-benefit indicator was analyzed.
- Effect measures: the quantitative association of GHG abatement with ancillary health gains was estimated.

2.4. Study selection

Three of the present authors (JHG, JL, and SHG) independently screened the results of the literature search for the potential relevance, based on the information presented in article titles and abstracts. The full text of each article identified as potentially relevant by either one or more review authors was retrieved. The same three authors independently assessed the eligibility of full text articles according to inclusion criteria. When the eligibility assessment varied among review authors, a discussion was held to reach consensus.

2.5. Data extraction

Two authors (JHG and JL) extracted data independently from the final selected references using a pre-designed data extraction form. Studies that met the eligibility criteria were retrieved and the following key information was obtained: publication date, study region, sectors involved, mitigation measures, climate benefits, and health co-benefits. The data were then cross-checked and any discrepancies or disagreements were discussed by the data extractors and resolved through consensus.

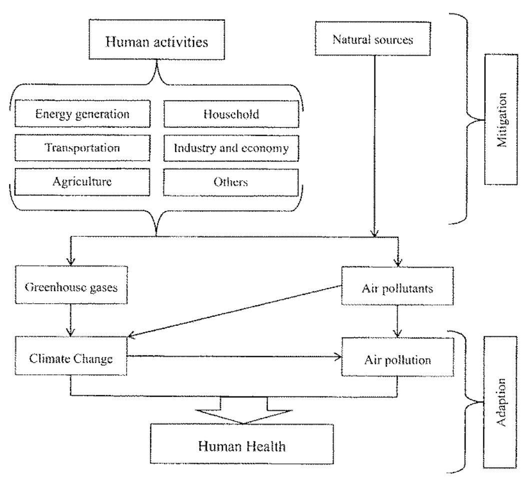

Fig. 2. Potential pathways that greenhouse gas mitigation measures result in health co-benefits.

2.6. Quality assessment

Two authors (JHG and XBL) independently assessed the quality of all included studies. The STROBE approach (Strengthening the Reporting of Observational Studies in Epidemiology) (Vandenbroucke et al., 2007; von Elm et al., 2007) was selected and adapted to describe the reporting quality of the final identified studies. As in previous systematic reviews, the adapted STROBE checklist (Appendix A) was employed to create a binomial scoring system (criterion met = 1, criterion not met = 0) (Aimone et al., 2013; Gao et al., 2014). The score percentage (reporting quality) of each included article was based on the numbers of reporting quality criteria met divided by the total numbers of criteria involved during the quality assessment. Studies that were adjusted for potential confounding factors, quantified health gains of different GHG reduction targets, or monetized health co-benefits of reducing GHG emissions were given higher quality ratings.

2.7. Data synthesis

Because different methods, models, assumptions, GHG reductions policy scenarios, and exposure-response coefficients were applied, cross-study aggregate estimates (meta-analysis) could not be performed. Instead, data synthesis largely consisted of reporting key findings from individual studies and narrative summaries were provided.

3. Results

A total of 10,319 records were identified from the databases and websites, and 94 additional articles were retrieved through references, expert advice, and email alerts (uptodate notifications). After removing duplicates, the titles and abstracts were scanned for relevance. Based on the inclusion criteria, studies that did not involve quantitative association between GHG emissions reduction and health co-benefits were excluded. Then, 205 articles were screened for a full text examination and 36 peer-reviewed articles were retained (Fig. 3).

The identified articles are described in Table 2. In general, the 36 retained studies involved ten developed countries, seven developing countries, and seven global level regions. The association between GHG reductions and health co-benefits was investigated almost entirely by modeling studies, located in one or more of the following sectors: energy generation, transportation, agriculture and food, households, and industrial and economic processes. Seven of the retrieved articles reported the health co-benefits of comprehensive mitigation strategies involving multiple sectors. According to the adapted STROBE checklist, the reporting quality scores for the articles ranged from 57.69% to 86.21%, with 80.56% of the records (27/36) having scores above 70%, indicating relatively high reporting quality.

3.1. Energy generation sector

The health co-benefits of GHG mitigation measures in energy generation, such as low carbon energy production, better energy efficiency, and re-balancing the structure of energy use, were evaluated in several studies. In China, a study by Aunan et al. examined the co-benefits of six abatement measures to reduce emissions (CO_2, PM_{10} and SO_2) related to the use of coal. The authors concluded that increased energy efficiency and the use of "clean coal" technologies are win–win options from a social perspective, and include co-benefits (avoiding losses of 75,000–7,723,000 life years) (Aunan et al., 2004). If GHG reduction targets are set 15% below business-as-usual (BAU) emissions in 2020, Wang and Smith project health benefits from energy efficiency improvements and fuel substitution in China for residential and power generation sectors. They estimated a 4% reduction in the projected mortality, relative to the BAU (Wang and Smith, 1999). A similar study from China found that compared with the BAU, low-carbon energy measures (e.g. improving energy efficiency, expanding natural gas use, and wind electricity generation) could prevent 9870–23,100 deaths in 2020 due to the corresponding reductions in ambient PM_{10} (particulate matter [PM] with an average aerodynamic diameter of 10 μm or less) (Chen et al., 2007). He et al. modeled the benefits of an aggressive energy policy scenario that enhanced air pollution control along with improved energy efficiency and structure and projected that compared with the BAU, by 2030, 1469 million fewer metric tonnes (MT) of CO_2 would be emitted and 135,811 deaths from all causes would be avoided as a result of 12–32% decline in air pollutant concentrations (He et al., 2010). Rive and Aunan conducted another study in China to investigate the benefits of energy-related Clean Development Mechanism (CDM) projects that installed renewable energy, upgraded technologies, and promoted fuels switching, and reported that the CDM projects had simultaneous win-win-win effects on air quality, public health and agriculture (Rive and Aunan, 2010).

Table 1
Search strategy and protocol.

Step 1: Keyword Searches
① "greenhouse gas" OR "GHG" OR "carbon" OR "CO_2" OR "black carbon" OR "methane" OR "ozone"
② "capture" OR "cut" OR "low" OR "limit" OR "mitigation" OR "reduce" OR "sequestration"
③ "benefit" OR "co-benefit" OR "effect" OR "impact" OR "cost" OR "disease burden" OR "health"
In the Title/Abstract for all fields: "①" AND "②" AND "③"
Step 2: "Original and Empirical Study" Filter
Does the primary-sourced study focus on the two aspects that involving both of greenhouse gas emissions reduction and the corresponding public health co-benefits?
Step 3: "Quantitative analysis" Filter
Does the study evaluate or analyze the associations between greenhouse gas emissions reduction and public health co-benefits quantitatively?

Cifuentes et al. investigated the cumulative health impacts of reducing GHG emissions by adopting energy efficiency and fuel substitution measures in four cities: México City, São Paulo, Santiago, and New York from 2000 to 2020 (Cifuentes et al., 2001a). The authors concluded that with respect to BAU in 2020, adoption of these measures could reduce GHG emissions by approximately 13% and prevent about 64,000 (95% confidence interval [CI]: 18,000–116,000) premature deaths as a result of a 10% reduction in exposure to PM_{10} and O_3 associated with GHG mitigation. On a global level, Markandya and colleagues estimated the health benefits of various strategies, such as alternative technologies and fuels, greater use of nuclear power and renewable energy, and carbon capture and storage technology associated with coal burning. They reported that with a 50% reduction target by 2030, compared with BAU, the health gains of full trade scenario in the European Union, China, and India would be approximately 100, 500, and 1500 life-years per million people, respectively. The economic value of the health co-benefits would offset the costs of GHG mitigation, especially in India where levels of pollution is high and mitigation costs are relatively low (Markandya et al., 2009). In another assessment, based on the Representative Concentration Pathway 4.5 (RCP 4.5) scenario, it was estimated that decreasing fossil fuel use and energy demand while increasing forest cover, biofuels use, and carbon capture and geologic storage, could restrict global mean temperature increase to about 2.3 and avoid 2.2 ± 0.8 million premature deaths associated with corresponding reductions in $PM_{2.5}$ and O_3 (West et al., 2013).

3.2. Transportation sector

Less motor vehicle use, and a proportional increase in higher-combustion efficiency and lower-emission vehicles might reduce GHG emissions and avoid premature deaths due to traffic-related air pollution. One study from Thailand investigated the benefits of a GHG reduction policy scenario that ramped up PM-oriented vehicle inspection and maintenance programs aimed at taking high-emitting vehicles off the road, targeting in particular diesel-fueled vehicles and motorcycles in the Bangkok area. Relative to the BAU scenario in 2015, it was estimated that the program could reduce GHG emissions by approximately 0.4 MT of CO_2 per person yearly, and prevent about 913 premature deaths due to a 25% reduction in roadside PM. The authors estimated that the positive economic impacts would outweigh the cost of policy implementation (Li and Crawford-Brown, 2011). When Woodcock and colleagues chose two settings – London, UK, and Delhi, India – to estimate the health effects of urban land transport by comparing alternative transport scenarios with BAU 2030 projections, they found that reductions in CO_2 emissions through the combination of active travel and lower-emission motor vehicles had the largest benefits (7439 disability-adjusted life years [DALYs] in London and 12,995 in Delhi), greater than those obtained by an increase in active travel or use of lower-emission motor vehicles only (Woodcock et al., 2009). The authors further argued that in order to reduce GHGs and simultaneously improve public health, transport policies should prioritize the needs of pedestrians and cyclists over those of motorists, and increase the acceptability, appeal, and safety of active urban travel. Similar health co-benefits of mitigation measure in transportation sector were also concluded in Basel, Switzerland and Kuala Lumpur, Malaysia, based on modeling investigations (Kwan et al., 2017; Perez et al., 2015).

Several studies have attempted to quantify the benefits of substituting motor vehicle travel with active travel (e.g. walking and cycling). In New Zealand, Lindsay and colleagues reported that despite an additional five cyclist fatalities from road crashes, shifting 5% of vehicle kilometers to cycling would decrease transport-related GHG emissions by 0.4%, and prevent about 122 premature deaths annually as a result of increased physical activity and reduced local air pollution. An important finding in this paper is that the health benefits of moving from motor vehicles to bicycles largely accrue from increasing physical activity, and these outweigh by a large margin the losses resulting from road crash injury (Lindsay et al., 2011). Rojas-Rueda et al. conducted a study in Barcelona, Spain to assess the health impacts of travel by bicycle in an urban environment. Compared with travel by car, an estimated 9062 MT of CO_2 emissions were reduced and 12 premature deaths avoided each year by the shift to cycling (Rojas-Rueda et al., 2011). Maizlish and colleagues quantified the health benefits of transportation strategies to reduce GHG emissions in the San Francisco Bay Area. Although increasing median daily walking and cycling from 4 to 22 min could increase the traffic injury burden by 39% (5907 DALYs), Maizlish et al. found the burden of cardiovascular disease and diabetes would decline by 14% (32,466 DALYs) and the GHG emissions would decrease by 14%. The authors concluded that increased physical activity associated with active transport could generate significant net improvements in public health (Maizlish et al., 2013). A study from Adelaide, South Australia modeled the effects of shifting vehicle kilometers of passenger vehicles to alternative transport (e.g. bicycle and public transport) on air quality, GHG emissions and public health, compared with the BAU 2030 scenario. It concluded that road traffic-related CO_2 emissions would decline by 191,313–954,503 MT annually and that 160–542 premature deaths and 2113–7674 DALYs could be prevented per year due to improved air quality, increased physical activity, and avoided traffic injuries (Xia et al., 2015). David Rojas-Rueda et al. estimated the health impact of increased cycling and increased walking in Six European cities, the authors reported that the two scenarios produced health

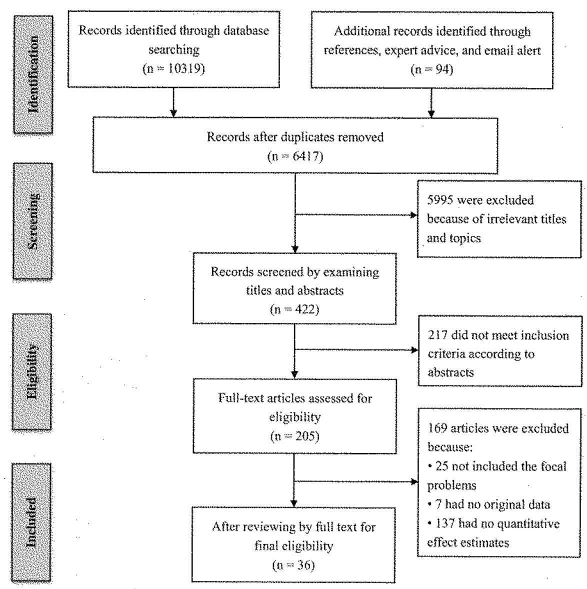

Fig. 3. Flow chart of screening process of the literature search.

Table 2
Summary of the identified studies on public health co-benefits of greenhouse gas mitigation ($n = 36$).

Author (date)	Study region	Involving sector (s)	Mitigation measures	Benefits for climate	Health co-benefits	Quality (%)
Energy generation and provision sector						
Wang and Smith (1999)	China	Energy in power, household sectors	Energy efficiency and fuel substitution	GHGs reduction is 15% below BAU scenario by 2020	A 4% reduction in the projected mortality of 14 million in China by 2020	70.37
Cifuentes et al. (2001a)	México, Chile, Brazil, and USA	Transportation and energy sectors	Reducing combustion and carbon intensity of fossil fuels	Lower GHG emissions in 2020 by 13% with respect to the BAU case	Avoiding 64,000 (95% CI: 18,000–116,000) premature deaths associated with a 10% reduction in PM and O_3 that because of GHG mitigation, and other health benefits	65.38
Aunan et al. (2004)	Shanxi, China	Industry, power, and rural households sectors	Six different abatement options that could reduce the emissions (CO_2, PM_{10} and SO_2) related to use of coal	The six abatement measures have CO_2 emission-reduction potential from 0.3 to 12.8 million tonnes respectively, and also reduce PM_{10} and SO_2 emissions	75,000–7,723,000 life years lost can be avoided from reduced emission of PM due to the six options for a time period of 90 years	82.14
Chen et al. (2007)	Shanghai, China	Energy, industry, economy, and residential sectors	Energy efficiency improvement, expanding natural gas use, and wind electricity generation	Energy efficiency improve 2% annually from 2000 to 2020, and various other low-carbon measures in natural gas use and wind electricity generation	Compared with the base case scenario, implementation of various low-carbon measures could prevent 9870–23,100 premature deaths because of PM_{10} reduction	73.08
Markandya et al. (2009)	EU, China, and India	Electricity generation	Shift technologies and fuels, decrease the use of coal, use carbon capture and storage, increase nuclear energy and the share of renewable energy	The total CO_2 emissions in 2030 is consistent with the 2050 reduction targets (50% reduction compared with emissions in 1990)	Compared with BAU, the health gains of full trade scenario in EU, China and India would be about 100, 500 and 1500 life-years per million people in 2030, respectively	85.19
He et al. (2010)	China	Energy involving industry, buildings, transportation, and household	Switch energy structure, improve energy efficiency, and control energy consumption	Emissions of CO_2 would reduce 1469 million metric tonnes (MT) compared with the 2030 projected BAU scenario	By 2030, 135,811 all causes mortality would be avoided compared with BAU scenario, and >100 billion US$ of health benefit can be achieved	65.38
Rive and Aunan (2010)	China	Energy	The Clean Development Mechanism (CDM) activities in China to 2012	Annual abatement from CDM projects is forecasted at 319 MT CO_2-eq/yr in 2010, rising to 560 MT CO_2-eq/yr in 2012	Monetized health benefit (avoided deaths) from PM reduction associated with CDM activities is 5359 million RMB (in 2005 terms) per year in 2010	71.43
West et al. (2013)	Global	Energy, economy, and forestry	Decrease fossil fuel use, increase nuclear and renewable energy, increase forest cover and biofuels, grow carbon capture and geologic storage	For RCP4.5, by 2100, CO_2 concentration would decrease from 760 ppm to 525 ppm, and the global mean temperature change is 2.3 relative to the pre-industrial	For RCP4.5, relative to a reference scenario, global GHG mitigation avoids 0.5 ± 0.2, 1.3 ± 0.5, and 2.2 ± 0.8 million premature deaths in 2030, 2050, and 2100	82.14
Transport system						
Woodcock et al. (2009)	London, UK, Delhi, India	Transportation	Use lower-carbon-emission motor vehicles (more efficient engines and fuel switching), and increase active transport	For UK, 60% reduction in transport CO_2 emissions from 1990 levels; while for India (focus on preventing the rise in emissions), 199% increase in CO_2 emissions from 1990	Compared with 2030 projected business-as-usual scenario, the combined mitigation strategy would give the largest benefits (7439 DALYs in London, 12,995 in Delhi, per million population in 1 year)	85.71
Li and Crawford-Brown (2011)	Bangkok, Thailand	Transportation	Enforcing enhanced vehicle inspection and maintenance (I/M) programs targeting diesel-fueled vehicles and motorcycles	The I/M program can produce a GHG emissions reduction of approximately 0.4 MT CO_2 per person per year	913 deaths could be avoided in 2015 associated with 25% PM emission reductions due to I/M programs when compare with the BAU scenario	77.78
Lindsay et al. (2011)	New Zealand	Transportation	Shifting short urban vehicle kilometers (5%) to cycling annually	Reduce transport-related greenhouse emissions by 0.4% each year due to reduced travel kilometers and fuel consumption	Saving 122 deaths annually as a result of increased physical activity and reduced local air pollution from vehicle emissions	74.07
Rojas-Rueda et al. (2011)	Barcelona, Spain	Transportation	Public bicycle sharing initiative, Bicing, promote the bicycle as a common means of transport	As a result of journeys by Bicing, annual CO_2 emissions were reduced by an estimated 9062 MT	As a result of physical activity associated with journeys by bicycle, compared with car users, 12.28 deaths were avoided annually	83.33
Maizlish et al. (2013)	California, America	Transportation	Increasing median daily walking and bicycling from 4 to 22 min (active transport)	Compared with the BAU, the GHG emissions would decrease by 14%	The corresponding burden of cardiovascular disease and diabetes could be reduced by 14% (32,466 DALYs) relative to the BAU	72.00
Perez et al. (2015)	Basel, Switzerland	Transportation	A 10% reduction of traffic on inner roads, and 50% of the private car fleet are based on electric vehicles	20% reduction in CO_2 emissions compared to reference scenario	Prevent 4 DALYs per 1000 population compared to reference 2010 scenario	82.14
Xia et al. (2015)	Adelaide, Australia	Transportation	Changing people's travel behavior toward alternative transport (increase cycling, public and active transport)	The annual reduction of road traffic-related CO_2 emissions would range from 191,313 to 954,503 MT per year depending on the scenarios	Compare with 2030 BAU, 160–542 deaths and 2113–7674 DALYs could be prevented due to improved air quality, improved physical activity and avoided traffic injury	82.14
Rojas-Rueda et al.	Six	Transportation	Increases in bicycle and	The two scenarios would also reduce	The two scenarios produced health	75.00

Table 2 (*continued*)

Author (date)	Study region	Involving sector (s)	Mitigation measures	Benefits for climate	Health co-benefits	Quality (%)
(2016)	European cities		walking trips to 35% and 50% of all trips of each city, respectively	CO_2 emissions in the six cities by 1139 to 26,423 metric tonnes per year	benefits in the six cities, with various extents	
Kwan et al. (2017)	Malaysia	Transportation	Travel modal shift from the private motor vehicles to the use of two upcoming mass rapid transit lines in Greater Kuala Lumpur	Reducing 337,800 t of CO_2-eq per year from private transportation, despite the fact that the use of motor vehicle in the station access-egress would offset 28% of the total savings	Preventing, per year, 5 deaths and 104 DALYs due to the reduced $PM_{2.5}$ concentration, 88 deaths and 6300 DALYs due to the decreased traffic injuries, and 90 deaths and 3200 DALYs because of the increased physical activity	83.33
Agriculture and food sector						
Friel et al. (2009)	UK, and Brazil	Agriculture and food sector	For UK, technological changes reduced emissions in agricultural sector, and an additional 30% reduction in livestock production, and the same reduction proportion of livestock production for Brazil	Attain a 50% reduction in greenhouse-gas emissions from the concentrations recorded in 1990 by 2030	Disease burden decrease by about 15% in UK and 16% in São Paulo city associated with 30% reduction in consumption of saturated fat and cholesterol from animal sources, which caused by the mitigation measures from agricultureand food sector	82.76
Scarborough et al. (2012)	UK	Agriculture and food sector	For scenario 1: 50% reduction in meat and dairy replaced by fruit, vegetables and cereals	19% reduction in agriculture GHG emissions compared with 2008 baseline scenario	36,910 (30,192–43,592) deaths delayed or averted per year compared with 2008 baseline, other scenarios have similar health benefits	69.23
Biesbroek et al. (2014)	Dutch	Food, land use	Substituting one-third (35 g) of the usual daily meat intake with vegetables, fruit-nuts-seeds, pasta-rice-couscous, or fish	The modeled meat-substitution scenario could reduce 4–11% GHG emissions, and 10–12% land use	In the modeled meat-substitution scenario, 6–19% survival rates were increased compared with the reference baseline	84.38
Milner et al. (2015)	UK	Agriculture and food sector	The average UK dietary intake were optimised to comply with the WHO recommendations	An incidental reduction of 17% in GHG emissions	Saving almost 7 million years of life lost prematurely over the next 30 years and increase average life expectancy by over 8 months	82.76
Springmann et al. (2016)	Global	Agriculture and food sector	Transitioning toward more plant-based diets that are in line with standard dietary guidelines	Reduce global food-related GHG emissions by 29–70% compared with a reference scenario in 2050	Reduce global mortality by 6–10% compared with a reference scenario in 2050	86.67
Farchi et al. (2017)	Italy	Agriculture and food sector	Reductions in beef consumption toward patterns more compliant with Mediterranean food pyramid targets (from the current 406 to 150 g/week/person)	According to the Mediterranean food pyramid scenario, CO_2-eq missions could be saved in the range 8000 ± 14,000 Gg per year	The deaths avoidable according to the reduction scenarios for beef consumption were between 2.3% and 4.5% for colorectal cancer, and 2.1–4.0% for cardiovascular disease	71.43
Residential and household sector						
Wilkinson et al. (2009)	UK, and India	Household energy	Strategy of combined fabric, ventilation, fuel switching, and behavioral changes in UK housing stock, and introduce 150 million low-emission household cook stoves in India	Saving 0.6 MT of CO_2 in UK, and 0.1–0.2 MT CO_2-equivalent in India, per million population in 1 year compare with the baseline scenario	The combined strategy in UK and cook stove program in India could avoid 850 and 12,500 DALYs respectively, per million population in 1 year with respect to the 2010 baseline scenario	86.21
Venkataraman et al. (2010)	India	Household sector	Develop cleaner biomass cook stoves and deploy them to all households that currently use traditional cook stoves	80 MT CO_2-eq per year or over 4% of India's total estimated GHG emissions could be avoided if such an initiative were in place today	About 570,000 premature deaths in poor women and children could be avoided	57.69
Industrial and economic process						
Dudek et al. (2003)	Russia	Industry, economy, energy, and forestry sectors	Technological modernization, market liberalization, and energy efficiency improvement	Giving Russia a GHG emission allowances surplus of >3 billion MT of CO_2	Saving about 35,000 lives each year because of the decrease of PM10 and SO_2 resulted from GHGs emissions reduction	62.96
West et al. (2006)	Global	Energy operations, landfills, and wastewater treatment	Using identified global CH_4 abatement options compiled in five industrial sectors	Reducing current global anthropogenic methane emissions by 20% (65 MT/yr) beginning in 2010 and sustained until 2030	Preventing ≈370,000 premature mortalities globally between 2010 and 2030 due to the ozone reduction associated with methane mitigation options	78.57
Anenberg et al. (2011)	Eight major world regions	Three major economic sectors	No presented	Anthropogenic BC emissions are halved globally and individually in eight major world regions and three major economic sectors	157,000 (95% CI: 120,000–194,000) premature deaths could be avoided annually worldwide because of $PM_{2.5}$ reduction associated with the halved BC emissions	72.41
Crawford-Brown et al. (2012)	Mexico	Economic activity, and energy	Climate change policies from the Nationally Appropriate Mitigation Actions of Mexico	For the decarbonisation scenario in 2050, Mexico alone reduces CO_2 emissions by 77%	Compare with the BAU case, 2718 premature deaths per year could be avoided due to reduced ozone and PM under the GHG policy	61.54
Others						
Chae and Park (2011)	Seoul, Korea	Various sectors: household, energy, waste	Integrated Environmental Strategies (IES) (e.g. fuel control and switching, use low emission vehicles, etc.)	Reduce CO_2 emissions of 2014 BAU levels by 10% accompanied with air pollutant reduction	5695 (95% confidence interval 2867–8377) premature deaths were saved as a total of the Seoul	70.37

(continued on next page)

		treatment, transportation, industry		(7326 kt of CO_2 emissions reduction)	Metropolitan Area based on the PM_{10} reduction associated with IES	
Anenberg et al. (2012)	Global	Various sectors (e.g. energy, household, food, transportation, etc.)	14 specific methane and black carbon (BC) emission mitigation measures	The measures for cook stoves could achieve a 25% decrease in BC and 80–90% decreases in other species (CO, organic matter, methane, *etc.*)	Relative to the 2030 reference scenario, 0.6–4.4 and 0.04–0.52 million annual premature deaths could be avoided globally because of reduced concentrations of $PM_{2.5}$ and ozone	81.48
West et al. (2012)	Global	Various sectors: agricultural, industrial and energy sectors	Deploys currently-available methane reduction technologies, and technological innovation	For the three scenarios (A, B, and C), the range of methane emission reductions is 75–180 MT per year in 2030 relative to the base scenario	For the three scenarios, 19,500, 37,800 and 57,200 premature mortalities could be avoided respectively, which associated with ozone reductions due to methane mitigation measures	68.00
Shindell et al. (2012)	Global	Agriculture, food, energy, household, transportation, etc.	14 identified measures targeting methane and BC emissions reductions	Reduce projected global mean warming ~0.5 by 2050 in comparison with the reference base	The strategy avoids 0.7 to 4.7 million annual premature deaths due to ozone reductions associated with mitigation measures in 2030	84.62
Rafaj et al. (2013)	Global, and key world regions (EU, China, India, and the United States)	Energy, household, transportation, industry, and agriculture, etc.	Various mitigation measures involving industrial processes and energy activities for reducing the emissions of air pollutants and GHGs	For mitigation scenario, global mean temperature does not increase beyond 2 °C, and global CO_2 emissions reduced by 80% in 2050 compared to the baseline emission level	By 2050, for China in the Mitigation scenario, loss in statistical life expectancy due to $PM_{2.5}$ is halved, and premature deaths attributable to ozone are reduced annually by 20,000 cases when compared with the Baseline, similar results also be observed in other key regions	73.08
Jensen et al. (2013)	UK	Agriculture and food, transportation household energy	Cleaner vehicles and increase active travel, reduce livestock production, improve energy efficiency of household, etc.	In 2030, the emission reduction of household, transport, and agriculture sectors would be 50%, 60%, 50% in different scale of UK, respectively	For the three kinds of mitigation strategies, the macro effects of health co-benefits produced from the health-related shocks are ranged from 448 to 18,854 (£ million)	76.92
Sabel et al. (2016)	Five European and two Chinese cities	Urban transport, building fabric and energy supply	Heat, powerplant fuel peat and oil changed to wood; biofuels for transport; 10% reduction in private car use and 50% growth in electric cars; building renovation, etc.	By 2020, all policies modeled reduced CO_2 emissions relative to the BAU, with different extents	With the exception of using biomass for domestic heating, the GHG reduction policies were likely to improve health, especially in areas few such policies have been adopted before, although the benefits tended to be slight	77.78

Abbreviations: BAU, business as usual; BC, black carbon; CDM, Clean Development Mechanism; DALYs, disability-adjusted life-years; EU, European Union; GHGs, greenhouse gas; MT, metric tonnes; PM, particulate matter; PM_{10}, particulate matter with an average aerodynamic diameter of 10 mm or less; $PM_{2.5}$, particulate matter with aerodynamic diameter 2.5 μm or less; RCP, Representative Concentration Pathway scenario; SO_2, sulfur dioxide.

benefits in all cities, while reduced CO_2 emissions in the six cities by 1139 to 26,423 MT per year (Rojas-Rueda et al., 2016).

3.3. Agriculture and food sector

The potential contributions of decreases in the consumption of food from animal sources (while meeting nutritional requirements) and improvements in agricultural technologies to the targets of GHG emissions reduction and public health have been investigated in different areas. Friel et al. conducted a study to estimate the co-benefits of mitigation strategies for the agricultural sector in the UK and São Paulo, Brazil. The authors concluded that a combination of agricultural technological improvements and a 30% reduction in livestock production could achieve a 50% GHG emissions reduction target by 2030 relative to the concentrations in 1990, and trim the burden of nutrition-related disease by approximately 15% in the UK and 16% in São Paulo (Friel et al., 2009). The authors also called on coordinated intersectoral actions worldwide in order to address potential challenges and provide affordable, healthy, and climate-friendly diets for all societies. Another study from the UK that modeled the health impacts of sustainable dietary scenarios estimated that a reduction in consumption of meat and dairy products replaced by fruit, vegetables and cereals or other low-emission foods would lead to a 3–19 reduction in GHG emissions, while delaying or averting 1999–36,910 premature deaths annually (Scarborough et al., 2012). Biesbroek et al. suggested that compared with the BAU, the modeled substitution of 35 g/day of usual daily meat intake with vegetables, pasta-rice-couscous, fruit-nuts-seeds, or fish could reduce GHG emissions by 4–11% while increasing survival rates of the targeted population by 6–19% (Biesbroek et al., 2014). Another study from the UK estimated that if the average UK dietary intake were optimised to comply with the WHO recommendations, there were almost 7 million years of life lost over the next 30 years could be saved, and incidentally reduced 17% GHG emissions (Milner et al., 2015). Compared with a reference scenario in 2050, Marco Springmann et al. concluded that transitioning toward more plant-based diets that are in line with standard dietary guidelines could reduce global food-related GHG emissions by 29–70%, while decreased global mortality by 6–10% (Springmann et al., 2016). Similar ancillary health gains from mitigation measure in food consumption were also reported in Italy (Farchi et al., 2017).

3.4. Residential and household sector

Studies have examined environmental and health impacts of GHG mitigation measures, including improvements in the efficiency of household energy and clean household stoves. Wilkinson et al. investigated the health and climate impacts of hypothetical strategies to improve energy efficiency in the UK housing stock and to introduce 150 million low-emission household cook stoves in India (Wilkinson et al., 2009). For housing in the UK, a mitigation strategy of combined building fabric, ventilation, fuel switching and behavioral changes brought about a savings of 0.6 MT of CO_2 and 850 fewer DALYs per million people per year with respect to the 2010 baseline scenario, while the cook stove program in India achieved savings of 0.1–0.2 MT of CO_2-eq and 12,500 fewer DALYs per million people per year. On this basis, household energy interventions may provide a cost-effective means to achieve both population health and climate mitigation goals (Wilkinson et al., 2009). Another study from India estimated the benefits of initiatives to develop low-emission biomass cook stoves in place of traditional stoves. The authors estimated savings of 80 MT of CO_2-eq per year and approximately 570,000 fewer premature deaths of poor women and children due to improved air quality (Venkataraman et al., 2010).

3.5. Industrial and economic processes

Dudek et al. estimated that market liberalization, market reforms, and technological modernization in Russia provided the country with a GHG emission allowance surplus of more than three billion MT of CO_2, while averting about 35,000 premature deaths per year due to the lower levels of PM_{10} and SO_2 that resulted (Dudek et al., 2003). West et al. investigated the health co-benefits of reducing current global anthropogenic methane emissions from industrial sector by 20% (65 MT/year) beginning in 2010 and sustaining the reductions through 2030. They found that approximately 370,000 premature deaths would be prevented globally due to reductions in surface ozone concentrations. Methane mitigation, the authors concluded, may be a cost-effective instrument to achieve gains for air quality, public health, climate, energy, and agriculture (West et al., 2006). Anenberg et al. explored the consequences of halving anthropogenic BC emissions in eight world regions and three major economic sectors. An abatement policy of this kind could avert 157,000 (95% CI: 120,000–194,000) premature deaths globally per year, it was estimated (Anenberg et al., 2011). Another study from Mexico modeled the health co-benefits of a 77% CO_2 emissions reduction throughout Mexican economy as a result of climate change mitigation policies and concluded that 2718 premature deaths could be avoided per year due to reduced ozone and PM concentrations (Crawford-Brown et al., 2012).

3.6. Other

Other papers reported ancillary health benefits of certain comprehensive climate-motivated strategies that touched multiple sectors (e.g. energy, transportation, industry, household, agriculture, or waste treatment). Chae and Park reported that an Integrated Environmental Strategies (IES) scenario in South Korea (fuel control, energy structure switching and use of low emission vehicles) could reduce CO_2 emissions by 10% compared with the 2014 figure, and avert 5695 (95% CI: 2867–8377) premature deaths associated with PM_{10}. These savings exceeded what would be obtained by individual scenarios involving air quality management or GHG reduction measures (Chae and Park, 2011). A study from the UK performed a health-focused, macroeconomic assessment of three contingent GHG mitigation strategies, namely, urban transport, food and agriculture, and household energy efficiency strategies. The results suggested that these strategies could reduce GHG emissions by 50–60 in the three sectors, respectively, while generally resulting in health co-benefits of varying cost-effectiveness (Jensen et al., 2013). On a global scale, Rafaj and colleagues modeled the impacts of global 2 targeted mitigation policies on climate, air quality and public health. They reported that global CO_2 emissions would need to decrease by 80% by 2050 with respect to the baseline emissions level. In China, losses in life expectancy due to $PM_{2.5}$ would be halved and premature deaths attributable to ground level ozone would be reduced annually by 20,000 (Rafaj et al., 2013).

Anenberg et al. simulated the influence of 14 individual CH_4 and BC emission control measures on climate and outdoor concentrations of $PM_{2.5}$ and O_3, and estimated the health benefits relative to the reference scenario for 2030. The measures could prevent 0.6–4.4 and 0.04–0.52 million premature deaths associated with $PM_{2.5}$ and O_3, respectively, around the globe each year (Anenberg et al., 2012). Similarly, Shindell and colleagues studied the effects of 14 identified measures targeting CH_4 and BC emissions on climate change and public health. Such measures could reduce global warming by approximately 0.5 by 2050, the authors concluded, and might prevent 0.7–4.7 million premature deaths annually due to decreased air pollution (Shindell et al., 2012). West et al. examined the health co-benefits of CH_4 emissions reduction scenarios in energy production, waste treatment, industry and agriculture sectors from a global perspective. Between 19,500 and 57,200 ozone-related premature deaths could be avoided in 2030 depending on the scenarios, this study reported (West et al., 2012). Clive E. Sabel et al. modeled the impact of adopted urban climate change mitigation policy scenarios in transport, buildings and energy sectors, and concluded that by 2020, with different extents, all policies modeled reduced CO_2 emissions, with additional health benefits (Sabel et al., 2016).

4. Discussion

We have summarized what is known about health co-benefits associated with GHG mitigation in energy generation, transportation, agriculture and food, household, and industry sectors at global, national and regional levels. Mostly positive associations between GHG emissions reduction and ancillary health gains were reported in the 36 studies that were retained from the literature search. This was true in both high- and low-income countries, and comprehensive measures tended to provide greater health benefits than single-sector interventions. To the best of our knowledge, this is the first time that current evidence of health co-benefits in relation to GHG reductions from various economic sectors has been comprehensively reviewed and summarized.

We found that GHG mitigation policies in five domains – energy generation, transportation, food and agriculture, household, and industry and economy – are often, although not always, health-promoting. In some cases, the positive health consequences are substantial, cost-effective, and attractive to multiple parties (Haines et al., 2009; Patz et al., 2014; Watts et al., 2017b). The health co-benefits of mitigation measures appear in a number of forms, depending on the sources of GHG emissions being reduced. For instance, reducing GHG emissions in energy generation sector impacts on health through the corresponding reductions of common air pollutants (Fig. 2), such as PM, BC, SO_2, and NOx (Chen et al., 2013; Crawford-Brown et al., 2012; Dudek et al., 2003). In the transportation sector, in addition to the co-control of GHGs and air pollutant emissions and the health gains from improved air quality, GHG mitigation activities such as the shift from vehicular to active travel act through other mechanisms, including increases in physical activity, social contact, and the opportunity to interact with the natural environment. Consequently, co-benefits may include reductions in cardiovascular disease, type 2 diabetes, colon and breast cancer and depression (Creutzig et al., 2015; Rissel, 2009; Woodcock et al., 2009; Xia et al., 2015; Xia et al., 2013). Reducing intake of foods from animal sources in high-consumption populations could reduce GHG emissions and substantially benefit public health, for example, via reductions in type 2 diabetes, ischemic heart disease, and the prevalence of obesity (Friel et al., 2009; Kelly et al., 2017; Macdiarmid, 2013; McMichael et al., 2007). Mitigation actions in the residential and household sector, such as improvements in combustion energy efficiency (Dora et al., 2011), substitution of traditional cooking and space heating practices with clean fuel technology and lower-emission household appliances (Ochieng et al., 2013; Venkataraman et al., 2010; Wilkinson et al., 2009), and saving energy through improvements in fabrics, fuel switching, and behavioral changes (Wilkinson et al., 2009) could bring about health co-benefits in addition to reductions in GHG emissions (Anenberg et al., 2013; Cifuentes et al., 2001b). For industrial and economic processes, air quality improvements and health gains could be achieved through measures that improve energy efficiency and promote the use of clean and renewable energy (Crawford-Brown et al., 2012; He et al., 2010; Ren et al., 2012; Zhai et al., 2011). Comprehensive strategies that involve multiple economic sectors could, in theory, multiply the health/climate co-benefits (Anenberg et al., 2012; Chae and Park, 2011; Shindell et al., 2012; Wilkinson et al., 2009).

An array of tools to estimate the health co-benefits of climate change mitigation are currently available. Two types of risk evidence, epidemiological and toxicological, are routinely used for environmental health assessments (McKinley et al., 2005; Smith and Haigler, 2008). Based primarily on the existing epidemiological evidence, a variety of methods such as comparative risk assessments (Friel et al., 2009; Markandya et al., 2009; Woodcock et al., 2009); complex mechanistic components (Wilkinson et al., 2009); and macroeconomic, technological, and behavioral models (Jensen et al., 2013; Rojas-Rueda et al., 2011; Shindell et al., 2012) were employed to model the co-benefits of GHG mitigation strategies. In general, studies of health co-benefits follow a path in which there are four key steps, including scoping/baseline, impact assessment, valuation procedures, and sensitivity/uncertainty analyses (Fig. 4) (Bell et al., 2008; Patz et al., 2008; Remais et al., 2014; Smith and Haigler, 2008).

Due to variations in study design, mitigation scenarios, exposure-response functions, model assumptions and selection of methods, it is often difficult to compare health co-benefits assessments even if the study area and target time scales are identical (Bell et al., 2008; Haines et al., 2009; Remais et al., 2014). In order to conduct the most robust evaluation of ancillary health benefits, studies have recommended relying on the most defensible and transparent methods, the application of multiple approaches, and extensive sensitivity analyses (Bell et al., 2008; Patz et al., 2008). Effort is now being applied by international agencies such as WHO and researchers in the field to improve the consistency and portability of models, so that assessments can be readily repeated, extended and modified to assist policy-makers (Kelly et al., 2017; Majid Ezzati et al., 2004; Smith and Haigler, 2008; Watts et al., 2015; Watts et al., 2017a). Although uncertainties and ambiguities remain, these methods may represent the best possible compilation and practice of knowledge to date regarding how to carry out fair, balanced, and meaningful evaluations of activities to mitigate climate change and protect human health (Bell et al., 2008; Patz et al., 2008; Smith and Haigler, 2008). Thus, shared international commitments or voluntary engagements in the use of standard methods to estimate the health co-benefits of GHG abatement should be encouraged.

To date, few health co-benefit assessments have been conducted in developing countries, and the gap is particularly noticeable in Africa and the Middle East. Hundreds of millions of people in these areas suffer high levels of environmental pollution and are also struggling with poverty, lack of secure water and sanitation services, malnutrition, and natural disasters (Anenberg et al., 2010; Haines et al., 2009; Patz et al., 2008). The health disparities that exist currently in these regions will be magnified by climate change and ecosystem disruption, meaning the countries or populations most vulnerable to climate change are, ironically, those least responsible for causing the issue (Barros et al., 2014; Chae and Park, 2011; Pachauri et al., 2014b; Smith et al., 2014; West et al., 2012; Whitmee et al., 2015). Those studies that have paid attention to co-benefits of GHG reductions in developing regions generally report the potential for climate and health benefits are considerable (Haines et al., 2009; Shindell et al., 2012; West et al., 2012; West et al., 2013). Potentially, the largest health gains of all can be made in developing regions include but are not limited to the reasons presented in Table 3. The health co-benefits of GHG abatement may contribute to reducing inequality in GHG emissions reduction responsibilities and in the health consequences of climate change between low- and high-income countries (Chae and Park, 2011; Haines et al., 2009; Patz et al., 2008; Quam et al., 2017). Many developing countries wish to simultaneously promote economic growth and at the same time cut pollution, limit GHG emissions, and protect public health concerns. These goals are not necessarily inconsistent with one another, and are profoundly important, because the active participation of developing countries in GHG reduction efforts is essential in curbing global warming (Chae and Park, 2011; Shindell et al., 2012). The present review revealed that comprehensive mitigation strategies involving multiple economic sectors generally provide greater health gains and higher GHG emissions reduction that are both welfare-enhancing and cost-effective (Anenberg et al., 2012; Jensen et al., 2013; Shindell et al., 2012; West et al., 2012; Woodcock et al., 2009). For countries with limited economic resources facing severe air pollution issues, the implementation of integrated measures is crucial to simultaneously reducing air pollutants and GHG emissions in order to maximize health co-benefits (Fig. 2) and to prepare for future agreements on climate change mitigation (Chae and Park, 2011; Pachauri et al., 2014b; Watts et al., 2015).

4.1. Challenges and uncertainties in estimating health co-benefits

Estimating health co-benefits of GHG emissions reduction is, in some ways, alien to conventional epidemiological approaches and assessment studies, presenting several challenges or uncertainties (Table 4) (Bell et al., 2008; Haines et al., 2009; Pachauri et al., 2014b; Patz et al., 2008; Remais et al., 2014; Smith and Haigler, 2008; Watts et al., 2015; Younger et al., 2008). Simply observing long-term trends in GHG abatement-related health outcomes and attributing these changes directly to mitigation measures are insufficient. Health professionals should work closely with those involved in strategic planning and performance appraisals in relevant sectors to ensure that the assumptions and scenarios on which they are based are transparent and founded on the best available evidence (Bell et al., 2008; Haines et al., 2009).

Several important sources of uncertainty arise in relation to the key steps of health co-benefits assessment. Given the nature of the information on which the co-benefits assessments must draw, the limitations in data quality and availability and the debate over exposure–response functions for health outcomes, estimating the total health gains from the decrease in air pollution associated with GHG emissions reductions remains a challenge (Bell et al., 2008; Chae and Park, 2011; Cifuentes et al., 2001a). There is substantial compositional variation worldwide for air pollutant mixtures and some evidence suggests that the toxicity of the mixtures may vary (Smith et al., 2009). The concentrations and components of air pollution mixtures, the specific pollutants responsible for adverse effects, concentration-mortality relationships, population characteristics, health status, population-specific activity patterns and lifestyles, climate and seasonal characteristics, and medical care infrastructure may differ substantially among different regions (Anenberg et al., 2011; Aunan et al., 2004; Gao et al., 2017; Markandya et al., 2009). Transferring risk estimates (e.g. baseline mortality rates, exposure-response functions, or health economic assessment tools) from one population to another is also encumbered with uncertainties (Anenberg et al., 2011; Bae and Park, 2009; Bell et al., 2008; Haines et al., 2009; West et al., 2006).

On the one hand, underestimates may characterize many parts of the assessment process in modeling studies for the following reasons: health effects of only one or a few air pollutants are considered, not all of the common pollutants (Cifuentes et al., 2001a; Markandya et al., 2009; Xia et al., 2015); the true harmful agent is not the pollutant under study, while related pollutants or groups of pollutants with similar sources or formation pathways are included in the evaluation models (Bell et al., 2008); health impacts due to exposure to indoor air pollution, forest fires and dust are often not included (Chen et al., 2007; Pechony and Shindell, 2010; West et al., 2013); in some cases only acute exposure impacts and short-term health co-benefits are estimated (Bell et al., 2008; Kunzli et al., 2001); future population growth and certain subpopulations are neglected during the health co-benefits assessment (Anenberg et al., 2012; West et al., 2013); only the well-known health consequences associated with environmental hazards are evaluated, while the unknown health endpoints or less severe health events are not considered (Anenberg et al., 2011; Haines et al., 2009; Ito et al., 2005); a number of health and economic endpoints are unquantified because of inadequate exposure-response relationships (Bell et al., 2008; Voorhees and Uchiyama, 2007); potential savings in GHG emissions are not included (Friel et al., 2009); and

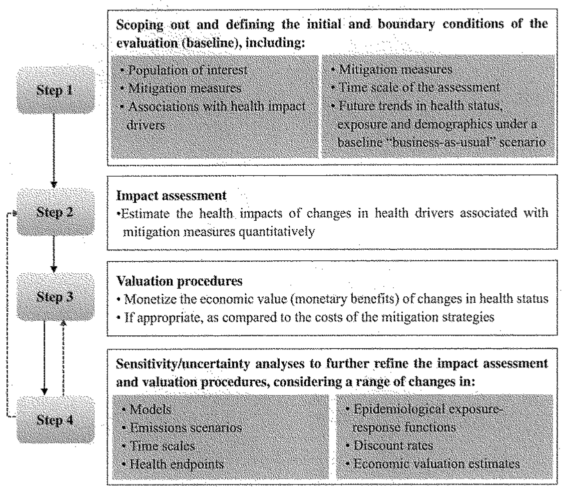

Fig. 4. Structure and key steps of approaches commonly used in health co-benefits assessment of GHG mitigation.

indirect health gains due to positive impacts of GHG reductions on ecosystems, water supplies and quality, and agriculture are not included (Cheng and Berry, 2013; Cifuentes et al., 2001a; Shindell et al., 2012; West et al., 2006).

On the other hand, some assumptions in assessment models may lead to overestimation of the health co-benefits of GHG mitigation strategies for the following reasons. First, the estimated health benefits may be based on assumptions for an immediate and/or maximum level of national participation and full implementation of each future mitigation strategy and reduction scenario. In reality, there are political, practical and institutional barriers when implementing policy options and related effects on public health will only become evident over time (Chae and Park, 2011; Friel et al., 2009; Haines et al., 2009). Second, the magnitude of the health effects might be modified in subsequent years because of changes in population structure, baseline mortality rates, background frequency of specific diseases, and social health-care interventions (Chae and Park, 2011; Collaborators, 2015; Curioni et al., 2009). Third, reduction scenarios developed to conduct health co-benefits assessments are not consistent with the actual decreases in pollutant emissions, especially for societies undergoing rapid development (Haines et al., 2009; Klimont et al., 2013; Smith et al., 2009; West et al., 2013). Finally, in food and agriculture sector, assumptions are made that reductions in the production of livestock will directly result in commensurate reductions in population's intake of saturated fat and cholesterol from animal sources (Friel et al., 2009).

In terms of the challenges and uncertainties associated with many parts of the health co-benefits assessment process in modeling studies, additional consideration and research is needed to reduce relevant underestimation or overestimation and to clarify the overall potential of GHG mitigation strategies that improve (or in some cases, negatively impact) public health. For instance, although epidemiological-based studies on numerous regions have advantages over single-city studies as they are less subject to sample size concerns, choices regarding exposure–response functions, health effect thresholds, or health economic assessment tools should be based on selecting a city or region that matches or is similar to that of the health co-benefits assessment or these studies should develop and apply city-specific parameters and indices to minimize related uncertainties (Bell et al., 2008; Chae and Park, 2011; Dominici, 2002; Remais et al., 2014; Swanson et al., 2014). It is necessary to create a set of assumptions to develop models that quantify the health co-benefits of GHG emissions reduction. Different assumptions may significantly impact the inputs, lead to substantial variations in outputs and estimates of the assessment models (Haines et al., 2009; Xia et al., 2015; Zhang et al., 2016). Thus, a series of sensitivity analyses exploring alternative assumptions regarding future trends and relations between relevant policy scenarios and health outcomes are needed in order to assess the uncertainties and applicability of key parameters and the impacts of related assumptions on the co-benefits assessments (Bell et al., 2008; Haines et al., 2009; Remais et al., 2014).

Table 3
Potential reasons for the larger health gains of GHG mitigation can be made in developing regions.

Items	Reasons	References
1	• Rely mainly on the inefficient combustion of biomass fuels for household energy	(Venkataraman et al., 2010; Wilkinson et al., 2009)
2	• Highly populated regions of the world	(Shindell et al., 2012)
3	• Populations are typically exposed to higher concentrations of air pollutants	(Anenberg et al., 2011; West et al., 2013)
4	• Have the highest baseline mortality rates	(West et al., 2012)
5	• Air quality policies and regulations to limit pollutants emissions are lacking or unenforced	(Patz et al., 2014; Rafaj et al., 2013)
6	• Populations are vulnerable because of poor nutrition, health infrastructure and access to health care	(Haines et al., 2009; Watts et al., 2015; Whitmee et al., 2015)

Table 4
Challenges and uncertainties in the health co-benefits assessment of GHG emissions reduction.

Number	Challenges/Uncertainties
1	The development of credible scenarios for GHG emissions under "business-as-usual" and mitigation projections over relevant time course
2	The energy structure, transportation patterns, land use, building construction, technology innovation, levels of exposure to health drivers, and demographic characteristics may change substantially along with time, which have major implications for public health
3	Different population subgroups (age, gender, racial or socio-economic groups) may face disproportionate health impacts from air pollution or other environmental hazards
4	There are large number of health outcomes potentially affected by GHG reductions
5	There are short- to medium-term as well as the long-term health benefits associated with GHG mitigation actions
6	The varying lag times between changes in exposure and changes in health outcomes
7	Different economic valuations of health outcomes between developed and non-industrialized countries
8	Controversial aspects of key parameters such as discount rates and the terms involved in the exposure-response functions

4.2. Strengths and limitations

The present study has some noteworthy strengths. Firstly, it is the first comprehensive review conducted specifically to assess the quantitative relationship between GHG emissions reduction and health co-benefits in different economic sectors. The health co-benefits associated with GHG mitigation measures can provide policy makers with additional incentives, raising their willingness to go beyond curtailing climate change and to reduce the emissions of both GHGs and air pollutants (Bollen et al., 2009; Crawford-Brown et al., 2012; Patz et al., 2014; Watts et al., 2017b). Secondly, we summarized evidence relating to the health co-benefits of GHG abatement measures in five economic sectors. The findings provide a more complete understanding of the multiple effects of GHG mitigation strategies, improve the ability to marshal additional political support, and inform decision-making (Cheng and Berry, 2013; Crawford-Brown et al., 2012; Kelly et al., 2017). Thirdly, the potential mechanisms and pathways through which GHG reductions bring health co-benefits were discussed. This information may provide insight into the obstacles that might be encountered in implementing GHG mitigation policies and how they can be overcome (Crawford-Brown et al., 2012; Nemet et al., 2010; Nocera et al., 2015). Lastly, current challenges and uncertainties associated with the health co-benefits assessments of GHG reductions were explored. The discussion may offer substantial information with regard to the pros and cons of different approaches used to estimate the health benefits. Despite the wide range of uncertainties characterizing many parts of the process of modeling studies, appealing health co-benefits resulting from GHG mitigation strategies can be anticipated (Aunan et al., 2004; Cifuentes et al., 2001a; Haines et al., 2009; Matus et al., 2008; Quam et al., 2017).

Several limitations of this review must be acknowledged. First, only studies published in English were included in the present review. Thus, information of studies in other languages could not be captured. Second, this study may be limited due to its emphasis on original, peer-reviewed journal articles and potentially useful evidence in other studies on the topic of health co-benefits of GHG mitigation may have been missed. For example, relevant reports or books from UN-related organizations (e.g. WHO, UNFCC, and IPCC) and other non-governmental organizations were excluded. However, we cited and presented this information extensively in our discussion. Third, despite the fact that a comprehensive literature search was conducted, it is unlikely that all of the relevant studies were identified and publication bias cannot be completely eliminated.

5. Conclusion

In the present paper, the available evidence of the quantitative associations between GHG emissions reduction and public health co-benefits were identified and summarized. The results generally suggested that GHG mitigation strategies in energy generation, transportation, food and agriculture, household, and industry could, simultaneously, bring ancillary health benefits, while comprehensive measures across various sectors tend to provide greater health gains. In addition to raising awareness, findings from this review can provide valuable information for central and local governments, non-governmental organizations, policy makers, and other relevant stakeholders concerned with the development and implementation of low carbon technologies and policies. Additionally, the potential health co-benefits and cost savings that offset or even outweigh the costs of implementing abatement measures can improve the acceptability of GHG mitigation strategies. This can help policy makers to identify the most cost-effective mitigation measures in achieving the given reduction objectives and to prioritize the use of resources in the fight against climate change.

In order to avert climate change, international negotiations are in progress regarding further GHG reductions and increasing the number of countries with binding commitments to reduce GHG emissions. During the 2015 UNFCCC COP21 (the 21st session of the Conference of the Parties), for the first time in over 20 years of UN negotiations, universal agreement was achieved on both climate change and mitigation actions. The strategic significance of the health co-benefits of GHG mitigation measures is crucial because policies aimed at reducing GHG emissions often receive weak support in many countries, but may gain support if the health co-benefits are included in cost-effective analyses. This would help bridge the development gap between low- and high-income countries and strengthen the rationale for converging GHG mitigation schedules. Thus, it appears likely that the health co-benefits may not only offset the costs of GHG mitigation policies to some extent, but may also offer a unique opportunity to promote the development and implementation of low carbon policies. In addition, quantitative information on the extent and magnitude of the health co-benefits related to GHG reductions may be of particular interest for policy makers and climate negotiators when faced with difficult choices regarding specific mitigation strategies that are vital components of international, national, or regional actions to protect the population from the dangers of climate change.

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Conflicts of interest

The authors all declare they have no actual or potential competing financial interests.

Authors' contributions

JHG and QYL conceptualized, designed and initiated the study, and drafted the initial manuscript. JHG, JL, SHG and XBL involved in the literature search, study selection, data extraction, and quality assessment. JHG, SK, SV, PW, AW, HXW, JW, XQS, YKZ, JZ and QYL involved in the development of methodology and discussion of article structure, and reviewed and revised the manuscript. All authors read and approved the final manuscript as submitted.

Appendix A. Supplementary data

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TOPICAL REVIEW

Ancillary health effects of climate mitigation scenarios as drivers of policy uptake: a review of air quality, transportation and diet co-benefits modeling studies

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Abstract

Background: Significant mitigation efforts beyond the Nationally Determined Commitments (NDCs) coming out of the 2015 Paris Climate Agreement are required to avoid warming of 2 °C above pre-industrial temperatures. Health co-benefits represent selected near term, positive consequences of climate policies that can offset mitigation costs in the short term before the beneficial impacts of those policies on the magnitude of climate change are evident. The diversity of approaches to modeling mitigation options and their health effects inhibits meta-analyses and syntheses of results useful in policy-making.

Methods/Design: We evaluated the range of methods and choices in modeling health co-benefits of climate mitigation to identify opportunities for increased consistency and collaboration that could better inform policy-making. We reviewed studies quantifying the health co-benefits of climate change mitigation related to air quality, transportation, and diet published since the 2009 Lancet Commission 'Managing the health effects of climate change' through January 2017. We documented approaches, methods, scenarios, health-related exposures, and health outcomes.

Results/Synthesis: Forty-two studies met the inclusion criteria. Air quality, transportation, and diet scenarios ranged from specific policy proposals to hypothetical scenarios, and from global recommendations to stakeholder-informed local guidance. Geographic and temporal scope as well as validity of scenarios determined policy relevance. More recent studies tended to use more sophisticated methods to address complexity in the relevant policy system.

Discussion: Most studies indicated significant, nearer term, local ancillary health benefits providing impetus for policy uptake and net cost savings. However, studies were more suited to describing the interaction of climate policy and health and the magnitude of potential outcomes than to providing specific accurate estimates of health co-benefits. Modeling the health co-benefits of climate policy provides policy-relevant information when the scenarios are reasonable, relevant, and thorough, and the model adequately addresses complexity. Greater consistency in selected modeling

choices across the health co-benefits of climate mitigation research would facilitate evaluation of mitigation options particularly as they apply to the NDCs and promote policy uptake.

Introduction

The Nationally Determined Contributions (NDCs) underlying the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) committed countries to deep reductions in global greenhouse gas (GHG) emissions to hold the global average temperature below a 2 °C increase above pre-industrial levels. The agreement is an important step forward, but by 2030 significant emissions reductions beyond the current NDCs will be required to limit warming within the 2 °C threshold (Fujimori *et al* 2016), prompting countries to consider the range of climate policy options and their broader impacts.

The cost of implementing mitigation policies that could achieve GHG emissions reductions agreed to in the Paris Agreement is estimated to be several percent of global gross domestic product by mid-century (Boyd *et al* 2015). However, economic assessments rarely include associated health co-benefits even though mitigation policies and technologies influence health by modifying health-related exposures such as non-GHG air pollutants, physical activity, and diet. Conceptual frameworks demonstrating links between air quality, transportation, and diet-related climate mitigation activities and health exposures and outcomes are presented in figure 1. Ignoring cost savings due to health impacts provides an unbalanced assessment of the net impacts of required mitigation activities.

The health co-benefits literature has expanded significantly since publication of *The Lancet* series of papers linking climate mitigation and health in November 2009 (Haines *et al* 2009). *The Lancet* papers provided a quantitative and methodological foundation for evaluating the costs and health co-benefits of mitigation policies and activities. Since then, two papers (Hosking and Campbell-Lendrum 2012, Smith *et al* 2016) reviewed the literature on the ancillary effects of mitigation activities on health outcomes, and a third (Nemet *et al* 2010) reviewed valuations of air quality co-benefits of mitigation and their relevance to policy cost-benefit analysis, but did not discuss quantification of health outcomes specifically. Hosking and Campbell-Lendrum (2012) produced a scoping review evaluating the match between the needs of policy-makers and the available research relating to climate change and quantification of health-specific outcomes. Their review was limited to research published as of June 2010 and since the World Health Assembly (WHA) established five research priority areas related to climate change-related health threats in 2008 (WHA 2008). Although climate change and health studies nearly doubled in the two years investigated, the authors identified only 12 studies of co-benefits and co-harms associated with climate mitigation and a dearth of studies pertaining to co-benefits in developing regions. Smith *et al* (2016) conducted a systematic, semi-quantitative review applying published estimates of health co-benefits to quantify the relative magnitude of health and environmental effects related to implementation of the UK Committee on Climate Change (CCC) 2008 to 2027 carbon budget (Smith *et al* 2016).

For co-benefits studies to support a case for or against a particular climate policy, Jack and Kinney (2010) suggest they must specify: meaningful scenarios, translation of policy into behavior, influence of behavior on emissions, relationship of emissions to health-determinant exposures, and quantification of health outcomes as a result of exposure. In the authors' words, 'the policy impact of the co-benefits literature will be proportional to its ability to link credible models of economic behavior, environmental processes, and health' (Jack and Kinney 2010). Noting the persistent diversity in modeling choices among the health co-benefits of mitigation studies, Remais *et al* (2014) also recommended increased rigor in the treatment of uncertainty and discount rates, inclusion of the range of ancillary health impacts (i.e. positive and negative effects), collaboration with policy makers in analytical choices, and consideration of low-probability, high-impact events such as nuclear accidents. Most recently, Liu *et al* (2017) suggested that in order for a model to provide policy-relevant science it should (1) be universal so the outputs are comparable, (2) facilitate rapid-calculation for simulating multiple scenarios, and (3) utilize input data that is accessible and straightforward.

We review studies published over the last eight years modeling the health co-benefits of mitigation policies and activities related to air quality, transportation, and diet. Our aim is to document the diversity of approaches, modeling methods, policy scenarios, assumptions, and time slices of the collected studies so that they may be considered with respect to their utility for policy making and evaluation. Climate mitigation policy may involve a range of strategies and interventions in many sectors such as building, industry, infrastructure, and agriculture, but to achieve a manageable scope while still representing the diversity of modeling choices and approaches, we limited this review to air quality, transportation, and diet, for which there is substantial health co-benefits modeling in the literature. We also identify research areas requiring consistency to inform policy decisions and promote policy uptake.

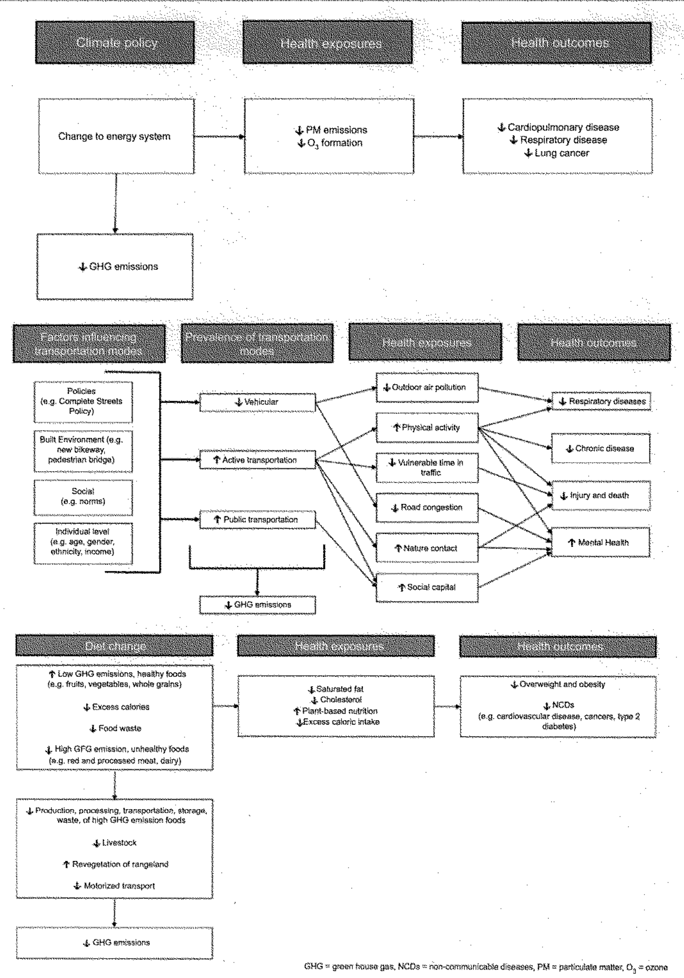

Figure 1. (*a*) Conceptual framework linking climate mitigation and health outcomes via air quality. (*b*) Conceptual framework linking climate mitigation and health outcomes via transportation. (*c*) Conceptual framework linking climate mitigation and health outcomes via diet.

Methods

We conducted a comprehensive review of quantitative estimates of health co-benefits of climate change mitigation policies in the areas of air quality, transportation, and diet initiatives starting with and published since *The Lancet* series, specifically November 2009 through January 2017. We searched PubMed, Medline, Embase, and Web of Science using the search terms 'health co-benefits' and 'climate mitigation' and synonyms for each sector (see supplementary table 1 available at stacks.iop.org/ERL/12/113001/mmedia for a complete list of search terms). Because our intent was to be comprehensive, the focus was on identifying all potentially relevant literature. For example, within the timeframe of interest in PubMed, the 11 combinations of search terms for air quality identified 496 potential citations; the 17 combinations of search terms for transportation identified 2818 potential citations; and the 8 combinations of search terms for diet identified 99 potential citations. Larger numbers of potential citations were identified using Embase and Web of Science, with large overlap. We also reviewed citations in articles uncovered in our searches and included publications brought to our attention by co-benefits researchers.

The inclusion criteria were that the abstract indicated the study was a modeling study that (1) quantified population level health outcomes, (2) related to changes in exposure(s), and (3) correlated with a specified climate mitigation scenario or policy. Studies meeting these criteria and focusing on the primary sectors of interest were included for full review. A standardized information capture matrix (refer to supplementary tables 2, 3 and 4) was developed *a priori* and used by the reviewers (KMC, KLE, JJH, RdB, RKS, MLG, and DAC). Studies were compared with regards to scenario construction, policy relevance, baseline, health-related exposures, health outcomes, geographic and temporal scale, and, when reported, health co-benefit valuation and proportional emissions reduction.

Some studies estimated health endpoints as a means toward monetizing co-benefits but did not explicitly describe their modeling or report health outcomes (e.g. Buonocore *et al* 2016, Siler-Evans *et al* 2013). While mortality could be back calculated using an estimate of the value of a statistical life, these studies did not meet our inclusion criteria because they did not report a quantification of a health outcome. However, studies that calculated mortality estimates from valuations themselves, such as studies employing the Health Economic Assessment Tool for walking and biking, which outputs monetary savings (e.g. Creutzig *et al* 2012), were included because they quantify and report a health outcome as an intermediate step. Studies that calculated impacts on the Canadian Air Quality Health Index (AQHI) (e.g. Kelly *et al* 2012) were also excluded because AQHI is not a specific health outcome.

Rebound, defined as when the savings (either in health outcomes or GHG emissions reductions) are reinvested in other activities that generate GHG emissions or disease, has the potential to negate some or all of the savings from mitigation efforts (Font Vivanco *et al* 2016). Rebound has important policy implications, but is not within the scope of this review.

Results

Forty-two studies published from November 2009 through January 2017 met the inclusion criteria and quantified health co-benefits of climate mitigation, including 24 addressing air quality exposures (supplementary table 2), 12 estimating exposures related to transportation such as physical activity (supplementary table 3), and six that modeled diet-related exposures (supplementary table 4).

Overall, studies quantifying the health co-benefits of climate mitigation efforts adhered to the scoping framework outlined by Remais *et al* (2014) and specified: mitigation strategy, association with health drivers, population, time scale, and baseline trends in demographics, health-related exposures, and health, and finally, health impact assessment (i.e. change in health driver and health outcome). Most, but not all, studies conducted sensitivity or uncertainty analysis. Just over half reported the health co-benefits in monetary terms in addition to specific health outcomes. Studies utilized a range of population-specific data sources where available and in many cases employed standard sector-specific economic, atmospheric, transportation, health impact, and climate models. Studies relied on epidemiological literature to specify concentration response functions describing the relationship between exposure and health outcome, often stratified by relevant population segments. In most instances, studies had to rely on epidemiological studies derived from populations other than the study population.

Studies took one of two approaches to defining the modeled scenario: emissions-focused or behavior-focused (figure 2). An emissions-focused approach, typical of but not exclusive to air quality co-benefits studies, investigated the health outcomes associated with mitigation scenarios that impact GHG emissions and have a secondary but simultaneous effect on health-related exposures such as air pollutants. Behavior-focused studies considered a change in a behavior at the population level, such as a reduction in motor vehicle transport or reduced consumption of meat, that impacts both health-determining exposures and GHG emissions. The behavior-focused approach was typical of transportation and diet health co-benefits studies.

Theoretical frameworks were used to elaborate the pathways between an intervention and its climate and health effects, and could be used to specify which pathways were and were not included in the scope of the analysis (e.g. Liu *et al* 2017, Xia *et al* 2015, Woodcock *et al* 2009). Causal loop diagrams were used in one case to illustrate positive and negative feedbacks and complexity in the modeled system (Macmillan *et al* 2014).

Air quality

Combatting climate change can reduce air pollution through two main mechanisms: (1) directly, by reducing the climate penalty on air quality (described below), and (2) indirectly, by reducing co-emitted air pollutants. In the US, the latter mechanism will have the greatest impact on air pollution and therefore on

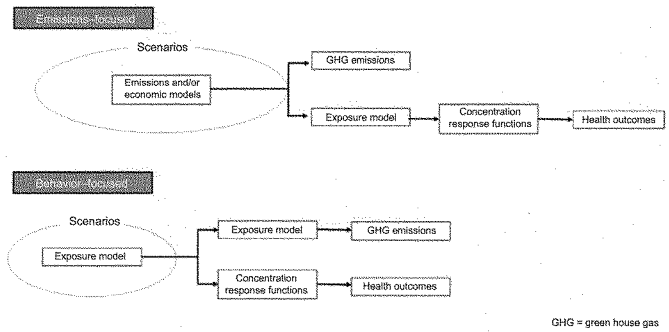

Figure 2. Two approaches to defining modeling scenarios in health co-benefits of climate mitigation studies

health at least until mid-century (Garcia-Menendez *et al* 2015). Power plants, certain industrial processes, mobile sources, and agricultural activities are sources of GHG emissions, including carbon (CO_2) and methane, that contribute to anthropogenic climate change (IPCC 2014). At the same time, these sources can emit a range of pollutant particles and gases that directly or indirectly affect health and increase the risk of premature deaths (Burnett *et al* 2014, Lepeule *et al* 2012, Krewski *et al* 2009). Ambient air pollution from particulate matter (PM) and ozone (O_3) was estimated to cause nearly 4.5 million deaths worldwide in 2015 (Cohen *et al* 2017). Therefore, reducing emissions from these sources could contribute to reducing GHG emissions and would benefit public health. Further, higher temperatures associated with climate change may increase health risks by increasing the secondary formation of PM and O_3, a phenomenon dubbed the 'climate change penalty' on air pollution (Silva *et al* 2013, Wu *et al* 2008, Fiore *et al* 2015).

There is a growing literature estimating the health co-benefits of reducing co-emitted pollutants and the climate change penalty. The 24 included studies take a diversity of approaches in estimating health co-benefits in terms of geographic scale, specificity of the scenario analyzed, policy relevance, pollutant exposures, health outcomes, valuation, and other factors (supplementary table 2). Although all report health co-benefits from the mitigation policies investigated, the range of approaches makes it difficult to synthesize beyond general statements.

Approaches

Motivations for the studies ranged from estimating current co-benefits of a specific policy proposed for a city or country to estimating future co-benefits globally under different mitigation scenarios. Therefore, the geographic and temporal scales differed. The choices of geographic and temporal scale further influenced the specificity of the scenario analyzed, with more detailed scenarios generally assessed at smaller scales.

The level of detail in each step in the analytic chain (i.e. estimating emissions related to a mitigation policy or scenario, modeling resultant changes in air quality, estimating the health impacts based on concentration-response functions) varied, making synthesis of studies challenging. Some studies started with detailed models developed to generate insights into the costs of mitigation policies (e.g. Rao *et al* 2013); the resultant changes in air pollutants were then coupled with a limited number of health concentration-response functions to estimate co-benefits. These studies had more depth in exploring mitigation options but less in exploring the wide range of possible health co-benefits, and thus may underestimate the extent of health co-benefits. Other studies started with detailed models of how a range of health outcomes can be affected by exposure to air pollutants. For example, West *et al* 2013 focused on several causes of premature mortality. These models were generally developed for other purposes, such as estimating the costs and benefits of air pollution regulation (e.g. BenMAP). A limited mitigation scenario was coupled with these models to estimate co-benefits. These studies explored a narrower range of mitigation options, but provided a more detailed assessment of health co-benefits.

Policy scenarios

Studies examined policies relevant at local, national, or international scales. The specificity of some policy scenarios, while useful for examining specific policy choices, restricted their generalizability to other technologies or contexts. For example, Gilmore *et al* (2010) examined a 500 MW sodium–sulfur battery charged during off-peak times of the day and discharged during peak times to replace four hours of electricity generation from two types of electricity generating peaking plants in New York, US. Eight studies focused on national level policies aimed at overall reductions in CO_2 to achieve national mitigation goals, energy efficiency measures, improvements in electricity generation, *inter alia*; for example comparing the US Clean Energy Standard with cap and trade policies (Saari *et al* 2015, Thompson *et al* 2014). Other studies focused on informing international negotiations on mitigation policies. One such study estimated the health co-benefits in the US of implementing a global carbon tax to achieve radiative forcing levels of 3.7 or 4.5 W m^{-2} in 2100 (Garcia-Menendez *et al* 2015). Rao *et al* (2013) compared multiple possible air pollution, energy access, and climate policies to identify which would be associated with the largest health co-benefits.

Policy baselines

Baselines to the policy scenario are important for co-benefit estimates because they determine background air quality and the level of additional achievable reductions via counterfactuals. Several near-term studies used current legislation (or a scenario of legislation) to ensure comparability in the baseline and estimated health co-benefit (e.g. West *et al* 2012). RCP 8.5 (Representative Concentration Pathway of GHG emissions that results in 8.5 W m^{-2} in 2100, approximately the current emissions pathway), for example, was used as the baseline for several studies to represent future conditions under a no mitigation policy scenario (e.g. Schucht *et al* 2015). There are limited differences in global mean surface temperature across the RCPs until 2050, so RCP 8.5 is often used as a baseline for projections later in the century.

Temporal scales

Temporal scales in the study sample ranged widely from present to 2100. The purpose of the study dictated the period of interest. The 2030s and 2050s were frequently used in projections of the magnitude and pattern of the risks of climate change (IPCC 2014), although longer simulations are typically needed to assess climate stabilization.

Sources of GHG emissions

Studies varied in the sources and species of GHG covered by the policy scenario. Sources ranged from the full economy to fossil-powered electricity, buildings, agriculture, and transportation. As mentioned, these sources were targeted through specific policies or more general scenarios. Balbus *et al* (2014) took a different approach, analyzing ten options in the transportation, buildings, and power plant sectors that would account for one US 'wedge' of GHG reductions amounting to 19 $GtCO_2$ cumulative reduction over 50 years. Three studies focused on sources of methane and black carbon (Sarofim *et al* 2017, Anenberg *et al* 2012, West *et al* 2012), while others focused on CO_2 or CO_2e.

Modeling considerations

Studies varied in their modeling approaches including their level of sophistication at different points in the pathway from policy to air pollution. Some use detailed analyses to estimate the effect of policies on emissions (e.g. Crawford-Brown *et al* 2013), and emissions on concentrations (e.g. Shindell *et al* 2012). The effects of policies on emissions were estimated by selecting blanket reductions (e.g. Markandya *et al* 2009), using engineering calculations (e.g. Balbus *et al* 2014), or employing scenarios developed with models of electricity, transportation, or economic systems (e.g. Anenberg *et al* 2012), or a combination thereof, e.g., within an integrated assessment model (e.g. Rao *et al* 2016). Atmospheric response to emissions was estimated by chemical transport models to estimate co-benefits from co-emissions, or coupled with climate inputs or feedbacks to capture direct benefits from reducing the climate change penalty. Such methodological variety is often deliberate and appropriate for a specific policy application. However, it introduces an additional difficulty when attempting to draw comparisons across studies by adding variability related to model choice in addition to other sources of variability.

Concentration-response function considerations

The studies considered a range of adverse health outcomes, including premature mortality from cardiorespiratory diseases, lung cancer, and acute respiratory infections. Studies of morbidity estimates included hospital admissions, long-term health care, asthma admissions, and restricted activity days.

When no-effects thresholds were applied, they ranged from 7.5–50 $\mu g\ m^{-3}$ for $PM_{2.5}$, although there is evidence for risk below this range (Lepeule *et al* 2012). Thresholds were typically derived from studies conducted in high-income countries, so there are questions regarding the appropriateness of applying the same functions and thresholds in low- and middle-income countries, where concentrations of air pollutants can be much higher. Further, some studies assumed concentration-response relationships were linear and others used non-linear functions (e.g. Rao *et al* 2013). Additionally, the health benefits of reductions in ambient air pollution can be difficult to model without knowing the background contribution of household air pollution or secondhand smoke to total exposures (Burnett *et al* 2014).

Results

Health co-benefits were reported as reductions in disability adjusted life years (DALYs), years of life lost (YLL), and mortality. The broad range of policy scenarios limits more detailed statements than mitigation policies would result in health co-benefits, with the extent of co-benefits varying by policy specifics, air pollutants considered, and analytic choices of geographic and temporal scale, demographic and socioeconomic changes over the study period, and health outcomes included.

Fourteen of the included studies then monetized the estimated health co-benefits to estimate the extent to which these benefits could offset the costs of implementing the policy. Although all showed some degree of offset of the policies assessed, the differences across the studies in how this was calculated makes general statements challenging.

Nonetheless, studies that compared the effects of co-emitted pollutants to that of the climate change penalty suggest that the first is the most significant, at least by mid-century, for ozone (Selin *et al* 2009) and fine particulate matter (Garcia-Menendez *et al* 2015). In addition, several studies reported an estimate of the dollars of air quality co-benefits per ton of CO_2 avoided. The range across these studies was \$2–380 ton^{-1} of CO_2 avoided, with a maximum nearly double that of earlier reviews yielding \$2–196/ton CO_2 (Nemet *et al* 2010), and ranges even higher to \$700–5000 ton^{-1} for CH_4 (Sarofim *et al* 2017, Shindell *et al* 2012).

Relevance and inclusion of co-harms

While these studies presented overall air quality benefits, several indicated the potential for dis-benefits of climate policy. For example, increased health risks occurred in localized areas due to NO_x titration of ozone (Thompson *et al* 2014). In addition, changes in health-related exposure due to regulation or lack of regulation are not constrained to that area, and 'leakage' of health risks was observed in specific unregulated regions or sectors under specific policies (Thompson *et al* 2016). Thus, distributional considerations could identify dis-benefits for certain stakeholders even if a policy yielded overall health co-benefits.

Transportation

Twelve studies modeling health outcomes related to emissions reductions scenarios targeting the transportation sector met our inclusion criteria (supplementary table 3). While transportation studies can also include air quality, they included multiple other health impacts and focused on a sector that generates a significant fraction of GHG emissions. In the United States, transportation is the second largest contributor to GHG emissions, accounting for 26% of emissions by economic sector in 2014 (USEPA 2015). The proportion of emissions accounted for by transportation increases as more renewable energy is used in other sectors. For example, transportation contributes 36% of the GHG emissions in the US state of California, the largest emission of any sector (California Environmental Protection Agency Air Resources Board 2016). In New Zealand, where over 80% of electricity is generated by hydropower and geothermal and wind sources, road transport is responsible for 40% of energy emissions (Ministry for the Environment 2017). Therefore, reducing transportation emissions will be important for achieving global, national, and local targets.

Transportation choices affect health in many ways. Car use, for example, increases risk of exposure to: traffic-related injury, physical inactivity, air pollution, and noise, among others (Nieuwenhuijsen and Khreis 2016). Traffic emissions may cause 185 000–330 000 annual premature deaths globally (Nieuwenhuijsen and Khreis 2016). However, the casualties of transportation related inactivity outweigh those due to air pollution. In New Zealand, for example, it is estimated that shifting 5% of vehicle kilometers to cycling would avoid about 116 deaths a year due to increased physical activity, and there would be 5–6 fewer deaths a year caused by pollution from vehicle emissions (Lindsay *et al* 2011). Conditions that are linked to transportation include cardiovascular disease, diabetes, mental illness, some cancers, and obesity, and among children: low birth weight, reduced cognitive function, respiratory infection, and decreased lung function (Nieuwenhuijsen and Khreis 2016). Therefore, transportation policies offer powerful opportunities to reduce related morbidity and mortality and cut GHG emissions at the same time.

Approaches

Using behavior-focused approaches, most transportation studies developed hypothetical scenarios involving replacement of a proportion of personal automobile use with walking, cycling, and use of public transportation (Stevenson *et al* 2016, Xia *et al* 2015, Macmillan *et al* 2014, Woodcock *et al* 2013, Rojas-Rueda *et al* 2011, Grabow *et al* 2012, Lindsay *et al* 2011). Three studies started from an emissions-focused premise evaluating the required shifts in transportation modes (e.g. Creutzig *et al* 2012, Woodcock *et al* 2009, Shindell *et al* 2016). The remaining two studies evaluated both types of scenarios (e.g. Sabel *et al* 2016, Maizlish *et al* 2013). Research design increased in sophistication over time, starting from simple models based on assumptions of policy or behavior implementation and general distribution of benefits, to more sophisticated approaches including stratified designs that acknowledged the age-dependency of co-benefits and co-harms (e.g. Woodcock *et al* 2013).

Policy scenarios

Not all included studies had a policy assessment; however, many of them had policy implications and/or laid the groundwork for future policy analyses. For instance, some of the studies could provide support for the enactment of Complete Streets policies, establishment of a bikeshare program, or introduction of congestion charges and other price interventions to reduce use of motor vehicles. Complete Streets policies support active transportation through the routine design, maintenance, and operation of streets and communities that are safe and accommodating for all people, regardless of age, ability, or mode of transport (Carlson *et al* 2017). On the other hand, some of the scenarios were policy packages developed with stakeholder engagement (e.g. Creutzig *et al* 2012, Woodcock *et al* 2009 and 2013). Shindell *et al* (2016) estimated the climate and health benefits of reducing US emissions consistent with a 2 °C increase in global mean surface temperature; these analyses assumed transportation reductions avoiding 0.03 °C warming in 2030 and 0.15 °C in 2100.

Policy baselines
Study settings varied widely, from cities to regions to national assessments, and there was little commonality in the interventions themselves, which consisted of various combinations of walking, cycling, and taking public transport. The baseline against which policy scenarios were measured was 'business as usual' (e.g. Macmillan *et al* 2014, Sabel *et al* 2016).

Temporal scales
Studies focused on the health benefits of increasing physical activity by replacing a portion of car trips with active transportation either today or within the next few decades. One study (Shindell *et al* 2016) projected health co-benefits to the end of the century, but the majority presented results for a decade in the first half of the century. The baselines were generally present day or a recent period.

Sources of GHG emissions
Burning fossil fuels is the primary source of transportation emissions; over 90% of the fuel used for transportation is petroleum-based, including gasoline and diesel. Studies reviewed included operational GHG emissions from motor vehicle road traffic, in particular commuter motor vehicles.

Modeling considerations
Over time, studies employed increasingly sophisticated approaches to estimate the co-benefits and co-harms of increasing active transport and considered the benefits of increased physical activity alongside the risks of injury and road traffic fatalities, and exposure to air pollution, noise, well-being, and other factors. Increasing method sophistication included use of age, gender, and fitness stratification (Woodcock *et al* 2013), consideration of social and cultural factors (e.g. the extent to which biking is considered normal or even favored), and inclusion of infrastructure parameters (e.g. the extent and safety of bike lanes). More recent studies used system dynamics modeling to address the complexity inherent to transportation policy including system feedbacks, interacting variables as drivers of system behavior, and time-dependency of cause-and-effect relationships that may produce trade-offs between long-term and short-term policy effects (Macmillan *et al* 2014).

Concentration- and exposure-response function considerations
The studies relied on quantifications of the adverse health consequences of exposure to air pollution. The studies analyzed cardio-respiratory diseases, other chronic diseases, road traffic fatalities, obesity, well-being (e.g. mental health), and other health outcomes, with mortality the most frequent endpoint considered. The studies were conducted predominantly in high income countries; it is uncertain the extent to which they would be applicable to low- and middle-income countries where infrastructure, density of settlement, traffic conditions, and vehicle speeds vary greatly. Stevenson *et al* (2016) is an example of a transportation modeling study that investigated co-benefits in a range of lower and higher income countries.

Transportation health co-benefits modeling studies focused on classic health outcomes such as cardiovascular disease, overweight, and all-cause mortality. Other important health-related effects of reduction in motor vehicle transport may be included in future studies. For instance, with one exception (Maizlish *et al* 2013), these models have not yet incorporated social-emotional wellbeing and mental health outcomes affected by social severance (e.g. diminished social interactions in neighborhoods divided by roads with high volumes of motor traffic).

Results
Significant reductions in DALYs, YLL, and/or mortality were reported from active transport even when potential injuries were considered (see supplementary table 3). A more detailed synthesis is not possible because of differences across the studies in baselines and time slices. Detailed longitudinal assessments, such as those incorporated in the ITHIM tool (Woodcock *et al* 2013), are needed to fully capture the cumulative benefits of increased physical activity.

Lindsay *et al* (2011), Macmillan *et al* (2014), Grabow *et al* (2012), and Shindell *et al* (2016) estimated the economic benefits. Lindsay *et al* (2011) estimated a savings of over NZ$1 million per 1000 commuter cyclists per year in New Zealand, and Shindell *et al* (2016) estimated near-term benefits of about US$250 billion annually in the US for implementing ambitious policies promoting clean energy and vehicles, depending on assumptions and the discount rate used; these benefits would likely exceed implementation costs. Grabow *et al* (2012) also estimated economic benefits of $8.7 billion annually over the course of the months when it would be the most feasible for active transportation in the 11 largest cities in the Upper Midwest of the US. Macmillan *et al* (2014) provided a detailed cost-benefit analysis incorporating implementation costs of commuter cycling policies and their health-related savings due to reduced mortality, hospitalizations, and disease incidence.

Relevance and inclusion of co-harms

One concern of increased active transport is potential exposure to cycle-car and pedestrian-car crashes. Injuries and crashes were considered along dimensions of striking vehicle mode, exposure per distance traveled, vehicle or non-vehicle occupant type (e.g. cyclist, pedestrian, heavy vehicle, etc.), road type and severity of injury (Creutzig *et al* 2012, Xia *et al* 2015, Lindsay *et al* 2011, Woodcock *et al* 2009). Transportation and land use are tightly connected such that the balance of benefits and co-harms in a shift to more active transport depends on infrastructure. A 50% increase in cycling in a city with an extensive cycling infrastructure would make only a small difference in injury rates compared to cities where bicycle lanes are less common. In cities in which cycling is uncommon, the safety-in-numbers effect of reduced injury incidence with increasing bicycling prevalence is likely to result principally from growing pressures to invest in safer bicycling infrastructure (Macmillan *et al* 2014, Jacobsen 2003).

Diet

As globalization and related social, economic, and demographic shifts continue, populations generally undergo a nutrition transition marked by increased consumption of animal source foods, added sugar, and processed foods (Popkin and Hawkes 2016). Consistent associations are found between these diets and high levels of noncommunicable disease (NCD) and GHG emissions, and between diets containing mostly minimally processed plant foods, whole grains, and pulses and lower levels of NCD and GHG emissions (Jones *et al* 2016, Auestad and Fulgoni 2015, Hallström *et al* 2015, Tilman and Clark 2014). Among foods, red meat has the highest GHG emissions and has been associated with health conditions including cardiovascular disease (Pan *et al* 2012, Sinha *et al* 2009), stroke (Kaluza *et al* 2012), type 2 diabetes (Pan *et al* 2011, Micha *et al* 2010), and some cancers (Cho *et al* 2003, Cross *et al* 2007, Ma and Chapman 2009, Norat and Riboli 2001). Accordingly, dietary change presents an important opportunity for obtaining health-climate co-benefits.

However, relationships between overall diet healthfulness and reduced GHG emissions are somewhat inconsistent, in part because sugar and snacks are often found to have relatively low GHG emissions compared to animal sourced foods and even compared to fresh produce, especially when it is air freighted or grown in heated greenhouses (Jones *et al* 2016, Payne *et al* 2016, Auestad and Fulgoni 2015, Hallström *et al* 2015). The variation is also attributable to considerable heterogeneity in study designs and data sources.

We identified six model-based assessments of the health-climate co-benefits of diet scenarios. Two were global in scope and considered the relative health co-benefits of diet changes by region (Springmann *et al* 2016, 2017). One study focused on the US (Hallström *et al* 2017), and the three others provided estimates for the UK (Aston *et al* 2012, Friel *et al* 2009, Scarborough *et al* 2012), with the latter also providing a São Paulo, Brazil case study. Most focused on reducing meat consumption or livestock production in regions with high consumption patterns, although Springmann *et al*'s model (Springmann *et al* 2016, 2017) included regional analyses and developing countries.

All studies considered health co-benefits from reduction of exposures related to meat intake, which variously included saturated fat from animal sources, cholesterol, and red and processed meat products. Springmann *et al* (2016), (2017) and Hallström *et al* (2017) investigated diet more comprehensively by also considering exposures such as increasing consumption of plant foods and from substituting lower-emission alternatives for meat, total energy, refined sugar, and whole versus processed grain intake. Health outcomes included coronary heart disease in all cases and often diet-related cancers, stroke, and type 2 diabetes.

Approaches

All six diet studies explicitly included both climate and health benefits of changing diets, but with different approaches. Three of the studies began with a simultaneous consideration of both climate and health impacts of diets (i.e. behavior-focused). Aston *et al* assumed that the food system accounted for one third of UK GHG emissions, and that animal products are especially emissions intensive. They calculated the proportion of the UK population with different diets based on consumption of red and processed meat, then calculated the changes in GHG emissions and relative risk (RR) of NCDs if high consumers of animal foods had diets of low consumers. Springmann *et al* (2016) began with the assumption that animal based foods are both a major source of GHG emissions and NCDs, and that diet change could be 'more effective than technological mitigation options for avoiding climate change.' They then estimated the GHG emissions and RR of NCDs for four dietary scenarios that progressively excluded more animal-sourced foods. Hallström (2017) created counterfactual healthy alternative diets statistically associated with changes in the RR for three NCDs, calculating the GHG emissions of producing these diets and even of the health care system related GHG emission savings.

The other three studies began with climate change mitigation strategies (i.e. emissions focused). Friel *et al* 2009 modeled the effect of four strategies (technological changes and a 30% reduction in production in UK livestock industry) needed to reduce GHG emissions in the UK to meet official mitigation targets for 2030. They then estimated changes in population level intake of saturated fat and cholesterol, and the resulting effect on prevalence of ischemic heart disease and stroke. Scarborough *et al* (2012) used the UK CCC carbon budget diet scenarios, designed as a climate intervention, and then estimated population level health impacts. Springmann *et al* (2017) assumed that 'GHG emissions related to food production will have to become a critical component of policies aimed at mitigating climate change,' and modeled a climate change mitigation policy of consumption taxes on all food commodities based on their GHG emissions. They then calculated dietary and weight related RR of health outcomes.

Policy scenarios

Of the diet studies, only Springmann *et al* (2017) discussed specific policies for achieving the modeled diet changes. Acceptability of the modeled diets at the individual and population level was not dealt with in these studies. In general, the objective was to 'explore a range of possible environmental [climate] and health outcomes...to encourage researchers and policymakers to act' (Springmann *et al* 2016). Exploration of policies for achieving diet change and their acceptability of modeled diets is an area of active research and policy development (Garnett *et al* 2015), but no studies addressing these questions met our inclusion criteria.

Policy baselines

The policy scenarios in the included diet studies were often compared with actual dietary patterns as the baseline. For example, policy scenarios included sex-specific doubling of the proportion of vegetarians, a wider adoption of eating habits approximating the diets of those in the existing lowest quintile of meat consumption, or observed vegetarian and vegan intakes (Aston *et al* 2012, Springmann *et al* 2016). Another approach was to consider published dietary guidelines or food exposures for which there was strong evidence of a correlation with disease, or a combination of the above approaches (Hallström *et al* 2017). Baselines typically reflected existing diets or were based on UN Food and Agriculture Organization (FAO) forecasted diets.

Temporal scales

Diet modeling studies presented results for a single year (or in one case, two years) between 2010 and 2050.

Sources of GHG emissions estimates

The studies all used life cycle assessments (LCAs) from other sources, but selected and adjusted values to some extent to make them more appropriate. The health benefits per CO_2e were highly dependent on the assumptions, methods, and data in the LCAs used as sources of CO_2e per unit of the foods in the baseline and counterfactual diets. The temporal, spatial, and structural boundaries used in LCAs can have large effects on CO_2e per unit of food, such as whether to include land use change or food waste. For example, only three of the studies (Springmann *et al* 2016, 2017, Halström *et al* 2017) incorporated wasted food; given that an estimated 30% of the global food supply is wasted, the impact on estimates can be considerable (FAO 2013).

Modeling considerations

There was considerable variation related to diet definitions, the relationship between diet and health outcomes, and the influence of diet on GHG emissions in the modeling choices and underlying assumptions of the reviewed studies. Policy scenario diets were defined *de novo* by using assumptions about health or climate benefits or both, or by modifying existing diets based on assumptions about effects on GHG emissions, or health, or both. Some studies defined them prior to the study according to climate change mitigation policies. There was also diversity in the extent of actual food intake exposures included in the models regarding components of meat or of meat products and inclusion of refined sugars and pulses. The most extensive model used was DIETRON; that is parameterized by total energy, fruit, vegetables, fiber, total fat, monounsaturated fatty acids, polyunsaturated acids, saturated fatty acids, trans fats, dietary cholesterol, and salt (Scarborough *et al* 2012).

Effects of diets, component foods, food compounds, or diet-related proximal risk factors (e.g. overweight and obesity) on health were evaluated in terms of the effect of change in the relative risk of non-communicable diseases (most frequently CHD, cancers, type 2 diabetes), or change in mortality, YLL, or DALYs. Climate impact was used to define diets alone or in combination with other parameters, and/or was modeled in terms of GHG emissions per diet, food unit, or production unit (e.g. livestock). Most studies did not include indirect feedbacks from diet change on climate in their models, for example the effect of land use change resulting from decreased consumption and production of animal foods (see below: co-harms). Hallström *et al* (2017) included the reduction in GHG emissions due to reductions in health care costs as a result of healthier diets.

Exposure–response function considerations

Population-attributable fractions (PAFs)/population impact fractions (PIFS) are used to estimate changes in morbidity and mortality due to scenario diets, based on diet or body weight risk factors from observational (correlational, cross-sectional) or experimental (randomized controlled trial) data from epidemiological studies, or meta-analyses of these data (Scarborough *et al* 2012, Springmann *et al* 2016, Springmann *et al* 2017, Hallström *et al* 2017).

Results

There was great variability in populations, definitions of diet components and diseases, risk estimates, and methods, making it difficult to directly compare health outcomes per CO_2e avoided. Overall, however, the scenarios modeled in these studies yielded considerable reductions in chronic disease and mortality, and in GHG emissions. For example, Springmann *et al* (2016) estimated that a 25%–190% increase in fruit and vegetable consumption, and 56%–78% reduction in meat consumption could result in 5.1 million global deaths avoided from coronary heart disease, stroke, cancers, and type 2 diabetes, and a reduction of 11.4–8.1 Gt year^{-1} of food-related GHG emissions. They further estimated that shifting the global population to vegetarian diets, and increasing produce consumption by 54% would result in avoiding 8.1 million deaths and a reduction of 11.4–3.4 Gt year^{-1} of food-related GHG emissions by 2050. They estimated the economic benefits at $1–31 trillion, or 0.4%–15% of global GDP in 2050.

Relevance and inclusion of co-harms

It is important to note that while there are co-benefits for many foods, and actual and model diets, this is not universal. There can be tradeoffs, or co-harms, between climate and health effects. Whether diets generate co-benefits or co-harms depends on how they are defined, and their definitions in terms of climate and health vary greatly. For example, compared with the existing US diet, the 2010 diet recommended by the USDA for improved nutrition increased GHG emissions 12% (Heller and Keoleian 2015). The main reason was that reduced meat consumption was balanced by an increase in dairy consumption, and to a lesser extent by an increase in seafood, fruit, oils and vegetables. However, the health benefits of dairy can be obtained in foods without the potential health costs of dairy (not considered by the USDA), and the USDA-recommended vegan diet with excess caloric intake eliminated reduced emissions from the current diet by 53%, suggesting that reducing or eliminating dairy may be critical for avoiding co-harms from some recommended diets.

Existing diets that have co-benefits in terms of some component foods or compounds may have co-harms in terms of others, and this varies between diets. For example, Payne *et al* (2016) reviewed 16 studies, including 100 existing dietary patterns, almost all in the Global North. They evaluated the relationship between diets containing nutrients (which they independently estimated) that are bad for health (e.g. saturated fat, salt), and those that are good for health (e.g. micronutrients), and the GHG emissions of the diets. They found that the majority of diets with lower GHG emissions had higher sugar and lower micronutrients, and that these diets had equal or higher levels of mortality and non-communicable diseases.

Of the studies included in this review, only the Springmann *et al* 2016 analysis considered co-harms of diet change directly. That study considered the ways that the projected dietary change might result in undernutrition among vulnerable populations, concluding that the corresponding health benefits outweigh these harms. They recognized there were disparities in who would benefit and be harmed.

An important class of co-harm is rebound, an issue particularly pertinent to dietary considerations, and which was dealt with in very few of the studies reviewed. Rebound can result when savings in the food or health care systems due to diet change are invested in activities that generate GHG emissions or disease that take back some of the benefits of the modeled scenarios. Rebound can also be negative and function as a co-benefit by reinforcing the intended effect of the scenario by investing health care savings from improved diets in improving access to fruits and vegetables, or revegetation of rangeland no longer needed for animal production, to increase carbon sequestration. While rebound is, as noted, outside the scope of this review, it is an important consideration for future co-benefits studies.

Discussion

Overall, despite the diversity in methods, scenarios, exposures, temporal scales, and other considerations, two important conclusions can be drawn from our review of health co-benefits studies. First, these studies consistently demonstrated that the health co-benefits of mitigation policies and technologies offset a significant portion of their implementation costs. Second, health co-benefits accrue sooner than the direct benefits of reducing GHG emissions. That is, in many instances, implementing some mitigation policies appears to make sense because of the improvements to population health even without considering the benefits for achieving climate policy.

Unfortunately, at this stage, meta-analyses of the literature are not possible because of the diversity of approaches and assumptions. The power of this research to support policy change would be increased with greater consistency (Jack and Kinney 2010, Remais *et al* 2014). This diversity reflects the range of questions being asked, the different scales at which analyses are being applied, and highlights the interest in estimates of the health co-benefits of possible climate mitigation policy choices.

However, some degree of diversity can be beneficial because local scale analyses that compare a limited set of policy choices are important for local decision makers to support choosing among specified mitigation options, and identifying those that maximize health co-benefits and greenhouse gas emission reductions. These studies must focus on the specific question(s) of interest. That the analyses might not have relevance elsewhere is a secondary and minor consideration.

The policy relevance of studies focusing on larger temporal and spatial scales, particularly those designed to explore the current or future health co-benefits associated with a change in air pollution, transportation, or diet, would be enhanced by agreeing on a limited set of population, health outcomes, scenarios, time slices, and discount rates. This is not to suggest limiting studies to a subset of the range of possible choices, but to recommend that studies at least model a consistent set of choices; doing so would promote meta-analyses and the possibility of adding results across several studies to estimate co-benefits over larger geographic scales.

Modeling approaches determine modeling choices

The inherently interdisciplinary nature of health co-benefits analyses persists in limiting the availability of studies that meet the sort of rigor and credibility across physical and societal systems prescribed by authors who noted the apparent lack of policy traction (Jack and Kinney 2010, Nemet *et al* 2010, Remais *et al* 2014). While some have attempted systems-level credibility (Thompson *et al* 2014), the researcher's perspective continues to dictate assumptions, data sources, sophistication, and comprehensiveness. In the short term, initiating analyses from a climate policy perspective (as in integrated assessment models) will likely continue to focus on the drivers of costs and GHG emissions, while initiating analyses from a health perspective will likely continue to examine a broader range of risks and outcomes.

Construction of scenarios determines policy relevance

In the reviewed studies, scenarios were constructed from hypothetical ideals, concrete policies (existing or proposed), future socio-technological scenarios, expert opinion, global guidelines (e.g. WHO/FAO), or in collaboration with local stakeholders. Where specific policies (e.g. COP21) or recognized scenarios exist (e.g. RCPs), their use enhances relevance and comparability. Studies based on mitigation strategies dependent on individual level changes in health behaviors (e.g. some of the dietary and active transportation studies) are limited in their ability to inform current climate change mitigation policy because policy does not consider individual behavior change or health. However, proposed policies may be more effective in obtaining organizational support, and in achieving results, by including climate-health co-benefits. Potential health benefits may also incentivize individual behavior change and encourage shifts in institutional policies, such as those related to food procurement.

In developing new policies, stakeholder participation can be crucial. Participatory system dynamics modeling (Macmillan *et al* 2014) involves stakeholders in producing a supported 'dynamic causal theory' and addresses the interdisciplinary and interlinked nature of co-benefits research with systems-level representations. For example, causal loop diagrams (e.g. Macmillan *et al* 2014) and conceptual frameworks describe the model scope and causal theory assumed by the model and can assist with determination of policy levers for influencing desired health and emissions outcomes. Due to inherent complexity and uncertainty, modeling studies elucidate the complex interactions between policy, GHG emissions, and health rather than predict a particular outcome at a point in time (Macmillan *et al* 2014).

Treatment of data gaps

Lack of data availability for some model inputs means that certain co-benefits or co-harms cannot be fully quantified. Modelers used a variety of techniques to address these data gaps. For instance, in air quality studies when comprehensive representative data were not available for particular countries or regions, concentration-response functions from epidemiological studies conducted in the US or other developed countries were used (e.g. West *et al* 2013). Also for example, Springmann *et al* (2016) collapsed categories from FAO data covering 110 regions and 32 food commodities and aggregated it to 107 regions and 16 commodities to match data availability for environmental and health analyses, and omitted global recommendations for food groups (i.e. fat, salt, whole grains, pulses) for which there were not adequate health data or recommendations. Hallström *et al* (2017) did not include diet-NCD links for which there was not the highest quality data pertaining to the RRs, so their result for GHG emissions reductions due to the health care effects of healthier diets was conservative. Sensitivity analyses were prevalent among studies in all three sectors to evaluate the influence of underlying sources of uncertainty and missing data (e.g. Sarofim *et al* 2017, Liu *et al* 2017, Xia *et al* 2015).

Treatment of time lag

Modeling studies must make assumptions related to the temporal dynamics of emissions, exposures, and health outcomes. Policy implementation in reality can be gradual and incomplete. There is also a lag between policy implementation and resulting changes in exposure, and changes in exposure rarely result in immediate health impacts. For example, there is a temporal gap between changes in diet-related GHG emissions and associated health impacts. The former would occur within several years of population dietary change, as food production shifted to accommodate demand, while health effects could be delayed by decades.

Most studies did not attempt to address the temporal dynamics of policy, exposure, climate and health effects, or incorporated no lag time because evidence suggests the impact on quantified benefits is small (Thompson *et al* 2014). Taking diet as an example again, in most models the climate and health effects were assumed to be equivalent to the diets having been adopted for some time, or the effects of the diets happening all at once. Other models assumed the results would be obtained by a climate change mitigation target year. Some researchers addressed the lag by employing the concept of 'committed impact' (i.e. counting the long-term impact of a change in exposure). Creutzig *et al* (2012) modeled the 'transition dynamics' of transportation policies to address implementation phasing, but still assumed instantaneous effects on health.

Incorporating complexities in health exposures

Estimates of health co-benefits are sensitive to the source of relative risks applied, the age- and sex-specific granularity applied, and the range of exposure concentrations considered, especially when the exposure-response curve is uncertain at the high end of exposures. For example, for some health risks there may be no safe level exposure, but epidemiology data may be incomplete at the extremes, so models may either assume there is an exposure threshold below which there is no measurable health effect, or assume no threshold and test for sensitivity at the limits for which data are available (e.g. West *et al* 2013). Furthermore, baseline health status and likelihood of behavior modification can influence susceptibility to exposure and vary by population segment, which impacts the distribution of health co-benefits. Many studies did not address these complexities. However, Maizlish *et al* (2013) considered age- and gender-specificity of physical activity and health outcomes, as well as decreased population level variability in commute speed and active travel participation with increased prevalence of cycling and walking (Maizlish *et al* 2013). Relevance of these types of complexities is determined by the research and policy objectives.

Interoperability between health models and integrative assessment models (IAMs)

Employing IAMs, such as those from the International Institute of Applied Systems Analysis, is a way for health co-benefits studies to expand on existing standardized models of large scale interactions among population, technology, socioeconomic factors, and emissions and link them to health outcomes. There are two main IAM approaches: IAMs that incorporate their own estimate of emissions to impacts, and IAMs that couple with a more comprehensive health impacts tool (pathway of emissions to concentrations to health). The former often uses simplified relationships of emissions to health impacts that neglect, for example, complex chemical nonlinearities (Thompson *et al* 2014). There is increasing sophistication in the tools used to link emissions directly to outcomes; however, there remains considerable disagreement between these approaches and caution is warranted in applying them beyond their context (Heo *et al* 2016). For both approaches, it would be helpful to increase the number and kind of health outcomes considered to more broadly reflect the range of health co-benefits that could arise. Increasing the interoperability between health and integrated assessment models would facilitate this inclusion.

Guidelines for accurate and transparent health estimates reporting (GATHER)

The WHO GATHER (Stevens *et al* 2016) include definitions of technical terms (health indicator, health estimates, data inputs, and covariates) and a checklist pertaining to study population, data inputs and analyses, results, and discussion. GATHER maintains that items on this checklist should be specified alongside published health estimates to facilitate reasonable comparisons across time and between different populations, and appropriate use of health estimates in policy, planning, and monitoring. Specifically, 'GATHER aims to define best practices for reporting of studies that synthesize information from multiple sources to quantitatively describe past and current population health and its determinants,' similar to what health co-benefits modeling studies do, although co-benefits studies often project future impacts.

Models of health co-benefits of climate mitigation span a global range in populations and data sources and are often constrained by data availability. Utility, comparability and synthesis of these models therefore depends on interpretation of their results and limitations. GATHER provides a best practice and standard method of documenting population-level health-related indicators and determinants.

Overall, the studies reviewed, while they do not specifically mention GATHER, for the most part comply with the guidelines. One area in which co-benefits studies do not always adhere to the GATHER guidelines is in the treatment of uncertainty. GATHER requires a quantitative measure of uncertainty, including methods for calculating uncertainty and articulation of which sources of uncertainty are and are not accounted for. Sensitivity analyses are prevalent but not ubiquitous among health co-benefits of climate mitigation studies.

Valuation of health co-benefits

The role of valuation of health co-benefits in the policy discourse and methods for estimating monetized health benefits have been described and discussed (Bell *et al* 2008, Springmann *et al* 2016a, Nemet *et al* 2010). Valuation approaches include: value of statistical life (used in cost/benefit analyses), value of life years lost with mortality analysis by age segmentation, benefits transfer approach, cost of illness (quantifies direct costs of morbidity), and willingness to pay (to reduce mortality risk), among others. Valuation approaches range from very narrow estimating only avoided health costs to very broad including net societal benefits. When accounting for health impacts in evaluating cost effectiveness of mitigation options, both the scope of health impacts modeled and the valuation approach must be considered.

Equity considerations

Equity is a major pillar of the causes, impacts, and solutions to climate change, yet few studies have considered the social distribution of health co-benefits. The study by Springmann *et al* (2016) on diet co-benefits is an exception. While some air quality models consider regional equity, there is a dearth of studies addressing socioeconomic dimensions, and we found no transportation studies that modelled the effects on health of climate mitigation through an equity lens.

The direct effects of climate mitigations are not experienced evenly, and the co-benefits and co-harms of climate mitigation policies may not be distributed equitably. Specifically, there is a pattern of inequity between the production of total and food system GHG emissions, and the vulnerability to climate change. Diet changes that would reduce GHG emissions could facilitate a shift in resources from wealthy populations to less wealthy populations, with reduced consumption in the former allowing for some increased consumption in the later, improving health in both. This was explicitly addressed only by Springmann *et al* (2016), whose scenarios reduced or eliminated (vegan diet) the food-related GHG emissions gap between high per capita emissions in the Global North and low per capita emissions in the Global South. Policy interventions to shift costs of diets in relationship to climate and health benefits, as explored in Springmann *et al* (2017), result in regressive outcomes. Those authors suggest complementary policy strategies to improve equity, such as excluding health-promoting foods from taxation and providing compensation to those most affected.

Conclusions

As noted throughout this review, while the studies of the benefits of air quality, transportation, and diet mitigation policies consistently report health co-benefits, meta-analyses and syntheses of results are stymied by the diversity of approaches, modeling methods, policy scenarios, assumptions, time slices, and evaluation metrics. Increasing consistency across the air quality, transportation, and diet studies would begin to provide more comprehensive estimates of health co-benefits and to explore potential synergies and dis-benefits of baskets of mitigation options.

To a large extent, the reviewed literature achieved many of the recommendations of Jack and Kinney (2010) in that the studies reported scenarios and relationships of emissions to health-determinants, and quantified health outcomes. However, reporting is clearly insufficient if the literature is to fulfill its potential for having a significant policy impact, particularly at larger geographic and political scales; greater consistency is needed to conduct syntheses and meta-analyses of the health co-benefits of mitigation policies. Achieving this consistency is critical as nations are developing baskets of mitigation options to achieve their NDCs to the Paris Agreement. As choices are made, policymakers will be ill informed without a holistic view of the costs and benefits of the options. Incorporating a larger basket of health outcomes would provide more accurate estimates of the magnitude of possible benefits. Further, as noted by Remais *et al* (2014), considering dis-benefits also would increase understanding of positive and negative aspects of mitigation policies.

This is not to say that scientific knowledge is the only or even the primary driver of policymaking (Verboom *et al* 2016). The processes by which policy- and decision-makers assess and use information is complex. Polices need to take into consideration not only scientific evidence, but also competing priorities, interests, and values, and perceptions of equity, fairness, and ethics (Bowen and Zwi 2005), among other considerations. Iterative engagement between researchers and policymakers increases the capacity of policymakers to assess, evaluate, and use data in support of complex-policy interventions, and the capacity of researchers to provide policy-relevant results (Langlois *et al* 2016). Increased availability and use of simplified, universal models that facilitate rapid calculation, such as the greenhouse gas policy assessment model (GHG-PAM) developed by Liu *et al* (2017), could help align scientific insight to policy-making needs and realities.

The literature can be roughly divided into studies that focus on quantifying the health co-benefits of a specific, local mitigation policy, which generally are concerned with short-term benefits; and those that focus on larger geographic and temporal scales. Local scale studies will increasingly be needed to inform policy-makers of the benefits associated with specific policy recommendations, to provide balanced estimates of the net cost of these policies and to help policymakers choose among sets of mitigation options. Because the scenarios used are in response to policy-maker needs, diversity will and must continue. However, agreeing on comparable health outcomes, the concentration-response relationships, and approaches to estimating the economic benefits would increase the policy relevance of health co-benefits research.

There is also a significant opportunity for national and regional studies to use comparable choices to enable synthesis and more robust quantifications of health co-benefits. Again, increased consistency in the health co-benefits considered, the concentration-response relationships employed, and approaches to estimating the economic benefits would improve comparability and bring together emissions-focused and behavior-focused approaches (figure 2). In addition, modelers can develop a limited set of scenarios and time slices to explore as part of their projections of health co-benefits; additional scenarios may be of interest to address the study questions. We recommend that a few scenarios be included in all studies with a view toward synthesis and meta-analysis. Specifically, projections done through 2020 should focus at least on 2030 and projections done through 2040 should focus at least on 2050, and all projections should include a normative scenario that combines marker scenarios RCP 2.6 and the sustainability pathway in the Shared Socio-economic Pathways (SSP1) (O'Neill *et al* 2017), as this will be the closest to achieving the Paris Agreement (Riahi *et al* 2017), or a scenario consistent with the underlying drivers (e.g. SRES B1 and SRES A2, respectively). A high emissions scenario such as RCP 6.0 or 8.5 and Regional Rivalry in the SSPs (SSP3) would be a scenario with high population and high emission growth that could be used as a counterfactual for projections past 2050. Using similar temporal and spatial scales as employed in integrated assessment models means the costs of mitigation policies from these models could be compared with the health co-benefits (e.g. West *et al* 2012). Achieving this could be promoted by partnering with the integrated assessment modelers. Doing so would increase the complexity of health co-benefits analyses and their potential usefulness.

Another increasing area of interest is to understand the equity dimensions of mitigation policies and to whom the health co-benefits accrue. It is easy to imagine that some air quality mitigation policies could provide greater benefits to communities downwind of coal-fired power plants, and that increasing active transport could benefit homes along major transportation routes if vehicular traffic is reduced. Reducing vehicle emission standards would further benefit these communities. Expanding the health co-benefits literature to consider particularly vulnerable communities and populations would help inform estimates of the extent to which mitigation policies also would have positive (or negative) equity dimensions.

These recommendations are within the context that model diversity itself has benefits (Ebi and Rocklov 2014). There is broad diversity across integrated assessment models used to estimate the costs of mitigation, but also sufficient consistency that model results can be compared and summed in some instances.

As the literature demonstrates, mitigation policies are very likely a 'win-win,' improving health in the shorter term while decreasing the magnitude of climate change-related health risks later in the century. Taking the health co-benefits into account provides more comprehensive estimates of mitigation policy costs and benefits, and may increase the political feasibility of mitigation policies because these health benefits are often significant, local, and immediate, accruing well before the climate benefits of reduced GHG emissions. Leveraging estimates of nearer-term, more proximal health benefits of climate mitigation policies and technologies is an opportunity to support policy uptake and implementation.

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14 Human Health

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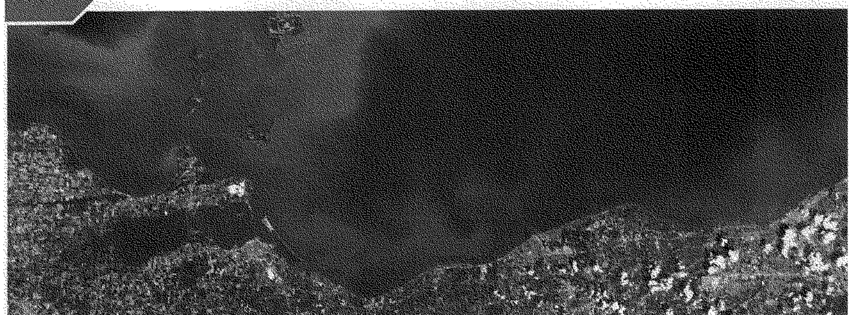
14 Human Health



Algal bloom in Lake Erie in the summer of 2015

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks. Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color.

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services. Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design.

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term. By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.

Executive Summary

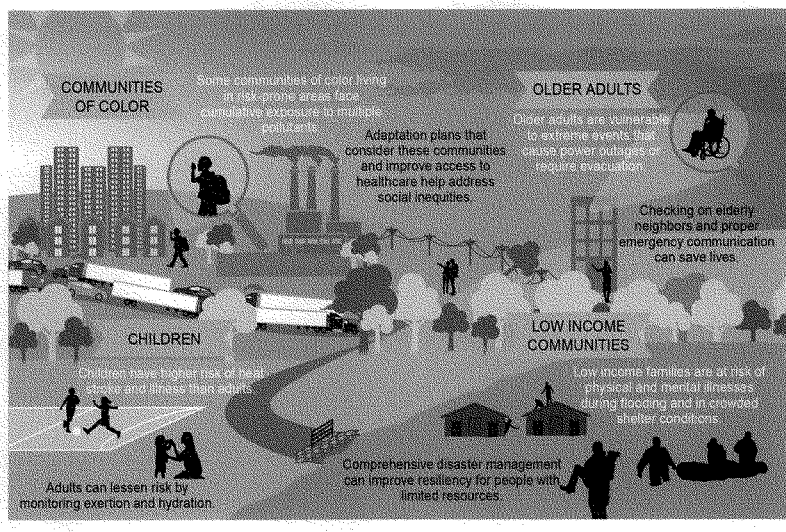
Climate-related changes in weather patterns and associated changes in air, water, food, and the environment are affecting the health and well-being of the American people, causing injuries, illnesses, and death. Increasing temperatures, increases in the frequency and intensity of heat waves (since the 1960s), changes in precipitation patterns (especially increases in heavy precipitation), and sea level rise can affect our health through multiple pathways. Changes in weather and climate can degrade air and water quality; affect the geographic range, seasonality, and intensity of transmission of infectious diseases through food, water, and disease-carrying vectors (such as mosquitoes and ticks); and increase stresses that affect mental health and well-being.

Changing weather patterns also interact with demographic and socioeconomic factors, as well as underlying health trends, to influence the extent of the consequences of climate change for individuals and communities. While all Americans are at risk of experiencing adverse climate-related health outcomes, some populations are disproportionately vulnerable.

The risks of climate change for human health are expected to increase in the future, with the extent of the resulting impacts dependent on the effectiveness of adaptation efforts and on the magnitude and pattern of future climate change. Individuals, communities, public health departments, health-related organizations and facilities, and others are taking action to reduce health vulnerability to current climate change and to increase resilience to the risks projected in coming decades.

The health benefits of reducing greenhouse gas emissions could result in economic benefits of hundreds of billions of dollars each year by the end of the century. Annual health impacts and health-related costs are projected to be approximately 50% lower under a lower scenario (RCP4.5) compared to a higher scenario (RCP8.5). These estimates would be even larger if they included the benefits of health outcomes that are difficult to quantify, such as avoided mental health impacts or long-term physical health impacts.

Vulnerable Populations



Examples of populations at higher risk of exposure to adverse climate-related health threats are shown along with adaptation measures that can help address disproportionate impacts. When considering the full range of threats from climate change as well as other environmental exposures, these groups are among the most exposed, most sensitive, and have the least individual and community resources to prepare for and respond to health threats. White text indicates the risks faced by those communities, while dark text indicates actions that can be taken to reduce those risks. *From Figure 14.2 (Source: EPA).*

A comprehensive assessment of the impacts of climate change on human health in the United States concluded that climate change exacerbates existing climate-sensitive health threats and creates new challenges, exposing more people in more places to hazardous weather and climate conditions.[1] This chapter builds on that assessment and considers the extent to which modifying current, or implementing new, health system responses could prepare for and manage these risks. Please see Chapter 13: Air Quality for a discussion of the health impacts associated with air quality, including ozone, wildfires, and aeroallergens.

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

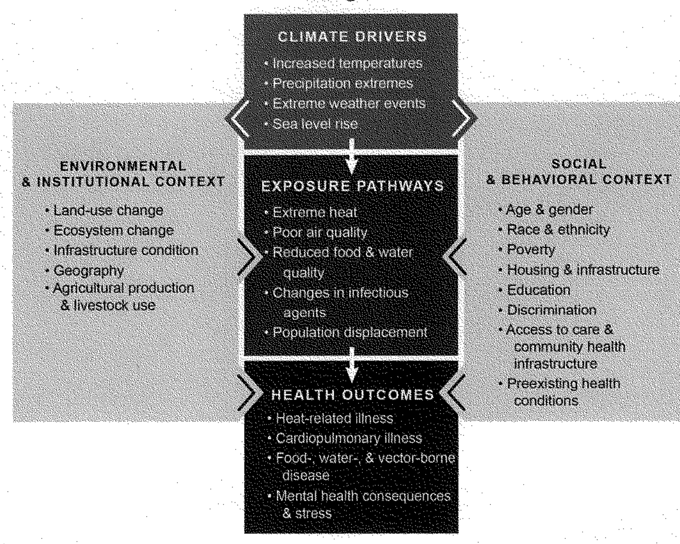


Figure 14.1: This conceptual diagram illustrates the exposure pathways by which climate change could affect human health. Exposure pathways exist within the context of other factors that positively or negatively influence health outcomes (gray side boxes). Key factors that influence vulnerability for individuals are shown in the right box and include social determinants of health and behavioral choices. Key factors that influence vulnerability at larger scales, such as natural and built environments, governance and management, and institutions, are shown in the left box. The extent to which climate change could alter the burden of disease in any location at any point in time will depend not just on the magnitude of local climate change but also on individual and population vulnerability, exposure to changing weather patterns, and capacity to manage risks, which may also be affected by climate change. Source: Balbus et al. 2016.[2]

The first paragraph in each of the following sections summarizes findings of the 2016 U.S. Climate and Health Assessment,[1] and the remainder of each section assesses findings from newly published research.

Extreme Events

More frequent and/or more intense extreme events, including drought, wildfires, heavy rainfall, floods, storms, and storm surge, are expected to adversely affect population health.[3] These events can exacerbate underlying medical conditions, increase stress, and lead to adverse mental health effects.[4] Further, extreme weather and climate events can disrupt critical public health, healthcare, and related systems in ways that can adversely affect health long after the event.[3]

Recent research improves identification of vulnerable population groups during and after an extreme event,[5] including their geographic location and needs (e.g. Bathi and Das 2016, Gotanda et al. 2015, Greenstein et al. 2016[6,7,8]). For example, the 2017 hurricane season highlighted the unique vulnerabilities of populations residing in Puerto Rico, the U.S. Virgin Islands, and other Caribbean islands (Ch. 20: U.S. Caribbean, Box 20.1).[9]

Temperature Extremes

High temperatures in the summer are conclusively linked to an increased risk of a range of illnesses and death, particularly among older adults, pregnant women, and children.[18] People living in urban areas may experience higher ambient temperatures because of the additional heat associated with urban heat islands, exacerbating heat-related risks.[19] With continued warming, increases in heat-related deaths are projected to outweigh reductions in cold-related deaths in most regions.[18]

Analyses of hospital admissions, emergency room visits, or emergency medical services calls show that hot days are associated with an increase in heat-related illnesses,[20,21] including cardiovascular and respiratory complications,[22]

Box 14.1: Health Impacts of Drought and Periods of Unusually Dry Months

In late 2015, California was in the fourth year of its most severe drought since becoming a state in 1850, with 63 emergency proclamations declared in cities, counties, tribal governments, and special districts.[10,11] Households in two drought-stricken counties (Tulare and Mariposa) reported a range of drought-related health impacts, including increased dust leading to allergies, asthma, and other respiratory issues and acute stress and diminished peace of mind.[10] These health effects were not evenly distributed, with more negative physical and mental health impacts reported when drought negatively affected household property and finances.

Drier conditions can increase reproduction of a fungus found in soils, potentially leading to the disease coccidioidomycosis, or Valley fever.[3,12] Coccidioidomycosis can cause persistent flu-like symptoms, with over 40% of cases hospitalized and 75% of patients unable to perform their normal daily activities for weeks, months, or longer. Higher numbers of cases in Arizona and California are associated with periods of drier conditions as measured by lower soil moisture in the previous winter and spring.[13]

Overall, the impacts of drought on hospital admissions and deaths depend on drought severity and the history of droughts in a region.[14] Complex relationships between drought and its associated economic consequences, particularly the interactions among factors that affect vulnerability, protective factors, and coping mechanisms, can increase mood disorders, domestic violence, and suicide.[15,16,17] renal failure,[23] electrolyte imbalance, kidney stones,[24] negative impacts on fetal health,[25] and preterm birth.[26] Risks vary across regions (Ch. 18: Northeast, Box 18.3).[27] Health risks may be higher earlier in the summer season when populations are less accustomed to experiencing elevated temperatures, and different outcomes are observed at different levels of high temperature.[28,29] See Chapter 13: Air Quality for a discussion of the associations between temperature, air quality, and adverse health outcomes.

Vector-Borne Diseases

Climate change is expected to alter the geographic range, seasonal distribution, and abundance of disease vectors, exposing more people in North America to ticks that carry Lyme disease or other bacterial and viral agents, and to mosquitoes that transmit West Nile, chikungunya, dengue, and Zika viruses.[30,31,32] Changing weather patterns interact with other factors, including how pathogens adapt and change, changing ecosystems and land use, demographics, human behavior, and the status of public health infrastructure and management.[33,34]

El Niño events and other episodes of variable weather patterns may indicate the extent to which the risk of infectious disease transmission could increase with additional climate change.[33,35,36]

Increased temperatures and more frequent and intense extreme precipitation events can create conditions that favor the movement of vector-borne diseases into new geographic regions (e.g., Belova et al. 2017, Monaghan et al. 2016, Ogden and Lindsay 2016[31,37,38]). At the same time, very high temperatures may reduce transmission risk for some diseases.[39,40] Economic development also may substantially reduce transmission risk by reducing contacts with vector populations.[41] In the absence of adaptation, exposure to the mosquito *Aedes aegypti*, which can transmit dengue, Zika, chikungunya, and yellow fever viruses, is projected to increase by the end of the century due to climatic, demographic, and socioeconomic changes, with some of the largest increases projected to occur in North America.[31,32] Similarly, changes in temperature may influence the distribution and abundance of tick species that transmit common pathogens.[38,42,43]

Box 14.2: Transboundary Transmission of Infectious Diseases

Outbreaks occurring in other countries can impact U.S. populations and military personnel living abroad and can sometimes affect the United States. For example, the 2015–2016 El Niño, one of the strongest on record,[44] may have contributed to the 2014–2016 Zika epidemic in the Americas.[31,45,46,47,48] Warmer conditions may have facilitated expansion of the geographic range of mosquito populations and increased their capacity to transmit Zika virus.[40] Zika virus can cause a wide range of symptoms, including fever, rash, and headaches, as well as birth defects. The outbreak began in South America and spread to areas with mosquitoes capable of transmitting the virus, including Puerto Rico, the U.S. Virgin Islands, Florida, and Texas.

Water-Related Illnesses and Death

Increasing water temperatures associated with climate change are projected to alter the seasonality of growth and the geographic range of harmful algae and coastal pathogens, and runoff from more frequent and intense rainfall is projected to increasingly compromise recreational waters and sources of drinking water through increased introductions of pathogens and toxic algal blooms.[49,50,51,52,53,54]

Projected increases in extreme precipitation and flooding, combined with inadequate water and sewer infrastructure, can contribute to viral and bacterial contamination from combined sewage overflows and a lack of access to potable drinking water, increasing exposure to pathogens that lead to gastro-intestinal illness.[55,56,57,58,59] The relationship between precipitation and temperature-driven transmission of waterborne diseases is complex and site-specific, with, for example, some areas finding increased numbers of cases associated with excessive rainfall and others finding stronger associations with drought.[60,61,62,63,64,65] Heavy rainfall, flooding, and high temperatures have been linked to increases in diarrheal disease[62,64,66,67] and can increase other bacterial and parasitic infections such as leptospirosis and cryptosporidiosis.[65,68] Increases in air temperatures and heat waves are expected to increase temperature-sensitive marine pathogens such as *Vibrio*.[60,69,70,71]

Food Safety and Nutrition

Climate change, including rising temperatures and changes in weather extremes, is projected to adversely affect food security by altering exposures to certain pathogens and toxins (for example, *Salmonella*, *Campylobacter*, *Vibrio parahaemolyticus* in raw oysters, and myco-toxigenic fungi).[72]

Climate change, including changes in some extreme weather and climate events, can adversely affect global and U.S. food security by, for example, threatening food safety,[73,74,75] disrupting food availability, decreasing access to food, and increasing food prices.[76,77,78,79,80,81,82] Food quality also is expected to be affected by rising CO_2 concentrations that decrease dietary iron,[83] zinc,[84] protein,[85] and other macro- and micronutrients in crops[86,87,88] and seafood.[89,90] Projected changes in carbon dioxide concentrations and climate change could diminish expected gains in global nutrition; however, any impact on human health will depend on the many other drivers of global food security and factors such as food chain management, human behavior, and food safety governance.[91,92,93,94]

Mental Health

Mental health consequences, ranging from minimal stress and distress symptoms to clinical disorders, such as anxiety, depression, post-traumatic stress, and suicidality, can result from exposures to short-lived or prolonged climate- or weather-related events and their health consequences.[4] These mental health impacts can interact with other health, social, and environmental stressors to diminish an individual's well-being. Some groups are more vulnerable than others, including the elderly, pregnant women, people with preexisting mental illness, the economically disadvantaged, tribal and Indigenous communities, and first responders.[4]

Individuals whose households experienced a flood or risk of flood report higher levels of depression and anxiety, and these impacts can persist several years after the event.[95,96,97,98] Disasters present a heavy burden on the mental health of children when there is forced displacement from their home or a loss of family and community stability.[99] Increased use of alcohol and tobacco are common following disasters as well as droughts.[15,16,100,101] Higher temperatures can lead to an increase in aggressive behaviors, including homicide.[102,103] Social cohesion, good coping skills, and preemptive disaster planning are examples of adaptive measures that can help reduce the risk of prolonged psychological impacts.[102,104,105]

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks. Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color.

The health impacts of climate change are not felt equally, and some populations are at higher risk than others.[106] Low-income communities and some communities of color are often already overburdened with poor environmental conditions and are disproportionately affected by, and less resilient to, the health impacts of climate change.[106,107,108,109,110] The health risks of climate change are expected to compound existing health issues in Native American and Alaska Native communities, in part due to the loss of traditional foods and practices, the mental stress from permanent community displacement, increased injuries from lack of permafrost, storm damage and flooding, smoke inhalation, damage to water and sanitation systems, decreased food security, and new infectious diseases (Ch. 15: Tribes; Ch. 26: Alaska).[111,112]

Across all climate risks, children, older adults, low-income communities, some communities of color, and those experiencing discrimination are disproportionately affected by extreme weather and climate events, partially because they are often excluded in planning processes.[113] Other populations might experience increased climate risks due to a combination of exposure and sensitivity, such as outdoor workers, communities disproportionately burdened by poor environmental quality, and some communities in the rural Southeastern United States (Ch. 19: Southeast).[114,115,116]

Vulnerable Populations

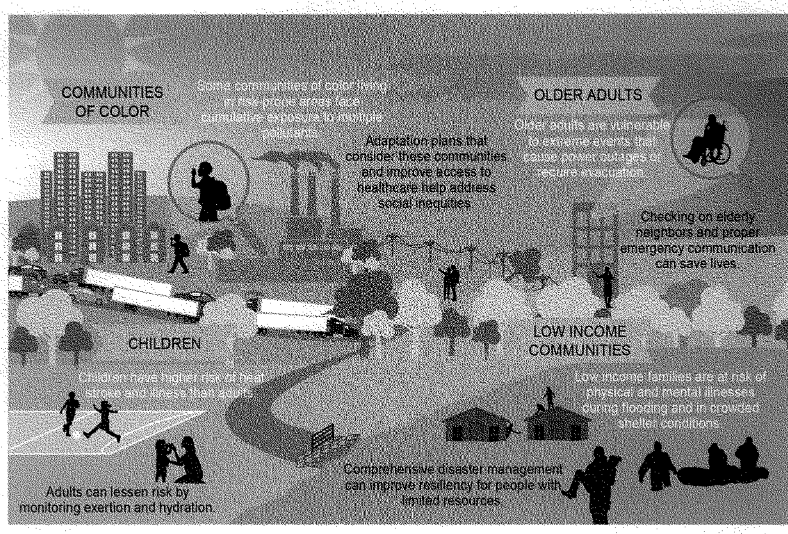


Figure 14.2: Examples of populations at higher risk of exposure to adverse climate-related health threats are shown along with adaptation measures that can help address disproportionate impacts. When considering the full range of threats from climate change as well as other environmental exposures, these groups are among the most exposed, most sensitive, and have the least individual and community resources to prepare for and respond to health threats. White text indicates the risks faced by those communities, while dark text indicates actions that can be taken to reduce those risks. Source: EPA.

Additional populations with increased health and social vulnerability typically have less access to information, resources, institutions, and other factors to prepare for and avoid the health risks of climate change. Some of these communities include poor people in high-income regions, minority groups, women, pregnant women, those experiencing discrimination, children under five, persons with physical and mental illness, persons with physical and cognitive disabilities, the homeless, those living alone, Indigenous people, people displaced because of weather and climate, the socially isolated, poorly planned communities, the disenfranchised, those with less access to healthcare, the uninsured and underinsured, those living in inadequate housing, and those with limited financial resources to rebound from disasters.[107,109,117,118] Figure 14.2 depicts some of the populations vulnerable to weather, climate, and climate change.

Building Resilient Communities

Projections of climate change-related changes in the incidence of adverse health outcomes, associated treatment costs, and health disparities can promote understanding of the ethical and human rights dimensions of climate change, including the disproportionate share of climate-related risk experienced by socially marginalized and poor populations. Such projections can also highlight options to increase population resilience.[119,120,121] The ability of a community to anticipate, plan for, and reduce impacts is enhanced when these efforts build on other environmental and social programs directed at sustainably and equitably addressing human needs.[122] Resilience is enhanced by community-driven planning processes where residents of vulnerable and impacted communities define for themselves the complex climate challenges they face and the climate solutions most relevant to their unique vulnerabilities.[110,123,124,125] A flood-related disaster in central Appalachia in spring 2013 highlighted how community-based coping strategies related to faith and spirituality, cultural values and heritage, and social support can enhance resilience post-disaster.[126]

Communities in Louisiana and New Jersey, for example, are already experiencing a host of negative environmental exposures coupled with extreme coastal and inland flooding. Language-appropriate educational campaigns can highlight the effectiveness of ecological protective measures (such as restoring marshes and dunes to prevent or reduce surge flooding) for increasing resilience. Resilience also can be built by creating institutional readiness, recognizing the importance of resident mobility (geographic movements at various scales such as commuting, migration, and evacuation), acknowledging the importance and support of social networks (such as family, church, and community), and facilitating adaptation to changing conditions.[127,128]

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services. Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design.

Adapting to the Health Risks of Climate Change

Individuals, communities, public health departments, healthcare facilities, organizations, and others are taking action to reduce health and social vulnerabilities to current climate change and to increase resilience to the risks projected in coming decades.[129]

Examples of state-level adaptation actions include conducting vulnerability and adaptation assessments, developing comprehensive response plans (for example, extreme heat),[110,130] climate-proofing healthcare infrastructure, and implementing integrated surveillance of climate-sensitive infectious disease (for example, Lyme disease). Incorporating short-term to seasonal forecasts into public health programs and activities can protect population health today and under a warming climate.[129] Over decades or longer, emergency preparedness and disaster risk reduction planning can benefit from incorporating climate projections to ensure communities are prepared for changing weather patterns.[131]

Local efforts include altering urban design (for example, by using cool roofs, tree shades, and green walkways) and improving water management (for example, via desalination plants or watershed protection). These can provide health and social justice benefits, elicit neighborhood participation, and increase resilience for specific populations, such as outdoor workers.[107,132,133]

Adaptation options at multiple scales are needed to prepare for and manage health risks in a changing climate. For example, options to manage heat-related mortality include individual acclimatization (the process of adjusting to higher temperatures) as well as protective measures, such as heat wave early warnings,[134] air conditioning at home, cooling shelters,[135] green space in the neighborhood,[136,137] and resilient power grids to avoid power outages during extreme weather events.[138]

Early warning and response systems can protect population health now and provide a basis for more effective adaptation to future climate.[139,140,141] Improvements in forecasting weather and climate conditions and in environmental observation systems, in combination with social factors, can provide information on when and where changing weather patterns could result in increasing numbers of cases of, for example, heat stress or an infectious disease.[31,45,142,143,144] Such early warning systems can provide more time to pre-position resources and implement control programs, thereby preventing adverse health outcomes. For example, to help communities prepare for extreme heat, federal agencies are partnering with local entities to bring together stakeholders across the fields of public health, meteorology, emergency management, and policy to develop useful information systems that can prevent heat-related illnesses and deaths.[145] Adaptation efforts outside the health sector can have health benefits when, for example, infrastructure planning is designed to cool ambient temperatures and attenuate storm water runoff[146,147] and when interagency planning initiatives involve transportation, ecosystem management, urban planning, and water management.[148] Adaptation measures developed and deployed in other sectors can harm population health if they are developed and implemented without taking health into consideration.

Box 14.3: Healthcare

The U.S. healthcare sector is a significant contributor to climate change, accounting for about 10% of total U.S. greenhouse gas emissions.[149] Healthcare facilities are also a critical component of communities' emergency response system and resilience to climate change. Measures within healthcare institutions that decrease greenhouse gas emissions could significantly reduce U.S. emissions, reduce operating costs, and contribute to greater resilience of healthcare infrastructure. For example, U.S. hospitals could save roughly $15 billion over 10 years by adopting basic energy efficiency and waste-reduction measures (cumulative; no discount rate reported).[150] Combined heat and power systems can enhance hospitals' resilience in the face of interruptions to the power grid while reducing costs and emissions in normal operations.[151]

Box 14.3: Healthcare, continued

Hospitals at Risk from Storm Surge by Hurricanes

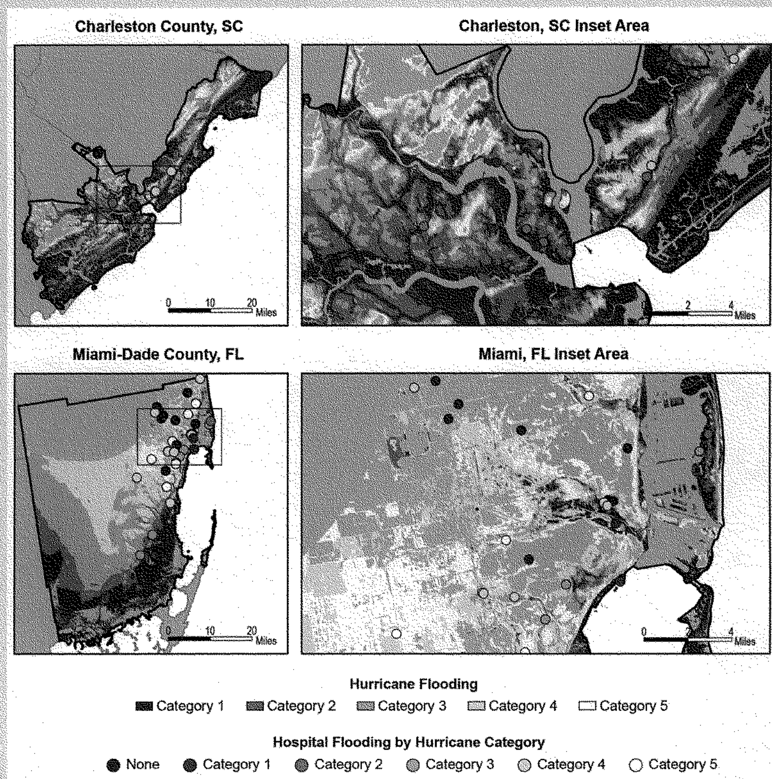


Figure 14.3: These maps show the locations of hospitals in (top) Charleston County, South Carolina, and (bottom) Miami-Dade County, Florida, with respect to storm surge inundation for different categories of hurricanes making landfall at high tide. Colors indicate the lowest category hurricane affecting a given location, with darker blue shading indicating areas with the greatest susceptibility to flooding and darker red dots indicating the most vulnerable hospitals. Four of the 38 (11%) hospitals in Miami-Dade County face possible storm surge inundation following a Category 2 hurricane; this could increase to 26 (68%) following a Category 5 hurricane. Charleston hospitals are more exposed to inundation risks. Seven of the 11 (64%) hospitals in Charleston County face possible storm surge inundation following a Category 2; this could increase to 9 (82%) following a Category 4. The impacts of a storm surge will depend on the effectiveness of resilience measures, such as flood walls, deployed by the facilities. Data from National Hurricane Center 2018[152] and the Department of Homeland Security 2018.[153]

Box 14.3: Healthcare, *continued*

In addition, healthcare facilities may benefit from modifications to prepare for potential consequences of climate change. For example, Nicklaus Children's Hospital, formerly Miami Children's, invested $11.3 million in a range of technology retrofits, including a hurricane-resistant shell, to withstand Category 4 hurricanes for uninterrupted, specialized medical care services.[151] The hospital was able to operate uninterrupted during Hurricane Irma and provided shelter for spouses and families of storm-duty staff and some storm evacuees. Assessment of climate change related risks to healthcare facilities and services can inform healthcare sector disaster preparedness efforts. For example, analyses in Los Angeles County suggest that preparing for increased wildfire risk should be a priority for area hospitals.[154]

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term. By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.

Reducing greenhouse gas emissions (Ch. 29: Mitigation) would benefit the health of Americans in the near and long term.[1,155] Adverse health effects attributed to climate change have many potential economic and social costs, including medical expenses, caregiving services, or lost productivity, as well as costs that are harder to quantify, such as those associated with pain, suffering, inconvenience, or reduced enjoyment of leisure activities.[156] These health burdens are typically borne by the affected individual as well as family, friends, employers, communities, and insurance or assistance programs.

Under a lower scenario (RCP4.5) by the end of this century, thousands of lives could be saved and hundreds of billions of dollars of health-related costs could be avoided compared to a higher scenario (RCP8.5).[157] Annual health impacts (including from temperature extremes, poor air quality, and vector-borne diseases) and health-related costs are projected to be approximately 50% less under a lower scenario (RCP4.5) than under a higher scenario (RCP8.5) (methods are summarized in Traceable Accounts) (see also Ch. 13: Air Quality).[37,157,158,159,160,161,162,163,164,165,166,167] The projected lives saved and economic benefits are likely to underestimate the true value because they do not include benefits of impacts that are difficult to quantify, such as mental health or long-term health impacts (see the Scenario Products Section in App. 3 for more on scenarios).

Temperature-Related Mortality

The projected increase in the annual number of heat wave days is substantially reduced under a lower scenario (RCP4.5) compared to a higher scenario (RCP8.5), reducing heat wave intensities[161,168] and resulting in fewer high-mortality heat waves[162,168] without considering adaptation (Figure 14.4). In 49 large cities in the United States, changes in extreme hot and extreme cold temperatures are projected to result in more than 9,000 additional premature deaths per year under a higher scenario by the end of the century, although this number would be lower if considering acclimatization or other adaptations (for example, increased use of air conditioning). Under a lower

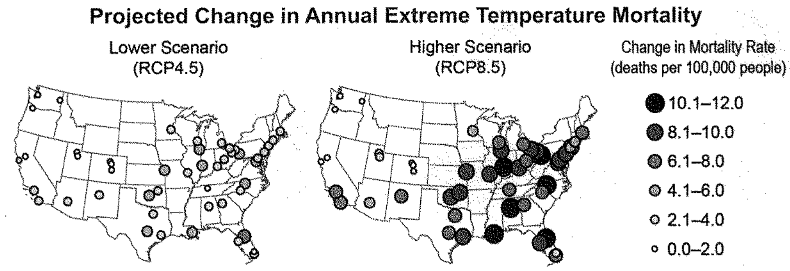


Figure 14.4: The maps show estimated changes in annual net mortality due to extremely hot and cold days in 49 U.S. cities for 2080–2099 as compared to 1989–2000. Across these cities, the change in mortality is projected to be an additional 9,300 deaths each year under a higher scenario (RCP8.5) and 3,900 deaths each year under a lower scenario (RCP4.5). Assuming a future in which the human health response to extreme temperatures in all 49 cities was equal to that of Dallas today (for example, as a result of availability of air conditioning or physiological adaptation) results in an approximate 50% reduction in these mortality estimates. For example, in Atlanta, an additional 349 people are projected to die from extreme temperatures each year by the end of century under RCP8.5. Assuming residents of Atlanta in 2090 have the adaptive capacity of Dallas residents today, this number is reduced to 128 additional deaths per year. Cities without circles should not be interpreted as having no extreme temperature impact. Data not available for the U.S. Caribbean, Alaska, or Hawai'i & U.S.-Affiliated Pacific Islands regions. Source: adapted from EPA 2017.[157]

scenario, more than half of these deaths could be avoided each year. Annual damages associated with the additional extreme temperature-related deaths in 2090 were projected to be $140 billion (in 2015 dollars) under a higher scenario (RCP8.5) and $60 billion under a lower scenario (RCP4.5).[157]

Labor Productivity

Under a higher scenario (RCP8.5), almost two billion labor hours are projected to be lost annually by 2090 from the impacts of temperature extremes, costing an estimated $160 billion in lost wages (in 2015 dollars) (Ch. 1: Overview, Figure 1.21).[157,167,169] States within the Southeast and Southern Great Plains regions are projected to experience higher impacts, with labor productivity in jobs with greater exposure to heat projected to decline by 3% (Ch. 19: Southeast).[164,170] Some counties in Texas and Florida are projected to experience more than 6% losses in annual labor hours by the end of the century.[157,160]

Infectious Diseases

Annual national cases of West Nile neuroinvasive disease are projected to more than double by 2050 due to increasing temperatures, among other factors,[30,171] resulting in approximately $1 billion per year in hospitalization costs and premature deaths under a higher scenario (RCP8.5; in 2015 dollars).[37] In this same scenario, an additional 3,300 cases and $3.3 billion in costs (in 2015 dollars) are projected each year by the end of the century. Approximately half of these cases and costs would be avoided under a lower scenario (RCP4.5).[37,157]

Water Quality

By the end of the century, warming under a higher scenario (RCP8.5) is projected to increase the length of time recreational waters have concentrations of harmful algal blooms (cyanobacteria) above the recommended public health threshold by one month annually; these bacteria can produce a range of toxins that can cause gastrointestinal illness, neurological disorders, and other illnesses.[157,165] The increase in the number of days where recreational waters pose this health risk is almost halved under a lower scenario (RCP4.5).

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Traceable Accounts

Process Description

The chapter evaluated the scientific evidence of the health risks of climate change, focusing primarily on the literature published since the cutoff date (approximately fall 2015) of the U.S. Climate and Health Assessment.[1] A comprehensive literature search was performed by federal contractors in December 2016 for studies published since January 1, 2014, using PubMed, Scopus, and Web of Science. An Excel file containing 2,477 peer-reviewed studies was provided to the author team for it to consider in this assessment. In addition to the literature review, the authors considered recommended studies submitted in comments by the public, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. The focus of the literature was on health risks in the United States, with limited citations from other countries providing insights into risks Americans are or will likely face with climate change. A full description of the search strategy can be found at https://www.niehs.nih.gov/CCHH_Search_Strategy_NCA4_508.pdf. The chapter authors were chosen based on their expertise in the health risks of climate change. Teleconferences were held with interested researchers and practitioners in climate change and health and with authors in other chapters of this Fourth National Climate Assessment (NCA4).

The U.S. Climate and Health Assessment[1] did not consider adaptation or mitigation, including economic costs and benefits, so the literature cited includes research from earlier years where additional information was relevant to this assessment.

For NCA4, Air Quality was added as a report chapter. Therefore, while Key Messages in this Health chapter include consideration of threats to human health from worsened air quality, the assessment of these risks and impacts are covered in Chapter 13: Air Quality. Similarly, co-benefits of reducing greenhouse gas emissions are covered in the Air Quality chapter.

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change (*very high confidence*), with the adverse health consequences projected to worsen with additional climate change (*likely, high confidence*). Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

Description of evidence base

Multiple lines of evidence demonstrate statistically significant associations between temperature, precipitation, and other variables and adverse climate-sensitive health outcomes, indicating sensitivity to weather patterns.[1] These lines of evidence also demonstrate that vulnerability varies across sub-populations and geographic areas; populations with higher vulnerability include poor people in high-income regions, minority groups, women, children, the disabled, those living alone, those with poor health status, Indigenous people, older adults, outdoor workers, people displaced because of weather and climate, low-income residents that lack a social network, poorly planned communities, communities disproportionately burdened by poor environmental quality, the disenfranchised, those with less access to healthcare, and those with limited financial resources to rebound from disasters.[108,109,110,111,118,172] Recent research confirms projections that the magnitude and pattern of risks are expected to increase as climate change continues across the century.[173]

Major uncertainties

The role of non-climate factors, including socioeconomic conditions, population characteristics, and human behavior, as well as health sector policies and practices, will continue to make it challenging to attribute injuries, illnesses, and deaths to climate change. Inadequate consideration of these factors creates uncertainties in projections of the magnitude and pattern of health risks over coming decades. Certainty is higher in near-term projections where there is greater understanding of future trends.

Description of confidence and likelihood

There is *very high confidence* that climate change is affecting the health of Americans. There is *high confidence* that climate-related health risks, without additional adaptation and mitigation, will *likely* increase with additional climate change.

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks (*high confidence*). Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color (*high confidence*).

Description of evidence base

Multiple lines of evidence demonstrate that low-income communities and some communities of color are experiencing higher rates of exposure to adverse environmental conditions and social conditions that can reduce their resilience to the impacts of climate change.[106,107,108,109,110] Populations with increased health and social vulnerability typically have less access to information, resources, institutions, and other factors to prepare for and avoid the health risks of climate change.[107,132,133] Across all climate-related health risks, children, older adults, low-income communities, and some communities of color are disproportionately impacted. There is high agreement among experts but fewer analyses demonstrating that other populations with increased vulnerability include outdoor workers, communities disproportionately burdened by poor environmental quality, communities in the rural southeastern United States, women, pregnant women, those experiencing gender discrimination, persons with chronic physical and mental illness, persons with various disabilities (such as those affecting mobility, long-term health, sensory perception, cognition), the homeless, those living alone, Indigenous people, people displaced because of weather and climate, low-income residents who lack a social network, poorly planned communities, the disenfranchised, those with less access to healthcare, the uninsured and underinsured, those living in inadequate housing, and those with limited financial resources to rebound from disasters.[106,107,108,110,118]

Adaptation can increase the climate resilience of populations when the process of developing and implementing policies and measures includes understanding the ethical and human rights dimensions of climate change, meeting human needs in a sustainable and equitable way, and engaging with representatives of the most impacted communities to assess the challenges they face and to define the climate solutions.[124,125]

Major uncertainties

The role of non-climate factors, including socioeconomic conditions, discrimination (racial and ethnic, gender, persons with disabilities), psychosocial stressors, and the continued challenge to measure the cumulative effects of past, present, and future environmental exposures on certain people and communities will continue to make it challenging to attribute injuries, illnesses, and deaths to climate change. While there is no universal framework for building more resilient communities that can address the unique situations across the United States, factors integral to community resilience include the importance of social networks, the value of including community voice in the planning and execution of solutions, and the co-benefits of institutional readiness to address the physical, health, and social needs of impacted communities. These remain hard to quantify.[127,128]

Description of confidence and likelihood

There is *high confidence* that climate change is disproportionately affecting the health of children, older adults, low-income communities, communities of color, tribal and Indigenous communities, and many other distinct populations. And there is *high confidence* that some of the most vulnerable populations experience greater barriers to accessing resources, information, and tools to build resilience.

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services (*medium confidence*). Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design (*low confidence*).

Description of evidence base

Health adaptation is taking place from local to national scales.[129,148,174] Because most of the health risks of climate change are also current public health problems, strengthening standard health system policies and programs, such as monitoring and surveillance, are expected to be effective in the short term in addressing the additional health risks of climate change. Modifications to explicitly incorporate climate change are important to ensure effectiveness as the climate continues to change. Incorporating environmentally friendly practices into healthcare and infrastructure can promote resilience.[151]

Major uncertainties

Overall, while there is considerable evidence of the effectiveness of public health programs,[110,129,130] the effectiveness of policies and programs to reduce *future* burdens of climate-sensitive health outcomes in a changing climate can only be determined over coming decades. The relatively short time period of implementing health adaptation programs means uncertainties remain about how to best incorporate climate change into existing policies and programs to manage climate-sensitive health outcomes and about which interventions will likely be most effective as the climate continues to change.[174,175] For example, heat wave early warning and response systems save lives, but it is not clear which components most effectively contribute to morbidity and mortality reduction.

Description of confidence and likelihood

There is *medium confidence* that with sufficient human and financial resources, adaptation policies and programs can reduce the current burden of climate-sensitive health outcomes.[110,151,176,177] There is *low confidence* that the incorporation of health risks into infrastructure and urban planning and design will likely decrease climate-sensitive health impacts.

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term (*high confidence*). By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions (*likely, medium confidence*).

Description of evidence base

Benefits of mitigation associated with air quality, including co-benefits of reducing greenhouse gas emissions, can be found in Chapter 13: Air Quality. This Key Message is consistent with and inclusive of those findings.

Multiple individual lines of evidence across several health topic areas demonstrate significant benefits of greenhouse gas emission reductions, with health impacts and health-related costs reduced by approximately half under RCP4.5 compared to RCP8.5 by the end of the century, based on comprehensive multisector quantitative analyses of economic impacts projected under consistent scenarios (Ch. 13: Air Quality).[37,157,158,159,160,161,162,163,164,165,166,167] The economic benefits of greenhouse gas emissions reductions to the health sector could be on the order of hundreds of billions of dollars annually by the end of the century.

Heat: Greenhouse gas emission reductions under RCP4.5 could substantially reduce the annual number of heat wave days (for example, by 21 in the Northwest and by 43 in the Southeast by the end of the century);[161] the number of high-mortality heat waves;[162,168] and heat wave intensities.[161,168] The EPA (2017)[157] estimated city-specific relationships between daily deaths (from all causes) and extreme temperatures based on historical observations that were combined with the projections of extremely hot and cold days (average of three years centered on 2050 and 2090) using city-specific extreme temperature thresholds to project future deaths from extreme heat and cold under RCP8.5 and RCP4.5 in five global climate models (GCMs). In 49 large U.S. cities, changes in extreme temperatures are projected to result in over 9,000 premature deaths per year under RCP8.5 by the end of the century without adaptation ($140 billion each year); under RCP4.5, more than half these deaths could be avoided annually ($60 billion each year).[157]

Labor productivity: Hsiang et al. (2017)[167] and the EPA (2017)[157] estimated the number of labor hours from changes in extreme temperatures using dose-response functions for the relationship between temperature and labor from Graff Zivin and Neidell (2014).[169] Under RCP8.5, almost 2 billion labor hours are projected to be lost annually by 2090 from the impacts of extreme heat and cold, costing an estimated $160 billion in lost wages. The Southeast[164,170] and Southern Plains are projected to experience high impacts, with labor productivity in high-risk sectors projected to decline by 3%. Some counties in Texas and Florida are projected to experience more than 6% losses in annual labor hours by the end of the century.[157,160]

Vector-borne disease: Belova et al. (2017)[37] and the EPA (2017)[157] define health impact functions from regional associations between temperatures and the probability of above-average West Nile neuroinvasive disease (WNND) incidence to estimate county-level expected WNND incidence rates for a 1995 reference period (1986–2005) and two future years (2050: 2040–2059 and 2090: 2080–2099) using temperature data from five GCMs. Annual national cases of WNND are projected to more than double by 2050 due to increasing temperatures, resulting in approximately $1 billion per year in hospitalization costs and premature deaths. In 2090, an additional 3,300 annual cases are projected under RCP8.5, with $3.3 billion per year in costs. Greenhouse gas emission reductions under RCP4.5 could avoid approximately half these cases and costs.

Water quality: Chapra et al. (2017)[165] and the EPA (2017)[157] evaluate the biophysical impacts of climate change on the occurrence of cyanobacterial harmful algal blooms in the contiguous United States using models that project rainfall runoff, water demand, water resources systems, water quality, and algal growth. In 2090, warming under RCP8.5 is projected to increase the length of time that recreational waters have concentrations of harmful algal blooms (cyanobacteria) above the recommended public health threshold by one month annually; greenhouse gas emissions under RCP4.5 could reduce this by two weeks.

Food safety and nutrition: There is limited evidence quantifying specific health outcomes or economic impacts of reduced food safety and nutrition.

Major uncertainties

While projections consistently indicate that changes in climate are expected to have negative health consequences, quantifying specific health outcomes (for example, number of cases, number of premature deaths) remains challenging, as noted in Key Message 1. Economic estimates only partially capture and monetize impacts across each health topic area, which means that damage costs are likely to be an undervaluation of the actual health impacts that would occur under any given scenario. Economic estimates in this chapter do not include costs to the healthcare system.

Description of confidence and likelihood

There is a *high confidence* that a reduction in greenhouse gas emissions would benefit the health of Americans. There is *medium confidence* that reduced greenhouse gas emissions under RCP4.5

compared to RCP8.5 will *likely* reduce lost labor hours by almost half and avoid thousands of premature deaths and illnesses projected each year from climate impacts on extreme heat, ozone and aeroallergen levels (Ch. 13: Air Quality), and West Nile neuroinvasive disease. There is *medium confidence* that the economic benefits of greenhouse gas emissions reductions in the health sector could *likely* be on the order of hundreds of billions of dollars each year by the end of the century. Including avoided or reduced benefits of risks that are difficult to quantify, such as mental health or long-term health consequences, would increase these estimates.

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Appendix II

Additional Material for the Record

LETTER SUBMITTED BY REPRESENTATIVE LIZZIE FLETCHER

June 28, 2016

Dear Members of Congress,

We, as leaders of major scientific organizations, write to remind you of the consensus scientific view of climate change.

Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research concludes that the greenhouse gases emitted by human activities are the primary driver. This conclusion is based on multiple independent lines of evidence and the vast body of peer-reviewed science.

There is strong evidence that ongoing climate change is having broad negative impacts on society, including the global economy, natural resources, and human health. For the United States, climate change impacts include greater threats of extreme weather events, sea level rise, and increased risk of regional water scarcity, heat waves, wildfires, and the disturbance of biological systems. The severity of climate change impacts is increasing and is expected to increase substantially in the coming decades.[1]

To reduce the risk of the most severe impacts of climate change, greenhouse gas emissions must be substantially reduced. In addition, adaptation is necessary to address unavoidable consequences for human health and safety, food security, water availability, and national security, among others.

We, in the scientific community, are prepared to work with you on the scientific issues important to your deliberations as you seek to address the challenges of our changing climate.

American Association for the Advancement of Science
American Chemical Society
American Geophysical Union
American Institute of Biological Sciences
American Meteorological Society
American Public Health Association
American Society of Agronomy
American Society of Ichthyologists and Herpetologists
American Society of Naturalists

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[1] The conclusions in this and the preceding paragraph reflect the scientific consensus represented by, for example, the U.S. Global Change Research Program, the U.S. National Academies, and Intergovernmental Panel on Climate Change. Many scientific societies have endorsed these findings in their own statements, including the American Association for the Advancement of Science, American Chemical Society, American Geophysical Union, American Meteorological Society, American Statistical Association, Ecological Society of America, and Geological Society of America.

American Society of Plant Biologists
American Statistical Association
Association for the Sciences of Limnology and Oceanography
Association for Tropical Biology and Conservation
Association of Ecosystem Research Centers
BioQUEST Curriculum Consortium
Botanical Society of America
Consortium for Ocean Leadership
Crop Science Society of America
Ecological Society of America
Entomological Society of America
Geological Society of America
National Association of Marine Laboratories
Natural Science Collections Alliance
Organization of Biological Field Stations
Society for Industrial and Applied Mathematics
Society for Mathematical Biology
Society for the Study of Amphibians and Reptiles
Society of Nematologists
Society of Systematic Biologists
Soil Science Society of America
University Corporation for Atmospheric Research

REPORT SUBMITTED BY REPRESENTATIVE BILL FOSTER

Breakthrough Energy

Advancing the Landscape of Clean Energy Innovation

February 2019

Prepared for Breakthrough Energy by
IHS Markit and Energy Futures Initiative

IHS Markit

ENERGY FUTURES INITIATIVE

Foreword

We are pleased to submit our report, "Advancing the Landscape of Clean Energy Innovation." In this report we describe today's U.S. ecosystem of clean energy innovation from the perspectives of technological potential, investment patterns, institutional roles, and public policy.

The report identifies critical strengths and weaknesses of this ecosystem and offers recommendations for making that ecosystem more effective. It examines the different technology readiness stages through which innovation passes and the importance of feedback among those stages. It also discusses the significant opportunities to accelerate the pace of clean energy innovation that are presented by rapid advances occurring today across a myriad of technologies originating outside the energy sector.

We would like to emphasize three observations from our report.

- First, the U.S. has shown over many decades an unparalleled capacity to nurture energy innovation. This capacity reflects a rich and durable collaboration among government, universities, research institutions, industry, and entrepreneurs. This collaboration is grounded in the belief that energy innovation contributes importantly to economic growth, energy security, and environmental stewardship.
- Second, even with our capacity to innovate, and even with the emergence of innumerable technological opportunities, there are significant challenges in moving forward with clean energy technology. These challenges arise from the sheer size and complexity of existing systems, the degree to which these systems are embedded in our economy, and the high public expectations of safety and reliability they must meet. Energy systems traditionally have evolved incrementally.
- Third, these challenges can be met only by building on the collaborative strengths that our ecosystem has already demonstrated. Clean energy innovation depends on a national commitment to technological research; private-sector efforts to develop, apply, and commercialize products incorporating that research; and public policy.

In this report we convey the need for a comprehensive approach involving both public and private sectors in order to expand the current landscape of clean energy innovation and accelerate its processes. We hope that our report contributes to an understanding of the challenges presented and the approaches needed to address those challenges effectively. There is no final word on the subject. We see this report as a contribution to a continuing national dialogue and hope that it will stimulate further discussion, understanding, and action.

We are grateful for the opportunity that Breakthrough Energy and its partners have provided to explore this topic and recognize their commitment to advancing a meaningful and timely national dialogue. We hope that our report informs an appreciation of the complexity, reach, inherent dynamism, and promise of the U.S. clean energy innovation landscape and of the leadership that the United States can continue to provide.

Ernest J. Moniz
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The analysis and conclusions of this report are those of IHS Markit and Energy Futures Initiative. IHS Markit and Energy Futures Initiative are solely responsible for its contents.

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Executive Summary

The United States has been at the forefront of energy innovation for many decades. One of the most important reasons is the unique and extensive collaboration along the entire chain of innovation, from basic research to deployment, that engages the federal government, national labs and research institutes, universities, private sector, and state and local governments. This system has given the U.S. a global advantage for many decades.

The increasing focus on clean energy technology solutions and the potential for disruptive changes in energy systems points to the need for an objective review of the current clean energy innovation ecosystem. How does the clean energy innovation system work? What are its strengths and weaknesses? Is it up to the challenges? And how can it be improved and accelerated?

These are the questions that this study seeks to answer. Significant opportunities for clean energy innovation are presented by the changing U.S energy supply profile; by advances in platform technologies such as digitalization and big data analytics; by expansion of electrification in the transportation and industrial sectors of the U.S. economy and the resulting electricity dependence of these sectors; by increases in urbanization and the emergence of smart cities; and by broad social and economic forces pushing to decarbonize energy systems in response to the risks posed by global warming and associated climate change.

Clean energy innovation supports multiple national goals: economic competitiveness, environmental responsibility, energy security, and national security. In serving these goals the need to address climate change is the challenge that calls most urgently for accelerating the pace of clean energy innovation.

Key features of energy systems, however, impede accelerated innovation. Energy is a highly capitalized commodity business, with complex supply chains and established customer bases, providing essential services at all levels of society. These features lead to systems with considerable inertia, focus on reliability and safety, aversion to risk, extensive regulation, and complex politics. Existing innovation processes face challenges as they work within these boundary conditions. The rapid pace of international energy investment, the commitments of most countries to Paris climate goals, and the ability of some countries such as China to rapidly increase clean energy investments challenge the preeminent position of the U.S. in clean energy innovation.

Successful clean energy innovation on a large scale in the U.S. requires alignment of key players, policies, and programs among the private sector, the federal government, and state and local governments. This report considers these alignment needs through an assessment of the roles of these various groups. It also identifies critical clean energy technologies. It further suggests the value of regional efforts to advance innovation, and discusses ways in which federal tax policy could accelerate innovation. The report offers recommendations in each of these areas.

The Role of the Private Sector

The private sector is central to clean energy innovation, providing entrepreneurial vision, channeling financial resources, and connecting innovation to the rest of the energy system and the economy. At the same time, fundamental dynamics of the energy sector present significant challenges to clean energy innovation, stemming from basic industry characteristics and from the difficulty of capturing the full value of clean energy through market transactions alone. Innovators in clean energy face significant challenges in securing financial support and in demonstrating the compatibility of new technologies with existing systems. Over the past several years, venture capital has reduced its engagement in clean energy innovation, and traditional energy companies are exploring new models and mechanisms for innovation and investment.

While the initial stages of clean energy innovation are supported by a diverse, world-class set of U.S. research institutions, the innovation support system weakens as inventions move toward commercialization. The clean energy incubators that have emerged in recent years have so far tended to support software solutions. The availability of testing facilities for product demonstration is limited by the small number of facilities suitable for sustained testing and by their specialization.

Because of the energy system's long cycles of adoption, a broad range of approaches should be deployed to make it easier for adopters to understand, anticipate, and support the innovations that are being generated at the early stages of the innovation process. These efforts include, on the part of energy companies, open innovation, standardization of procurement requirements, encouragement of innovation testing either through dedicated evaluation staffs or through performance metrics, and active outreach to become familiar with innovations at the development stage or earlier. They include, on the part of innovators, early attention to the needs of adopters as indicated by expressed needs and by the past performance of innovation efforts.

Investments are needed from foundations and from federal, state, and local governments to expand the availability of open-access testbeds and strengthen the effectiveness of incubators in accelerating commercialization of innovative technologies. Some of these investments could fund research into best practices and performance results of incubators and testbeds and of state and local programs supporting innovation.

Because clean energy innovation incentivizes only modest financial investments at precommercial stages, and because strategic corporate investment is focused primarily on those innovations recognized as useful to business objectives, strategic philanthropic investors and coalitions of industry investors with long-term horizons could play an important role in identifying and supporting promising technology ventures that are otherwise not commercially viable in the near term.

Recommendations for Near-Term Actions

- Adopters of new technology, such as utilities, should consider a variety of approaches to support the innovations that are being generated at the early stages of the innovation process, including: open innovation; standardization of procurement specifications; encouragement of innovation testing (either though dedicated evaluation staffs or through performance metrics); and active outreach to become familiar with innovations at the development stage or earlier.
- Strategic philanthropic investors and coalitions of industry investors with long-term horizons should play an active role in identifying and supporting promising technology ventures that are otherwise not commercially viable in the near term.
- Foundations, as well as federal, state, and local governments, should make investments to expand the availability of open-access testbeds and incubators to accelerate commercialization of innovative technologies (e.g. Cyclotron Road).

Technologies with Breakthrough Potential

A shared agenda of primary technology objectives can help ensure that programs pursued by multiple stakeholders in the clean energy space are timely, durable, and mutually supportive. It can give entrepreneurs and creative innovators a framework for assessing the prospects of a particular area of initiative and the steps needed to sustain critical innovations over long time spans, and it can give corporate adopters, financial investors, and policymakers visibility into the evolving future of clean energy.

A four-step methodology is suggested for identifying breakthrough technologies to address national and global challenges and help meet near, mid- and long-term clean energy needs and goals. These steps consider technical merit, potential market viability, compatibility with other elements of the energy system, and consumer value. Application of these considerations to a list of 23 potential technology candidates yields a key technology shortlist:

Storage and battery technologies

Advanced nuclear reactors

Technology applications for industry and buildings as sectors that are difficult to decarbonize

- Hydrogen
- Advanced manufacturing technologies
- Building energy technologies

Systems: electric grid modernization and smart cities

Deep decarbonization/large-scale carbon management

- Carbon capture, use, and storage at scale
- Sunlight to fuels
- Biological sequestration

Recommendations for Near-Term Actions

- Federal investments in energy research, development, demonstration, and deployment (RDD&D) should be planned within a portfolio structure that supports potential breakthrough technologies at various timescales. There should be special focus on a critical subset of those technologies deemed to have very high breakthrough potential.
- Federal energy RDD&D portfolio investments should adopt a formal set of major evaluation criteria—such as technical merit, market viability, compatibility, and consumer value—with specific metrics for each criterion. These criteria should be used to prioritize programming and budget allocation decisions, as well as to develop public-private partnerships.
- Public and private sector stakeholders should collaborate in planning for and piloting of emerging technologies. A key component of these efforts is systems-level development plans that delineate technical challenges and risks; R&D pathways; cost and schedule assumptions; institutional roles (including public-private partnership opportunities); pathways to commercialization and diffusion; economic benefits; and consumer value.
- The Department of Energy (DOE) should lead a national effort to update the Basic Research Needs Assessments, originally initiated in 2001, to inform the assessments of emerging technologies with breakthrough potential, as well as the development of system-level roadmaps.

The Federal Government Role

The Federal government has long played a central role in supporting energy innovation. Through research grants, loan programs, tax incentives, laboratory facilities, pilot programs, and public-private partnerships, it has set the direction and pace of energy R&D, with profound impact on the national economy.

The principal agency funding clean energy innovation is the Department of Energy (DOE), which administers about 75 percent of all Federal energy R&D spending. DOE performs its role in partnership with its 17 national laboratories, academia, states, regions, other agencies, and the private sector. There are, however, several other Federal agencies with significant clean energy innovation budgets, including: the Department of Defense (DOD), the Department of Transportation (DOT), and the Department of Agriculture (USDA). Portfolios at these agencies are mission-focused, however, as opposed to being broadly based across all energy sectors.

As the primary Federal funder of energy R&D, DOE has played a critical role in changing the U.S. energy landscape over several decades. Shortly after its establishment in 1977, DOE characterized U.S. shale basins and supported the development of key drilling technologies that enabled horizontal drilling. It has had an ongoing and central role in developing supercomputing, an enabling technology for digitalization, artificial intelligence, smart systems, and subsurface characterization. Its investment in phasors and sensors support the smart grid. The Advanced Research Projects Agency — Energy (ARPA-E) – a DOE program —

has led to the creation of dozens of clean energy start-up companies which have raised more than $2.6 billion in private-sector follow-on funding.

However, DOE's performance in advancing clean energy innovation would benefit from several institutional modifications. For example, the fuels-based organizational structure of the DOE, which has been in existence since 1979, is not optimized for modern energy systems and needs. It tends to lead to budget allocations by fuel, rather than prioritization by innovation potential.

The lack of long-term stable and predictable funding is also a concern for future R&D efforts at DOE. Although the Federal clean energy RD&D portfolio is significant (approximately $6.4 billion in FY 2016 if expenditures by all Federal agencies and by DOE on basic science research are included), some prominent government and industry leaders have recommended the need for funding levels at two to three times the current levels based on the energy industry's current value to the economy (roughly $1.37 trillion). While the Bipartisan Budget Act of 2018 (BBA) set new caps for discretionary spending that are as much as 25 percent higher than the Administration's budget — providing considerable headroom for near-term increases in spending for clean energy innovation — this agreement extends through FY 2019 only. The highly uncertain budget outlook for FY 2020 makes it difficult to plan an effective energy innovation portfolio focused on technologies with high breakthrough potential.

Recommendations for Near-Term Actions

- Congress and the Administration should initiate efforts to reorganize the Federal energy RDD&D portfolio and the Department of Energy toward a fuel- and technology-neutral structure that (1) aligns with the highest priority opportunities, (2) enables systems-level integration, and (3) avoids gaps in crosscutting programs.
- Congress and the Administration should consider dedicated funding sources for energy innovation as a means to ensure predictable and increasing levels of clean energy RDD&D funding based on international and cross-sectoral benchmarks.
- Federal policymakers should expand demonstration projects for key breakthrough technologies, while ensuring accountability via stage-gated project management, risk-based cost sharing, and assignment of demonstration project oversight to a single office within DOE.
- DOE and other agencies, as appropriate, should increase collaboration with the private sector and academia, including:
  - Instituting a multi-year and multi-agency portfolio planning process with broad-based stakeholder involvement from the private sector and academia.
  - Expanding use of prize authority to foster competition and open innovation.
  - Simplifying public-private partnerships with flexible financial vehicles like Technology Investment Agreements.

The Role of State, Local and Tribal Governments

State and city governments have regulatory authority over most of the myriad consumer, commercial, and industrial activities that collectively shape the country's patterns of energy use. They play central roles in advancing clean energy innovation, above all by creating markets for the application of clean energy technologies and encouraging diffusion of those technologies through supportive financial mechanisms.

Cities are crucial clean energy innovation testbeds. Urbanization trends make "smart cities" especially important as technology platforms for a clean energy future. Enhanced federal-state-city, public-private, and private-private partnerships can help unleash smart city innovation for tailored urban services, mobility, and standard-of-living improvements in the 21st century. "Smart" improvements could also provide significant value to rural communities by enabling decentralized generation and manufacturing, improving energy efficiency, and supporting economic development.

The contribution of state, local, and tribal governments to clean energy innovation could be further strengthened by development of program best practices and standardization, capacity and resource enhancement, increased funding, and modernization of ratemaking and business models. Programs that support and promote clean energy and energy innovation require significant state and local administrative resources and expertise; offices and officials that run them often have limited resources. Also, traditional ratemaking policies and methodologies at the state and local level can act as barriers to deployment of innovative energy technologies due to their reliance on proven track records associated with reliability and cost savings.

Recommendations for Near-Term Actions

- States should consider adopting technology-neutral clean energy portfolio standards and zero-emissions credits in order to strengthen markets for clean energy innovation — to include renewables and other forms of zero or low-carbon energy.
- State and local regulatory agencies should consider new ways in which existing ratemaking principles could be adapted to incentivize utilities to deploy established clean energy technologies, test emerging energy technologies, and realize value from behind the meter technologies.
- States should collaborate to identify best practices in the deployment of clean energy technologies, including financing mechanisms, consumer protections and equitable sharing of benefits among all socio-economic groups and geographic locations.

The Role of Regional Clean Energy Innovation Ecosystems

Many of the innovation opportunities and risks faced by the energy sector are highly regional in nature and are appropriately managed by strategies tailored to each region's specific needs. Strong regional relationships, for example, are observable among innovation, job creation, and technology deployment in the solar and wind energy industries.

Many energy innovation clusters in the U.S. are in the process of evolving into fully integrated innovation ecosystems. While federally funded RDD&D historically has not been well connected to state and regional economic development, activating these regional clusters to break down the barriers among federal, state, and local resources will create new synergies. National labs could serve as anchors for these efforts. While Federal support is important, regional leadership is critical. State and local governments, the private sector, universities, and philanthropies all have important roles in developing the particular strengths and shaping the particular contributions of regional innovation ecosystems.

Recommendations for Near-Term Actions

- Universities, private industry, philanthropies, state and local governments, and DOE should seek to expand and strengthen incubator capabilities within regional clusters to provide additional tools to enable innovators to conduct R&D and prototyping.
- DOE national laboratories, other federal laboratories, and Federally Funded Research Centers (FFRCs) can serve as anchors for regional clean energy innovation — and should be given sufficient flexibility in the expenditure of discretionary funds to support regional clean energy innovation options.

Mobilizing Increased Private Sector Investment in Energy Innovation

For U.S.-based entities, budget caps, reduced discretionary spending, and the Tax Cuts and Jobs Act (TCJA) will put downward pressure on Federal spending but will incentivize corporations to increase significantly business investments over the next decade (with estimates of up to $1.5 trillion in incremental new investment, some of which could be targeted to energy innovation and infrastructure. Attracting these funds into clean energy innovation will depend on success in aligning the various elements of the innovation ecosystem discussed in this report: public policies that encourage a robust pipeline of research and that create markets for clean energy applications, combined with private-sector institutions that facilitate the commercialization of innovations.

The TCJA left unchanged the existing tax credits for renewable energy (wind, solar and geothermal), but did not extend the so-called "orphan" tax credits for fuel cells, combined heat and power projects, geothermal heat pumps, and new nuclear power plants. Most of these credits had expired at the end of 2016. The Bipartisan Budget

Act of 2018 (BBA), passed in February, modified and extended the nuclear power PTC; other credits were extended only through 2017 and their fate is uncertain.

In addition, the BBA included expanded provisions for carbon dioxide (CO_2) capture, utilization and storage (CCUS). The new 45Q provisions have the potential to significantly enhance the development and market diffusion of CCUS technologies and processes in both industrial and power applications, creating commercial opportunities both in the U.S. and abroad. The provisions provide greater market and financing certainty to help attract additional follow-on investment from the private sector.

Recommendations for Near-Term Actions

- DOE should set aside a small portion of its existing applied energy RDD&D funding to support accelerated de-risking of near-commercial innovative energy technologies and systems on an accelerated basis, to make these options more attractive for private capital investment.
- The new Section 45Q provisions expanding tax credits for carbon dioxide (CO_2) capture, utilization, and storage (CCUS) have the potential to significantly enhance the development and market diffusion of CCUS technologies and processes in both industrial and power applications, creating commercial opportunities both in the U.S. and abroad. Congress should consider additional measures to facilitate and accelerate CCUS deployment, including addressing uncertainties regarding long-term post-injection carbon management, monitoring, reporting and verification.

Full report can be found at: http://www.b-t.energy/reports/advancing-the-landscape/

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Environmental Health

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Hospitalizations for heat-stress illness varies between rural and urban areas: an analysis of Illinois data, 1987–2014

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Abstract

Background: The disease burden due to heat-stress illness (HSI), which can result in significant morbidity and mortality, is expected to increase as the climate continues to warm. In the United States (U.S.) much of what is known about HSI epidemiology is from analyses of urban heat waves. There is limited research addressing whether HSI hospitalization risk varies between urban and rural areas, nor is much known about additional diagnoses of patients hospitalized for HSI.

Methods: Hospitalizations in Illinois for HSI (ICD-9-CM codes 992.x or E900) in the months of May through September from 1987 to 2014 ($n = 8667$) were examined. Age-adjusted mean monthly hospitalization rates were calculated for each county using U.S. Census population data. Counties were categorized into five urban-rural strata using Rural Urban Continuum Codes (RUCC) (RUCC1, most urbanized to RUCC5, thinly populated). Average maximum monthly temperature (°C) was calculated for each county using daily data. Multi-level linear regression models were used, with county as the fixed effect and temperature as random effect, to model monthly hospitalization rates, adjusting for the percent of county population below the poverty line, percent of population that is Non-Hispanic Black, and percent of the population that is Hispanic. All analyses were stratified by county RUCC. Additional diagnoses of patients hospitalized for HSI and charges for hospitalization were summarized.

Results: Highest rates of HSI hospitalizations were seen in the most rural, thinly populated stratum (mean annual summer hospitalization rate of 1.16 hospitalizations per 100,000 population in the thinly populated strata vs. 0.45 per 100,000 in the metropolitan urban strata). A one-degree Celsius increase in maximum monthly average temperature was associated with a 0.34 increase in HSI hospitalization rate per 100,000 population in the thinly populated counties compared with 0.02 per 100,000 in highly urbanized counties. The most common additional diagnoses of patients hospitalized with HSI were dehydration, electrolyte abnormalities, and acute renal disorders. Total and mean hospital charges for HSI cases were $167.7 million and $20,500 (in 2014 US dollars).

Conclusion: Elevated temperatures appear to have different impacts on HSI hospitalization rates as function of urbanization. The most rural and the most urbanized counties of Illinois had the largest increases in monthly hospitalization rates for HSI per unit increase in the average monthly maximum temperature. This suggests that vulnerability of communities to heat is complex and strategies to reduce HSI may need to be tailored to the degree of urbanization of a county.

Keywords: Heat stress illness, Temperature, Climate change, Temperature-heat stress illness relationship, Urban-rural differences

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Background

Illness associated with heat is the most common cause of weather-related deaths in the United States [1]. Heat-stress illness (HSI) ranges in severity from relatively mild heat cramps to life-threatening heat stroke [2, 3]. HSI was the primary cause of environmental exposure-related injuries treated in emergency departments in the U.S. from 2001 to 2004 [4]. Estimates of total health care costs based on Medicare claims data associated with hyperthermia were more than $36 million for 2004–2005 [5]. The observed rise in temperature over the past fifty years in the U.S. [6] and globally [7] is expected to continue this century. Consequently, the HSI disease burden is expected to increase.

High ambient temperature is associated with mortality [8], though most of the studies that describe that association focus on urban areas [9, 10] or urban heat waves [11–18]. Studies have typically described a non-linear relationship between temperature and mortality rate however, there is much variation based on location [10, 19]. This spatial heterogeneity suggests that populations may adapt to regional norms. Areas unaccustomed to heat, such as cities in the north, are more vulnerable and demonstrate higher mortality rates at lower absolute temperatures [10, 20]. These relationships also vary by confounding factors such as population density, socioeconomic status, and access to air conditioning [21]. The elderly, very young, and those with underlying medical conditions are the most vulnerable to heat-related mortality [22–24].

Similar to findings with mortality, studies have shown a non-linear relationship between temperature and morbidity [17, 23, 25–27]. These studies have focused on a variety of outcomes impacted by heat, including cardiovascular disease, respiratory diseases, and asthma [25, 27–29]. Recent studies utilizing emergency dispatch data demonstrated that morbidity rates are strongly associated with temperature increases [30–32]. Among the elderly, emergency department visits and hospitalizations for a variety of health conditions are more frequent during extreme heat events [25, 33–35]. Less research has focused on morbidity due to HSI itself, as opposed to morbidity due to other conditions impacted by heat [33, 36].

While research on heat-related morbidity has focused on urban areas, agricultural workers appear to be vulnerable to heat-related mortality [37] and morbidity [38, 39] due to their increased exposure to high temperatures, and perhaps the physical exertion that is required by their jobs. The rate of heat-related occupational fatalities is approximately 20 times higher for crop production workers than for U.S. workers overall (0.39 vs. 0.02 per 100,000 workers) [37]. Nevertheless, there has been limited research focusing on the variability in HSI between urban and rural areas. A study looking at HSI in North Carolina found the highest rates of morbidity and strongest associations with increasing temperature in the most rural areas studied [40]. Similarly, a study using Environmental Public Health Tracking Data found higher rates of emergency department visits for HSI in rural areas in all 14 states considered [41]. Limited research on heat morbidity in rural areas may be due to lack of adequate data in rural areas and also due to an interest in the urban heat island effect [23].

In this study, we use health, weather, and urbanization data from the state of Illinois to assess differences in associations between summer temperatures and hospitalizations for HSI as a function of urbanization. We also characterize clinical and economic aspects of HSI hospitalizations. Characterizing the relationship between temperature and urbanization on HSI rates will improve our understanding of the ambient temperature-HSI morbidity relationship and it can be useful for public health preparedness efforts.

Methods

Hospitalization data

We utilized hospital discharge data from the Illinois Department of Public Health (IDPH) Hospital Discharge Database. The database includes discharge data from 97% of Illinois hospitals; the remaining non-member hospitals are located in Cook County, a primarily urban area encompassing the city of Chicago, and account for 7% of all Cook County hospitalizations [42]. Each record includes patient demographics, county of residence, and up to nine diagnoses codes. Diagnoses were coded using the International Classification of Diseases, 9th Revision, Clinical Modification (ICD-9-CM). Heat-related illness was defined as including diagnosis of ICD-9-CM 992.x, effect of heat or light, that includes heat stroke, heat syncope, and heat exhaustion, or ICD-9-CM E900, accidents due to heat as any one of the diagnoses (up to nine per case) recorded. Due to the low number of cases with relevant diagnoses, data were provided aggregated monthly. Cases were limited to the summer months, May through September, for the 28-year period from 1987 to 2014.

Age-adjusted mean summer monthly HSI hospitalization rates were calculated per 100,000 population for each county by year using direct standardization methods. To account for changes in the population over the 28-year study period, the study period was divided into three time periods and corresponding population data were used to calculate rates. For the years 1987–1994, the 1990 Census data [43] was used as the denominator, for years 1995–2004, the 2000 Census data [43] was as the denominator, and for the years 2005–2014, the 2010 Census data [43] was used as the denominator. Nine age categories were created, 0–9 years, 10–19 years, 20–29 years, 30–39 years, 40–49 years, 50–59 years, 60–69 years, 70–79 years, and ≥80 years of age. Average summer monthly HSI hospitalization rates by county are shown in Fig. 1.

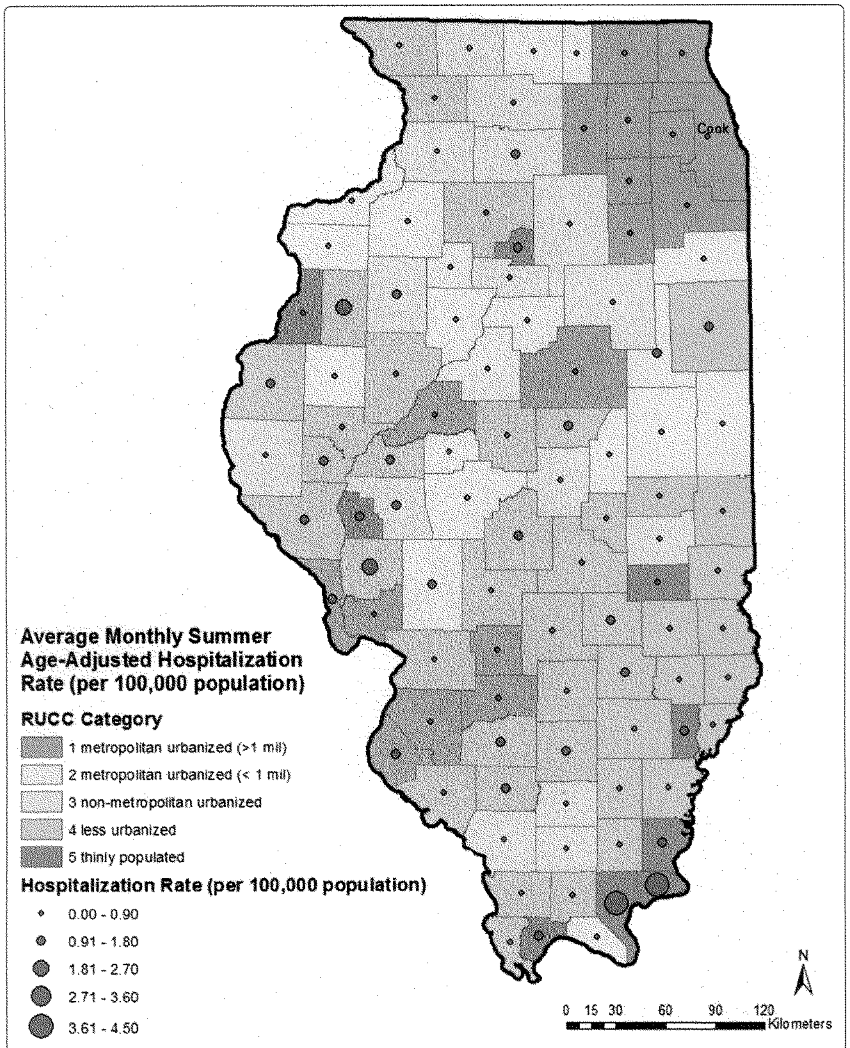

Fig. 1 Map of Illinois showing urban/rural classifications and average monthly summer age-adjusted hospitalization rate for heat-stress illness (per 100,000 population) by county for the 28-year study period. Cook: Cook County, that contains the City of Chicago

Urban/rural stratification

Counties were categorized into five urban/rural strata using Rural Urban Continuum Codes (RUCC) [44]. The original nine continuum codes were aggregated into five strata for this analysis: RUCC1 (original RUCC1), metropolitan urbanized, (>1 million population); RUCC2 (original RUCC2 and RUCC3), metropolitan urbanized (< 1 million population); RUCC3 (original RUCC4 and RUCC5), non-metropolitan urbanized; RUCC 4 (original RUCC6 and RUCC7), less urbanized; RUCC5 (original RUCC8 and RUCC9), thinly populated.

Temperature data

Daily weather data for the 28-year study period were obtained from the Midwest Regional Climate Center [45]. These data were collected from 235 weather stations located throughout the state of Illinois. Of these, 81 stations only provided data on precipitation and were not used for this analysis. The remaining 154 stations provided data on temperature for some or all of the 28-year study period. Most counties had at least one station that provided data and several had more than one station (Fig. 2). Counties without a monitoring station were assigned temperature from the nearest monitoring station. Data collected at each station included daily maximum, minimum, and mean temperature. Utilizing all available data for the county, we calculated average monthly maximum temperature, minimum temperature, and mean temperature, in degrees Celsius, for each summer month, May–September, in the study period.

Covariate data

For each Illinois county, we complied the percent of population below the poverty level, percent of population that was non-Hispanic Black, and percent of population that was Hispanic [43]. Covariate data for the years 1987–1994, 1995–2004, and 2005–2014 were obtained from the 1990, 2000, and 2010 Census, respectively.

Statistical analysis

We assessed associations between monthly average maximum temperature and age-adjusted monthly rates of hospitalizations for HSI at the county-level. All analyses were stratified by the five urbanization strata. The association between monthly mean temperature with monthly county hospitalization rates for HSI were assessed using random slope, random intercept multi-level linear regression models. County of residence was considered a fixed effect and temperature as the random effect (Eq. 1). In addition, analyses were adjusted for county level covariates including, percent of population below the poverty level, percent of the county population that was non-Hispanic Black, and percent of population that was Hispanic.

$$Y_{ij} = \beta_0 + \beta_1 X_i + b_{0i} + b_{1i} x_{ij} \qquad (1)$$

Where:

Y_{ij} = outcome rates (HSI hospitalization) for the i^{th} county and the j^{th} month,

X_i = indicator variable for the i^{th} county (fixed effect),

x_{ij} = exposure measurement (mean temperature) for the i^{th} county and the j^{th} month (random effect).

In this model X_i represents a fixed effect for each county and x_{ij}, the mean temperature, accounts for a random effect. Models were also adjusting for county-level population below the poverty level, percent of the county population that was non-Hispanic Black, and percent of population that was Hispanic.

Results are reported as a change in hospitalization rate per 1 °C change in maximum monthly average temperature and 95% confidence intervals (CIs). To evaluate whether urban/rural differences in HSI rates might be attributable to a severe heat wave in 1995 that impacted much of the Midwest, including Illinois, and resulted in an estimated 739 fatalities [18] in the most populous urban county in Illinois (Cook County), analyses were conducted with and without 1995 data. Analyses were conducted using R version 3.3.1 (R Foundation for Statistical Computing) and SAS (SAS Institute, Cary, NC), version 9.4.

This work, that involved the analysis of a dataset that had personal identifiers removed or grouped into categories (such as age) was determined not to involve human research subjects by the UIC Institutional Review Board (Protocol 2013-0172).

Clinical and economic analyses

Comorbidities of individuals hospitalized for HSI were identified using the nine additional ICD-9-CM diagnosis codes. Conditions that are clearly chronic (essential hypertension, diabetes) were not considered. Those that are acute (syncope or fainting; dehydration with electrolyte abnormality), chronic but potentially worsened by heat stress, or acute due to heat stress (renal insufficiency, atrial fibrillation) were considered. Furthermore, some conditions (urinary tract infection) may have developed after the patient had been admitted to the hospital. The hospital discharge dataset contained information about length of stay and charges for each admission that we tabulated. We used the U.S. Bureau of Labor Statistics data to convert hospital charges to 2014 dollars [46].

Results

From 1987 to 2014, 8856 hospitalizations for HSI occurred in Illinois in the months of May through September. Of those, 136 were not residents of Illinois (primarily these individuals were residents of Missouri

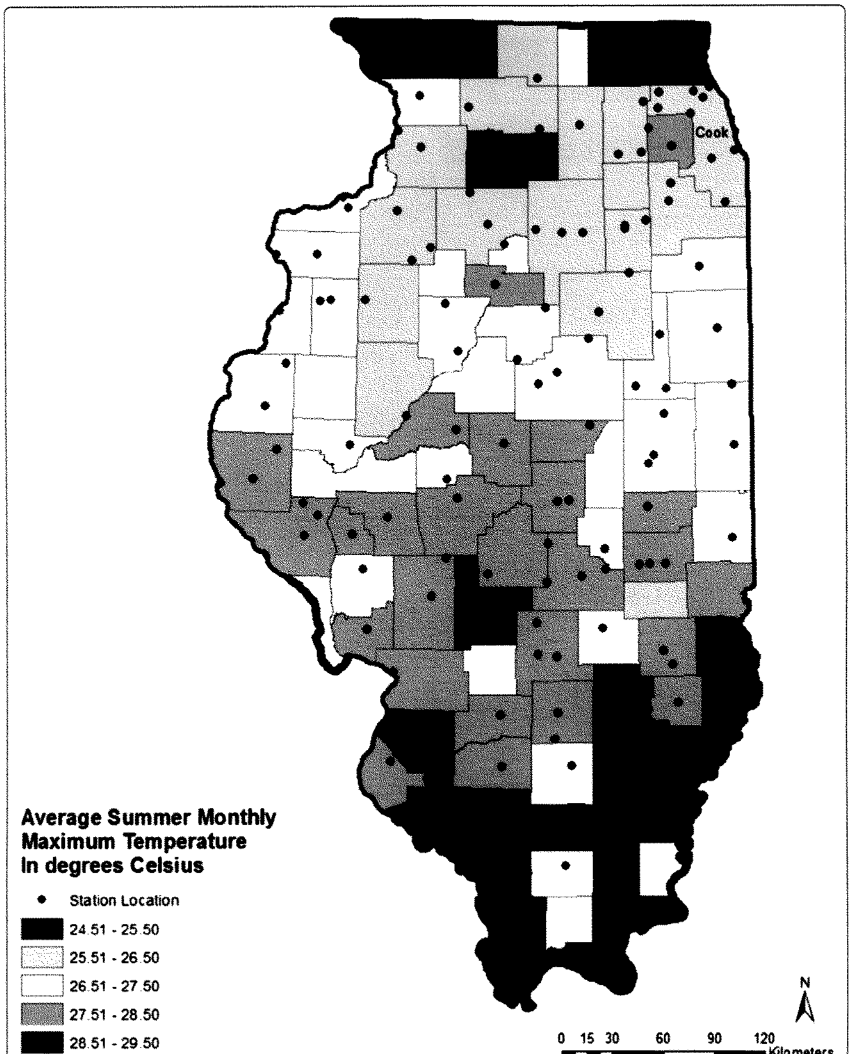

Fig. 2 Map of Illinois showing annual average summer monthly maximum temperature in degrees Celsius by county and locations of weather stations. Cook: Cook County, that contains the City of Chicago

or Indiana) and 148 were residents of Illinois with an unknown county of residence, leaving 8667 residents of Illinois whose county of residence was known. All analyses described herein are limited to these 8667 cases. The annual mean number of HSI hospitalizations was 308 cases (range: 69–1511). Excluding 1995, the annual mean was 254 cases (range: 69–508). Males accounted for 5322 (61.7%) of cases. The largest number of HSI hospitalizations and highest rate was seen in those aged ≥80 years (Table 1). Within each age category, rates of hospitalizations generally increased within decreasing urbanicity. However, in the older age category, 80+ years, the highest rates were seen in the metropolitan (>1 million population) counties.

HSI hospitalization rates varied substantially across counties (Fig. 1). The mean summer age-adjusted rate per county ranged from 4.46 cases/100,000 population (Pope County) to <1 case/100,000 population (16 counties). Cook County, that contains the City of Chicago, accounted for 3731 (44.6%) of all cases over the 28-year period, but the lowest age-adjusted rate (0.13/100,000 population). Nearly half (49.1%) of HSI hospitalizations among Illinois residents occurred during the month of July; excluding data from 1995 that percent was 42.6%. In general, the highest summer temperatures are seen in the southern part of the state, which is also the least urbanized area of Illinois (Fig. 2).

A significant association between mean monthly maximum temperature and HSI hospitalization rates by county was observed for Illinois overall (Fig. 3). For Illinois counties overall, a 1 °C increase in maximum monthly average temperature was associated with a 0.12 increase in rate of hospitalizations per 100,000 population (95% Confidence Interval (CI): 0.07, 0.17). The strongest association, though not significant at a $p = 0.05$ level, was seen in the most thinly populated stratum, where a 1°C increase in maximum monthly average temperature was associated with a 0.34 (95% CI: −0.10, 0.78) increase in HSI hospitalization rate per 100,000 population. By comparison, a 1°C increase in maximum monthly average temperature was associated with a 0.02 (95% CI: −0.003, 0.04) increase in HSI hospitalization rate per 100,000 population in the metropolitan urban (> 1 million population) stratum. Excluding the 1995 data had minimal impact on the monthly temperature-monthly hospitalization association, with the exception of the thinly populated strata, that demonstrated a large decrease in the effect estimate (Fig. 3).

Sensitivity analysis included an evaluation of associations with monthly minimum temperature and mean monthly temperature. Due to the high correlation between maximum, minimum and mean temperature, there was minimal change in effect estimates and the overall trends demonstrated remained the same (data not shown).

The mean and median length of an HSI hospital stay was 3.7 and 2.0 days, respectively (range: 1–122 days). Total and mean per person hospital charges in 2014 dollars were $167.7 million and $20,050, respectively. The most common concurrent diagnoses among HSI cases were dehydration, electrolytes/acid-base abnormalities, and acute renal failure (Table 2). Other concurrent conditions known to be associated with heat stress include syncope and rhabdomyolysis. Rhabdomyolysis, that can lead to multisystem organ failure, was more common in the younger age categories (chi square $p < 0.0001$). While individuals <50 years of age accounted for 26.2% of HSI hospitalizations overall, they accounted for 50.3% of HSI cases complicated by rhabdomyolysis. In addition, several chronic conditions were common among cases of HSI,

Table 1 Number and overall rate of summer hospitalizations of heat-stress illness (per 100,000 population) over the 28-year study period by rural/urban stratification (RUCC1–metropolitan urbanized (> 1 million population); RUCC2–metropolitan urbanized (< 1 million population); RUCC3–non-metropolitan urbanized; RUCC 4–less urbanized; RUCC5–thinly populated) and by age categories

RUCC	Counties (N)	<10y Count (rate)	10–19y Count (rate)	20–29y Count (rate)	30–39y Count (rate)	40–49y Count (rate)	50–59y Count (rate)	60–69y Count (rate)	70–79y Count (rate)	≥80 y Count (rate)	All Count (rate)
RUCC1 – metropolitan, (> 1 million pop.)	17	79 (0.05)	270 (0.16)	137 (0.07)	409 (0.22)	614 (0.36)	706 (0.53)	726 (0.79)	1114 (1.87)	1454 (4.11)	5510 (0.453)
RUCC2 – metropolitan (< 1 million pop.)	19	26 (0.09)	79 (0.25)	53 (0.17)	78 (0.25)	123 (0.39)	157 (0.60)	151 (0.78)	176 (1.30)	187 (2.18)	1029 (0.458)
RUCC3 – non-metropolitan urbanized	15	7 (0.05)	61 (0.37)	38 (0.24)	68 (0.43)	82 (0.50)	111 (0.80)	74 (0.67)	124 (1.51)	141 (2.61)	706 (0.594)
RUCC4 – less urbanized	42	16 (0.08)	121 (0.57)	58 (0.31)	155 (0.74)	155 (0.70)	178 (0.96)	181 (1.20)	194 (1.71)	268 (3.61)	1325 (0.850)
RUCC5 – thinly populated	9	0 (0.00)	8 (0.71)	11 (1.26)	11 (1.08)	12 (1.04)	11 (1.07)	15 (1.61)	17 (2.48)	11 (2.86)	98 (1.158)
All	102	128 (0.05)	539 (0.22)	298 (0.12)	721 (0.28)	986 (0.41)	1164 (0.60)	1146 (0.83)	1624 (1.74)	2061 (3.60)	8667 (0.503)

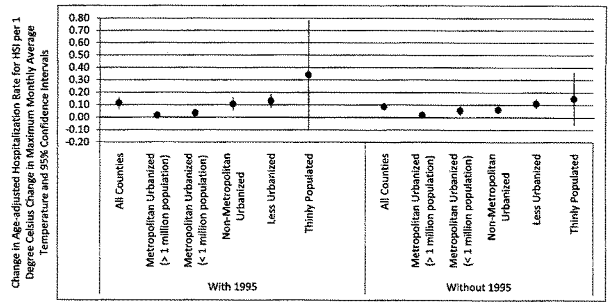

Fig. 3 Estimated change in heat-stress illness per 1 °C change in maximum monthly average temperature (after adjustment for county percent below poverty level, percent population Black, and percent population Hispanic) and 95% confidence intervals for all counties and by rural/urban stratification (RUCC1–metropolitan urbanized (> 1 million population); RUCC2–metropolitan urbanized (< 1 million population); RUCC3–non-metropolitan urbanized; RUCC 4–less urbanized; RUCC5–thinly populated) for all study years, 1987–2014, and excluding 1995, the year of the heatwave

hypertension (27%), diabetes (8.8%), congestive heart failure (7.4%), and chronic obstructive pulmonary disease (5.1%).

Discussion

We assessed the association between the average maximum monthly temperature and rates of HSI hospitalization among Illinois counties. We utilized data for at 28-year study period, 1987–2014 focusing on the summer seasons (May to September). Previous epidemiological literature has focused on urban areas. Our study covers the entire state of Illinois and therefore we were able to assess differences by urban/rural strata.

We collapsed the nine rural urban continuum codes [44] into five strata to assess the relationship between mean monthly maximum temperature and hospitalizations for HSI along the continuum of urban metropolitan to thinly populated areas. In Illinois, we found that HSI hospitalization rates and the temperature-hospitalization response function was the strongest in the thinly populated strata. This stratum is the most isolated strata from the urban and suburban centers in the state. These results are consistent with recent studies that demonstrated elevated risk in rural areas for emergency room visits for HSI across the U.S. [41, 47] and in North Carolina [40], though those studies did address hospitalization.

There are several possible factors contributing to susceptibility of the most rural areas to heat-stress illness. Studies of urban heat waves have demonstrated that living alone, lack of air conditioning, and underlying medical conditions are risk factors for mortality [13, 15]; these same factors may affect residents in rural areas. Particularly in Illinois, following the 1995 heat wave, several prevention measures were put in place in the City of Chicago, including heat warning systems, community outreach initiatives, and cooling centers [13]. Similar efforts may not have been implemented to a comparable extent in rural areas.

In Illinois, the counties identified as thinly populated are also agricultural counties. The relatively high proportion of the population engaged in physically-demanding, outdoor work in those counties may account for the steeper slope of the temperature-HSI association (Fig. 3). Our data demonstrated a more pronounced difference in rates by urban/rural strata in those less than 60 years of age, suggesting that occupational factors might place workers at risk for HSI that is consistent with previous literature [37, 38]. Previous literature regarding the use

Table 2 Most common co-morbid diagnoses listed with hospitalizations for heat-stress illness in Illinois, 1984–2014. Note that percentages do not sum to 100% as hospitalized patients typically had multiple diagnoses

Diagnosis	ICD-9 codes	Frequency (percent)
Dehydration	276.5, 276.51, 276.52	3694 (42.6)
Electrolyte, acid-base abnormality	276.1, 276.2, 276.3, 276.4, 276.7, 276.8, 276.9	1445 (16.7)
Acute renal failure	584, 584.5, 584.6, 584.7, 584.8, 594.9	1021 (11.8)
Urinary tract infection	599.0	808 (9.3)
Syncope (fainting)	780.2	781 (9.0)
Rhabdomyolysis	728.88	549 (6.3)
Atrial fibrillation	427.31	514 (5.9)
Respiratory failure	518.81	299 (3.5)
Altered mental status	293.0, 780.02	92 (1.1)

of hospitalization data has suggested that hospitalizations in rural areas may be underreported compared with urban areas [40]; therefore, the effect demonstrated in rural areas may be an underestimate of the true effect of heat in rural areas of Illinois.

Exposure to extreme heat is known to have a complex set of physiological effects on multiple organ systems. We found fluid and electrolyte balance and acute failure to be the two most common comorbidities associated with HSI in Illinois that is consistent with previous studies [48, 49]. Increased risk of hospitalization among the elderly for fluid and electrolyte disorders, renal failure, urinary tract infection, septicemia, and heat stroke heat wave days compared with non-heat wave days has been documented [50]. The costs associated with heat events can also have significant impacts. Previous analyses of the California heat wave, which lasted about 15 days, estimated the total costs to be $5.4 billion dollars (in 2008 dollars) of which $2.8 billion was the cost of hospitalizations [25, 51]. While our results are not directly comparable, since we are not evaluating a specific heat wave, we found that total hospitalizations in Illinois for HSI cost $167.7 million dollars (2014 dollars) for the 28-year study period. Additionally, the $167.7 million in hospital costs is only a portion of the total economic burden. The total of 32,564 days spent in hospitals by those with HSI represents a substantial burden of indirect costs. Improved and targeted awareness campaigns regarding the health impacts of heat may reduce the burden of associated healthcare costs.

Our analysis is limited in a few ways. First, the number of HSI hospitalizations is likely to be underestimated. Prior studies have identified HSI hospitalizations as we have, based on either an ICD-9-CM code of 992 or E900 or both [12, 52]. However, a limitation of this approach is that health care providers must recognize that an individual's symptoms – that can be non-specific – are due to heat in order for the condition to be coded as being heat-related. Morbidity due to a variety of health conditions, including renal, cardiac, and respiratory diagnoses can increase with heat. A study of Medicare beneficiaries found that only a small subset of excess heat-related hospitalizations were coded with ICD-9 codes 992 or E900 [53]. Thus, although these ICD-9 codes may be relatively specific for HSI they may have limited sensitivity for the broad range of illness exacerbated or caused by heat exposure when the role of ambient heat is not recognized by clinicians. Therefore, the estimated 8667 cases of HSI hospitalizations described here are likely an underestimate of the burden of disease attributable to ambient heat in Illinois during 1987–2014. Due to the low number of hospitalizations, we were provided monthly aggregated data that limited the types of analyses possible. We were could not consider a case-crossover analysis which would have been appropriate for this acute and rare outcome. In addition, we did not have the statistical power required to consider daily associations but needed to aggregate by month. Therefore, we were not able to assess lagged associations between temperature and hospitalizations for HSI but rather, were only able to assess monthly associations. Second, maximum temperature exposure was based on county of residence identified in the hospitalization dataset. It is possible that heat exposure may have occurred in a different county. However, this would bias our results to the null and we expect this error to be minimal in Illinois as neighboring counties do not experience significantly different temperature patterns. A third limitation is the use of hospital charges to estimate the direct medical costs of HSI hospitalizations. Billed hospital charges are inflated above cost, and thus, do not accurately capture the direct medical costs of HSI hospitalizations in Illinois. Fourth, it is not known to what degree general disparities in access to hospital care in rural vs. urban areas may contribute to the differences in HSI hospitalizations among Illinois counties.

Reduction of HSI risk in thinly population rural areas may require different strategies than in urban areas, given the low population density and high prevalence of agricultural work. Input from emergency preparedness specialists would be useful in identifying effective methods for alerting people, particularly those working in agriculture, with timely updates from local offices of the National Weather Service. Such alerts might include reminders for rest, water, and shade breaks. County health departments in rural areas, organizations that address health and social needs in rural areas, and agricultural extension offices could identify cooling centers and promote their use if such initiatives would be shown to be acceptable to local communities. Educational initiatives for rural health care providers could include methods to increase awareness among residents, to increase fluid intake during hot weather. Given the high frequency of acute renal failure and rhabdomyolysis, promoting fluid intake is critical, particularly for those who engage in exertional activities. Prevention efforts should account for U.S. National Climate Assessment [54] projections of more frequent and extreme heat events.

Conclusion

Our findings suggest that elevated temperatures may have a differential impact in rural counties compared with urban counties. Future research should be conducted at the individual level to understand specific pathways of exposure, such as occupational, that result in higher rates of HSI in rural communities. Prevention of heat-related illness in rural areas will require different strategies than urban areas, given lower population densities and higher prevalence of agricultural work. Collaboration among emergency management, community organizations, and local health departments is needed to reduce HSI risk in rural counties.

Abbreviations
HSI: Heat-stress illness; ICD-9-CM: International Classification of Diseases, 9th Revision, Clinical Modification; RUCC: Rural Urban Continuum Codes

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Availability of data and materials
The datasets generated during and/or analyzed for the current study are not publicly available since the hospitalization data utilized is not publically available but are available from the corresponding author on reasonable request and pending approval from the Illinois Department of Public Health.

Authors' contributions
JSJ conducted the analysis and wrote the manuscript. EG and LN contributed to the writing and editing of the manuscript. AS prepared the maps for the manuscript. SD conceptualized the study and helped guide the analysis. All authors read and approved the final manuscript.

Competing interests
All authors declare that they have no competing interests.

Consent for publication
Not applicable.

Ethics approval and consent to participate
This work that involved the analysis of a dataset that had personal identifiers removed or grouped into categories (such as age) was determined not to involve human research subjects by the UIC Institutional Review Board (Protocol 2013-0172).

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