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LANDSAT AT 50 AND THE FUTURE OF U.S. SATELLITE-BASED EARTH OBSERVATION

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE AND SCIENCE

OF THE

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

UNITED STATES SENATE

ONE HUNDRED SEVENTEENTH CONGRESS

SECOND SESSION

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SENATE COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

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LANDSAT AT 50 AND THE FUTURE OF U.S. SATELLITE-BASED EARTH OBSERVATION

THURSDAY, DECEMBER 1, 2022

U.S. SENATE,
SUBCOMMITTEE ON SPACE AND SCIENCE,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
Washington, DC.

The Subcommittee met, pursuant to notice, at 10:33 a.m., in room SR–253, Russell Senate Office Building, Hon. John Hickenlooper, Chairman of the Subcommittee, presiding.

Present: Senators Hickenlooper [presiding], Cantwell, Blumenthal, Lummis, and Fischer.

OPENING STATEMENT OF HON. JOHN HICKENLOOPER, U.S. SENATOR FROM COLORADO

Senator HICKENLOOPER. Great. Terrific. Welcome to the last Space and Science Subcommittee hearing of the 117th Congress, "Landsat at 50 and the Future of U.S. Satellite-Based Earth Observation."

I know I almost never mention on this committee—well, I try to mention it fairly frequently, but I am a former geologist and I have seen firsthand how the dynamic circumstances around our country, our world, how our world is constantly changing and the ecosystems across the globe in many ways support each other, oceans affect forests, and plains.

And we should understand what the phrase "surf turf" and what is above the Earth are all crucially interconnected. Observations from space allow us to better—get to a better understanding of changes in our planet over time. The CHIPS and Science Act reaffirms our Nation's commitment to science and to research.

Today, we are going to examine important scientific missions carried out by important partners in Government and academia, the commercial sector, all playing a role and all interconnected. Earth observation provides key data that serve many purposes. Farmers can serve or can measure soil moisture to make sure they can improve crop yields.

Weather, the National Weather Service forecast to alert residents of hurricanes and tornadoes. In the case of emissions, we can detect and increasingly measure fugitive emissions, such as methane, from oil and gas wells. In terms of Colorado, the two key issues that we have seen where Earth observation has become increasingly important, wildfire mitigation and drought management.

Some would go so far as to describe our droughts in the West now as so prolonged that they don't qualify to be considered

droughts. They are aridification or desertification. They are more permanent than generally what we think of a drought.

We have an image here of the East Troublesome Fire over my right shoulder here. It burned over 190,000 acres, destroyed over 350 homes, caused over a half a billion dollars of damage in Colorado.

And instruments built by Ball Aerospace, Colorado based company, were on the Landsat 8 satellite, captured images of the fire, the one on this far from my right. It is a natural color showing a smoke plume. But the second uses infrared light to show details of where you have the active fires, bright red, the burn scars are dark red, and the vegetation is green.

The second image I put up here as part of the show and tell is Lake Powell, the second largest reservoir in the entire country and part of the Colorado River Basin system. This ongoing drought, this aridification, is making water management a top conservation policy. Last fall's emergency release of water helped Lake Powell's hydroelectric power generation, but it was really a stopgap measure.

Lake Powell is currently filled to only 26 percent of its full capacity, the lowest level since 1967. And you see that in frightening clarity in that image. These images from Landsat showed the changing water levels between 1999 and 2021. And by any measure, these are drastic reductions in water levels over a relatively short period of time.

With today's hearing, we look forward to better understanding how our Federal, academic, and commercial earth observation activities can better complement each other, can be better orchestrated. How can we use this data to improve ecosystem conservation or adaptation? And what benefits can emerging technologies like artificial intelligence or cloud computing provide for future earth observation?

Today's witnesses include—while our array is a reminds me of the 1927 New York Yankees, you know, the—one of the greatest batting orders in the history of baseball. Today's witness panel brings immense expertise.

Dr. Steve Volz, Assistant Administrator for Satellite Information Services, and leads NESDIS—N-E-S-D-I-S, I should spell it out, at NOAA. Dr. Kate Calvin, Chief Scientist of NASA. Mr. Daniel Jablonsky is the CEO of Maxar Technologies, also based in Colorado. Mr. Kevin Gallagher leads the Landsat Program at the U.S. Geological Survey.

And Dr. Waleed Abdalati is the Director of C.U. Boulder's Cooperative Institute for Research in Environmental Sciences, CIRES, and served as co-chair of the recent Earth Science Decadal Survey.

With that, I will turn it over to Ranking Member Lummis for her opening statements, and then recognize Chair Cantwell and Ranking Member Wicker when they get here.

STATEMENT OF HON. CYNTHIA LUMMIS, U.S. SENATOR FROM WYOMING

Senator LUMMIS. Thank you, Chairman Hickenlooper. And thank you witnesses for joining us today. In the West, our land is a key part of our very lives, our every activity, and certainly part of our culture.

Whether it is agriculture, energy production, or our parks, Wyoming's land shapes our people, our economy, and both in nearly every way imaginable. Having detailed data on how that land changes over time, how it responds to the changing of the seasons, or how it is impacted by severe weather is extremely valuable and necessary to make informed decisions.

That is why I am glad we are holding this hearing today, so that we can highlight the importance of the Landsat Program by showing how it interacts with each of these issues. Through these images, we can better understand how seasonal changes affect crop yields, better insights into previously unknown locations for mineral deposits, and a deeper knowledge of how to prepare for snowmelt across the region.

The Landsat Program has provided significant resources to individuals and businesses operating in Wyoming, especially since the program moved toward open data for the public. It is my hope that we are able to emphasize the work already underway in the Landsat Program and prepare the program as we move into the future.

So, thank you all for being here, and I am really looking forward to your testimony and our discussion.

Senator HICKENLOOPER. Great. And I don't see—I think this is one of those moments where we have a lot of—there is a lot of stuff. There are a lot of balls in the air, so I think our Chair and our Ranking Member might be a little late or might become conflicted out.

Anyway, I think we can go to—begin to the—go to our expert witnesses. And Dr. Volz, why don't you begin? You are here by video. Since you are on video, you should get special consideration.

STATEMENT OF STEPHEN M. VOLZ, ASSISTANT ADMINISTRATOR, NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE, NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, U.S. DEPARTMENT OF COMMERCE

Dr. VOLZ. So, thank you, sir. And I wish I could be there in person, but I am happy to participate remotely and the opportunity to do so. Good morning, sir, Chair Hickenlooper, Ranking Member Lummis, and members of the Subcommittee.

As noted, I am Dr. Stephen Volz, the Assistant Administrator of NOAA's National Environmental Satellite, Data and Information Service. It really is an honor to speak to you, along with so many of my close partners at the anniversary of the Landsat Program, of NASA's creation, and of the launch of the TIROS–1 satellite and our own beginnings. We can trace our agency start in space to the collaborative scientific project known as the International Geophysical Year.

That effort in 1957 and 1958 spurred satellite development and highlighted the importance of global Earth observations. NOAA was established with a broad mission, to study, understand, and support the health of our oceans and atmosphere, and a unique charge, to predict how our environment changes and to predict the events of that environment for our people from hour to hour and from year to year.

We save lives, protect property, and enhance the American economy by monitoring and forecasting weather, water and the climate, and by informing our citizens every day. In that job, we deploy ships and planes, buoys, balloons, drones, and satellites. Satellite observations from NOAA and from our national and international partners account for around 90 percent by volume of all data used by NOAA's forecast models.

And satellites are essential to develop and extend critical planetary climate data records, which allow us to understand the changing planet. But we don't just use satellite data. NOAA defines and designs our Nation's environmental satellite system.

NASA manages their launch and their construction, and we operate the fleet of satellites over decades. Our three agency's missions are complementary. NASA develops the space technology and the fundamental understanding of how Earth systems operate.

USGS and NOAA track and investigate the causes and consequences of climate change, and NOAA exploits technologies and delivers observations and information that the Nation needs every hour of every day.

And together, we all develop science driven models of the Earth and climate system environment to advance our individual missions. And the need for better understanding of those systems is great and growing greater.

Our experience with hurricane observations and research has taught us lessons over the years, that better observations, research, and modeling lead to better forecasts and outcomes for our communities in the paths of storms. Improved observations from satellites, aircraft, and other data sources, and better research and data assimilation have led to improved forecasts.

Since Hurricane Andrew hit Florida in 1992, we have reduced hurricane tracking error by 75 percent and improved intensity forecast by 50 percent. We are facing hurricanes now that are stronger and more frequent than in the past, and we are dealing with more damaging extreme events, including wildfires, as you mentioned, and flooding occurring year round and nationwide.

We need to be able to precisely forecast fire and flooding events, as well as derechos and ice storms, not hours but days in advance in order to inform emergency managers and communities more effectively. We can do that, but we need better observations and better models to do it.

NOAA's next generation space architecture is benefiting from the successes of NOAA's geostationary low-Earth orbit satellite programs over the years, including different ways of block buying instruments and satellites, better ground systems, and the use of commercial data.

Our next generation geostationary satellites currently provide—[technical problems]—supporting severe weather and hazardous environmental condition watches and warnings, and the next-gen geostationary extended observations for GeoXO mission will continue and expand on the current GOES-R series, with planned observations through 2055. One of the GeoXO's advanced capabilities is something—it is called a hyperspectral infrared sounder.

This sounder will provide improved real time information about the vertical distribution of atmospheric temperature and water

vapor and will significantly enhance observations of wind speed and direction. And with these better data, we will be able to better track storms, predicting the behavior of fire and smoke around wildfires.

NOAA's current fleet of low-Earth orbit satellites, known as the JPSS series, and including the just launched JPSS–2, provide critical weather data and continuous climate data records. NOAA's future LEO satellites, low-Earth orbit, will supplement and eventually replace our current JPSS satellites, providing improved modeling, higher resolution, short and long term weather forecasts, and better preparing the Nation for extreme weather and events.

Defining our third leg is our Nation's current space weather system, and now includes NOAA's observations, and NASA, and other research missions and extended service life. NOAA's next—Space Weather Next will extend these observations and provide operational forecast, helping safeguard our power grids, civil aviation, and spacecraft and astronauts.

Finally, I would note, we know our citizens need weather and environmental information to thrive, and not just to survive in a changing world. NOAA and NESDIS are not just ready to do this, we were actually created for this mission.

So I thank you for your strong and continued support of our programs, and I am happy to answer your questions. Thank you.

[The prepared statement of Dr. Volz follows:]

PREPARED STATEMENT OF STEPHEN M. VOLZ, ASSISTANT ADMINISTRATOR, NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE, NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, U.S. DEPARTMENT OF COMMERCE

Chairman Hickenlooper, Ranking Member Lummis, and Members of the Subcommittee, I am Dr. Stephen Volz, the Assistant Administrator of the National Oceanic and Atmospheric Administration's (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS). Thank you for the opportunity to participate in today's hearing. I am pleased to join the other witnesses, Kate Calvin of NASA, Kevin Gallagher of the U.S. Department of the Interior, Waleed Abladati of the Cooperative Institute for Research in Environmental Sciences, and Daniel Jablonsky of Maxar Technologies, to discuss the 50th anniversary of the Landsat Program, the 62nd anniversary of the launch of TIROS–1 and the beginning of NOAA's environmental satellite program, and the 64th anniversary of the creation of NASA.

All three of our agencies provide important and complementary support to the wellbeing and economic vitality of our Nation and can trace our roots back in part to the International Geophysical Year (IGY), 1957–1958.[1] The scope of the IGY included global collaboration in 11 different Earth sciences: aurora and airglow, cosmic rays, geomagnetism, glaciology, gravity, ionospheric physics, precision mapping, meteorology and radiation, oceanography, seismology, and solar activity. The IGY also sparked the monitoring of several key atmospheric variables including the atmospheric carbon dioxide concentration at Mauna Loa in Hawaii and the total amount of ozone above Halley Bay in Antarctica. These activities spurred the development of rockets and satellites, highlighted the importance of regular and synchronized global observations, and established collective activities to provide access to and archive of the tremendous data and information through the establishment of World Data Centers.

In 1960, NASA and the Department of Defense launched the TIROS–1 satellite, the world's first dedicated weather satellite and the predecessor for our Polar Operational Environmental Satellites and Joint Polar Satellite System (JPSS). This was followed by the development and launch of our early Geostationary Operational Environmental Satellites (GOES). The Department of the Interior's U.S. Geological Survey (USGS) and NASA developed the Landsat series, which is the longest con-

[1] *www.nasa.gov/feature/70-years-ago-scientists-establish-the-international-geophysical-year*

tinuous, space-based record of Earth's land in existence. With respect to the immense amount of data our agencies have gathered, we each operate globally recognized world data centers that the international community relies upon and provides U.S. leadership in these areas. At NOAA, the National Centers for Environmental Information continues to be a national and international repository of space-based and *in situ* weather and climate, space physics, and geomagnetic data and the World Magnetic Model, and also houses the World Ocean Database. USGS is a leader in land use/land change data, and NASA is a leader in a wide range of space-based data and research.

Partnerships among the agencies remain strong with interdependence at the operations level, co-dependence in the maintenance of long-term environmental data records, regular consultations through the National Academy of Sciences Decadal Surveys, and U.S. leadership in multilateral organizations. The participation of Dr. Waleed Abdalati highlights the essential value of the research and academic community in the continuing efforts to improve our understanding of the complex earth environmental systems which in turn lead to improved information products and services.

The participation of Mr. Jablonsky demonstrates that the aerospace industry plays an important role in maintaining U.S. leadership in space-based Earth observation. With successes over the past 10 years, the U.S. Government will increasingly seek ways to incorporate the commercial sector in our long-term plans and activities.

NOAA Builds on the Legacy of the International Geophysical Year

NOAA has a unique mission to understand, predict, and support the health of our oceans and atmosphere. From daily weather forecasts and severe storm warnings to fisheries management, coastal restoration, and data to enhance marine commerce, NOAA's products and services promote economic vitality, affecting more than one-third of America's gross domestic product. We work to save lives, protect property, and enhance the American economy through the timely delivery of trusted weather, water, and climate forecasts, analyses, and information.

For decades, NOAA has been at the forefront of the world's weather and climate enterprise. We are the global leader in observing the Earth to understand its interconnected physical and biological systems, and in disseminating knowledge from that understanding to people, communities, and industry every day and into the future. Our observation and information systems drive NOAA's weather, water, and climate products and services, which afford vital industries—shipping, fishing, agriculture, construction, energy and water resources, and more—the ability to predict and plan for the future. As a leading Federal source for operational weather, water, and space weather forecasts, and warnings, and climate assessments, we provide critical predictions and decision support tools by developing unique products that merge a variety of satellite and *in situ* data to address complex societal needs. In many cases our partner agencies (NASA, USGS, DoD) provide complementary and supplementary roles.

Satellite datasets, collected by NOAA, and our research and international partner agencies, are essential for NOAA predictions and monitoring across all scales and times, and account for around 90 percent of all data that is used by NOAA's operational forecast models. NOAA has the distinct and important role of planning for, jointly acquiring, and operating the Nation's operational environmental satellites, and working with our global partners to ensure our systems work together. Our satellites are relied upon 24 hours a day, seven days a week for weather, ocean, climate, and space weather data by NOAA, as well as individuals, businesses, and all levels of government to protect lives and property within the U.S. and around the world.

NOAA accomplishes this environmental satellite and data mission through strategic partnerships and operational cooperation with a number of federal, private, and international space organizations and academia. Our longest-standing and closest strategic partner in Earth observations from space is NASA. *NOAA's Mission* is "science, service, and stewardship to understand and predict changes in climate, weather, ocean and coasts; to share that knowledge and information with others; and to conserve and manage coastal and marine ecosystems and resources."[2] *NASA seeks* "new knowledge and understanding of our planet Earth, our Sun and solar system," and "to understand how biological and physical systems work at a fundamental level," with the intent to understand "how and why Earth's climate and environment (are) changing."[3] These complementary missions enable NOAA to ad-

[2] NOAA's Mission and Vision: *https://www.noaa.gov/our-mission-and-vision*
[3] *https://science.nasa.gov/about-us/smd-vision*

dress the observation and information needs to meet the operational service delivery demands of the Nation, including, among other services, environmental and climate predictions and analysis, and weather and water forecasts, warnings, and information.

NOAA and USGS Collaboration

NOAA has a long history of collaboration as well with the USGS, as both agencies share unique but complementary responsibilities to protect lives and property. One of the areas of longstanding collaboration is USGS's use of the NOAA GOES-Data Collection System (GOES DCS). USGS has deployed over 12,200 ground-based Data Collection Platforms (DCPs) to support its Water Resources Mission to collect and disseminate reliable, impartial, and timely data that are needed to understand the Nation's water resources. The majority of USGS water data is sent from remote DCPs to the NOAA GOES spacecraft, and is then received directly by USGS as a direct broadcast from the GOES spacecraft. This GOES DCS system is relied upon by USGS, the U.S. Army Corps of Engineers to monitor and transmit information on rivers, reservoir levels, and snowpacks in the American West. Much of this work is overlaid on Landsat images to depict the extent of floods.

Similarly, scientists at NOAA's Great Lakes Environmental Research Laboratory use satellites, remote sensing, buoys, and autonomous platforms to gather information on the Great Lakes to monitor and forecast the extent of harmful algal blooms. This includes the use of images from USGS's Landsat-8 to evaluate bloom location at a resolution of about 30 meters.[4] The Minnesota Sea Grant Program has developed remote sensing methods that can use both Landsat and Sentinel satellite imagery to provide census-level colored dissolved organic matter measurements across the state of Minnesota, providing essential information for the understanding and management of lakes.[5] Researchers with the Maine Sea Grant Program have also used USGS Landsat data to analyze the suitability of satellite data for use in site selection for oyster aquaculture.[6]

In addition to its work with NASA and USGS, NOAA also has strategic partnerships with the Department of Defense, the U.S. aerospace industry, and the international satellite Earth observation community. NOAA benefits from and leverages its partnerships with Cooperative Institutes and Minority Serving Institute Cooperative Science Centers for research to operations to research (R2O2R) and algorithm development to increase the value of NOAA's satellite data in addressing societal challenges, such as air quality in urban areas, monitoring change in the urbanized coastal environment (land and water), and weather forecasting in complex urban areas.

NOAA has provided essential environmental satellite data since the 1960s and we plan to do indefinitely. We are currently actively planning for the next generation of satellite constellations that will extend into the 2050s, equipping the Nation with a high-performing and reliable baseline of environmental satellite information. NOAA has benefited from the longstanding support of the U.S. Congress to provide oversight and appropriations for our satellite programs. I am pleased to join you to discuss the importance of our next-generation satellites and future environmental data for our Nation.

Meeting Shared and Complementary User Needs

At NOAA, we are continuously improving our satellite data and information to create products and services that meet evolving national and local needs and requirements. Over the past five years, even through the COVID–19 pandemic, NOAA has sustained meaningful interactions with numerous stakeholders to ensure that we understand the requirements of our primary users of our data services. We have also met with the customers of those users to understand their working conditions and to ensure that we provide the data in ways that address their downstream current and future needs.

Every day, we see communities grappling with environmental challenges due to unusual or extreme events that affect their health, security, and economic well being. Below are some examples of regions and populations that benefit from observations from NOAA satellites, as well as severe events that are characterized by NOAA satellite observations. These data and information additionally benefit USGS in meeting its user needs. Our partnership with the academic community provides

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4 How NOAA tracks harmful algal blooms. research.noaa.gov/article/ArtMID/587/ArticleID/2469/A-Look-Inside-How-NOAA-Tracks-Harmful-Algal-Blooms

5 Regional measurements of Minnesota's lakes using Landsat 8 imagery. 2020. repository.library.noaa.gov/view/noaa/34252

6 Oyster aquaculture site selection using Landsat 8 derived seas surface temperature, turbidity, and chlorophyll-a repository.library.noaa.gov/view/noaa/40053

critical support to address emerging areas that require targeted and dedicated research.

Coastal Populations. In 2020, the marine economy accounted for $361.4 billion, or 1.7 percent of current-dollar U.S. gross domestic product.[7] The concentration of people and economic activity at the coasts places pressures on ecologically sensitive coastal ecosystems and leaves residents and visitors vulnerable to coastal hazards such as hurricanes, erosion, sea level rise, and harmful algal blooms. To better understand these threats, the NOAA Ocean Service, NESDIS, USGS, NASA, and other Federal and state partners are involved in joint projects that use digital elevation models to better protect coastal communities from coastal inundation and coastal flooding.

Underserved Communities. The most severe harm from climate change falls disproportionately upon underserved communities—those who are least able to prepare for and recover from heat waves, poor air quality, flooding, coastal erosion, and other impacts. For example, through mapping of climate changes using satellite and *in situ* data, we know that African American individuals are more likely to live in areas with the largest projected increases in childhood asthma diagnoses and extreme temperature-related deaths[8]. NOAA, USGS, NASA, the Environmental Protection Agency, and others work collaboratively to ensure that forecasts and warnings reach and are understood by the most vulnerable citizens and communities, protecting human health. As a specific response to this need, we are committed to ensuring our websites are compliant with Section 508 of the 1973 Rehabilitation Act, including ensuring our information is accessible to visually and hearing impaired individuals.

Farmers. Key production regions for food grains in central California and the central U.S. are experiencing severe drought this year. According to the U.S. Department of Agriculture, as of August 2, 2022, drought affected at least 45 percent of the production acreage for barley, cotton, rice, sorghum, winter wheat, and hay.[9] NOAA and USGS, through programs such as the National Integrated Drought Information System, play important roles in ensuring that the agricultural communities have access to its Earth observed and *in situ* data to mitigate or minimize the effects of drought and aridification that is ongoing across the Western U.S.

Arctic. The warming in the Arctic is occurring at two to three times the global average rate and is projected to continue. Older, thicker sea ice that once covered the central Arctic ocean is now almost entirely gone.[10] Extreme events and increasing variability throughout the Arctic impact the safety and wellbeing of communities within and far away from the Arctic and carry implications for U.S. national security interests.[11] Using Landsat data, NOAA, NASA, and USGS scientists actively collaborate in Alaska and the Arctic region to better understand the climate processes that are underway and how those relate to changes in global weather patterns, the existence of a persistent ice-free Arctic, and to national security. The National Weather Service (NWS) uses Landsat imagery to supplement other satellite sources to map river ice hazards which can be responsible for severe flooding.

Wildfires. Drought and persistent heat set the stage for extraordinary wildfire seasons from 2020 to 2022 across many western states.[12] Such a rapid increase in the number and intensity of wildfires has become a major threat to lives, property, public health, electricity supply, water resource quality, and local and regional economies in the western U.S. and beyond. NOAA, NASA, USGS, and other Federal agencies are important partners in supplying actionable information from our space-based assets to the wildland community to support the time-critical detection and active management of wildfires.

Floods. Floods are the most common and widespread of all weather-related natural disasters.[13] In just the three months of June through August 2022, major flooding or flash floods occurred in six states, including in Death Valley National Park and Yellowstone National Park. Before, during, and after flooding events, NOAA, USGS, NASA, and the U.S. Army Corps of Engineers work in close partnership with vulnerable communities to address flooding and make use of digital elevation models to better protect communities, informing vulnerable populations about potential

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[7] *Marine Economy Satellite Account, 2014–2020.* Bureau of Economic Analysis. 2022

[8] *Climate Change and Social Vulnerability in the United States: A Focus on Six Impact Sectors.* Environmental Protection Agency.

[9] USDA summary of agricultural products affected by drought. USDA. August 2022.

[10] Arctic Report Card: Update for 2021. NOAA. 2021.

[11] Department of Defense Arctic Strategy. DOD. 2019.

[12] Wildfire Climate Connection. Noaa.gov. August 2022.

[13] Severe Weather 101. NOAA National Severe Storms Laboratory.

inundation. NOAA's NWS also routinely uses Landsat imagery to map the extent of flooding.

Heat. Heat is the leading cause of all weather-related deaths in the United States.[14] In the summer of 2022, more than 150 million people were placed under heat warnings and advisories. As part of the National Integrated Heat Health Information System, NOAA launched *Heat.gov* in July 2022 to provide decision-makers and the public with clear, timely, and science-based information to reduce the health risks of extreme heat. NOAA, NASA, and USGS work closely together with partners at Federal, State, and local levels to support affected populations prepare for, endure, and recover from extreme heat events.

Harmful Algal Blooms. Harmful algal blooms (HABs) occur when algae grow out of control in marine, Great Lakes, and freshwater environments. These HABs may produce toxic or harmful effects on people, infrastructure, fish, shellfish, marine mammals, and birds, and threaten access safe drinking water supplies. HABs have been reported in every U.S. coastal state, and their occurrences are on the rise, increasingly affecting the health of marine ecosystems and people. Resource managers at Federal, State, local, and Tribal levels share responsibilities to protect these resources and people from HAB hazards; data from EO satellites provides foundational data to detect and monitor HAB outbreaks.

Space Weather. According to the National Research Council, disabled electric power grids and collateral impacts from geomagnetic storms could result in economic and societal costs of up to $2 trillion per large storm, and it could take four to ten years for full recovery of grids.[15] By monitoring space weather from space using NOAA and NASA satellites, and USGS and National Science Foundation (NSF) ground assets the NWS Space Weather Prediction Center is able to warn users and commercial partners to safeguard these national assets from space weather events.

Orbital Debris. A hazard that all members of this panel face is the exponential rise in the amount of orbital debris that pose threats to orbiting spacecraft. The NOAA Office of Space Commerce is working with the Department of Defense, NASA, and commercial companies to stand up a cloud-based Open Architecture Data Repository where debris can be tracked and shared with all space operators.

NOAA is helping to meet these challenges through the provision of trusted and validated data and information as well as user-ready products and services. The scope of the challenge is enormous, and NOAA must innovate to meet the need, leverage new technological solutions, develop broader business models and partnerships with public and private sectors, and demonstrate organizational agility to adjust to changing needs, opportunities, and risks. We must do this all while meeting our critical mission to deliver environmental observations without interruption.

The increasing number of extreme events and increasing risks of harm to communities from those events necessitates enhanced information to meet this challenge. We need to monitor fire events with better resolution and more rapid response, to observe and forecast water quality and HABs with better resolution and forecasting, and to monitor and predict the intensification and trajectory of hurricanes, tornadoes, and derechos better and faster. Our communities need better information that is designed and scaled to meet their local and specific needs in light of increased extreme weather events and environmental changes. New technologies, developed by the commercial sector and often demonstrated by NASA research satellites through direct cooperation with NOAA, must be integrated into NOAA's next-generation satellite architecture to enable us to more completely deliver to users the most impactful observations and data.

NOAA's Next-Generation Satellite Architecture

NOAA's next-generation satellite programs will provide enhanced observations into the 2050s to meet increasing and evolving needs, contributing both continuous and innovative environmental information to diverse end users. NOAA will also modernize its information systems architecture by including seamless integration of NOAA and partner satellite data and *in situ,* ship, plane, and drone observations from our internal NOAA partners, and from a growing community of commercial providers. Developing these next-generation satellites takes a decade or longer from concept to launch and full deployment, but we are committed to and excited about this work.

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[14] *Weather Related Fatality and Injury Statistics.* National Weather Service.

[15] National Research Council 2009. Severe Space Weather Events Understanding Societal and Economic Impacts: A Workshop Report: Extended Summary. Washington, DC: The National Academies Press. *https://doi.org/10.17226/12643.*

In recognition of societal needs to adapt to and mitigate the effects of extreme weather and various hazards, NOAA's next-generation satellites will include advanced imagers that are relied upon to detect a wide range of hazards such as hurricanes, floods, and wildland fires. Harnessing the advances in high performance computing, artificial intelligence/machine learning, and the cloud, NOAA will provide additional capabilities to process and deliver data and information to users such as communities, emergency managers, and city planners to inform their activities and actions.

The requirement to sense the atmosphere for temperature, pressure, and water vapor input for weather and environmental numerical models remains one of NOAA's top priorities for its next-generation systems. To provide needed protections to coastal communities, NOAA plans to add an ocean color imager in geostationary orbit that will complement and vastly augment capabilities in the polar orbit to detect harmful algal blooms. The capabilities from NOAA's satellites are relied upon by NASA, USGS, many other Federal and state agencies, and the commercial sector.

Definition of the next-generation satellite programs is underway, and definitive life cycle costs have not been finalized. Arriving at approved program scopes and final life cycle costs, along with the relevant technological review assessments, will be done in close coordination and consultation with NASA and the Department of Commerce's Office of Acquisition Management.

NOAA's 2014–2017 Satellite Observing System Architecture study evaluated alternative architectures for its next-generation missions. The study indicated key takeaways for consideration in NOAA's next-generation satellite constellation plans including an integrated system of observations from NOAA and international and commercial partners. NOAA is using this comprehensive assessment to guide the design and development framework for the future architecture, and continues to develop NOAA's next-generation plans based on new information and resource constraints.

Our next-generation plans are also informed by our space engineering experience over past decades, such as the successes of the GOES–R Series and JPSS programs, the experiences of our domestic and international partners, and the U.S. commercial space sector. These lessons learned and coordination activities are focused on delivering reliable and continuous data and information for users.

NOAA relies on the U.S. aerospace industry for support throughout the lifecycle of satellite acquisition–from instrument and spacecraft bus development to launch vehicle and services to development and deployment of the antennas and ground systems. As NOAA works with industry, it is increasingly assessing the ability of commercially provided data to fill specific mission requirements. Through the Commercial Data Program, NOAA has purchased radio occultation data that are currently being integrated into its weather forecast models. As the commercial sector demonstrates the ability to deliver data that meet NOAA mission requirements, we will continue to engage and acquire these commercially-based data as part of our overall next generation satellite architecture plans.

Implementing NOAA's Next-Generation Satellite Architecture

To best facilitate user needs across orbits and observations, NOAA's next-generation satellite architecture includes three portfolios: geostationary observations, low Earth orbit, and space weather observations (see Figure 1).

The next-generation architecture also includes an evolved support system to operate the satellites and use the data. This includes supporting our satellite operators while integrating more and varied observing system elements. It also involves evolving the ground infrastructure into a system that supports all satellites and ensures the data are reliable and shareable. We will transform the "bits and bytes" received from around the world into timely, actionable, and reliable environmental information and create new data products and services. NOAA's future architecture will also ensure the quality, accuracy, and preservation of the Nation's historical environmental data archives while augmenting this vast repository with new datasets, merged products, and integrated observations from NOAA, U.S., and global observing systems.

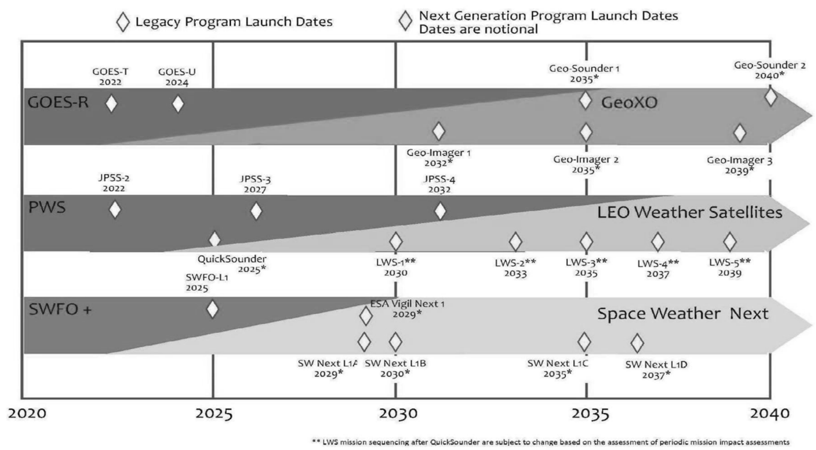

Figure 1: Notional Flyout of NOAA's Next-Generation Satellites

Geostationary Observations. NOAA's geostationary Earth orbiting (GEO) satellites provide the only continuous observations of weather and hazardous environmental conditions over the Western Hemisphere—from the eastern Atlantic to the western Pacific and from the Arctic Circle to the southern tip of South America. Information generated from our GOES system helps protect the lives and property of the one billion people who live and work in the Western Hemisphere with continuous, near-real-time observations and warnings.

NOAA's Geostationary Extended Observations (GeoXO) program is the next generation of GEO capabilities that will enable the continuous improvement of terrestrial weather prediction and warning, and will provide information enabling better climate adaptation and mitigation, healthy oceans, and resilient coastal communities and economies. As the follow-on program to the current GOES–R Series, GeoXO will provide continuity of critical geostationary data with its first launch in 2032 and planned observations through 2055. Due to the significant capabilities proposed, GeoXO is our largest investment through the 2030s, and due to the criticality of providing continuous observations, GeoXO has an aggressive 11-year development schedule.

The GeoXO pre-formulation phase included extensive, direct outreach to thousands of end users in many dozens of organizations as well as observation value assessments. It also included Observational System Simulation Experiments, an analysis of observations relative to the NOAA mission service areas, and consultation with the NOAA Observing System Council to define future observational needs and select the recommended payload instruments for GeoXO. End users require continuity of existing observations for short-term forecasting, severe weather watches and warnings, and monitoring of a range of hazardous environmental conditions such as tropical storms, lightning and winds, flooding, snow, wildfires, volcanic ash, and others. Current and future instruments in NOAA's GEO support NOAA's weather mission with essential information to notify and protect people and property across the country. These observations, together with the 50-year record of GOES observations, also provide an essential climatological data record supporting NOAA and national climate analyses and a range of climate products and services.

Following outreach to users on their satellite data needs, NOAA is now conducting industry studies to evaluate the technology readiness and costs of potential new instruments.

- A hyperspectral infrared sounder promises to improve localized forecasts and nowcasting by enhancing weather forecasting models,[16] which is critical as extreme weather events including storms, tornados, and hurricanes become more frequent and more severe.
- An atmospheric composition instrument could provide a new platform to monitor air quality, track transport and dispersion of hazardous emissions (volcanic,

[16] Geostationary Extended Observations (GeoXO) Hyperspectral InfraRed Sounder Value Assessment Report. 2021. repository.library.noaa.gov/view/noaa/32921

smoke, chemical, and radioactive), and monitor greenhouse gasses.[17] Air pollution results in at least 100,000 premature deaths and nearly $1 Trillion in damages each year in our Nation.[18] GeoXO's atmospheric composition capabilities could improve the guidance that NOAA provides every day to national, state, and local environmental authorities who issue pollution alerts.

- A geostationary ocean color instrument could complement instruments in low Earth orbit to expand NOAA's ocean observing system to support the blue economy, increase coastal resilience, and help enable NOAA's oceans, coastal, and fisheries services. This information is also valuable to other non-federal users to better assess ocean productivity and health, ecosystem change, aquaculture and fisheries management, coastal and inland water quality, seafood safety, and hazards such as harmful algal blooms. Economic analyses estimate the health effects of HABs at over $1 billion per year and that more timely and precise forecasts have potential to reduce the duration fisheries must be closed to avoid seafood poisoning.[19]

GEO satellites allow near real time data sharing partnerships that provide global benefit for weather forecasting and environmental monitoring activities. GEO data will be leveraged in innovative global inputs that supplement low Earth orbiting (LEO) observations. NOAA observations will be matched with similar satellite missions deployed in the same period by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) over Europe and by the Japanese Meteorological Agency and Korean Meteorological Agency over the western Pacific and Asia, to create a GEO ring of observations. These combined observations will provide global data sets for use by NOAA and our international partners to meet global modeling system and mission service needs. NOAA has previously benefited from acquisition efficiencies, just as other partners have utilized U.S. instrument vendors to meet their own mission needs.

Low Earth Orbit. LEO satellites from NOAA, NASA, and international partners provide a half century of unbroken climate data records and are the backbone of global weather forecasting models. These satellites detect and monitor hazards such as fires, droughts, floods, poor air quality, coral bleaching events, unhealthy coastal waters, and others. NOAA itself collects about half of the LEO data we use every day to meet our ongoing mission needs with the balance provided by our interagency and international partners. NOAA satellites in the LEO portfolio will supplement, and eventually replace, the current JPSS satellites.

The next generation of NOAA LEO satellites will leverage commercial space capabilities for increased flexibility. Together with NOAA's fleet and aircraft observations, NOAA's LEO satellite data will support the missions of all NOAA services including weather forecasting, fisheries management, ocean and coastal monitoring, and the research that supports these activities.

For accurate forecasts, weather models integrate measurements from microwave (MW), infrared (IR), and radio occultation (RO) sounders on polar satellites. These observations are especially important in polar regions where geostationary and in situ observational data are sparse. For example, JPSS provides critical data for nearly all weather forecasting in Alaska, and this is critical for aviation and the maritime industry. Ozone measurements also track the contours of the ozone layer and the extent of stratospheric ozone. Improved MW, IR, and RO soundings with more frequent observations and better spatial and vertical resolution have the potential to improve modeling and allow for higher-resolution short-and long-term weather forecasts.

A distributed constellation of satellites will provide greater diversity in data needed by the weather forecast models to cover all facets of the event under investigation, a resilient system less susceptible to individual satellite failures, and a higher refresh rate for measurements, which enables higher-accuracy weather forecasts and improvements in other key applications.

NOAA's next-generation LEO satellites would also provide vital data for wind speed, sea surface temperature, and ocean color. Hyperspectral ocean color imagery at improved spatial resolution would improve our understanding of harmful algal blooms and phytoplankton dynamics to give managers tools to mitigate economic impacts. The LEO observations would complement similar ocean color observations

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[17] A Value Assessment of an Atmospheric Composition Capability on the NOAA Next-Generation Geostationary and Extended Orbits (GEO–XO) Missions. 2020. repository.library.noaa.gov/view/noaa/27224

[18] Goodkind, A. L., Tessum, C. W., Coggins, J. S., Hill, J. D., Marshall, J. D. (2019) Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions. Proc. Natl. Acad. Sci., 116(18), 8775–8780.

[19] The Value of Geostationary Ocean Color. 2021. repository.library.noaa.gov/view/noaa/33278

from geostationary orbit. NOAA is working with NASA to assess and integrate the upcoming Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission observations into our mission services, an example of research for operational use. Enhanced atmospheric composition sensors for methane, carbon dioxide, sulfur dioxide, ozone, nitrogen dioxide, carbon monoxide, and other pollutants will enable more timely and accurate forecasts of air quality hazards and allow NOAA to assess climate change both granularly and holistically. It is important to note that this increased amount and diversity of data going into forecast models may also require the models using the data to adapt and increase their computing power.

NOAA's next-generation satellite architecture for the LEO program serves users by collecting and delivering the following global observations: MW soundings and imagery, hyperspectral IR soundings, RO soundings, visible-IR imaging including day-night band imagery, measurements of atmospheric composition including ozone, ocean surface winds, ocean color, radio detection and ranging imagery, 3D winds, and ocean surface height. NOAA will continue to evaluate and prioritize these data demands as we scope the program.

Space Weather Observations. Space weather observations aid in safeguarding fundamental power grid infrastructure, civil aviation, and on-orbit assets and astronauts. Building on the Space Weather Follow-On program, the Space Weather Next (SW Next) program will reliably provide critical space weather products and services to observe and identify this hazard and support the needs of diverse users across the U.S. and around the globe. These users will include the electric power and airline industries, utility and telecommunications companies, commercial and government satellite operators, U.S. and foreign governments, and the space weather research and academic communities.

Observations from NOAA's SW Next program will be combined with complementary data collected by Federal and international partners and will be processed through NOAA's Office of Satellite Ground Services to provide the necessary information flow for space weather forecasts. This data and information flow will enable NOAA's Space Weather Prediction Center (SWPC), the Office of Space Commerce, and other operational users to deliver actionable information that protects critical power grid infrastructure and civil aviation, and provides essential space situational awareness.

SW Next will maintain and extend space weather observations from a range of different observing points, selected to most efficiently provide the comprehensive knowledge of the sun and the near-earth space environment. These observation points could include LEO, GEO, highly elliptical orbit, and Lagrange Point 1 (L1) and Lagrange Point 5 (L5) orbits. As an initial step, NOAA has signed an agreement with the European Space Agency (ESA) to collaborate on a space weather mission flying at L5. NOAA will provide a coronagraph, ESA will provide the spacecraft, other instruments, and operations, and both Agencies will exploit the observations for science and operations. These observations will provide near-real-time coronal mass ejection imagery, solar wind, solar imaging, coronal imagery, solar wind parameters, magnetospheric particles, and ionosphere parameters, and other relevant observations required to support space weather forecasts provided by SWPC.

This work supports space weather forecasts as authorized by the *Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act* (P.L. 116–181), with the leadership and support of this Committee, and as driven by the National Space Weather Strategy and Action Plan (March 2019). Several complementary projects within SW Next will provide continuity and resiliency of space weather observations from multiple orbits with launches in the 2020s, early 2030s, and onward. Just as with our LEO portfolio, it is important to note that this increase in the amount and diversity of the data must be accompanied by improvements in our space environment and weather models, requiring the models to adapt and increase their resolution and available computing power.

Space weather observations are needed from a multitude of orbit views, so NOAA is pursuing partnerships to augment the SW Next architecture. This year for the first time, NOAA is working with NASA and the NSF to engage the National Academy of Science, Engineering and Medicine (NASEM) to complete the Decadal Survey for Solar and Space Physics 2024–2033. NOAA will use the NASEM recommendations to inform its observing system decisions, and to improve coordination with NASA and the NSF while addressing combined observational objectives. In addition, SW Next is developing a methodology to understand the impacts of observational capabilities on user needs such as alerts, watches, and warnings. We are engaging with users to better understand how our products and services support end-user decision-making. This process will aid in prioritizing NOAA program requirements and in assessing potential economic and societal benefits. The SW Next program is

evaluating its alternatives to determine the most cost-effective architecture to meet user needs and will continue to leverage user engagement to identify and prioritize user needs across the enterprise.

Conclusion

NOAA's next-generation satellite architecture provides the environmental space-based observations needed for critical weather forecasts and to meet the growing needs of the Nation in a changing environment. NOAA's integrated next-generation observing system will leverage new and existing technologies and partnerships at all levels, and will combine data from various sources, allowing us to deliver significantly improved products and services to our users. The urgency of our changing environment requires action now to better fulfill NOAA's essential mission to protect lives, property, critical infrastructure, and our economy.

The challenges our Nation and planet face demand the continued partnership of Federal agencies, each of which brings longstanding expertise in our respective areas. Alongside and in cooperation with the commercial sector's activities, academia, international partners, and investments in NASA, USGS, and NOAA's next-generation satellites will allow us all to better serve the Nation.

Senator HICKENLOOPER. Great, great. Thank you, Dr. Volz. Now we will move over to Dr. Calvin.

STATEMENT OF DR. KATE CALVIN, CHIEF SCIENTIST, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Dr. CALVIN. Thank you. When we look down at earth from space, we see this amazing, indescribable, beautiful planet. It looks like a living, breathing organism. These are the words of Astronaut Ron Garan, who spent 6 months looking down at Earth from the International Space Station in 2011. They capture how inspiring it is to observe the Earth from space.

In the years ahead, we will need Earth observations more than ever for science and for inspiration. Earth observations are key to helping society understand and effectively respond to changes in climate and are increasingly used in a range of societal applications.

NASA's launch of the first Landsat satellite in 1972 marked the start of a continuous record of land measurements from space that continues unbroken to this day.

Today, NASA operates a fleet of over two dozen satellites and instruments on the International Space Station. Earth observations from space are the foundation of much of what we know about our planet as a system.

Earth observing satellites, like NASA's long running Terra, Aqua, and Aura satellites, and the more recent GRACE follow on, ICESat–2 and Sentinel 6-Michael Freilich have measured changes in vegetation, carbon dioxide, the mass of ice sheets, sea level, and much more.

Earth observations are also a foundation for a range of applications, including weather prediction, disaster response and recovery, wildfire response, land use planning, water resource monitoring, agricultural support, food security, air quality monitoring, and aviation safety.

For example, OpenET is an application that uses publicly available NASA, USGS Landsat data to provide information to farmers and ranchers can use to estimate the amount of water being taken up on their fields or used by their crops. And this information gives them—this water will usually need to be replaced through irriga-

tion or rainfall, so this enables them to use water more efficiently and better plan irrigation.

NASA continues to lead by innovating the state-of-the-art in remote sensing technologies and following scientific needs to bring new types of Earth observations into existence. We will soon launch the surface water and ocean topography, or SWOT mission, which will improve our understanding of oceans and terrestrial surface waters, including providing the first global survey of water running through rivers and lakes.

We are also formulating the Earth System Observatory, a set of satellites, instruments, and missions that when complete will provide a more comprehensive view of the planet. When combined with SWOT and PACE missions, the Earth System Observatory will measure all major components of the Earth system, including the human Earth interface.

NASA continues to innovate in measuring and monitoring of greenhouse gases from space. With the carbon dioxide monitoring, OCO–2 and OCO–3 satellites, NASA's EMIT mission has demonstrated the capability of detecting the presence of methane, a potent greenhouse gas. In the data that EMIT has collected since being installed on the International Space Station this July, we have identified more than 50 super emitters globally.

NASA also announced earlier this year a new contract for commercial data acquisition with GHGSat, that which uses satellites to identify methane emissions. Following in the footsteps of NASA's other commercial data vendors, including Planet, Maxar, and Spire, GHGSat will provide their data to NASA for evaluation to determine the utility for advancing NASA's science and application goals.

NASA plays an essential role in supporting the continuity of Earth observations through its expertise in flight programs and integrating innovation into new satellite architectures, partnering with NOAA and USGS. We launched GOES-T and JPSS–2 this year and look forward to GeoXO and the low earth orbit architectures.

Landsat Next is just entering formulation. We also merge interagency and international data to allow the characterization of short term variability and long term trends in things like radiation, ozone, and aerosols.

As part of a growing emphasis on providing actionable data and information to a broad range of users, NASA is planning to launch an Earth Information Center. This Earth Information Center will provide a wide range of Earth data and information to the public and stakeholders.

But the initial focus will be on prototyping capabilities for greenhouse gas monitoring and information system that will integrate data from a variety of sources with a goal of making greenhouse gas data more accessible and usable to policymakers, researchers, and even students.

And as always, we thank you, Congress, for your support of NASA's Earth Science. We thank you for the opportunity to share this exciting work we are doing to advance Earth observation and maximize its impact, and we look forward to your questions.

[The prepared statement of Dr. Calvin follows:]

PREPARED STATEMENT OF DR. KATE CALVIN, CHIEF SCIENTIST, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

INTRODUCTION

"When we look down at Earth from space, we see this amazing, indescribable, beautiful planet. It looks like a living, breathing organism." These are the words of astronaut Ron Garan, who spent six months looking down at Earth from the International Space Station in 2011. They capture how inspiring it is to observe Earth from space. Garan is one of many NASA astronauts whose relationship with our home planet has been transformed by his time in space. When people see our Earth as a blue marble from space, they see it is finite, fragile, and interconnected.

Space is the best vantage point we have for both seeing and studying our changing planet. Earth observations gathered from space are the basis for so much of the scientific data and information that tells us what we know about Earth and how it is changing. In the years ahead, we will need Earth observations more than ever, for science *and* for inspiration, as we grapple with the growing impacts of climate change on our planet. Earth observations are key to helping society understand and effectively respond to changes in climate and are increasingly used in a range of societal applications.

Earth Observations as the Foundation

NASA has been observing and measuring Earth from space for over 60 years, beginning with the launch of the world's first dedicated Earth Science mission in 1960. The TIROS–1 weather satellite only lasted 78 days, but it was a precursor mission to today's Earth observing satellites. Twelve years later, NASA's launch of the first Landsat satellite in 1972 marked the start of a continuous record of land measurements from space that continues unbroken to this day. Fast-forward to 2022 and there are over 1,000 Earth observing satellites in orbit today, with more being launched each month. These satellites have different capabilities, sizes, and architectures, and are hosted and operated by a range of entities, including other U.S. government agencies, other governments, and a growing private sector.

Through decades of Earth observing missions and innovation, NASA started a revolution and laid the groundwork for the golden age of Earth observations we see ourselves in today. Today, NASA operates a fleet of over two dozen Earth observing satellites and instruments hosted on the International Space Station (ISS). We continue to push the state-of-the-art in Earth remote sensing from space and take critical measurements of nearly every component and constituent of the changing Earth. We also build and launch environmental satellites for our Federal agency partner NOAA, and we work in close partnership with USGS through the interagency Sustainable Land Imaging program to design, develop, and launch USGS' Landsat series of land imaging satellites. And NASA is pleased to see the success of an industry we have supported emerging as a robust partner across a number of areas related to earth observation. .

Earth observations from space are the foundation of much of what we know about our Earth systems. Datasets from Earth observing satellites like NASA's long-running Terra, Aqua, and Aura satellites and the more recently launched Gravity Recovery and Climate Experiment (GRACE–FO), ICESat-2, and Sentinel 6-Michael Freilich, underpin climate research, and they are key to developing and testing and verifying Earth system models.

We also work with people on the ground around the world to solve problems as they unfold. Earth observations are the foundation for a range of applications, including weather prediction, disaster response and recovery, wildfire response, land use planning, water resource monitoring, agricultural support, food security, air quality monitoring, and aviation safety. For example, OpenET is a program that uses publicly available NASA–USGS Landsat data to provide information to farmers and ranchers on evapotranspiration, so they can estimate the amount of water being taken up or used by their fields and crops and that will usually need to be replaced through irrigation or rainfall. This enables them to use water more efficiently and better plan irrigation.

Together with our other government partners, we are measuring, studying, and informing the world about our changing Earth. We are disseminating the data and knowledge collected for the benefit of humankind. And we are researching the new technologies and paving the way for the next generation of Earth observation missions. Our latest endeavor is NASA's Earth System Observatory (ESO), a series of missions in development that will launch later this decade that will give us a 3D holistic view of the changing globe.

Innovating the Next Generation of Earth Observations

The ESO responds to the top recommendations from the National Academies of Sciences, Engineering, and Medicine's 2017 Earth Science and Applications from Space Decadal Survey, including missions targeting the Academies' priorities for observation: aerosols, clouds, convection and precipitation; mass change, surface biology and geology, and surface deformation and change. Formulation activities are underway for the first four major ESO missions targeting these designated observables. NASA just received recommendations from an ESO Independent Review Board (IRB), which took a close look at ESO's science goals, management and programmatic structures, and preliminary mission architectures. The IRB reviewed technical concepts formulated by NASA for the ESO to ensure their robustness, considered the ESO's ability to achieve NASA's plans, and checked to ensure lessons learned regarding large missions were incorporated into this effort.

In October, NASA announced the first mission opportunity within the new Earth System Explorer Program, another priority from the 2017 Decadal Survey. For the Earth Explorer missions, NASA is seeking submissions of proposals for a medium-sized PI-led mission that will investigate one or more targeted observables identified by the Decadal Survey. With a focused programmatic scope, Explorer missions can be developed relatively quickly and complement the science goals of the larger Earth System Observatory. They will allow investigators to propose gathering high priority observations, including, for example, greenhouse gases, that are not part of the ESO suite of missions.

NASA continues to innovate in the measuring and monitoring of greenhouse gases from space, building on the legacy of our Orbiting Carbon Observatory-2 (OCO–2) and OCO–3 missions, which are able to measure vertical columns of carbon dioxide concentrations in Earth's atmosphere and track how CO_2 concentrations vary globally and how they are changing over time. NASA's new Earth Surface Mineral Dust Source Investigation (EMIT) mission, which launched successfully in July, has demonstrated the crucial capability of detecting the presence of methane, a potent greenhouse gas. Since July, the EMIT science team has identified more than 50 methane super-emitters globally.

NASA also announced earlier this year a new contract for commercial data acquisition with GHGSat, Inc., of Canada, which uses satellites to collect methane and carbon dioxide measurements that can help identify greenhouse gas sinks and sources. Following in the footsteps of NASA's other commercial data vendors, including Planet, Maxar, and Spire, GHGSat will provide their data to NASA for evaluation to determine the utility for advancing NASA's science and application goals.

The data and information provided by EMIT, commercial missions like GHGSat, and future missions like these, can help decision-makers better identify, understand, and address methane emissions.

Ensuring Continuity of the Global Climate Record

With a number of NASA's flagship Earth research satellite missions, including Terra, Aqua, and Aura, reaching end-of-life over the next few years, an important ongoing conversation has emerged across the Earth observations community about how to ensure the continuity of the data provided by missions on which the research and applications communities have relied for decades. These conversations include questions about the roles that other Federal agencies, as well as our international partners, and private sector, can play.

With a new budget line in the FY 2023 Budget, NASA is pursuing key climate continuity measurements and advancing open science by leveraging cutting edge data science techniques. In addition, the first Earth Venture Continuity (EVC) mission, Libera, was selected in February 2020 and will maintain the 40-year data record of the balance between the solar radiation entering Earth's atmosphere and the amount absorbed, reflected, and emitted. NASA plans to announce an opportunity and solicit proposals for a second EVC mission in 2023.

NASA plays an essential role in supporting continuity of data records provided by our interagency partners' satellites, including in building and launching NOAA's environmental satellites, on a reimbursable basis for NOAA, and helping develop future satellite architectures for both NOAA and USGS. NASA develops and maintains critical continuity data records using reprocessed NOAA operational satellite measurements merged with those of NASA and other agency and international partners, allowing detection and characterization of both short-term variability and long-term trends in essential quantities, such as Earth radiation, ozone, and aerosol concentrations. NASA provides flight program management expertise and a focus on innovation to partnered missions, driving Federal science through new approaches and observation technologies.

For example, NASA has been working closely with USGS to finalize the next-generation system architecture for the Landsat Next satellite and will begin formulation activities for the mission activities shortly. NASA's goal has been striking a balance between incorporating the latest land imaging technologies with ensuring Landsat's continuous long-term record of land imagery and data within the budget that the Administration and Congress can provide. Landsat Next, now expected to launch as a "triplet" configuration of three platforms, will join Landsat 8 and Landsat 9 on orbit in adding to the continuous long-term record of land imaging that began with the first Landsat in 1972.

We also expect to expand our commercial interaction working with the private sector to add their capabilities to our own to benefit American citizens. NASA's pioneering data purchases have allowed us to see what small commercial satellite operators can provide now and what they might in the future, as well as better set the terms of future procurements and licensing of data for science. We hope our work in this area will support this industry as it grows.

Earth Observations for Earth Action

As part of a growing emphasis on providing actionable data and information to a broad range of users, NASA is planning to launch an Earth Information Center (EIC) next year. The EIC will provide a wide range of Earth and climate data and information to the public and stakeholders, but the initial focus will be on prototyping capabilities for a greenhouse gas monitoring and information system that will integrate data from a variety of sources with a goal of making GHG data more accessible and usable to Federal, State, and local governments, researchers, the public, and other users.

To implement this effort NASA is collaborating with other agencies including the Environmental Protection Agency (EPA) to enhance greenhouse gas monitoring and make greenhouse gas data more accessible to a broad range of users. NASA will work jointly with other agencies to develop the greenhouse gas monitoring and information system. The greenhouse gas monitoring and information system will support regular updates to national gridded greenhouse gas anthropogenic activity-based data. The system will also combine EPA's anthropogenic emission data with atmospheric-based data on natural emissions and fluxes, and enable the identification and quantification of emissions from large anomalous events, leveraging aircraft and satellite data.

Through open-source science, NASA provides knowledge, resources, tools, and technologies to benefit humanity. This provides opportunities for those outside of NASA to create new applications using NASA observations, as well as leverage existing applications. For instance, it can help other government agencies or NGOs as they address societal or environmental challenges and make decisions in a range of sectors. NASA is also continuing to improve our engagement with the public on Earth Science and share information about our planet that can only be fully unlocked by observing it. NASA is also innovating its partnerships, with the goal of exploring new paths to applications and impact. NASA capabilities mean opportunities for engagement with a wide range of sectors, from agriculture to oil and gas. We are looking at ways to engage with philanthropies, state agencies, and to connect with citizens broadly through open science as well as targeting our outreach through the lens of environmental justice.

CONCLUSION

Increasingly, we see our work in Earth observations through the lens of its importance to global climate change. Each climate tipping point presents its own multifaceted ecological or societal challenge. For each, we ask how science and Earth observations can inform responses, by individuals, nations, and the world. The global climate observing system from space is critical because only from space can we track the status over time of each of these climate tipping points and other Earth system changes holistically all around the world. Our monitoring could provide the first and most clear warning signs that a climate tipping point is near or has been reached.

And as always, we look to Congress for guidance on priorities and partnerships, noting congressional interest in science relating to everything we do. We thank you for this opportunity to share something of our approach to Earth observation and look forward to your questions.

Senator HICKENLOOPER. Thank you, Dr. Calvin. Mr. Jablonsky.

STATEMENT OF DANIEL JABLONSKY, PRESIDENT AND CHIEF EXECUTIVE OFFICER, MAXAR TECHNOLOGIES

Mr. JABLONSKY. Chairman Hickenlooper, Ranking Member Lummis, Chair Cantwell, Ranking Member Wicker, and esteemed members of the Subcommittee on Space and Science, thank you for holding this hearing to discuss the important topic of Earth observation in honor of 50 years of Landsat.

My name is Dan Jablonsky, and I am the President and CEO of Maxar Technologies. I have been a part of the Earth observation industry for just over a decade, and before joining the private sector, I was a surface warfare officer and nuclear engineer in the U.S. Navy. I am honored to be here today.

Maxar, based in Westminster, Colorado, is a leader in commercial earth intelligence and space technology, solutions, and a proud long standing partner to the U.S. Government and the commercial industry.

Maxar owns and operates a fleet of very high resolution earth observation satellites and soon will be launching WorldView Legion, our next generation Earth observation satellites and the first to be built in-house.

After the passage of the Land Remote Sensing Policy Act of 1992, we were granted the first commercial Earth Observation License, opening the door to the Earth observation industry. Since then, satellite imagery has become integral to everyday life.

Earth observation capabilities identify, monitor, and address problems that impact the security and economic well-being of every American. For example, Earth observation data helps with natural disaster relief and recovery.

Using imagery from satellites and analytical techniques, we can help forecast potential damage and point on the ground response teams to locations efficiently, identifying areas that have been damaged by hurricanes, provide precision 3D mapping to optimize relief efforts, and across vast stretches of public and private lands help responders identify and fight wildfires. Earth observation applications also unlock commerce and mobility.

Geospatial data is the bedrock for many businesses and applications that generate significant value for the economy. For example, Google Maps uses Maxar satellite images to not only help users navigate the world, but also to locate and find their way to local businesses, offices, schools, and all other types of locations.

In more recent years, the commercial, remote sensing industry has been exploring ways to go beyond the pixel. Machine learning, autonomous change detection, and object identification are helping decisionmakers get to answers quicker.

At Maxar, we are pushing the edge on 3D mapping, taking our images and making them three dimensional, ushering in a new era of insight, augmented reality, and immersive experiences. Critically, the commercial sector is advancing U.S. leadership in space. Commercial satellite support crucial civil and national security missions. As we look to the future of our industry, we must also look to space sustainability.

I thank Senators Hickenlooper, Lummis, Cantwell, and Wicker for introducing the ORBITS Act, a great step in protecting and maintaining a sustainable space environment for the future. I sup-

port this effort and look forward to working with you to find new commercial solutions to solve today's most challenging problems.

Maxar stands ready to do its part to help build a sustainable space environment and usher in the next 50 years of Earth observation advancements. Thank you to the Subcommittee for holding this hearing, and the opportunity to speak to you on this important topic.

I am happy to answer any questions you have at this time.

[The prepared statement of Mr. Jablonsky follows:]

PREPARED STATEMENT OF DANIEL JABLONSKY, PRESIDENT AND CHIEF EXECUTIVE OFFICER, MAXAR TECHNOLOGIES

Chairman Hickenlooper, Ranking Member Lummis, full Committee Chair Cantwell and Ranking Member Wicker, and esteemed Members of the Subcommittee on Space and Science:

Thank you for holding this hearing to discuss the important topic of Earth observation in honor of 50 years of Landsat. My name is Dan Jablonsky, and I am the President and CEO of Maxar Technologies, a role in which I have served in since January 2019. I have been a part of the remote sensing industry for the past decade and before joining the private sector, I was a surface warfare officer and nuclear engineer in the U.S. Navy. I am honored to be a part of this hearing today.

About Maxar

Maxar is a leader in commercial Earth intelligence and space technology solutions and a trusted, end-to-end partner to the U.S. government and the commercial industry. As a U.S. company with locations across the country, Maxar designs, manufactures, and operates communications and Earth observation satellites; space exploration spacecraft; solar electric propulsion systems; on-orbit satellite servicing vehicles; and robotics for ongoing space operations and exploration.

In 1993, the U.S. Department of Commerce granted WorldView Imaging Company, later known as DigitalGlobe, a legacy Maxar company, the first license for commercial Earth observation from space. Maxar's Earth observation satellites have provided imagery to support critical national security and disaster response missions ever since. Most recent examples include intelligence related to the war in Ukraine and damage assessments to support recovery efforts related to Hurricanes Fiona, Ian, and Nicole. We are proud to serve as a trusted partner to the U.S. government—providing data-driven insights, analysis, and recommendations, delivering current, high-resolution satellite imagery, and enabling 3D data for analysts and decision makers to better monitor, understand, and respond to current events, deter threats, and ensure national and global security.

For more than 60 years, Maxar has supported U.S. leadership in space, manufacturing more than 280 spacecraft, supporting numerous civil space missions including the National Aeronautics and Space Administration's (NASA) upcoming Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission.

Additionally, we operate, and for the past 20 years have operated, the most advanced constellation of commercial Earth imaging satellites in the world. We are headquartered in Westminster, Colorado, and have a dedicated workforce of over 4,000 across the country including at our facilities in California, Florida, Michigan, Missouri, Virginia, and Puerto Rico.

Landsat at 50

We are here today to mark the 50th anniversary of the launch of the first satellite in the Landsat series by the U.S. Geological Survey (USGS) and NASA in 1972. The fifty-year archive of Landsat observations has supplied invaluable, empirical evidence that has helped build confidence in Earth observation technology and created a shared understanding of how the Earth is changing. Since that time, Earth observation technology and the U.S. space industrial base have advanced rapidly.

As we celebrate this important milestone and look to the future of U.S. satellite-based Earth observation, I would like to discuss three important topics today:

- The value Earth observation technology provides to society and how Earth observation technology can be harnessed to solve some of the biggest problems facing humanity.
- The important role the commercial space sector plays advancing U.S. leadership in space.

- The steps industry and Congress should take to help ensure America continues to lead on Earth observation technology.

Earth Observation Technology Helps Solve Complex Problems

Earth observation technology is key to solving some of the biggest problems facing humanity and enables a better understanding of the world around us. Earth observation capabilities help identify, monitor, and address problems that threaten the security and economic well-being of every American, and aid in the improvement of the lives of people across the globe.

In order to most effectively use Earth observation data to address today's issues, and issues that will arise in the future, Maxar uses innovative artificial intelligence, machine learning, and algorithm techniques to extract answers quickly in order to assist decision makers. The amount of information coming from space is best used by applying these techniques to get actionable information. We all know the danger of overgrown trees near powerlines and the impacts a downed line can have. However, we have applied unique algorithms which can tell the height of vegetation based off data we obtain from our Earth observations which can then be used for utility corridor monitoring—helping customers understand when vegetation near powerlines needs to be trimmed.

Extreme Weather and Disaster Response

Each year, thunderstorms, floods, tornadoes, hurricanes, and other weather-related events, cause an average of approximately 650 deaths and $15 billion in damage in the U.S. About one-third of the U.S. economy—some $3 trillion—is sensitive to weather and climate.[1] Earth observation provides decision makers and first responders with essential information to help them protect lives and property when extreme weather events occur. Not only is imagery essential, but technologies like Shortwave Infrared (SWIR) on Maxar's WorldView-3 satellite help first responders identify where wildfires are most active.

Other applications like our Open Data Program provide critical and actionable information to assist response efforts. Associated imagery and crowdsourcing layers can provide information to the front lines at high speed. Using machine learning and satellite imagery, the government has been able to help forecast potential damage and point on-the-ground response teams to areas that have been damaged by hurricanes.

Maxar's 20+ year imagery archive provides a digital history of our planet that allows change assessment over time. With our extensive archive and our ability to detect change over time, our data is regularly used to track droughts, glacial melt, and as with response efforts, the damage caused by wildfires, floods, hurricanes, and other natural disasters. For example, our imagery and automated algorithms were used to map new standing bodies of water after the Hunga Tonga Hunga Ha'apai volcano eruption and subsequent tsunami.

Maxar's WeatherDesk helps anticipate and mitigate the changing weather conditions by accessing global weather forecasts and observations that support better business, mission, and operations decision-making. Recently, Maxar developed an award-winning high performance computing solution using NOAA's weather forecasting model in the cloud and our WeatherDesk team collaborated with Amazon Web Services, Inc. to optimize this solution and deliver a detailed global weather forecast 58 percent faster, reducing a 100-minute process to roughly 42 minutes.

Agriculture and Food Security

Agriculture is a multibillion-dollar industry that contributes a total of $1.053 trillion of national Gross Domestic Product and 11 percent of employment when derivative industries (*e.g.,* food services, textile production) are considered.[2] Earth observation technology plays a critical role in supporting the agriculture industry by supplying farmers with information about when to plant crops and their estimated yields. It also plays an important role in food security, providing an early warning when food supply may be at risk. For example, earlier this year, Maxar's WeatherDesk was used to predict a significant decline in Ukrainian crop harvest, which typically helps to feed parts of the world facing food scarcity, due to the war.

Critical Infrastructure

Earth observation technology supports critical infrastructure. Maxar's Precision3D Telco Suite enables 5G radio network providers to plan telecommunications networks by accurately mapping terrain to avoid signal disruptions. This is possible

[1] *https://www.noaa.gov/weather*

[2] *https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/ag-and-food-sectors-and-the-economy/*

due to Maxar's use of imagery data, artificial intelligence, and automation. Maxar also provides insight to analysts on critical energy infrastructure projects in the oil and gas sectors, helping to preserve finite resources. Our satellite images also provide critical data for mobility and logistics operations across the U.S.

National Security

Over the last two decades, Maxar has been a trusted partner to the U.S. government, providing commercial Earth observation capabilities in support of national security, including the response to the ongoing war in Ukraine—ensuring that policymakers have uninterrupted access to time sensitive, actionable satellite imagery. The transparency provided by satellites showed the world the buildup of Russian troops along the border of Ukraine, tracked the early days of the invasion, and have been used to document atrocities carried out by the Russian military.

Maxar is also helping the U.S. government to harness commercial capability in support of warfighters with its ability to transform 2D satellite imagery into 3D models and precision point clouds, a set of data points in space which create a 3D model. This allows us to provide more information to intelligence analysts, as well as highly accurate and sophisticated geolocation data to warfighters. As a result, Maxar's 3D data and capabilities are helping to usher in a new era of insight, simulation, and modeling.

Advancing U.S. Leadership in Space

Maintaining a robust domestic commercial space industrial base and ensuring the U.S. government is harnessing the full breadth of commercial capability—including advanced Earth observation capabilities—is fundamental to advancing American strategic interests in space. Commercial satellites increase America's overall resiliency in space, providing the U.S. government with greater capacity and capability for civil space and national security space missions.

The National Space Policy recognizes this strategic imperative, stating in part that "a robust, innovative, and competitive commercial space sector is the source of continued progress and sustained U.S. leadership in space."[3] Leaders in the intelligence community (IC) have called the commercial sector not "just a priority, [it's] a must," and, "part of [the IC's] infrastructure," and affirmed the importance of making sure the U.S. industrial base is and remains competitive.[4]

Fortunately, the partnership between domestic commercial providers and the U.S. government is only getting stronger. Recently, the U.S. government increased its acquisition of commercial imagery across several U.S. industry providers to meet the growing demand for imagery and data across the U.S government. The commercial sector has also made big investments of its own and is working to harness its new and developing capabilities for the benefit of U.S. government customers. Programs like NOAA's GeoXO satellite system and NASA's TEMPO satellite instrument stand to benefit from these leading-edge technologies, including the use of artificial intelligence and machine learning, which reveal useful patterns in massive amounts of data–helping customers reduce resources while increasing scale and speed.

At Maxar, we're looking forward to the enhanced capacity coming online soon from our next-generation WorldView Legion satellites, which will more than triple Maxar's capability to collect 30 cm-class resolution imagery and enable up to 15 revisits per day—providing unrivaled commercial capability, including even greater persistent monitoring of priority areas of interest, accelerated change detection, and timely analysis at scale.

These are just some examples of how the U.S. industrial space base is helping to provide America with a technological edge in space.

Overcoming Challenges to Sustained U.S. Leadership in Space

Today, there are more than 4,500 active satellites and millions of other space objects orbiting Earth.[5] Despite the growth of commercial capabilities, commercial Earth observation providers face a space environment that is increasingly complex, making the challenge of preserving the space environment through responsible space traffic and debris management all the more urgent. Human-made objects traveling in Earth's orbit—including the debris caused by recent Chinese and Russian anti-satellite tests—pose a serious risk to satellites, spacecraft, and the people on board.

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[3] *https://www.space.commerce.gov/policy/national-space-policy/*

[4] *https://www.nro.gov/Portals/65/documents/news/speeches/2021/7Oct21_GEOINT_Symposium.pdf*

[5] *https://sia.org/commercial-satellite-industry-growing-as-it-continues-to-dominate-expanding-global-space-business-sia-releases-25th-annual-state-of-the-satellite-industry-report/*

In 2016, Maxar's own WorldView-2 satellite was hit by a small piece of untracked debris. Fortunately, this had no impact on WorldView-2's ability to operate, but it provides a stark example of the dangers posed by space junk zipping around the world at 17,000 miles per hour: any collision could impact our ability to access the technological advancements we take for granted today, including GPS, weather monitoring and prediction, satellite imaging, satellite communications, and more. All these technologies rely on safe access to low Earth orbit.

Maxar has long been a proponent of limiting space debris and harnessing commercial technologies, such as propulsion, to support responsible space traffic management. To do our part, Maxar joined a group of global commercial space companies in signing on to the World Economic Forum's Space Industry Debris Statement, which encourages companies to "work together to inform and help governments create a practical set of regulations for the sustainable use of space."[6] We are also testing a new commercial solution from LeoLabs to help monitor and track space debris.

However, the U.S. government is best positioned to set an example for the rest of the world to follow. Just as it did thirty years ago when Congress passed the Land Remote Sensing Policy Act to establish rules of the road for the then-nascent commercial satellite-based Earth observation industry, America can help build a global framework for responsible operations in space. The Administration has been an important leader in this work, bringing key government and industry leaders together to understand how we can collaborate to create enforceable policies. And, I want to recognize and thank Subcommittee Chairman Hickenlooper (D–CO), Ranking Member Lummis (R–WY), and full Committee Chair Cantwell (D–WA) and Ranking Member Wicker (R–MS), and the rest of the Subcommittee and full Committee for their leadership on the importance of protecting and maintaining a sustainable space environment through the introduction of the Orbital Sustainability (ORBITS) Act. We support the ORBITS Act and we look forward to continuing to work with the Committee and Congress to develop solutions that will make space sustainable and maintain American leadership. There's still much work to do, but U.S. leadership is critical in bringing the rest of the world along.

Conclusion

Despite these challenges—as the Landsat program demonstrates—America can achieve great feats in space when we work together toward a common goal. The Landsat program has provided observations for 50 years, changing how we see and understand our planet. Thanks to the ingenuity of the commercial sector, and our strong partnership with the U.S. government, I am excited and optimistic for what the next 50 years will bring.

But that future will not be realized unless stakeholders across government, industry, and the research community work together to preserve the space environment by developing clear rules that govern space debris and space traffic management.

Maxar stands ready to do its part to help build a sustainable space environment and usher in the next 50 years of Earth observation advancements. Thank you to the Subcommittee for holding this hearing and the opportunity to speak on this important topic. I'm happy to answer any questions you may have at this time.

Senator HICKENLOOPER. Thank you, Mr. Jablonsky. And with the proviso that for part of my professional life I wanted to be on the U.S.—in the U.S. Geological Survey, Mr. Gallagher.

STATEMENT OF KEVIN GALLAGHER, ASSOCIATE DIRECTOR FOR CORE SCIENCE SYSTEMS, U.S. GEOLOGICAL SURVEY, DEPARTMENT OF THE INTERIOR

Mr. GALLAGHER. And we would certainly welcome you.

[Laughter.]

Mr. GALLAGHER. Chairman Hickenlooper, Ranking Member Lummis, members of the Subcommittee and Committee, I am pleased to testify before you today during such a dynamic and innovative time in Earth observation science.

On behalf of the U.S. Geological Survey, I would like to recognize and express our appreciation for the support we have received from Congress over many years for our role in Earth observation and

[6] *https://www3.weforum.org/docs/WEF_Space_Industry_Debris_Statement_2021.pdf*

mapping, and in particular, Senate Resolution 721, celebrating the 50th anniversary of Landsat and its unique contributions to the Nation. Thank you

The Department of the Interior and the USGS have a long history of providing observations of the Earth, including its topography, biology, geological and water resources, and natural hazards such as earthquakes, volcanoes, wildfires, and coastal change.

The USGS has been involved in the Landsat program since the late 1960s, when the Department of the Interior charted a bold vision for the use of space technology to sustainably manage the Earth's natural resources.

The unique data from Landsat enables scientists and analysts around the globe to detect, measure, map, and monitor critical changes on Earth. Local, tribal, State, and Federal agencies all rely upon Landsat data and products to help them understand ongoing changes to their lands, surface waters, coastlines, ecosystems, and natural resources.

In fact, Landsat is the most widely used land remote sensing data within Federal agencies, and it is the most frequently cited land dataset in peer reviewed science literature. Landsat data provide enormous economic benefits in the U.S. and around the world, far surpassing the Government's investment in the Landsat satellites.

In the U.S. alone, Landsat is estimated to provide over $2 billion in annual economic benefits and has been a vital component of the training curriculum for generations of American scientists. Two unique attributes make Landsat the gold standard for all civil and commercial land imaging, the accuracy and precision of the data, and the long and unbroken record of the data.

Landsat data is incredibly versatile, supporting applications across the Nation for agriculture monitoring and forecasting, water resource management, forest health and productivity, and wildfire mapping and remediation. In fact, the Office of Science and Technology Policy led Earth observation assessments done in 2012 and 2016.

Ranked Landsat's impact across societal benefit areas as second only to the global positioning system. Much like GPS, weather data—and weather data, Landsat data is a public utility used daily to help us better understand and sustainably manage our dynamic planet.

In recognition of the significant cross-Government impact of Landsat, the DOI and NASA established the Joint Sustainable Land Imaging Program in 2016 to provide a long term commitment to historically compatible Landsat observations. This has been, by all accounts, a highly successful partnership.

Within the SLI Program, NASA is responsible for satellite development and launch, and the USGS provides ground system development and flight data operations, which are conducted at the USGS Earth Resources Observation and Science Center in Sioux Falls, South Dakota. In September 2021, NASA launched Landsat–9, the first mission in the SLI partnership.

Landsat–9 has been amazingly successful, working in tandem with Landsat–8 to deliver highly calibrated multispectral imagery

greater than the landmass of North America and South America combined, every day.

The follow on SLI mission called Landsat Next will be far more capable than Landsat–9, meeting users' evolving needs for improved spectral, spatial, and temporal resolution critical to identifying and characterizing land surface in areas like urban areas, agricultural, coastal, the cryosphere, and lands increasingly impacted by drought and wildfire.

Landsat has experienced a remarkable surge in popularity and continued relevance. In 2022, the USGS fulfilled more Landsat data access requests, at last count more than 4 billion, than in the entire previous 49 year history of the program.

That demand for Landsat data is linked to its global utility, free and open access in the cloud, and most importantly, the program's unrelenting commitment to maintaining the accuracy and precision of the data.

The SLI Landsat Next mission will ensure that future generations will continue to reap the benefits of the Landsat series of measurements. I am excited about the future of Landsat and appreciate the opportunity to speak with you today.

[The prepared statement of Mr. Gallagher follows:]

PREPARED STATEMENT OF KEVIN GALLAGHER, ASSOCIATE DIRECTOR FOR CORE SCIENCE SYSTEMS, U.S. GEOLOGICAL SURVEY, DEPARTMENT OF THE INTERIOR

Chairman Hickenlooper, Ranking Member Lummis, Members of the Subcommittee and Committee, I am pleased to testify before you today during such a dynamic and innovative time in Earth observation science. The Department of the Interior (DOI) and the U.S. Geological Survey (USGS) have a long history of providing observations of the Earth, including its topography; biological, geological and water resources; and natural hazards such as earthquakes, volcanoes, wildfires, and coastal change. True to its mission, the USGS is providing science for a changing world.

History of Landsat

The USGS has been involved in the Landsat program since the late 1960s, when the DOI charted a bold vision for the use of space technology to sustainably manage the Earth's natural resources.

The first Landsat satellite was launched on July 23, 1972. It has been succeeded by a series of Landsat satellites that, over 50 years, have drawn a comprehensive portrait of our planet from 400 miles in space. The unique data from Landsat enable scientists and analysts around the globe to detect and monitor critical changes on Earth. Local, Tribal, state, and Federal agencies all rely upon Landsat data to understand ongoing changes to their lands, surface waters, coastlines, ecosystems, and natural resources. Landsat is the most widely used land remote sensing data source within Federal agencies to carry out their missions every day.

Landsat data provides enormous economic benefits in the U.S. and around the world, surpassing the investments in the Landsat technology. In the U.S. alone, Landsat is estimated to provide over $2 billion in annual economic benefits. When including benefits to other nations, Landsat's total annual economic benefits is estimated to be nearly $3.5 billion. Two unique attributes make Landsat the "gold standard" for all civil and commercial land imaging: 1) the accuracy and precision of the data, and 2) the long and unbroken record of this data.

The U.S. Group on Earth Observation-led Earth Observation Assessments have ranked Landsat's space system impact as second only to the Global Positioning System (GPS). Much like GPS and weather data, Landsat data is used daily to help us better understand and sustainably manage our dynamic planet—and to improve our ability to combat climate change. In 2019, the U.S. Global Change Research Program identified Landsat as a "critical observatory for climate and environmental change research due to the unbroken length of the Landsat record and its ability to monitor remote regions with surface features such as glaciers, rainforests, permafrost, and coral reefs."

In recognition of the significant cross-government impact of Landsat, the DOI and the National Aeronautics and Space Administration (NASA) established the joint Sustainable Land Imaging (SLI) program in 2016 to provide continued, historically compatible, and operational land-surface observations for public science and services. The 2014 and 2019 National Plans for Civil Earth Observations both endorsed the SLI Program. In September 2021, NASA launched Landsat 9, the first mission in the SLI partnership. The next SLI Mission, known as Landsat Next, is in its planning phase and is intended to replace Landsat 8, which has been in orbit since 2013. The USGS has rigorously documented requirements for the next mission to meet users' ever-increasing need to monitor, understand, and predict complex changes to our Nation's land and water surfaces. Landsat Next will also ensure that projected climate-change impacts on our landscapes can be rigorously measured, assessed, and sustainably managed.

Applications of Landsat Data

Landsat is incredibly versatile for a wide range of applications. In addition to the widely recognized benefits for the Federal government and the commercial sector, Landsat is also used internationally. International space agencies use Landsat data and work with the USGS and NASA to align with our systems' data and products to be more interoperable for all users. International non-governmental organizations make use of Landsat data to provide local assistance for developing nations.

Landsat data is used for a wide variety of domestic applications. In Colorado, for example, Landsat has important applications for agriculture, water, forests, and development of natural resources. In Wyoming, Landsat's thermal infrared sensor collects data on Yellowstone National Park's thermal areas, including those previously unknown. As seen with the recent hurricane in Florida, Landsat supports research and response efforts on hurricane and storm surge impacts including assessing tree loss and vegetation damage, structure damage, flooding, water quality, storm surge debris, coastline shift, and long-term vegetation recovery in urban and natural ecosystems. (See Appendix A for graphics/images of these applications.)

Partnership with the Commercial Sector

The commercial sector is a vital part of the Landsat program. Under government contracts and Federal supervision, commercial firms build the satellites; build and launch the rockets that carry them into space; construct the ground systems that collect, archive, process, and distribute these data to users; perform the flight operations of the satellites in space; and host the data in the commercial cloud for users to gain better access.

Recently, there has been an exciting rise of commercially developed and commercially operated satellites. Today, the commercial industry has successfully built and deployed constellations of small, low-cost, low-orbiting satellites that provide high-resolution, high-revisit optical imagery. This data is useful for a wide variety of applications, some of which are available to Federal agencies through existing commercial data contracts. This data can augment and complement the coarser-resolution, broader area coverage baseline measurements made by Landsat and other government-sponsored observatories.

However, commercially owned global satellite systems currently lack the complicated and expensive calibration capabilities to provide the long-term science-quality imagery required to fully meet government objectives. In 2020, the NASA/USGS SLI Architecture Study Team (AST) provided recommendations for an SLI architecture beyond Landsat 9. The AST found that Landsat's moderate-resolution shortwave infrared and thermal infrared imagery—crucial for meeting Landsat global survey applications—are not projected to be commercially viable in the next ten years, requiring a government-led solution to ensure data continuity. The AST also found that commercial data in the visible and near-infrared spectrum could augment Landsat data to satisfy additional user needs. Through multiple AST listening sessions, the commercial sector clearly conveyed its desire for the government to maintain its gold standard systems like Landsat for use in their commercial imagery calibration and new product development.

The AST's findings related to the value of Landsat's unique radiometric and geometric calibration standard to the commercial sector were echoed by the Landsat Advisory Group (LAG), a subcommittee of the Federal Geographic Data Committee National Geospatial Advisory Committee, which provides advice to the Federal government on the Landsat Program and includes representatives of commercial Earth observation companies like Maxar and Planet. Multiple white papers published by the LAG in recent years have articulated the value of Landsat to the commercial sector, particularly as a trusted reference source to help calibrate their own sensors.

The Role of Federal agencies

The U.S. government has a vital role to play in prioritizing and applying science-quality Earth observations to support local, Tribal, state, and national decisions on sustainable land, water, and resource usage; especially in the face of extreme weather events and accelerating climate-change impacts. This role includes making this data freely and openly available in the public domain to serve as authoritative datasets for science conducted at the global, regional, and local levels. Landsat offers consistent, global, full-spectrum coverage, with observations calibrated consistently over many decades. Landsat notably includes spectral bands that may not be profitable in the commercial sector but that meet governmental and societal needs for global applications like monitoring consumptive water use, climate change, agriculture, and deforestation.

Another essential role for Federal agencies is to continue to support development of standards and specifications that support the interoperability of Earth observations. The DOI and the USGS work closely with national and international organizations to improve the interoperability among governmental and commercial Earth observation data sources. This improved interoperability will benefit all users and commercial providers by improving the ability to access multiple datasets to meet their science and operational needs.

Landsat participates and is well represented in numerous international forums including the Group on Earth Observations (GEO), the Committee on Earth Observation Satellites (CEOS), the International Charter: Space and Major Disasters, and has numerous bilateral partnerships around the world. In fact, Landsat has led the world through the development of its Analysis-Ready Data products being distributed in the commercial cloud. Landsat's Collection 2 data—a complete reprocessing of the entire data archive—was the very first to be certified as CEOS-Analysis Ready Data compliant. Analysis-Ready Data is the key to future interoperability of all Earth observation satellite data sets, greatly increasing their value for all applications.

Opportunities for Collaboration between the Federal Government and the Commercial Sector

The USGS is excited about emerging commercial data sources. Current commercial imagers cannot provide global, full-spectrum coverage with the science quality necessary to meet the needs of government users. As stated earlier, some commercial firms rely on the calibrated Landsat data as a trusted reference source to evaluate and improve their own systems' performance. There are ways for the government to work with the commercial Earth observation industry to benefit both sectors. Federal agencies continue to perform extensive evaluations of federal, state, local, and Tribal user needs, as well as the needs of international users and the public. These studies consistently identify an increasing potential for commercial data to provide imagery at higher resolutions and greater frequency than Landsat to address urgent and short-term environmental events such fires, floods, and other disasters. In addition, the USGS, NASA, NOAA, and other agencies work together with commercial data providers in an activity called the Joint Agency Commercial Imagery Evaluation (JACIE), which provides an independent characterization of commercial imagery and products and shares those results across the remote sensing community. This helps facilitate the use of commercial products while helping providers better understand how their products are used across the Federal government.

The technologies for imagery collection, transmission, storage, processing, and dissemination continue to improve. In the future, the Federal government will need to determine the optimal roles for commercial and government capabilities in these areas, taking into consideration the growing capabilities, potential lower costs, licensing approaches of commercial systems, and the broad range of requirements across the user community, to include data accessibility and redistribution. In addition to satellite systems, there is a growing potential for the commercial sector to provide ground stations and mission operations as services, potentially reducing or eliminating the need and associated costs for government-owned satellite operations centers and ground-station infrastructure. The Federal government will also need to determine how commercial advancements best support data processing, long-term management, and distribution, with the Federal government continuing to certify data authenticity and maintain the official, long-term public data archive.

The Future

Federal agencies continue to develop science-quality Earth-observing systems to provide the foundational data of a multi-source "data ecosystem" of U.S. government, U.S. commercial, and international sources. Commercial Earth observation

systems will increasingly be licensed to provide new and improved data for all. Through these combined efforts, the U.S. continues to strengthen our global leadership position in the development, launch, and operations of Earth observation systems. Further, our ongoing efforts to develop standards and infrastructure support the goal of interoperability and widespread access to optimize the exploitation of all Earth observation data.

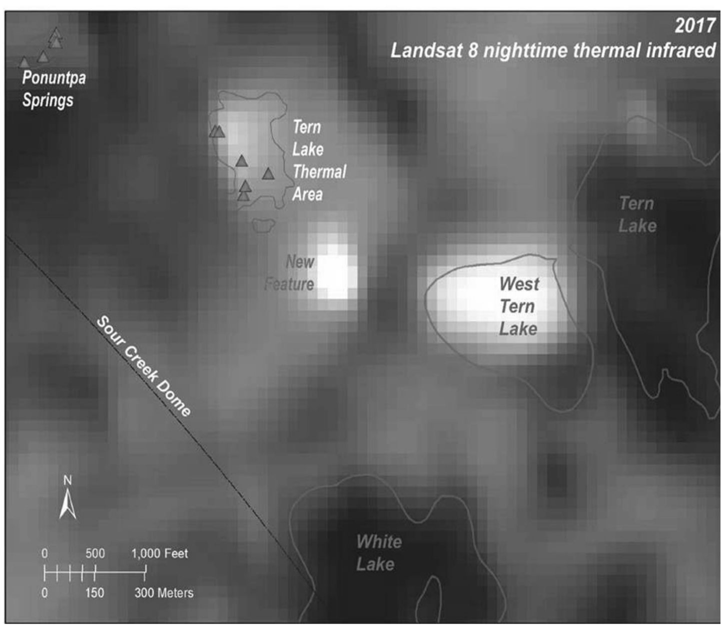
Landsat will remain the indispensable “tool in the toolbox” for decision support to government authorities and private sector decision-makers. Its precision will calibrate other government, commercial, and international observations. Its spectral and spatial characteristics will complement the data generated by others and support new information products and support services.

Landsat provides a domestic baseline capability that complements, rather than competes with, other international systems. While other systems may offer individual improvements in terms of spatial resolution, temporal revisit, or spectral performance, Landsat, with its five-decade record of robust collection, calibration and archiving, and its longstanding service as a global reference to cross-calibrate other missions, improves not only the quality of those systems but the overall quality of the global “system of systems”.

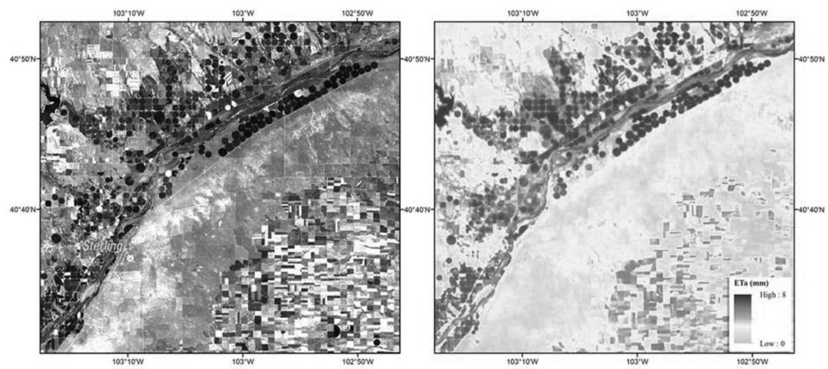
Conclusion

Landsat has experienced a remarkable surge in popularity and continued relevance. In 2022, the USGS has fulfilled more requests for Landsat data—at last count, more than 4 billion requests—than in the entire previous 49-year history of the program. That demand for Landsat data is linked to its global utility, free and open access in the cloud, and most importantly, the program’s unrelenting commitment to maintaining the accuracy and precision of these data into the future. It is that commitment to data quality that will perpetuate Landsat’s reputation as the gold standard for all civil and commercial land imaging in the foreseeable future. I am excited about the future of Landsat and appreciate the opportunity to speak with you all today. Thank you.

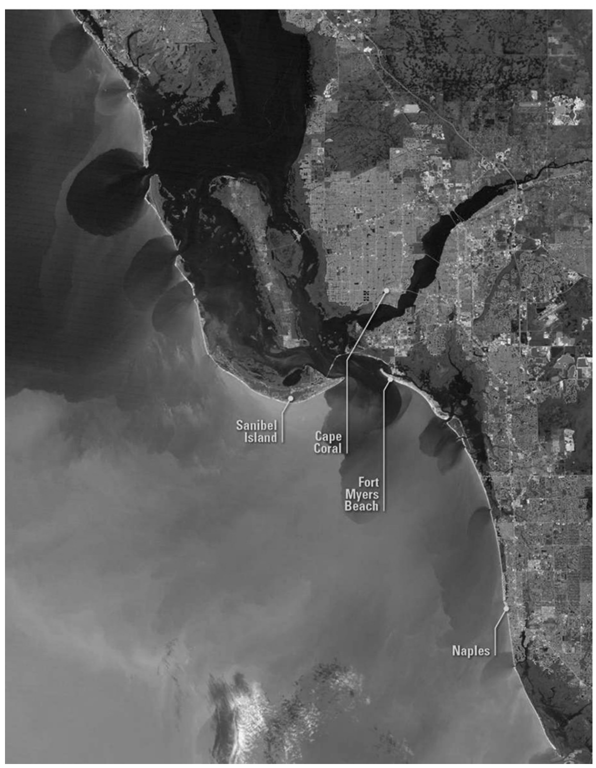
[APPENDIX A: EXAMPLE IMAGES OF LANDSAT SCENES]



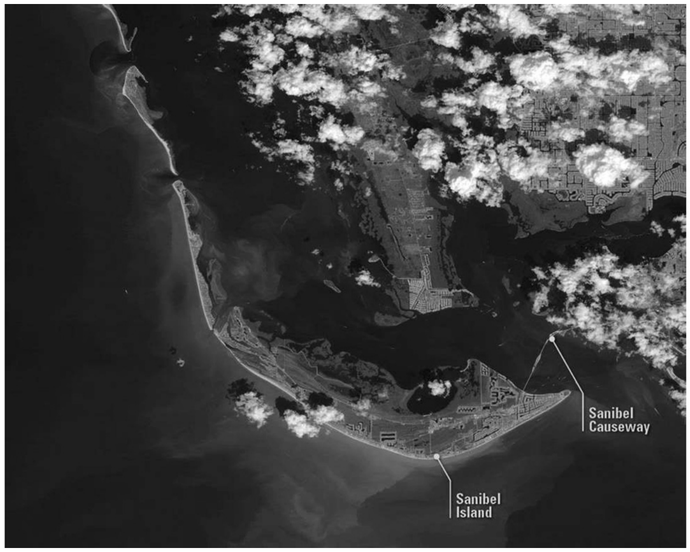
WYOMING: This Landsat 8 image from the night of April 20, 2017, shows a newly emerged thermal area, labeled New Feature (white pixels indicate warmth), between the Tern Lake Thermal Area and West Tern Lake in Yellowstone National Park in Wyoming. Red triangles indicate individual mapped thermal features, such as geysers or springs. Image credit: U.S. Geological Survey.



COLORADO: These images, using data acquired by Landsat 8 on the morning of July 31, 2018, near Sterling in northeastern Colorado, show natural color surface reflectance of agricultural fields on the left and the actual evapotranspiration (ET) on the right. Evapotranspiration is the quantity of water removed from surfaces by evaporation and plant transpiration. The circles indicate center-pivot irrigation systems, and evapotranspiration measurements can help land and water managers make informed decisions about water use. Hay and corn are produced in the area, among other crops.



FLORIDA: Landsat 7 captured this image of the aftermath of Hurricane Ian in southwestern Florida, including floodwater and sediment in the ocean, on the morning of October 2, 2022. Sanibel Island is shown at the center with Fort Myers Beach and Cape Coral to the right. Naples is the gray urban area in the lower right.



FLORIDA: Landsat 9 captured this image of the aftermath of Hurricane Ian in southwestern Florida on the morning of October 6, 2022. Sanibel Island is shown in the center, with breaches in the Sanibel Causeway that connects the island with the mainland. (White clouds also appear in this image.)

FLORIDA: Landsat 9 captured this image of the aftermath of Hurricane Ian in eastern Florida on the morning of October 6, 2022. It shows the coast and New Smyrna Beach, which experienced extensive flooding.

GEORGIA: Landsat 9 captured this image of the aftermath of Hurricane Ian on the Georgia coast on the morning of October 6, 2022. It shows the area of Brunswick, Georgia (top left), and sediment spreading out from the shoreline.

Senator HICKENLOOPER. Right. Thank you. Dr. Abdalati.

STATEMENT OF WALEED ABDALATI, DIRECTOR, COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES; PROFESSOR, DEPARTMENT OF GEOGRAPHY, UNIVERSITY OF COLORADO, BOULDER

Dr. ABDALATI. Chair Hickenlooper, Ranking Member Lummis, and Chair Cantwell, Ranking Member Wicker, and other members of the Committee, thank you for the opportunity to testify today on the very important matter of the future of U.S. satellite-based Earth observations.

I greatly appreciate the work of this committee, and it is also a privilege to be here with representatives from civilian agencies and the private sector who develop and operate and analyze the data for the good of the American people and for the good of the world.

Observations from space serve us in many ways, from day to day planning, to national security, to public health, to resource management, to disaster management and recovery, feeding our people and understanding—and understanding the threats and challenges and opportunities associated with our changing climate.

Some of the benefits are directly derived from the observations themselves. You can just look and see, and but many are derived from their integration with models and complementary data. It is that ecosystem of information. That is critical and satellites are a fundamental component of that.

Ultimately, however, these observations play a key role in enabling and empowering us to understand what tomorrow will bring, and whether that tomorrow is literally tomorrow or the coming week, the next day or week, as the case is with weather forecast, or whether it is the next growing or dry season, as in the case of seasonal forecast, or years and decades down the road, as is the case with climate projections.

This knowledge and information equip our Nation and society as a whole for success in managing environmental challenges and capitalizing on environmental opportunities. We have made remarkable strides in Earth observation since the launch of the first TIROS satellite more than 60 years ago, when it transmitted its blurry images of Earth for two and a half months.

These observations have become integral to our lives, and there is still much to learn and tremendously important benefits to be realized. The work of the agencies represented here today has been indispensable in enabling us to understand our environment, how it is changing, and what those changes mean for life on earth.

They have done so by developing new observing technologies and capabilities, as well as pioneering and supporting the use of these capabilities for science and application purposes. And the work of the private—the work the private sector has brought forth has been innovative in developing ways of cost effectively carrying those observations forward, providing data and information that deliver great benefit to society.

This combined approach is important for continuing to develop new technological and scientific innovations, and for providing situational awareness needed to serve society, and innovative and cost effective ways.

And finally, the engineering and science communities that develop these capabilities and ensure their value is realized need to be recognized and sustained, as this committee certainly has and does.

Some of that community exists at universities like my own, some at Federal and federally supported facilities, and others in the private sector and elsewhere. But regardless of where these talents reside, most share the simple fact that they were initially cultivated at the Nation's colleges and universities.

So while investments in the development and use of these capabilities are absolutely critical, investments in the education and training of those who transform these visions and aspirations into society serving realities is crucial as well.

Environmental intelligence, as former NOAA Administrator Dr. Kathy Sullivan used to refer to it, positions our Nation and society for success in the face of whatever lies ahead. The space based observations ultimately deliver that intelligence and associated insights in ways that greatly serve the citizens of this country and the citizens of the world.

I thank you for your time and your attention on this very important matter, and I apologize for reading from a computer, but my written remarks are actually sitting in a taxi somewhere that brought me here, so——

[Laughter.]

Dr. ABDALATI. I am going to close this now and we can talk. But I wanted to get it right, so thank you.

[The prepared statement of Dr. Abdalati follows:]

PREPARED STATEMENT OF WALEED ABDALATI, DIRECTOR, COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES; PROFESSOR, DEPARTMENT OF GEOGRAPHY, UNIVERSITY OF COLORADO, BOULDER

SPACE-BASED EARTH OBSERVATIONS: FUNDAMENTAL TO PROSPERITY, SECURITY, AND RESILIENCE ON OUR CHANGING PLANET

Chairwoman Cantwell, Ranking Member Wicker, and members of the Senate Committee on Commerce, Science, and Transportation, thank you for the opportunity to testify on the very important matter of the future of U.S. satellite-based Earth observation. I greatly appreciate the work of this committee and its bipartisan efforts to examine the importance, state, and prospects for Earth observations from space. In addition, it is a privilege to be here with representatives from civilian agencies and the private sector who develop, operate, and analyze these capabilities for the good of the American people, and for the good of the world.

As we continue to live in a world in which our relationship with the environment is critical to our success and prosperity, the value of knowledge about our environment has never been more consequential. We live on a changing planet, and space-based observations of Earth not only provide us situational awareness that allows us to watch the story of that change unfold, but they provide us the information needed to understand the underlying causes, the evolution of their behaviors, and the implications for the future. They provide essential situational awareness and are a critical element of our national informational infrastructure that allow us to thrive in the face of environmental changes and challenges.

Satellite observations are a fundamental component of our everyday lives (Figure 1), often in ways that many people don't realize, strengthening our national security, supporting effective resource management, advancing global health, and supporting our national prosperity. These benefits directly result from the fact that satellite observations provide the context, scale, and perspective needed to understand our Earth environment in ways that can inform our actions to optimize our relationship with the planet on which we live, by understanding how it functions, adapting to and managing changes, and capitalizing on opportunities.

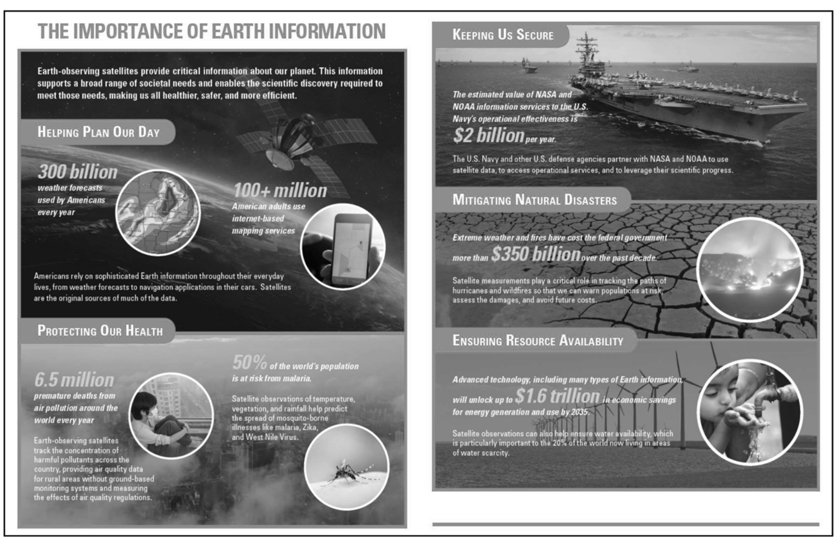


Figure 1: Many aspects of our individual and collective lives are positively impacted by data from space-based resources, often in ways that we do not recognize. SOURCES: Data available as follows: Helping Plan Our Day—Lazo et al., 2009; comScore, 2014. Protecting Our Health—WHO, 2016, 2017. Keeping Us Secure—Titley, 2016. Mitigating Natural Disasters—GAO Highlights, 2017. Ensuring Resource Availability—UN-Water, 2007; McKinsey Global Institute, 2017.

Figure from National Academy of Sciences Earth Science and Applications from Space 2017 (NAS, 2018).

These capabilities are applicable to many domains of societal interest that directly affect our economic and social well-being and our strength as a nation. Here I will speak to just a few.

Water Resources

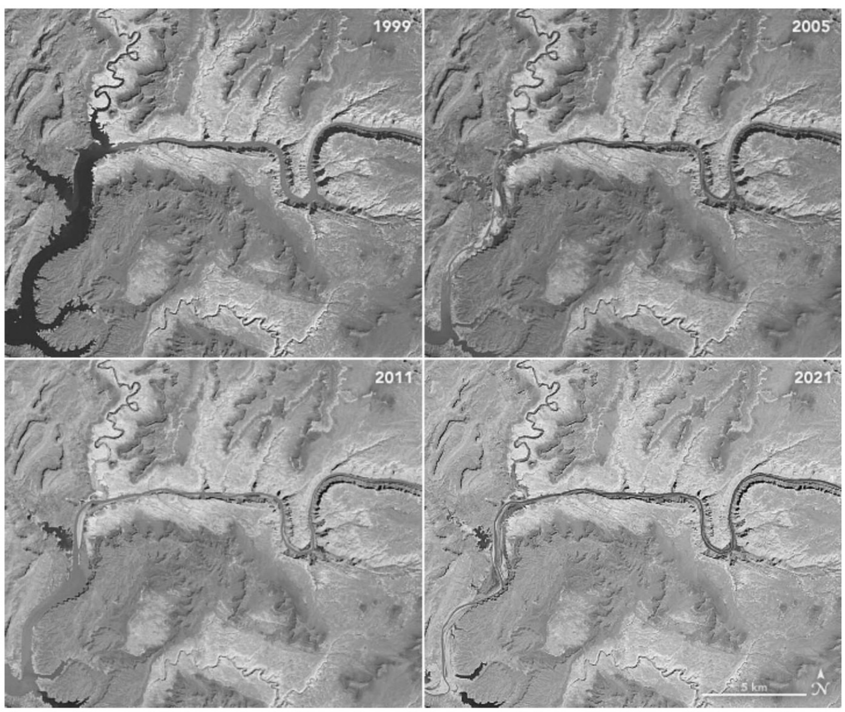
Water access and availability is perhaps the element that is most impactful to our societal well-being. With implications in the United States that go beyond simply access, into the domains of health, food production, recreation, and so much more. Globally, the access to water has further implications for migration and geopolitical stability (National Intelligence Council, 2021). Domestically, in recent decades, the western United States has been experiencing the worst drought in 1200 years (Williams *et al.,* 2022). Comprehensive observations of the elements that contribute to water transport and storage are required in order to (a) fully appreciate the nature of this drought, (b) understand the driving factors, (c) recognize the implications of the stresses on our water resources, and (d) manage these resources most effectively. Such observations are needed on a scale that is only available from space.

I recently had the opportunity to join Senators Michael Bennett and Mitt Romney on a short rafting trip down the Colorado River (Figure 2). The purpose of that bipartisan trip was to provide a shared first-hand and up-close look at the water stresses in the Colorado river basin. Also on the trip were a rancher, a water manager, a native tribal leader, and others whose lives and livelihoods are tied to the water. What was most striking about that trip was how low the water level was and how slowly the water flowed. Our tour guides talked about how it "used to be," with the relatively still water in the picture standing in stark contrast to what used to be whitewater rapids. While those anecdotes are accurate, to truly understand the situation requires a broader view. One in which Landsat, along with other observing capabilities, has played an important role. Figure 3 shows a time sequence of the Colorado River near Lake Powell (a highly-stressed and depleting reservoir). The sequence shows a reduction in water flowing through the river over time, part of a longer trend. Our ability to monitor the river width and flow, not just in this drought-stricken region, help us understand the scope and scale of the reduced water and put them into a broader context—the kind of context needed to manage water effectively. The importance of this ability is underscored by the fact that the Colorado River System alone provides essential water resources to seven western states: Colorado, Wyoming, Utah, New Mexico, Arizona, Nevada and California.

Figure 2. Senators Romney (left) and Bennet (right) rafting on the Colorado River on September 27, 2021. Photo: Spenser Heaps, Deseret News

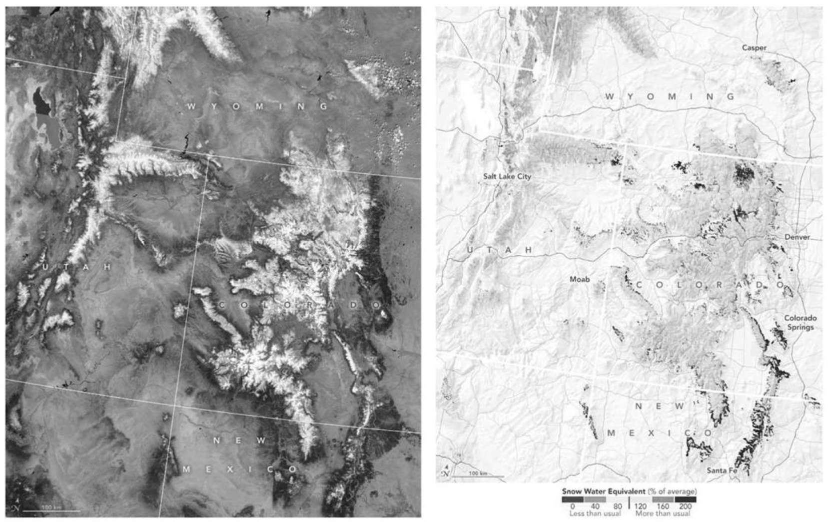
A key reason for the decreasing river flows is the fact that typical mountain snows that feed and recharge the rivers in the spring have been diminishing (Milly and Dunne, 2020). We know this too from satellite observations, combined with a sampling of ground-based measurements and hydrological models (informed by these observations) that make clear that the spatial extent of the snow cover and the associated water content are decreasing (Figure 4), and melt is occurring earlier and more rapidly (Musselman *et al.,* 2021). The result is lower river levels, reduced soil moisture (Figure 5), fewer water resources, and significant threats to agriculture, ranching, and tourism.

Moving further below the surface still, there is a space-based capability that allows us to go beyond the images of the surface (snow, timing of melt, river flow, and lake extent), and examine what subsurface storage. The Gravity Recovery and Climate Experiment (GRACE) satellite, and its successor (GRACE-Follow-on), have measured actual changes in sub-surface mass to provide an integrated assessment of overall water storage and how it is changing with time. It does so by measuring changes in the gravity field, which are directly tied to the mass that lies beneath the satellites, which fluctuates with water availability (Rodell *et al.,* 2016). As shown in Figure 6, there has been a drying trend in the Colorado River Basin



(https://earthobservatory.nasa.gov/images/148861/lake-powell-reaches-new-low)

Figure 3: Colorado River upstream of Lake Powell. The natural-color images above were acquired in March 1999, April 2005, May 2011, and April 2021 by the Landsat 5, 7, and 8 satellites. Springtime typically marks the lowest water levels before mountaintop snow starts to melt and run down into the watershed. The images capture years with the two highest and lowest levels over the past 22 years.
(https://earthobservatory.nasa.gov/images/148861/lake-powell-reaches-new-low)



https://earthobservatory.nasa.gov/images/149779/taking-stock-of-rocky-mountain-snowpack

Figure 4: Visible Infrared Imaging Radiometer Suite (VIIRS) Image of Rocky Mountain snow cover on April 7, 2022 (left) and map of snow water equivalent (water stored as snow) in the Rocky Mountains on April 1, 2022, as compared to the 2000–2020 average.

https://earthobservatory.nasa.gov/images/149779/taking-stock-of-rocky-mountain-snowpack

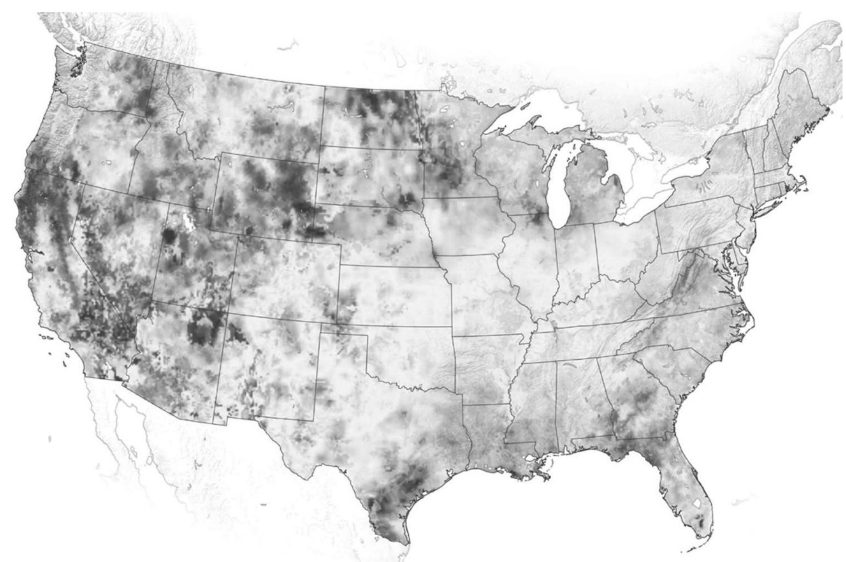


Figure 5: Soil moisture anomalies in the top meter of soil based in part on measurements NASA's Soil Moisture Active Passive (SMAP) satellite and vegetation indices from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on NASA's Terra and Aqua satellites.

https://scitechdaily.com/long-term-drought-grips-the-western-u-s-soils-and-plants-are-parched/

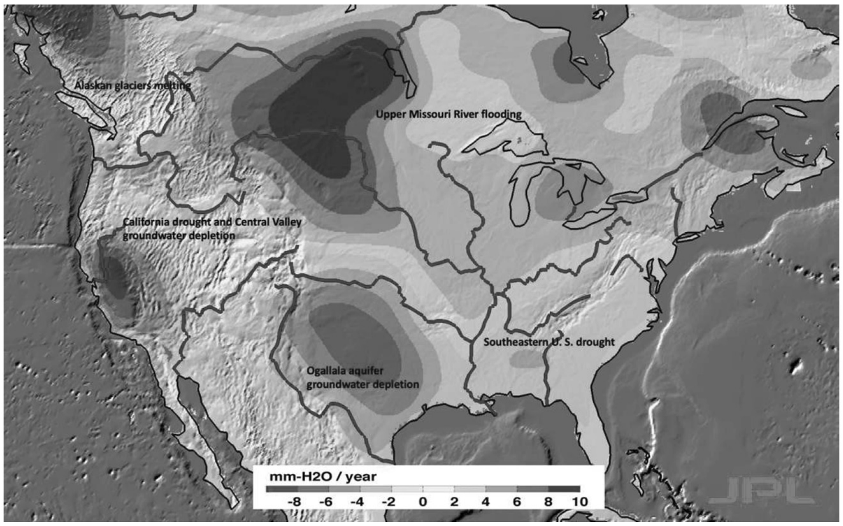


Figure 6: Changing Freshwater Availability from GRACE, 2002–2015, (Rodell et al., 2016)

In the immediate term, these observations and how they are used enable us to manage challenges associated with water access as our environment continues to change. In the longer term, their value is further amplified through their ability to inform practices related to farming, ranching, land use and more. As we observe and understand trends in our environment, we are better positioned to anticipate what the future holds in terms of water stresses and water availability. This advanced knowledge is critical to successfully positioning ourselves as a nation to manage the emerging challenges and capitalize on emerging opportunities.

Fires and other Hazards and Extreme Events

The costs associated with natural hazards and extreme events has been increasing significantly over the last 40 years (Figure 7). All of these types of events listed below are those that can be observed, predicted, understood, and most importantly, prepared for and managed with the aid of space-based observations.

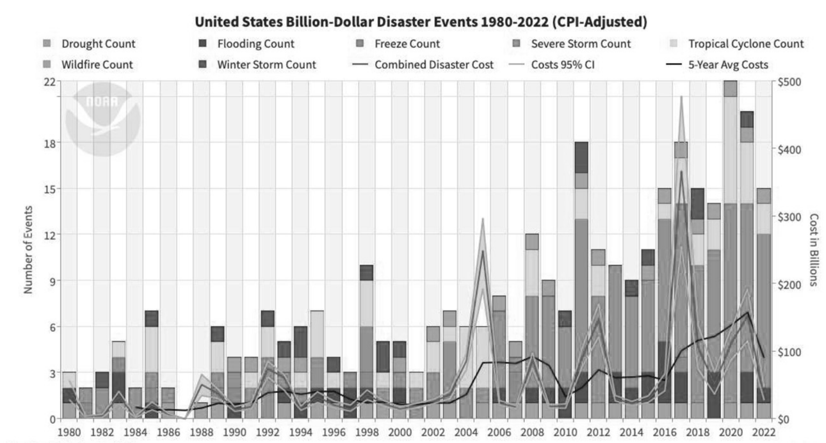


Figure 7: Number of billion-dollar disasters in the United States from 1980 to 2021. Each bar is colored to show the different types of billion-dollar disasters with the number of events (left vertical axis) and the associated costs (right vertical axis.). During the first nine months of 2022 there have been fifteen separate billion-dollar weather and climate disaster events. Figure is from NOAA National Centers for Environmental Information (NCEI) at https://www.ncei.noaa.gov/access/billions/time-series)

The parameters that drive or contribute to each of these disasters is derivable from space, and their prediction depends critically on space-based observations, integrated with ground-based measurements and modeling capabilities. Perhaps the most familiar example is the weather-related events, which are managed through weather forecasts that integrate satellite observations with sophisticated weather forecasting models.

Closely coupled to the above discussion on drought and water trends is the prevalence and impact of fires in the United States. This is a matter that literally hits close to home for me, as my town was devastated by the loss of 1100 homes in Colorado's Marshall Fire in December 2021. My family and I were forced to evacuate, and we returned the next day to neighborhoods that was destroyed and devastated.

As with water resources, satellite observations allow us to go beyond the local impacts to directly assess the presence and extent of fires, the nature of their burn scars, the time of recovery, and the trends in fires and their severity over the years. Moreover, topographic maps, as well as population and residential distribution maps, also supported by satellite images, complemented by weather and wind forecasting, help us understand the vulnerability of communities associated with fires. When coupled with drought information (such as the soil moisture and vegetation information described above), the susceptibility to fire can be assessed, both in real-time and in terms of longer-term vulnerability.

An analysis of the Monitoring Trends in Burn Severity data set (data set described in Eidenshink *et al.,* 2007), which integrates Landsat observations with Federal and state fire reports, have revealed a significant increase in wildfires, particularly in the western U.S. (Figures 8 and 9). When combined with population and development data, the human and economic vulnerability of these regions can be determined. With this increasing risk of fires and other natural hazards, understanding the vulnerability is critical to informing development and management strategies to limit the damage, and manage its threats to lives and property. The satellite observations are critical tools in doing so.

In the case of fires, an added capability, informed by space-based observations of fire location and intensity, to support health and disaster management is the modeling of smoke movement in the atmosphere. The High Resolution Rapid Refresh Smoke (HRRR smoke) model integrated satellite observations of atmospheric composition, and meteorological conditions, to predict, with great accuracy, the propagation of smoke during and after the Marshall Fire, enabling an understanding of where health-risks were high, as was done for the Camp Fire, California's most destructive fire in its history (Chow *et al.,* 2022). On a larger scale, it is possible to see not just smoke's migration and impact on air quality, but also the movement of pollution and its implications for visibility, temperature, air quality, and wind.

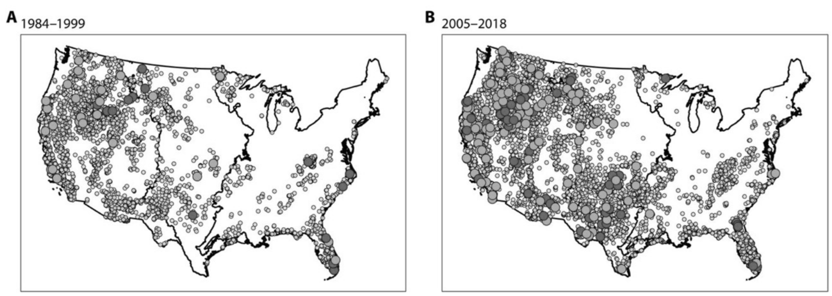


Figure 8: U.S. fires during the period 1984–1999 (Panel A) and 2005–2018 (Panel B). Small dots indicate nonextreme fires while extreme fires are represented with larger orange (area burned >99th percentile in 1984–1999) or red bubbles (area burned >99th percentile in 2005–2018)." The history of the aggregate fires and burned land, and their associated trends, are shown in Figure 9 below.

https://www.science.org/doi/10.1126/sciadv.abc0020

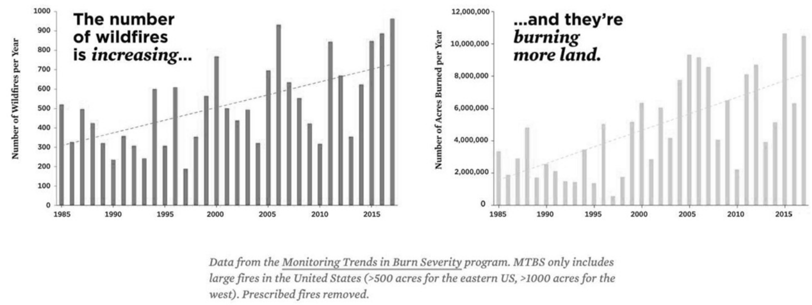


Figure 9: Number of wildfires in the U.S. (left) and area burned (right) from 1985 to 2015. The graphs are from *https://www.ucsusa.org/resources/infographic-wildfires-and-climate-change,* and the underlying data are from *https://www.mtbs.gov.*

While I have focused on drought and fires here, the same type of utility applies to other types of disasters. In the case of flooding, for example, the satellite observations (along with models) inform precipitation amounts, location of precipitation, storm trajectories, vulnerability to storm surges in coastal areas, river stage, landslide potential, and threats to people.

The fundamental role of satellites goes beyond understanding the level of risk and how it evolves over time (with Figure 8 providing a clear example of information to inform such an assessment). They also contribute to understanding the vulnerability to such risks in part through observations of infrastructure and population distribution, providing important information on how many people are in harm's way and what the potential impacts of such disasters may be. And finally, satellites play a key role in managing the aftermath of such disasters to inform recovery responses and priorities, by providing observations of the nature, location, and amount of damage, as well as the state of access routes to enable effective response. (Le Cozannet *et al.,* 2020).

Sea Level Rise

In a more global sense, but with direct ties to our Nation's shores, oceans have been rising since the late 1800s (Church and White, 2011). While the rise in seas prior to the satellite era was observed with tide gauges, it was difficult to accurately determine overall rate of global sea level rise and impossible to determine its regional character. It was not until the satellites provided global coverage that it was possible to observe such information. Since the first routine observations, beginning with the Topex mission in 1993, the data have shown the global trends in sea level rise of 3.3 mm/yr (which is higher than that of the previous century), as well as an increase in the rate of sea level rise over the nearly 30-year record (Figure 10).

More important than the global sea level rise, however is its spatial distribution, as some areas are rising more rapidly than the global mean, and some are rising more slowly, even lowering in some places (Figure 11). The nature of this distribution has to do with where heat is stored in the oceans, the sources of sea level rise, and the movement of the land in relation to forces acting on it—mainly isostatic adjustment in response to land ice changes. Satellite observations allow us to monitor the surface temperature and water movement, which combined with models allows us to understand the heat distribution and transport throughout the world's oceans. They also provide information on the behavior of the Earth's glaciers and ice sheets, the shrinking of which has been adding water to high-latitude regions of the Earth, while at the same time resulting in an upward movement of high-latitude land masses, and a lowering of land masses at low latitudes, as the solid earth responds to the lightening of the load near its polar regions.

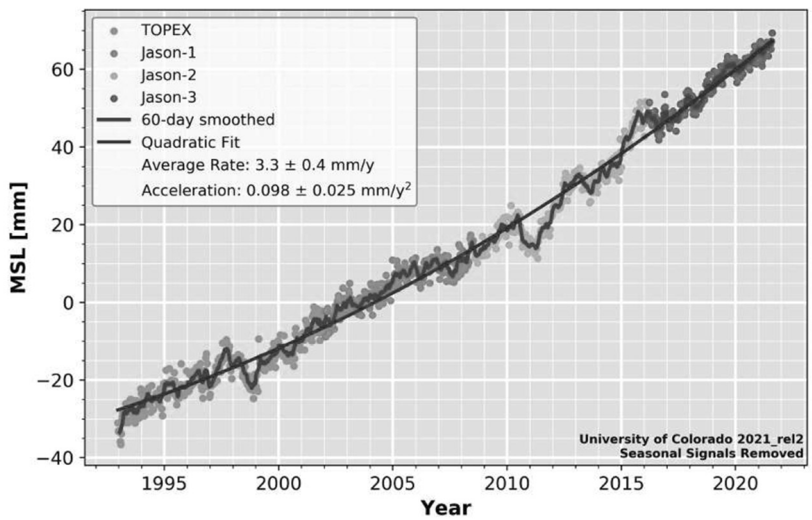


Figure 10: Global mean sea level rise from 1993–2022 derived from a sequence of satellite altimeters.
(https://sealevel.colorado.edu)

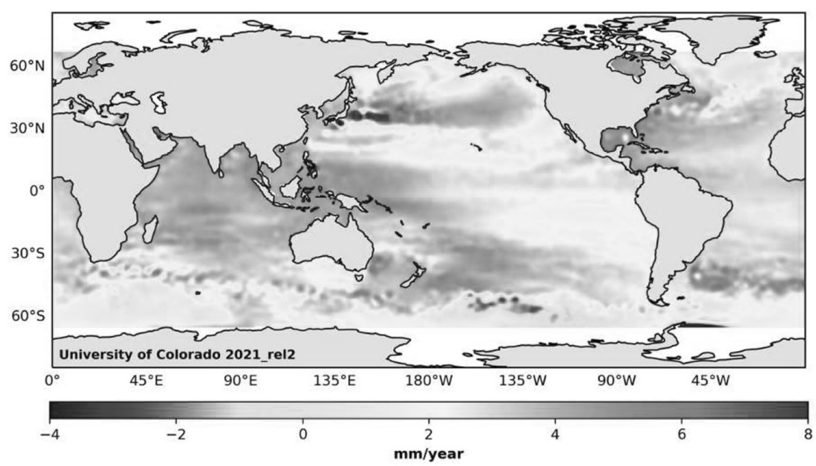


Figure 11: Regional trends in sea level rise for the 1993–2021 period.
(https://sealevel.colorado.edu)

All of these factors, observable and quantifiable from space, provide a picture of the rate of sea level rise, its causes, its regional distribution, and coastal vulnerability to storm surges. These storm-surge events are also observable from space, predicted by operational satellites, and the damage assessed by commercial and other satellite observations.

Quantifying sea level rise, understanding its spatial variability, assessing vulnerability, predicting coastal flooding, assessing the damage, and informing recovery are critical to our national interests, particularly considering that the effects of sea level rise on the order of 1 meter by 2100 is conservatively predicted to result in costs of hundreds of billions of dollars to the U.S. alone (Neuman *et al.,* 2015). Our understanding of vulnerability in this area and the likely implications is all made possible by satellite observations, not just of sea level rise itself, but of the factors that contribute to it, and the factors that ultimately result in the water from these rising seas invading our shorelines.

Sea ice

While much of what I have addressed to this point is tied to phenomena that we see or feel directly in our country and on its shores, there is another area, seemingly far removed from our everyday lives, in which satellites have been absolutely critical in observing change that has direct environmental, economic, and strategic impact. That is the disappearance of Arctic sea ice. The layer of ice that blankets the Arctic ocean is a driver in the weather and climate of this nation, and has direct ties to economic and strategic interests. Since 1978, we have been able to track the extent and concentration of sea ice cover (Figure 12), using both civilian satellites and non-classified data from defense satellites, and since 2003, we have also been able to track its thickness (Figure 13). Both the extent and thickness are changing in ways that will have a profound impact on how we live and function.

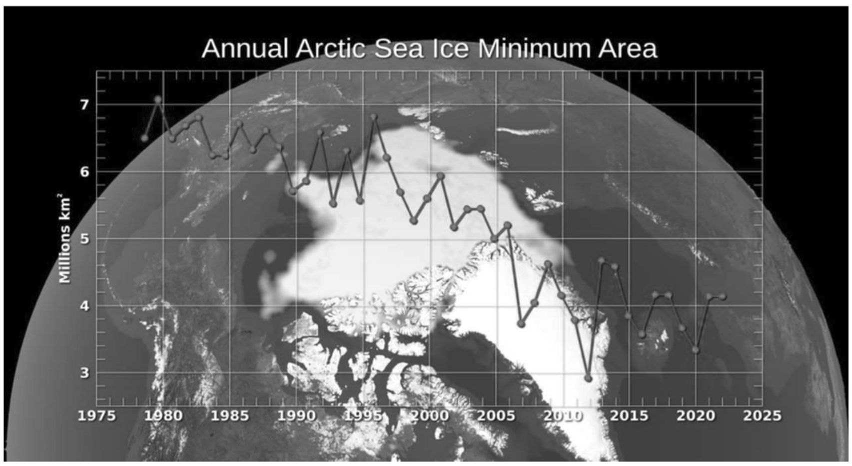


Figure 12: Annual extent of Arctic sea ice, at its minimum extent each year (late September) for the period 1978–2022. Minimum extent is indicative of the overall state, since it includes the ice that survives the summer melt season
https://svs.gsfc.nasa.gov/5036

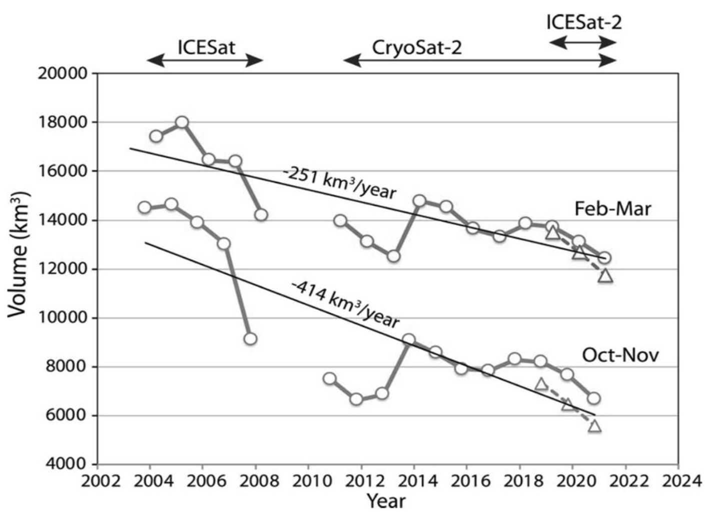


Figure 13: Arctic sea ice volume calculated from ICESat, CryoSat-2 and ICESat-2 ice thickness fields, for February–March (in red) and October–November (in blue). The Linear trends are calculated using estimates from longer time series of ICESat and CryoSat-2. (Kacimi and Kwok, 2022)

From a weather and climate perspective, modern civilization has never known an ice-free Arctic in the summertime, yet we are likely headed to such a state in the coming decades (Liu *et al.,* 2022). The implications range from a disruption in the Earth's radiation balance, as the darker ice-free water absorbs more sunlight than is the case in its ice-covered state, to changes in ocean circulation and associated weather and climate phenomena, as the melting ice freshens the Arctic waters. The impacts for North America of these changes could be felt on time scales of days (weather), to months (seasonal climate), to years and decades. Successfully managing these changes requires information on where and how they are occurring, as well as information on the associated changes in the atmosphere and ocean—all of which are supported by space-based observations.

From an economic standpoint, an ice-free Arctic can offer tremendous commercial and trade opportunities, as the Arctic ocean becomes seasonally navigable, greatly reducing the transport costs between North America and Asia. Understanding the navigability, and planning out the most cost-effective routes, however, requires situational awareness, which requires observations that only satellites can provide. One of the challenges in observing the Arctic is that it is frequently cloud-covered. Many of our Arctic-observing satellites operate in the microwave portion of the electromagnetic spectrum, which allows them to see through clouds, enabling the tracking of sea ice, and assessment of its thickness, and navigability. As the shrinking trend of Arctic sea ice continues, an understanding of that trend can inform investments into Arctic navigation capabilities that could ultimately have tremendous economic payoff.

From a strategic sense, an ice-free Arctic and increased economic activity, creates an exposed marine border and vulnerable operations in the Arctic that will require the kind of security considerations and management that has not been necessary in the past. Such management will require situational awareness on scales that are best achieved through satellite coverage.

It is important to recognize that the behavior of sea ice, as is the case with sea level rise, occurs on scales that require observations that span hundreds, even thousands, of kilometers. Such observations are far beyond the capability of any seafaring vessel. The satellites provide the scale of observation, and the context and perspective of change against a broader Earth system backdrop, to truly understand the nature, causes, and implications of such changes. It is also worth noting, with regard to the monitoring of Arctic sea ice and the shrinking high-latitude ice, the orbits of polar-orbiting or near-polar-orbiting satellites converge in the polar regions, offering far more frequent coverage then they do at lower latitudes, thus from a sampling perspective, polar regions are well-suited to satellite monitoring.

National Security

Finally, another extremely important dimension of U.S. interests, in which satellite observations are essential is in the national security space. Understanding threats to military infrastructure requires knowledge of the kind described above. As one example, the Norfolk Naval Station is the largest in the world, and because of its situation in coastal Virginia, the risks associated with sea level rise are of great importance. The assets that observe sea level rise and inform predictions, as well as observations that enable weather forecasting and climate projections have direct implications for this base and its operations. Other facilities are similarly subject to a range of environmental exposure for which knowledge of risks is essential for effective operations. Another domain in which satellite observations are very important is with respect to the theater of operations in conflicts involving U.S. forces. Knowledge in this domain requires intelligence on conditions on the ground and in the air, and how they will evolve throughout the operations period. In addition, the risks of conflict, which are driven by such matters as drought, resources, food access, etc., are informed by the access and information provided by satellite observations. Understanding population migration, strategic actions of parties of interest, all benefit from space-based observations. Many of these are acquired in the domain of the intelligence community and Department of Defense, but there are capabilities, such as weather forecasts, that are enabled by observations in the civil space domain that either fill gaps in or complement those in the classified domain.

This year the Office of the Director of National Intelligence (ODNI) released *The Annual Threat Assessment of the U.S. Intelligence Committee* (ODNI, 2022) in which it categorizes threats to National Security interests into eight topic areas:

- China,
- Russia,
- Iran,
- North Korea,

- Health Security,
- Climate Change and Environmental Degradation,
- Additional Transnational Issues, and
- Conflicts and Instability.

While the management of each of these threats benefit to some degree from space-based observations, Health Security and Climate Change and Environmental Degradation stand out as relying heavily on civilian satellite observations to enable their understanding and support predictions of future conditions and future threats. Similarly, as described above, assessing and anticipating conflicts and instability are supported by such observations as well. With regard to climate change specifically, the 2021 National Intelligence Estimate (National Intelligence Council, 2021) further supports the importance of understanding climate change in a national security context.

Sustaining Important Observations

The capabilities in space-based Earth observations have advanced tremendously over the last two decades, with companies such as Maxar, Tomorrow.io, IceEye, Planet, Capella, and others developing capabilities with direct applications for commercial and government markets. These capabilities do—or will—provide robust and timely monitoring of fundamental Earth system parameters that include visible and thermal imaging, precipitation monitoring, all-weather surface conditions, surface deformation, etc. These efforts are quite impressive and represent a significant advance in the Nation's capabilities to make cost-effective, economically valuable observations of the state of the Earth for various applications. There remain challenges however for securing important Earth observations for which there is great societal need, but no viable commercial business model. While the economic value of imagery, for example is intuitive, there are some variables needed to advance science, and that have a less direct benefit to specific applications of the sort that would generate paying customers.

While it may seem that such observations could be sustained by operational agencies, this is often not the case. Once NASA-sponsored efforts have demonstrated success in such observations, the resource-limited operational agency investments are, appropriately, targeted at fulfilling their operational function, such as weather forecasting, in the case of NOAA, or land surface change and land-resource management in the case of USGS. There are variables that are vitally important to our success as a nation and society in planning for an evolving future state, but that don't have an operational benefit that directly aligns with these agencies' core mission and that don't lend themselves to commercial viability. Some examples of the most critical include:

- carbon monitoring to understand the evolution of carbon, its sources and sinks and its implications for atmospheric warming,
- precipitation amount and type, to better understand precipitation processes, which are critical for assessing drought, flooding, and water availability,
- mass change to track the movement of water throughout the Earth, including aquifer depletion and replenishment, as well as ice sheet and glacier changes and their impacts on sea level rise,
- the monitoring of incoming and outgoing radiation to assess the Earth's energy balance, and the degree of warming and cooling and how it varies with time and space,
- stratospheric ozone, to assess exposure potential to harmful ultraviolet radiation,
- tropospheric ozone, to understand the health risks associated with increases,
- soil moisture to assess water availability (and its evolution) for plant growth and drought conditions, and
- ocean salinity, to improve understanding of ocean circulation characteristics and the movement of heat by and through the ocean, in particular between the equator and the poles.

There are other variables of interest, and in some cases, the military satellite observations provide data for civilian purposes (such as ocean winds). In other cases, private foundations provide support for very specific applications (*e.g.,* methane and carbon dioxide monitoring). We also rely on international partners for some measurements that are not part of the U.S. portfolio, as has historically been the case for synthetic aperture radar for example and will be the case for upcoming atmospheric composition observations.

U.S. Leadership

The United States has pioneered many space-based Earth observations and has also effectively partnered with international agencies to advance Earth observation and understanding. NASA has invested in and developed various technologies and capabilities that have pushed technological and scientific boundaries. Some of these sensors have transitioned to the operational communities; some have been taken on by the private sector, and some have been carried forward by international organizations. In this way, U.S. leadership in space-based observations has produced tremendous benefits for our Nation and humankind. Success in the future requires a continued innovation on the technical and scientific fronts, as well as on the programmatic front. This is where the broader space-based Earth observing enterprise requires investments in the research and development (primarily NASA), development and operational use (agencies such as NOAA and the USGS), and the innovation of the private sector, bringing low-cost approaches to critical observational needs. The challenge is that, while each of these entities does its part and does it well, there are significant gaps in the broader Earth observing enterprise that will impair our ability to anticipate and prepare for environmental challenges and opportunities that lie ahead.

In addition, U.S. leadership is challenged by the limited degree of domestic talent to work on such capabilities. There is currently a great deal of competition for the appropriate skilled workforce across all related disciplines in science and engineering, with some of the various smaller start-up companies providing significant competition for the larger more established entities (such as NASA centers or the larger contractors). On the one hand, this is very good, as these start-ups introduce novelty and ingenuity into the pursuits, but at the same time, a robust workforce that supports a diverse set of capabilities is essential for U.S. leadership in this arena.

The needs are primarily in basic engineering—aerospace, mechanical, electrical, computer, etc., which includes robotics and autonomy, and the universities remain the key source for entry-level engineers. The limiting factor, however, is at the mid-career level engineers who, in addition to their domain expertise and capabilities in systems engineering. In other words, people who are able to put all the components together to deliver a successful project. In addition, it is important that these systems engineers have a basic understanding of the science and applications for which these systems are being developed, so trade-offs can be assessed. Talent in this area is in high demand and of limited supply. They are aggressively sought by all types of organizations (small start-ups, large contractors, NASA centers, etc.), and competition is high. In some cases, the domestic labor workforce is not sufficient to meet these needs, and international talent needs to be brought in. For the U.S. space-based Earth observation enterprise, the challenges are not so much at the entry level, but in the availability of seasoned mentors, to help these entry-level engineers evolve into project leadership roles.

Conclusion

These are just a few examples of the critical importance that space-based observations play in our lives and how they contribute to our livelihoods, safety, and prosperity. There are too many to comprehensively address for this hearing, but these examples make the point that such observations can positively impact how we live in a day-to-day sense, how we thrive as a nation, and how we succeed as a society on a changing planet. The benefits from such observations are realized in many sectors. Among them are:

- everyday citizens, who rely on forecasts in such areas as weather and air quality to plan their days and even week's activities and make health risk exposure choices,
- the insurance industry, who relies on observations of risk, damage, and vulnerability to effectively insure the properties of people subject to potential environmental threats,
- land resource managers, who require intelligence on resource availability, risks and trends,
- water managers, who require information on current and predicted water availability, drought, usage, and related resources,
- coastal managers, who require information on sea level rise, land subsidence or uplift, coastal erosion, and storm forecasts,
- urban planners, who need to understand vulnerability of populations and structures to weather and climate related events, so they can plan accordingly,
- the transportation sector such as aviation and shipping (on land, sea, and via rivers), who need to understand and manage the navigability of rivers, the

skies, and the oceans, all of which have tremendous impacts on supplies and costs of goods,

- farmers, who need to know the degree to which factors affecting crop health, crop yield and optimum times for planting and harvesting,
- ranchers, who similarly need to know the health of lands for grazing,
- the recreation industry (*e.g.,* skiing, rafting, etc.), who rely on information about snowpack, river flow, vegetation health, etc. to plan their operations,
- those managing disaster response, who need to know avenues for evacuation and access;
- the military and national security community, who need to understand threats to their resources, potential areas of resource-driven environmental conflict, conditions in theaters of operations, and potential vulnerability of U.S. assets, and
- elected officials and other policymakers who rely on credible information for policies such as resource management, Federal flood insurance, rebuild vs. relocate decisions.

It is clear that space-based observations of Earth improve lives, enable us to manage environmental challenges, and provide great economic benefit. They do so by providing the context, scale, and perspective needed to characterize, understand, anticipate, manage, and respond to change. In so doing, they enable—and empower—individual, national, and societal success.

Thank you for the opportunity to testify and for your commitment to this important topic.

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Senator HICKENLOOPER. Thank you. Dr. Abdalati. And I was impressed that you were using—you know, not killing trees like the rest of us. I appreciate that. I now turn it over to our Chair Cantwell, who is an expert in her own right in not just technology, but in aerospace.

STATEMENT OF HON. MARIA CANTWELL, U.S. SENATOR FROM WASHINGTON

The CHAIR. Well, thank you, Mr. Chairman. And thank you, and to Senator Lummis, for holding this important hearing, and to our witnesses adding a lot of insight and valuable information about the success and opportunities for us in this area.

We know that the unmatched scientific legacy of the U.S. Geological Survey's Landsat program and the key partnerships that they have had with NASA have been successful. And of course, NASA being in the news now with the landmark Artemis I mission, which just reached a point at almost 270,000 miles from Earth, farther than any other human related spacecraft. I would like to start by congratulating them, NASA, and their Artemis program, as well as the workforce in my state and across the Nation who participated in this.

With 42 Washington companies contributing components for Artemis, our State remains an aerospace leader and NASA is keeping the United States in a world leadership position here as well. NASA, of course, does a lot more than explore space, and since its founding, it has had a mission to help us understand Earth, a mission shared by the USGS and the National Oceanic and Atmospheric Administration.

And for over 50 years, these agencies have been working with their academic and commercial partners and giving the U.S. a leadership role in developing and deploying satellite based remote sensing systems for monitoring the Earth. Now, I can't tell you how important we feel this is today.

In the case of Landsat, publicly available data yielded over $2 billion in annual benefits to U.S. users, and over $1 billion in annual benefits to users outside the United States. The total global Earth observation commercial market is projected to be almost $8 billion by 2030. You may have gone over all this data, OK.

But this data, these services, this market represents sustained growth and opportunities, particularly in areas like agriculture, to crop insurance, to urban planning, and a very important subject for

us in the Northwest and my colleagues here on this committee, wildfires.

In Washington, the data and processes of information by NOAA Western Regional Center in Seattle, which houses offices for the National Weather Service and National Environmental Satellite Data and Information Services, data from these offices are invaluable in helping us cope with these increasing wildfires.

During the season, and my colleagues I know in Western States saw this, an unbelievable increase in these instances. For example, the Bolt Creek Fire burned approximately 15,000 acres on the East of Seattle in King County.

We are used to having these fires on the other side of the Cascades, on the East side of the Cascades. We are not so used to having them on the West side of the Cascades. And Earth observation data were essential for real time fire mapping measurements, part of suppression in assessing post-hazard burns.

This is incredibly important because in this particular area it is very steep and it is one of our two highway passes across the Cascades, and without that data and information, nor that highway, it becomes very precarious.

So looking forward, we know that there is going to be a growing need around wildland fire prediction and long term adaptation. We must be vigilant about these fires. And residents who just suffered through the Bolt Creek fires have to worry now about landslides, which is why this—all of this information, as those of you who are involved in this already know, that that kind of fire damage leaves you very, very vulnerable.

So the United States must continue to sustain its growth in Earth observation capabilities in alignment with our community needs and scientific consensus, and the symbolic development of research and operational capabilities managed by NASA, NOAA, and USGS will, I believe, remain very critical to how the partners in the private sector also develop.

So I look forward to having an opportunity, Mr. Chairman—you know, I don't want to get ahead of you and Senator Lummis on questions, but thank you to the witnesses, and thank you for holding the hearing.

Senator HICKENLOOPER. Madam Chair, I think you are probably—your schedule, I can only imagine it. So if you would like to go first with questions, I think that is alright with me.

Senator LUMMIS. Absolutely.

Senator HICKENLOOPER. Ranking Member Lummis concurs.

The CHAIR. OK. So to our—Dr. Volz, thank you for being here, virtually I guess. I wanted to—could you speak how infrastructure funding that was part of the bipartisan infrastructure law, Fire Ready Nation Act of 2020 to strengthen NOAA's fire weather service capabilities, are helping us with the fire and keeping residents safe? And what else do you think we need to do to help expand this capacity within NOAA?

Dr. VOLZ. Thank you, ma'am, for the question. It is an excellent question, and we definitely appreciate the disaster supplemental funds, which provided the resources to us.

So with those particular funds in the supplemental, we have been able to accelerate the delivery—the development and delivery

of some fire products which take the information we get from our geostationary satellite GOES-R, and modeling—and working with our National Weather Service with modeling to make a better use of those products to our fire emergency managers, but also into such services as our high resolution rapid refresh model, which allows us to forecast the propagation of smoke and other effects that are coincident with the fire.

These are products that were in the pipeline that we know we are ready to do, but we were resource limited, and we were able to accelerate them, for example, with the inclusion of these disaster supplemental funds.

Looking forward, we definitely have seen the increase in the fire events and our next generation—we have a number of other products which we are continuing to improve, but in the next generation geostationary satellite, for example, the GeoXO, we have particularly targeted bands which are better focused on fire initiation and have increased the resolution on those so that we will be able to spot smaller fires faster and then give fire emergency managers a quicker response time to those fires.

And one of the amazing facts in my mind was that we are able to contain roughly 97 percent of the fires that occur, but those 3 percent we don't contain in the first hours are the ones that lead to the bulk of the damage around the country.

So if we can even improve that by 1 percent, we can significantly reduce the impact of major fires around—in the West and elsewhere in the U.S.

The CHAIR. So what do we need to do to execute on that from a satellite point—?

Dr. VOLZ. Well, we are continuing the development of the products and services. We are using the supplemental funds. But also GeoXO is now—it is in our program and is not confirmed yet. It is ready for the next step.

And we are actually taking it to the Department of Commerce in the next two weeks for the next step in initiation, and we hope to be able to—it will require funding for the first launch, will be in 2032.

And we will take the time between now and then to develop those satellites and to prepare the weather service and all of the whole ecosystem, as Dr. Abdalati said, of managers and responders to deal with the increased data when we get it. It is important that we get the investments to supplement and to deliver the next generation of enhanced observations that will meet the growing need.

The CHAIR. Well, this doesn't—I mean, I mean, I know look, there is a lot of satellite use and a lot of interest that people have. But in this case, we get from the Weather Service every, usually by May and then maybe an update later in the summer, this is where the hot spots are going to be.

They already have their projections. Here is who is really going to be at the brunt of this, you know, with weather forecast. So sometimes it might be Wyoming and it might be Colorado, and sometimes it is Washington and Oregon.

And even, you know, you can get a map that is very red in Alaska, and you are thinking, how can this be? But I know that my col-

leagues from Alaska can tell you it is real. They have had fires up there they never predicted.

So at that time, we would then dedicate satellite monitoring to say whatever those hot spots would be for a period of, what, a month, 2 months? So we literally would be calling out, you know, calling out these fires. What—describe what it is that we would do? I stumped our witness. I think they—I think they got——

Senator HICKENLOOPER. He might have gotten frozen.

The CHAIR. Yes. There you go. Can you hear us, Mr.—Dr. Volz?

Dr. VOLZ. I can hear you now. I am sorry. You froze for just a second. So, yes, I hear you.

The CHAIR. OK. My question was, are we targeting—we need satellite capability to target certain areas for, like, months at a time, I guess is the question?

Dr. VOLZ. No, I would say that is a misrepresentation that the GOES—the geostationary satellites are observing all the time, 24/7 with no interruption.

You mentioned the forecasting for a seasonal and the like, and that, we don't change our satellite assets to observe those differently based on high vulnerability versus low vulnerability, but it allows the communities to preposition to prepare emergency responses to those areas that may be listed as higher vulnerability.

What we can do, improve forecasting, ecosystem forecasting, understanding the health, the vegetation health, the soil moisture content, the general ecosystem, environmental factors to give even more higher resolution and higher?

[Technical problems.]

The CHAIR. Better broadband.

[Laughter.]

The CHAIR. Well, Mr. Chairman, I will—I think the point here I would make if Dr. Volz was back with us is just, so there is no reason why we shouldn't do this. So this is going to save us money. The three of us know how much fire damage is costing us.

And if you can prevent some of it by what we say are activities of hasty response, and if we can use our geo-system to do that, let's do it. So thank you, Mr. Chairman.

Senator HICKENLOOPER. Thank you. And I think that is, that sense of when you get to a fire soon enough, you dramatically transform the damage done.

The one thing you learn, every Governor in the West learns is that if you can get there in that first few hours when it is smoldering before it breaks into a blaze, you have got a very good chance of controlling it. Let me switch a little bit.

Dr. Calvin, how will NASA and the Earth Information Center, this is the news Senator Bill Nelson talked about in 2021, coordinate with other Federal agencies to address priorities, wildfires, but methane emissions, land use?

So much of this, and I think you all could speak on this in terms of the great challenges to orchestrate and to integrate all the different sources of data. So, speak to that, if you can start.

Dr. CALVIN. Yes. Thank you. And thank you for the question. I think what we all recognize is that there is increasing challenges. We have just been talking about wildfire and there is other agri-

culture and droughts, and we have a lot of information both at NASA and other Federal agencies.

And the idea behind the Earth Information Center is to bring that together and make that information accessible to people so that they can respond to the challenges they are seeing in their communities. And there are a lot of complementary sets of information or all around the Federal Government.

One of the prototypes that we are thinking of for the Earth Information Center is around greenhouse gas in monitoring and measurement. And here there is an interagency working group that has been actively working together on how you can bring that data together.

So how can you take the activity based inventories produced by EPA and combine it with satellite based observations from NASA, and other ground and surface space observations from other agencies and bring that all together to provide more complete information.

And so we look forward to working with our Federal partners to make that a reality.

Senator HICKENLOOPER. You know, and I am old enough, I think I am the only person here that is old enough to remember when Landsat first delivered images, real images. Before we had seen it in movies.

We had various art directors' perspective, what they thought it would look like, but it was so different when we saw it. And, you know, it really is to this day one of the most—to remember back to how amazingly transformational it was in our consciousness. It is hard to imagine today.

Mr. Jablonsky obviously there has been a rise in the commercial small sats, these constellations of small satellites, and a number of companies such as Maxar have demonstrated the ability to produce high resolution, very high resolution earth observation data.

What can small sats, if that is a word, it must be the word because it is written here—what can small sats with higher resolution imagers, how can they provide targeted observations over specific areas of interest? And what are some of the—what is an example of that?

Mr. JABLONSKY. Well, thanks, Senator. I think probably the best way to tee that up would be to describe the vast amount of data coming in from the commercial, as well as Government satellites, and how that is being, you know, dealt with to make—to help decisionmakers take action on it in a fairly rapid fashion.

So, for example, Maxar's satellites have 30 centimeter pixel size, so that anything with a, you know, larger than 30 centimeters in a frame becomes visible. That means we can not only see, but using artificial intelligence algorithms, count all the cars in a city in a single satellite pass and do that in seconds because of the revolutions that we have had in cloud computing, as well as machine learning algorithms and artificial intelligence in recent years.

It has been demonstrably, I think, very effective in matching that type of data with weather patterns, for example, to then help fight wildfires in the West. So not only understanding where the fires are, but when you overlay weather patterns and terrain and elevation and difficulty and road networks and where resources are,

figure out the best way to rapidly minimize the damages and impacts that might be happening while keeping life safe.

Because when people go out into the field, if they are on the wrong upslope and the wind changes, you know, that is when you can have a loss of emergency responders' lives. So, Maxar and other commercial providers collect massive amounts of the planet every day—millions and millions of square kilometers and terabytes and petabytes of data.

And it is too much for any one human to get through, so getting that data into the right places, making it accessible through cloud enabled environments and Internet enabled environments, so that the first responders in a command center in Wyoming or Colorado can get to that information quickly, and then overlay their decisions on to it, is what we are working on.

Senator HICKENLOOPER. Perfect. Dr. Abdalati, you have a great deal of experience working with NASA and NOAA. C.U. Boulder now has a research partnership with NOAA. Can you discuss the importance of interagency coordination to federally funded Earth observation missions, and maybe a concise suggestion or two for improvement?

Dr. ABDALATI. Well, certainly the coordination is absolutely critical because we have on, you know, upstream of the effort is the development of the technology, testing of the technologies, then deployment of the technologies to learn how to observe the parameters we need to observe.

And then further downstream, as you see in the case of Landsat, for example, are the satellites that support weather forecasting. We have the use of those capabilities to advance science, to advance applications, to provide information that inform our day to day planning.

So the spectrum of activities from discovery, and discovering how to discover, is at one end to the other end of using the information, turning that into something of direct value to people. So that doesn't happen with just NASA doing its part and then kicking it over to USGS or kicking it over to NOAA.

There needs to be this reach across agencies, and it does exist, where at the user end of things, more operational end of that continuum, the needs are articulated so that NASA further upstream can be working toward delivering something that can be of use.

And at the same time, as new capabilities emerge and are being developed, the operational agencies need to be aware of what the potential is. So that integration is absolutely critical. And as far as improving it, I will say this, it works well in an interaction sense.

Where I would suggest improvements is there are still things that fall through the cracks because NOAA, USGS has its mission—have their missions. NASA has its capabilities that it develops. And when the mission centric perspective, as is appropriate, is exercised by the agencies, they are looking at, OK, what do I have to fulfill my mission?

There are observations that need to be done, that need to be continued, that don't quite fit into the operational space, but have been developed and continue to be developed by NASA. And finding a way to keep those going, even though they support knowledge,

they support understanding our planet and how it operates, don't necessarily map to the operational function of the agency.

So some overarching entity that says, this is what the enterprise needs to carry out and I think that will improve it.

Senator HICKENLOOPER. I appreciate that. Thank you. Ms. Lummis.

Senator LUMMIS. Thank you, Mr. Chairman. Dr. Calvin, one of the things that our committee has been focused on is the growing concern about orbital debris. Is there a threat posed to the Landsat Program by growing amounts of orbital debris? Is this something you are focused on?

Dr. CALVIN. So at NASA, people think about this, and we agree that it is important to ensure that space is usable for years to come. Space debris and mega constellations are an issue that need to be addressed by U.S. leadership. And I think I can refer other colleagues within my agency for more information on that.

Senator LUMMIS. Thank you very much. Dr. Abdalati, being from the West, you know well the dangers of not only drought, but also some surprise flooding from snowpack melt in Wyoming.

We saw a lot of damage this spring around Yellowstone National Park, where we had a surprisingly rapid snow melt due to some unseasonably warm weather, and rain simultaneously. And so are there ways that Landsat can help mitigate these sorts of disasters?

Dr. ABDALATI. Well, the mitigation—what we can do is observe as they unfold. So we can mitigate the management of those kinds of disasters and preparation.

And it is not just Landsat, it is other observations because it requires understanding the potential for rain. You know, how much water is in the atmosphere? How much is going to fall out? How much snow, we call it snow water equivalent, is stored in the mountain. So, you mentioned rain.

Rain makes melt happen much faster. It is a much more efficient energy delivery system for melt. So it really requires the monitoring and forecasting of rainfall, temperature, the rate at which it will occur, the topography, because the runoff of the water dictates or is a big driver and flooding as well.

So all of those elements combined. Certainly Landsat is a component of it, but there is much more to be observed.

Senator LUMMIS. Thank you. Mr. Gallagher, as you know, Wyoming is rich in oil, gas, coal, uranium. It is my understanding that using images from Landsat, we were able to determine the subsurface composition of minerals and other deposits based on above ground particles.

Certainly it is true with uranium. We see that in Fremont County, Wyoming, as well as some other counties. How is the data collected by Landsat Program making our natural resource location and extraction more efficient, pinpointing it a little better?

Mr. GALLAGHER. Good. Thank you for the question. So, yes, it is true that the superficial geology, if you know the superficial geology, then it can tell you whether or not it is complimentary for minerals and oil and gas.

Landsat has some spectral bands that provide some—certain information about the surface. More broadly at USGS, we have other sensors that can do that as well. So in my mission area, I partner

with the Energy and Minerals Mission Area on a project we call Earth MRI.

So we are flying airborne instrumentation that is electromagnetic data that lets us see into the subsurface for the identification of critical minerals. So I just cite that as an example.

As my colleague said, they are really multiple sensors that give you that kind of information, both on the surface and subsurface, and Landsat has a role.

Senator LUMMIS. Thank you. Dr. Volz, are you still there? Can you hear me?

Dr. VOLZ. Yes, I can hear you fine. Go ahead.

Senator LUMMIS. Thanks. I want to expand on a question that was asked earlier. Are there data sets that can be used to help us combat wildfires in real time? As Chairman Hickenlooper stated, you know, if we can catch them early enough, we can really contain the damage. And I am curious about whether data sets can be used in that way?

Dr. VOLZ. What Dr. Abdalati just said a few minutes ago—Yes, we are getting—we are getting a lot of feedback.

Dr. VOLZ. All right, OK. But yes.

Senator LUMMIS. OK. Good, good. You answered my question. And—Yes. And then you reference up Dr. Abdalati's name, so I wonder if I might turn to elucidate a little bit.

Dr. ABDALATI. Yes, I am sorry, can you restate? You are asking if there are data sets that can be used?

Senator LUMMIS. Yes, that can help us identify in real time wildfire potential or——

Dr. ABDALATI. Oh, certainly. You know, and in fact, I personally, my neighborhood was destroyed by the Marshall Fire in Colorado. We lost 1,100 homes. Mine was not one of them. There was a lot of smoke damage.

But personally, as we were evacuating, I with my daughter and my coughing dog, I just looked around at how dry the land was and felt the wind, you know. And so it is information on wind speeds. It is information on drought.

Soil moisture is key because while it was likely human ignited fire, as most wildfires are, the conditions for the fuel for it were in the dryness of the soil and the vegetation, the winds that just caused it to rip through the neighborhood, the area.

So data sets are soil moisture, information on vegetation so we understand its health, how dry it is, is it kindling or is it, you know, green. Winds, precipitation, and all of these can be derived from not solely or exclusively, but from satellite observations, as some of which were mentioned here.

Landsat is a great element of that system. But there are also things like forecasting winds and understanding soil moisture and other data sets. So, yes, it is an integration of capability.

Senator LUMMIS. Thank you. And can I ask one more quick question? Do I have time for that?

Senator HICKENLOOPER. Sure.

Senator LUMMIS. Mr. Jablonsky, is there a way the private sector can work with the public sector's data sets and information to provide even more information?

Mr. JABLONSKY. Thank you, Senator. Absolutely. For example, on a private sector satellite, WorldView 3, we have over 20 multispectral bands, including shortwave infrared sensors.

And those shortwave infrared sensors can actually see through the smoke to determine the boundaries of a wildfire, where the hotspots are and help the teams on the ground as determined. It can also tell you when you think you have got a fire out, where you still have localized hotspots that you might need to take care of or work on.

And then Maxar and other commercial companies have weather desk type abilities. So, for example, our weather prediction capabilities are used commercially, but can also be used by Governments to determine crop health, to figure out economic indicators, and in areas like this, think about what a propagation pattern might look like in a localized area.

Senator LUMMIS. Thank you, panel. Really appreciate your testimony.

Senator HICKENLOOPER. Great. Senator Blumenthal.

STATEMENT OF HON. RICHARD BLUMENTHAL, U.S. SENATOR FROM CONNECTICUT

Senator BLUMENTHAL. Thank you, Mr. Chairman. Appreciate all of you on the panel being with us today. My guess is that not a lot of Americans understand or appreciate the immense value of the work that Landsat and similar kinds of systems do for our country, not to mention the vast potential value that they can add in terms of our understanding of the planet and our efforts to save it.

Connecticut's coastline, as you probably know, has a number of expansive estuaries like Long Island Sound that are teeming with flora and fauna, with other kinds of ecosystems that are threatened by global warming and human development, and natural disasters, and more. Landsat has been instrumental in better understanding Connecticut's waterways.

In 2018, the Interstate Environmental Commission studied hypoxia, as you know, there are zones lacking oxygen, indicating poor water quality in Long Island Sound, using Landsat data to help determine the contributing factors to that problem. And Landsat data has also been used to examine ocean conditions and so forth.

My question has to do with how accessible this data is to ordinary Americans, to environmental groups, to the public in general. I think you may have touched on this, Dr. Calvin, in one of your answers to Senator Hickenlooper, but perhaps you could elaborate on how this data can be made more publicly available and accessible to people who are interested in it, like citizens groups, environmental advocates, and others.

And I would be interested in views that others may have on that same question.

Dr. CALVIN. Yes. Thank you for the question. So all of NASA's satellite observations are publicly available, but one of the things we are working on at NASA is making them more accessible. They are often large datasets. You need a lot of technical expertise.

So some of the things we are doing is moving some of these to the cloud so that you don't need a supercomputer, and providing more trainings on the data, including some in Spanish language.

And then when I was answering Senator Hickenlooper's question earlier about the Earth Information Center, so part of what we are doing is trying to make it more accessible to the public.

And just one example of a tool we have now, we have a sea level rise tool, so you can look at coastal cities around the U.S. or around the world and see how much sea level has risen till now and how much it might rise in the future.

And we are continually working to make sure our data sets are usable to people and accessible.

Senator BLUMENTHAL. Others have comments? If not, Dr. Calvin, I am interested in the work that you have done on food and water. Can you talk generally about what we are seeing and learning about water quality in the United States, quantity and quality of water?

Dr. CALVIN. So we are seeing changes in the water cycle in general, more heavy precipitation events, more droughts. And a lot of what we can see with NASA's satellite observations, we can monitor and observe those changes.

And so we have talked a little bit earlier today about how we can see things like soil moisture and better understand that. We have a satellite launching 2 weeks from today called the Surface Water and Ocean Topography Mission, and this will provide us the first global survey of water running through rivers and lakes.

So any river larger than 100 meters in width, we will be able to see that. And then for oceans, we will get a better understanding of ocean circulation. And all of those things impact food.

So a lot of, you know, water scarcity work is looking at how much water do we have available, which the Surface Water and Ocean Topography Mission will tell us. And then we also need to know how much water we need.

And so some of the other satellites that NASA has that can give us information about irrigation needs and soil moisture would be important for that as well.

Senator BLUMENTHAL. You expect that that kind of analysis and factual collection will indicate some solutions, some steps we ought to take?

Dr. CALVIN. You know, the goal with NASA is to provide the information in an actionable ways that people can use that as their own to inform their decisionmaking. And so we will be working with stakeholders and users to understand what their questions are and provide information that is relevant to those.

Senator BLUMENTHAL. Thank you. Thanks very much, Mr. Chairman.

Senator HICKENLOOPER. Thank you. Now I have a question, a couple of questions more. I don't know—I suspect a Ranking Member Lummis might have a question extra.

Senator LUMMIS. You know, I do, but I know that they just scheduled a call to vote.

Senator HICKENLOOPER. I know, but I think we can be like 10 minutes late.

Senator LUMMIS. Good. OK.

Senator HICKENLOOPER. I think—this is a unique set. We have votes being scheduled against our will. I shouldn't say that. Why don't you go ahead and ask the question, and I will ask a question.

Senator LUMMIS. Well, I would like to explore, I thought it was fascinating to hear about the abilities of both Government, Landsat and satellite data, and private sector satellite data being used almost simultaneously and in a complementary way on some significant weather events or fire events.

And so I would just like to explore just a little more, Mr. Gallagher and Mr. Jablonsky, with how—who analyzes it? Let's say you have a significant hurricane off the coast, or you are watching it develop or some such observable event.

How do you coordinate between private sector information and Department of Interior information specifically?

Mr. GALLAGHER. Thank you for the question, Senator. So I will speak quickly about the Landsat data itself. We refer to Landsat data as medium resolution. So a little more on that. It is a pixel is 30 meters by 30 meters.

That is about the size of a baseball diamond. And so a Landsat seeing one image is actually about 13,000 square miles. So it is medium resolution. It is—you are seeing things at a scale of regional scale. So a lot of the commercial sources of data are much higher resolution. You heard our colleague here talking about submeter resolution through their imagery data.

So when an event like that occurs, the data is very complementary because the Landsat data is looking at the regional patterns, denuding of the landscape, loss of shoreline erosion, or high wind that takes out green infrastructure and human built infrastructure.

The lower—the higher resolution data is fed to emergency responders who are responding on the scene for what is needed in terms of immediate responses. Landsat data is usually used for longer term recovery.

How people access the data in real time? We have done in recent months and years efforts to put all the Landsat data in the cloud and make it immediately accessible in that way. And we also serve it, of course, through the USGS through a tool called Earth Explorer.

Senator LUMMIS. Thank you.

Mr. JABLONSKY. Just as an overlay on that, Senator. The Government has been far reaching in its efforts to get access to commercial resources and make them broadly accessible.

The largest program is the electro-optical commercial layer program with the National Reconnaissance Office, by which they spend significant amounts on commercial data and license that data in such a way that it is then broadly accessible to all U.S. Government personnel and for U.S. Government type programs.

It is a very taxpayer friendly way to buy something once and then propagate it throughout the entire ecosystem. Beyond that, then the National Geospatial Intelligence Agency has a program called Global EGD, or Enhanced Geospatial Delivery, which started as a small program over a decade ago in Afghanistan, about how do you get satellite data to people very quickly, that has now expanded to include worldwide reach.

So from the time the satellites go overhead until that imagery, very high resolution imagery is available to over hundreds of thousands of users across the Federal Government, it might be a matter of 10 to 30 minutes.

So, and it is broadly accessible. With a CAC Card in the U.S. military, you can just log in and get access. NASA has access. NOAA has access. One estimate was that the Federal Government saved over $1 billion by making that data accessible to the Census Bureau as they were doing their work.

So I think it is a very, you know, far reaching, expansive way to make that information available and strong support for those programs.

Senator LUMMIS. Thank you. Thank you, Mr. Chairman. Great hearing.

Dr. VOLZ. Senator Lummis, this is Steve Volz.

Senator LUMMIS. OK.

Dr. VOLZ. If I can make a comment on that. You brought the example up of hurricanes. I think that there is definitely complementarity between a very high resolution commercial sector and moderate resolution, as Kevin Gallagher mentioned.

But what is necessary is the pre-prep, is the preparation so that the information sources are planned in advance, the integration is done, the systems are compatible.

And it goes back to the point I think that Dr. Abdalati was saying is that we have a whole systems of observations, including commercial and Federal, and making them interoperable in the right environment so that when the event does occur, a hurricane or a fire, you are not arguing about whose data.

You are using an integrated system where the data are then seamlessly used. So it is not a question of getting—going through the CAC, as we just heard, and getting the data. But knowing the data are available and it is seamless in terms of time and in scale.

And that is where the operational system side works with the planning, and the dry runs, and we do this on a regular basis months in advance on an annual basis so that we have all of the players in the loop for utilizing the best data for the most—for every application as they come forward.

And that is what the collaboration really is key between the Federal, the commercial, and the local partners.

Senator LUMMIS. Impressive. Thanks.

Senator HICKENLOOPER. Yes. And there are companies, a number of companies, Palantir comes to mind, but companies that can help pull all those datasets from disparate sources together and make them help facilitate that interoperability that I think we all agree is a necessity.

My last question is just—and again, I still have at home my Landsat, the first book of imagery, I think was 1974 it came out and I just couldn't believe it. And I was, you know, as I—when I got my Masters in Earth Environmental Science, it became kind of my handbook in a funny way of how we could think about the Earth.

Back then, we didn't call it climate change. We called it the greenhouse effect, but everyone knew it. And many of those early

predictions back from the 1970s and 1980s and even the 1990s are being borne out in a frighteningly accurate way.

I just thought we could run down and let each of you just say a minute about the ability, and if you have a suggestion I am always looking for action items, but the ability to see methane is something that is a hot topic right now.

And, but it is not just methane, but the ability to really begin looking at this Earth as an organism that breathes and inhales and exhales, and what we need to do to be able to—part of this is communicate to the American public that this pollution is going to have real effects, but part of it is actually measuring it in such a way that we can respond to it.

So I will give you each 30 seconds or 40 seconds, because I think otherwise I am going to get shouted down by the powers that—the powers that be. Anyways, so let's start with—I guess we will start, Dr. Volz, now that we have you back and then we will go to Dr. Calvin and down the line. Be concise.

Dr. VOLZ. Thank you. In my 30 seconds, I would say it is really the integration of all of these. To understand how the earth is breathing, you need to look at it in a multispectral, multi-factors way, and that is bringing the data together and having them interoperable.

And we are doing that in moving all of our data systems, those records and the current observations, into a cloud based format so that we can bring these observations together, public and private, high resolution and low resolution, global, so that we can have that holistic understanding of the Earth.

And that allows us to do that forecast modeling and to explain the environmental systems better. Thank you.

Senator HICKENLOOPER. Great. Dr. Calvin.

Dr. CALVIN. Yes. So we are also working toward bringing together multiple observations of different satellites and instruments. They have different spatial resolution, different revisit rates, different gases that they can observe. And so bringing all that together and then continuing to innovate.

So IMET is an instrument installed on the International Space Station. Its primary science is around mineral dust, but the science team realized they could observe methane with it, and so they are now using it for that as well.

And so thinking about how can we be innovative about how we measure and monitor.

Mr. JABLONSKY. Several times we have spoken about cloud based activities, and Maxar moved approximately 120 petabytes of data fully into the Amazon cloud. So it is completely accessible and searchable, and algorithms can run over those entire datasets, which are a 20 year record of the planet.

The next big change now is to take all of the other datasets and position them geographically in an area so that they can all be—run with algorithms across the same dataset. So taking 3D precision data registration techniques, taking multiple sources of data, all getting them into that cloud infrastructure so that the data structures can be useful to do things like predict methane detection, to do all the things you want to do with it.

So that is the next big revolution.

Senator HICKENLOOPER. Great.

Mr. GALLAGHER. So Landsat has been this independent, unbiased witness for the last 50 years to all the changes that have taken place on Earth from 4 billion people to almost 8 billion people, and all the changes associated with that. It is a marvelous time series data.

And the next big revolution is to be able to mine data sets like that. First of all, maintain those data sets.

So 50 years from now, we have 100 years of observation data, but also to mine that time series using artificial intelligence and machine learning to do—to understand what happened before and how that brought us to today and make projections about where that is going to take us in the future.

Senator HICKENLOOPER. Right.

Dr. ABDALATI. And I would say it requires that we continually look at all the relevant parameters of the Earth's system. It isn't just watching it rain. It isn't just watching it flood. It is all the pieces of it and integrate them. And doing so requires looking in parts of the electromagnetic spectrum that our eyes can't see.

So it may not be something visible, but it is there. Water vapor is not something we really see, but understanding its content and, you know, quantity and movement is critical. So integrating all the parameters within the Earth system and observing it in a sustained and continued way.

And as far as communicating goes, you know, I would just say make what is not visible to people visible. You know, it is hard, as I said, to see water vapor. But there are animations. There are ways of depicting the moisture in the air that can really speak to people. And the agencies, I think, do a good job of that. We just need to continue to get it out there.

Senator HICKENLOOPER. Great. Well, thank you all. And I apologize. I could sit here, obviously an hour and go. Nothing I like more than getting a little more granular on some of these issues and having you all in one place. It is exhilarating.

So I have a number of other questions I want to put—you will get them. Well, they will get collected into the record. Thank you all for making the effort to come here.

And Dr. Volz as well. I think that we are, and I feel this, that we are on the edge of actually getting to the ways that we can demonstrate what the reality is and what the rate of change is, which is what the, you know, looking at these long-term data sets is so powerful.

We can see changes in the rate of change. I think we can get to a point where we can mobilize not just our country but the world and really address some of these issues much more successfully than we have in the last few decades.

So thank you for all your public service, private service and public service, and look forward to working with you all together.

Senators who wish to submit questions for the record, questions will be due December 15, and look forward to seeing you all again, sooner than later.

We are adjourned.

[Whereupon, at 11:52 a.m., the hearing was adjourned.]

A P P E N D I X

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. MARIA CANTWELL TO DR. KATE CALVIN

Intergovernmental Personnel Act (IPA): You are an employee of the Pacific Northwest National Laboratory (PNNL) on detail to NASA. Of course, PNNL's main campus is in Richland, WA with over 4000 employees, though you work at one of PNNL's satellite campuses in College Park in Maryland. These campuses conduct ground-breaking research on the environment, sustainable energy, and coastal/national security. Therefore, it is not surprising that NASA would want to tap into the talent at PNNL and hire you as their Chief Scientist and Senior Climate Advisor.

Question 1. Given the highly competitive market for technical talent in the space industry, what additional hiring authorities and/or programs would be helpful to NASA to attract individuals with the rights skills into the Agency?

Answer. NASA has existing special authorities, such as critical pay authority and hiring and pay flexibilities for STEM positions, that help us to attract specialized and highly skilled candidates. These authorities support our multi-year, overarching strategy to provide more agility across our entire workforce, including increased talent mobility and investment in non-permanent civil service appointments to support shorter duration projects and projects where required skills and knowledge change rapidly.

NASA has also implemented several new tools to create a workforce that is efficiently shaped and sized to meet the needs of the future. These tools include:

- Enhanced hiring flexibilities including direct hire authority which provides greater reach to external talent and faster time to hire;
- Talent Marketplace—an internal application where detail and lateral opportunities are shared with the workforce; and
- Increased use of rotations, temporary assignments and promotions, and just-in-time training to upskill, reskill or broaden capabilities of the existing workforce.

Wildland Fires: Washington State had the second-and third-worst fire seasons on record in 2020 and 2021. This year, warmer weather is extending the fire season in the Northwest by 2 months compared to the 1970s. NASA satellites and services play a critical role in the detection of fires as well as the tracking of fire and smoke.

That is why I fought for additional fire weather infrastructure in the Bipartisan Infrastructure Law and why Senator Sullivan and I introduced the Fire Ready Nation Act of 2022.

Question 2. What new capabilities or satellite monitoring strategies might NASA be able to employ with additional investments in the near-term to (1) identify regions that are prone to fires and (2) to monitor new "hot spot" areas as they develop with the goal of identifying and containing fires early in their life cycle. Specifically, which priority items (pre-, active-, and post-fire) could be accelerated to reduce the most damaging and costly impacts of fires?

Answer. Emerging approaches to airborne and satellite fire risk and vulnerability sensors include vegetation LIDAR and hyperspectral imaging to quantify fuel loading while passive microwave and synthetic aperture radar could monitor soil moisture. NASA is also exploring products such as OpenET (evapotranspiration data products derived from optical data and weather station data) to estimate live fuel moisture, which is likely more important than soil moisture for understanding fire risk.

NASA's pre-fire focus is on using existing and new sensors for soil moisture and fuels. The active-fire priority is developing new sensors for airborne or satellite platforms for eventual full-time, day and night observations of fire location and intensity. Post-fire efforts are focused on better monitoring burn scars and forecasting precipitation to understand debris flow and landslide potential.

Question 3. Could you highlight some of the next-generation Earth Observing instruments that NASA is working on now that will revolutionize our understanding of the Earth system in the future?

Answer. Within the FY 2024 budget request for Earth Science, NASA requests funding to initiate four Earth System Observatory missions: Surface Biology & Geology, Atmospheric Observing System—Sky, Atmospheric Observing System—Storm, and Mass Change. These missions will provide key information to guide efforts related to climate change, natural hazard mitigation, fighting forest fires, and improving real-time agricultural processes. In addition, the Budget request supports the initiation of the Landsat Next mission, which will ensure continuity of the longest space-based record of Earth's land surface and will provide new capabilities for the next generation of Landsat users.

The fifth ESO mission, Surface Deformation & Change, will remain in the pre-formulation study phase until FY 2026. This observable can be met by the NISAR mission when it launches in FY 2024.

NASA is also looking toward future selections that will advance our understanding of the Earth system. During FY 2024, NASA intends to make selections from the Earth Venture Instrument-6 Announcement of Opportunity (AO) and will release the fourth Earth Venture Suborbital AO. NASA will also release the first Earth Explorers AO in FY 2023, to provide competitive opportunities for medium-sized instruments and missions that address specific science and applications needs as identified in the most recent Earth Science and Applications Decadal Survey.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. KYRSTEN SINEMA TO DR. KATE CALVIN

Drought and Fire Monitoring: Fire season begins in late April in Arizona, as the Southwest experiences the most severe drought in twelve hundred years. This is one month earlier than the average start of peak fire season between May and June. Earlier this year, the Tunnel Fire north of Flagstaff burned over twenty thousand acres while the Crooks Fire consumed over six thousand acres south of Prescott. After the fires were extinguished, burn scars have led to significant flooding issues in Flagstaff and other areas in northern Arizona.

Question 1. How can researchers utilize Landsat data to examine the effects of drought and wildfire and help predict where future fire and flooding events may occur?

Answer. Landsat satellites have been collecting information about water supplies, forest fires, and land use since the 1970s. Landsat data is used to locate and allocate water resources, assess water pollution, and manage watersheds—all vital to understanding the effects of drought. Landsat also plays an important role in assessing the impact of fires on forest ecosystems and human society. Landsat satellites document the location and extent of burned areas, how severely fires burn, and the subsequent regrowth of the land after a forest fire. All this information helps land managers better manage our forests and other natural resources in the context of fire. When combined with soil moisture data, Landsat can also improve drought and deluge monitoring to better understand where fire and flood events may occur.

Question 2. How does your agency share this information with Federal and local emergency officials, Federal land management agencies, and water managers to inform their response to drought, wildfire, and flood risks?

Answer. NASA's Applied Sciences Disasters Program works with partners across Federal and State government, including Federal and local emergency services, with private sector organizations, and scientific and academic institutions, to leverage Earth observation (EO) data, products, and models to provide actionable data to relevant decisionmakers across communities in the United States and the world. For example, Landsat and other EO data is used to populate the NASA Disasters Mapping Portal, which provides near real-time information and specific products to respond to disasters, such as floods and wildfires. These products are open and accessible to all and empower a range of stakeholders to make more informed decisions, including those with limited GIS knowledge.

Question 3. Can your agency utilize Landsat data to predict or track urban areas that will experience the worst heat on a summer day, as well as the features of certain urbanized areas that contribute to or mitigate extreme heat areas? If so, can you describe the process for making those predictions?

Answer. Landsat data, together with other EO data, including NASA's Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), can

be used to identify extreme heat areas and understand the impact to surrounding communities. Landsat uses observations in the near-infrared part of the electromagnetic spectrum to determine which parts of a city are warmer or colder over time. This can be connected to other factors including Nitrogen Dioxide and other pollutants from automobiles to reconstruct the cause and effect of urban heat. Recent NASA research on urban heat, using sources like ECOSTRESS, has been able to identify particularly heat-vulnerable areas and allow local governments and their partners to consider mitigation approaches, like *thermal resistant paint,* as reflected in NASA work in Los Angeles.

Question 4. What steps have you taken to minimize the threats posed by space debris? Are there any actions Congress can take to help address this issue?

Answer. NASA's budget request for its debris-related activities is almost $40 million. Supporting the funds requested in the President's Budget is needed to continue the essential work on this issue. NASA's activities to address the challenge of space debris have four components: debris mitigation, debris tracking and characterization, debris remediation, and crosscutting policy research and analysis.

- *Mitigation.* Office of Chief Engineer (OCE) and Office of Safety and Mission Assurance (OSMA) are the Agency's orbital debris technical authorities. The Orbital Debris Program Office (ODPO) within OSMA is a leader in developing research and technologies to both accurately measure the debris environment and reduce the creation of debris during spacecraft operations. The Science Mission Directorate's (SMD) Heliophysics Division supports the development of on-orbit debris sensors and other space environment measurement tools.
- *Tracking and characterization.* NASA's Conjunction Assessment and Risk Analysis (CARA) Program is focused on better understanding the risks posed by space debris so that spacecraft can operate more safely. The Trajectory Operations Officer (TOPO) and Flight Dynamics Officer (FDO) at the Johnson Space Center provide conjunction risk analysis support to NASA human space flight missions, including ISS and vehicles visiting the ISS.
- *Remediation.* The Space Technology Mission Directorate (STMD) supports the development of low TRL debris remediation technologies that may one day be utilized to reduce the threat of existing space debris. NASA's Office of Technology, Policy and Strategy (OTPS) is studying costs and benefits of cleaning up space debris, with insights for NASA, industry, and policymakers.
- *Crosscutting Policy Research and Analysis.* OTPS conducts and sponsors economic, policy and social research and analysis related to solving the challenge of orbital debris.

RESPONSE TO WRITTEN QUESTION SUBMITTED BY HON. MARIA CANTWELL TO DANIEL JABLONSKY

Future of Computing and EO Data: Commercial companies such as Maxar have been critical in identifying flooding from Nooksack River and wildland fires in my state of Washington. In addition, commercial companies can augment Federal government datasets with advancements in artificial intelligence and cloud computing.

Maxar has partnered with companies in my state, including Microsoft and Amazon Web Services, to advance the use of cloud storage and computing in Earth Intelligence.

Question. Given these advancements, what is Maxar's vision for data processing, storage, and distribution over the next decade? How will this change access and decision making for U.S. citizens?

Answer. Maxar is focused on continuing to deliver the best data and analytics it can. With world-leading resolution for commercial imagery, we are continually advancing how our data can be used. Our Precision3D technology is creating a digital twin of the globe which will continue to make significant advancements in the use of Earth observations for logistics, mapping, and even in gaming. We are also focused on delivering actionable intelligence to our government partners with constantly improving timelines.

All of this is done with better processing and better storage. As Maxar continues to push forward and continues to lead the commercial sector with these products, the ability to process our data will be more important than ever. Data security and storage is of great importance, and we take our security measures seriously. Maxar's data is stored in the United States, and we take every effort to ensure that both our data and our satellites are secure through a variety of encryption techniques.

Our partnerships with data companies are invaluable and we look to continue to grow these opportunities.

As our technology continues to advance it will lead to better, more accurate, and more timely access for our decision makers. Specifically, we work closely with the private sector to provide solutions that make their businesses more effective. As mentioned, Maxar's data can provide better logistics to increase the efficiency of delivery routes. The 3D maps derived from Maxar's satellite imagery are also improving the rollout of 5G networks by showing obstructions that can impact signal. These are just a few examples of many on how commercial Earth observation data is playing a key role for decision makers in both government and the private sector.

RESPONSE TO WRITTEN QUESTION SUBMITTED BY HON. KYRSTEN SINEMA TO DANIEL JABLONSKY

Space Debris: One potential threat to our Landsat network is space debris that can damage or even destroy our satellites while they are in orbit. The Department of Defense's global Space Surveillance Network tracks over 27,000 objects of space debris, but thousands of other objects that are too small to observe can still represent a hazard.

Question. What steps have you taken to minimize the threats posed by space debris? Are there any actions Congress can take to help address this issue?

Answer. I thank Congress for understanding the immediate need to address space debris and look forward to finding ways Congress and the commercial sector can partner for solutions. Maxar's satellites are fully maneuverable which ensures that we have the ability to move out of the way of not only debris, but also other active satellites without maneuverability. Additionally, we deorbit our satellites long before current regulations require. Maxar is an active participant in the Commercial Integration Cell which is used to share information and best practices to maximize space situational awareness. Looking forward, in order to contribute to the growing need for space situational awareness, Maxar has invested in a technology called non-Earth imaging, which allows Maxar to image objects in space. This technology helped Maxar identify that our own satellite was hit by an untracked piece of space debris. It will be able to help diagnose the health of other satellites in the future as well.

I support the ORBITS Act and think that is a good first step in helping address orbital debris. Additionally, I think a better system for rules of the road will help because while we are focused rightfully so on current debris, we must also ensure that active spacecraft are not creating debris or the potential for collisions that would create debris fields. Congress having an active engagement with the commercial space sector and spacecraft operators will also help create policies that can begin to tackle the dangers posed by space debris.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. JOHN HICKENLOOPER TO DANIEL JABLONSKY

Commercial Capabilities I: Maxar is an ongoing participant in NASA's Commercial Smallsat Data Acquisition Program. A NASA evaluation report on the CSDA pilot highlighted the utility of commercial datasets accessed through the program and the benefits provided to commercial partners. End User License Agreements (EULAs) between NASA and CSDA partners are structured to promote data use and sharing while also not obstructing commercial growth. It is cost prohibitive for NASA to make these datasets fully public, and the evaluation report underscored that restrictive EULAs were making it more challenging for researchers to share and publish data.

Question 1. How has the CSDA program supported the growth of Maxar's EO capabilities? How could it be improved to promote greater use and access to commercial datasets while still promoting commercial growth?

Answer. I want to thank Congress for its leadership and support of the commercial remote sensing industry. Congress continues to ensure that commercial capabilities are leveraged for key programs and that they are adequately funded. NASA's Commercial Smallsat Data Acquisition (CSDA) program looks to procure commercial data for a variety of uses and to help tell the story of what is happening on Earth. Maxar has not been a major provider of data for the CSDA program, largely because NASA can receive much of the same data through the National Reconnaissance Office's (NRO) Electro Optical Commercial Layer (EOCL) contract. There may be opportunity in the future to provide increased access to data and products, but those

conversations are still ongoing. I'd encourage NASA to look at the licensing agreements of the EOCL contract, as they strike a good balance in maximizing use and publication of data, while still protecting commercial growth.

Commercial Capabilities II: There has been a rise in the launch of commercial "smallsats" and constellations. Companies such as Maxar have demonstrated the capabilities of these smallsats to produce high-resolution images of the Earth.

Question 2. What are the unique capabilities that commercial satellites provide that might supplement or complement Federal systems? How can commercial datasets with higher spatial and temporal resolutions be used to support the broader Earth Observation mission?

Answer. First, I'd like to clarify that Maxar's Earth observation satellites are not smallsats. Our current Earth observation satellites are 2800 kg in weight and 5.7 meters tall and our next gen Legion constellation are around 800 kg in weight and 3 meters tall—this size is necessary in order to carry optics that provide for very high-resolution imagery. That said, commercial satellites provide an opportunity for the Federal government to leverage the pace of innovation in the private space sector. The government can license images and analytics through contracts with companies like Maxar and use this to augment government missions. Commercial Earth observation data is unclassified and quickly sharable between agencies and even with allies during times of need. This shareability is a cost savings to the taxpayer as the government is only paying for the data once, and it can be used for national security missions, humanitarian missions, or even during natural disasters. For example, with our planned Legion constellation and worldview satellites that are in-orbit today, we will be able to aid Federal governments with disaster response and recovery with up to 15 times a day revisit, providing near real time information of the events unfolding on the ground to the first responders. Another example of our unique capabilities is Maxar's ability to build and maintain 3D models with very high detail and accuracy that can complement Federal programs such as 3DEP (3D Elevation Program from USGS). These 3D models are critical to understand the impacts of climate change and increasing intensity of disasters and how to develop resiliency plans to support our homeland security.

RESPONSE TO WRITTEN QUESTION SUBMITTED BY HON. MARIA CANTWELL TO KEVIN GALLAGHER

Landsat Data: Landsat has provided a virtually unbroken record of Earth Observation data for the last 50 years. As you said in your testimony, the U.S. Geological Survey has been intimately involved since the beginning of the program and has since 2008 provided free and open access to Landsat data. These data have become an invaluable resource for our Nation's infrastructure, informing urban planning, precision agriculture, and disaster response.

Question. Could you describe the importance of Landsat's historical dataset? What new data will the Landsat Next satellite bring, and how do you see the program evolving from there?

Answer. Both today's Landsat observations and the long-term data record to which they contribute provide unique value and impact Scientific and technology advancements in data storage, data processing, and algorithms have enabled Landsat's data record to give us new insights into changes occurring on our Nation's land surfaces, surface waters, and coastal regions.

Following the first Landsat mission, launched in July of 1972, we have had at least one satellite in the series collecting data and often two satellites, which is our current operational baseline. This baseline allows us to image the entire Earth's land surfaces every eight days. Landsat's multi-decadal, global data record is unique—no other Earth-observing satellite mission comes close to its timespan, its consistency, and its scientific accuracy. Two U.S. Group on Earth Observations-led interagency Earth Observation Assessment reports ranked Landsat as the most impactful Earth-observing satellite system used by Federal agencies. In short, Landsat is a unique "witness" to changes that have occurred across the globe over the last 50 years.

While Landsat senses phenomena visible to the human eye, it also can "see" in the near infrared (NIR), shortwave IR (SWIR), and thermal IR (TIR) regions of the electromagnetic spectrum.

Landsat's capabilities enable users to perform land use and urban development planning, observe soil moisture, accurately estimate agricultural water use, assess crop health, understand wildfire risk and forest recovery processes, and respond to

natural disasters, including flooding, drought, and wildfire, while also supporting many other societal applications.

The Landsat archive is open and accessible to all users. Utilizing cloud processing and storage, the U.S. Geological Survey (USGS) has reprocessed and re-released the entire dataset as Landsat "Collection 2". The dataset provides every Landsat measurement taken over the life of the Landsat program as a time-series of observations, thus enabling in-depth analysis of land cover changes over the past 50 years. In a little less than two years, the USGS has recorded over 4 billion user accesses to this data.

Throughout Landsat's history, the National Aeronautics and Space Administration (NASA) and the USGS have continually advanced its technology to better address users' growing needs for high-quality data. The earliest Landsat missions sensed the Earth in four spectral bands, and in the 1980s, Landsat utilized eight bands, including a thermal band. Today, Landsat 8 and 9 operate in 11 bands. The USGS has also advanced the mission's spatial resolution-the ability to resolve small or adjacent details in an image. The earliest Landsat satellites imaged at about 75-meter resolution, whereas Landsat 8 and 9 operate at 30-meter resolution—about the size of a baseball infield. Landsat Next will image in 26 spectral bands at resolutions as fine as 10 meters, more than doubling Landsat spectral and spatial resolution capabilities. Landsat Next will also improve revisit rates so that every location on Earth will be imaged every six days.

Landsat Next's spectral, spatial, and timeliness requirements are driven by the most detailed land imaging user needs ever available for Landsat formulation. We conduct our peer-reviewed user needs process across the USGS, the Department of the Interior (DOI), and other Federal agencies. This process connects our users' continually growing science and public service needs to specific Landsat Next spectral bands while maintaining Landsat Next's continuity with the historical data record.

Under the NASA–USGS Sustainable Land Imaging partnership, Landsat Next will provide the core, operational U.S. Government land-imaging capability for the Nation. The USGS will augment this core capability through partnerships with commercial and international satellite data providers, to serve an even broader array of user needs than can be served by a single system.

The Landsat Program is evolving on the ground as well as in space. We are improving the interoperability among Federal, commercial, and international land-imaging datasets. While Landsat already provides essential calibration utilized by the commercial satellite providers, which enhances interoperability, we intend to optimize user tools for discovering and accessing data across disparate archives-enabling a multi-source "data ecosystem"—so that users may apply multiple datasets (commercial and government) for improved land cover/land use analysis, monitoring, and forecasting. These capabilities and tools will help U.S. scientists answer some of the Nation's most pressing questions about resource management, disaster preparation, response, and mitigation, ecosystem health, and climate change resiliency.

Prior to launching Landsat Next, NASA and the USGS expect to determine Landsat Next's successor mission and analyze future commercial and international remote sensing capabilities to determine the best approach to address our users' future needs. We plan to work closely and collaboratively with NASA and other organizations as we chart our future course.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. KYRSTEN SINEMA TO KEVIN GALLAGHER

Drought and Fire Monitoring: Fire season begins in late April in Arizona, as the Southwest experiences the most severe drought in twelve hundred years. This is one month earlier than the average start of peak fire season between May and June. Earlier this year, the Tunnel Fire north of Flagstaff burned over twenty thousand acres while the Crooks Fire consumed over six thousand acres south of Prescott. After the fires were extinguished, burn scars have led to significant flooding issues in Flagstaff and other areas in northern Arizona.

Question 1. How can researchers utilize Landsat data to examine the effects of drought and wildfire and help predict where future fire and flooding events may occur?

Answer. Arizona is in a region where forest fires and drought are occurring more often and with increasing intensity. Landsat plays a critical role in wildfire science and in helping to prevent damage to life, property, and natural resources. Land managers and scientists use Landsat to predict wildfire, assess wildfire risks, and to understand their immediate and long term impacts. They also use Landsat to

map the rapidly growing wildland-urban interface, which is highly susceptible to wildfire damage.

Scientists use Landsat to characterize vegetation and fire fuel load. This characterization enables them to model different fire regimes and to support proactive vegetation and fire management to reduce fire risks and mitigate fire impacts, such as erosion and flooding. Land managers and scientists also use Landsat to assess the severity and extent of large fires as they plan recovery efforts, to estimate how much pollution burning releases into the air, and to monitor the post-fire recovery of burned areas.

Landsat can capture active fires and smoke plumes as they occur, showing images of large, rapidly developing fires in the West. Because Landsat instruments can detect surface temperature differences over broad areas, they can also help detect wildfires burning in remote regions.

Question 2. How does your agency share this information with Federal and local emergency officials, Federal land management agencies, and water managers to inform their response to drought, wildfire, and flood risks?

Answer. The USGS shares Landsat data and information products with partner agencies working to address these risks. Landsat enables natural resource managers to assess the severity and extent of large fires for planning recovery efforts. For example, the U.S. Department of Agriculture (USDA) U.S. Forest Service (USFS) Burned Area Emergency Response (BAER) team uses Landsat data to map vegetation, water, and soil changes immediately after a fire. With these maps, the USFS can identify the most severely burned areas and treat them to mitigate increased water runoff and erosion. BAER has been estimated to yield cost savings ofup to $35 million over a five-year period. By using Landsat data to map vegetation, water, and soil changes after a fire, response staff can identify the patchwork of burned areas left in the wake of the flames.

Landsat also enables fire fuel mapping through the joint USFS—DOI LANDFIRE program. This program supports a range of land management analysis and modeling for fire behaviors and informs strategic land management.

Worldwide, droughts can have disastrous impacts on lives and livelihoods. Landsat data show the impact of drought on vegetation at a scale that enables water managers to better allocate limited water resources. Landsat's unique thermal infrared data can map evapotranspiration (ET)—water evaporating from the ground or transpiring from the plants—to estimate water use, soil moisture, and drought impacts on vegetation and ecosystems. As climate change exacerbates drought conditions, Landsat can help improve water allocation to support more effective adaptation.

Landsat captures before and after images of flooding across the Nation and around the world, illustrating flood extent, vegetation loss, and structural damage. Landsat can also help monitor post-flooding impacts on water quality and long-term vegetation recovery. By using Landsat to map historic flooding patterns, USGS hydrologists can better predict future flood hazards.

Question 3. In particular, can you describe how the U.S. Geological Survey's Arizona Water Science Center in Flagstaff employs Landsat data when making forecasts regarding the Colorado River and Arizona watersheds?

Answer. While the Arizona Water Science Center's activities focus primarily on field work and in-situ observation, Landsat has complemented this work in the Colorado River Basin and Arizona watersheds. Irrigation accounts for over 40 percent of freshwater withdrawals in the United States. Increased demand for scarce water supplies has shifted water management strategies from increasing water supply to innovatively managing water use at sustainable levels. Landsat's unique thermal infrared data enables field-scale measurements of ET to accurately estimate consumptive water use. With the warming climate and increasing drought conditions, Landsat-based analyses provide a reliable, consistent, impartial, and non-proprietary data source to inform water rights negotiations and resolve water rights disputes. Landsat-based water use information is also combined with climate models to forecast future water use across the Colorado River Basin.

Prolonged drought has changed Arizona's watersheds, water quality and availability, riparian vegetation, and ecosystems. Scientists and land managers use Landsat to monitor vegetation type conversions, native and invasive species along the watersheds, inform watershed restoration efforts, and monitor restoration progress over time. One example involves their use of Landsat to monitor vegetation establishment and growth after installing rock detention structures—low-cost, low-tech, natural systems in dryland streams. Landsat data recorded 30 years of sustained or increased vegetation cover where these natural structures were installed, despite prevailing long-term drought conditions. Landsat observations demonstrated

that these nature-based solutions can help improve watershed condition and boost local climate change resilience.

Additionally, Flagstaff Science Center scientists have used Landsat data collaboratively with the San Carlos Apache Nation in Arizona, to support the Tribe's management of its natural resources. They have used Landsat to assist the National Park Service with understanding potential effects of climate change on wildlife habitat in park lands. The Center's staff has used Landsat data to derive global cropland extent maps to support food security and sustainable agricultural practices.

Heat Health: Large portions of central and southern Arizona experience extreme heat events, particularly during the summer months. Extreme heat can contribute to negative outcomes for individuals who lack access to air-conditioned residences or suffer from ailments that affect the ability of their bodies to regulate heat. 552 people died in Arizona from heat-related causes in 2021, and nearly 2,800 passed away over the past 10 years from heat-related causes.

Question 4. Can your agency utilize Landsat data to predict or track urban areas that will experience the worst heat on a summer day, as well as the features of certain urbanized areas that contribute to or mitigate extreme heat areas? If so, can you describe the process for making those predictions?

Answer. Yes, Landsat has informed municipal authorities' urban heat-island and green infrastructure efforts in various U.S. cities, including metropolitan New York City, Chicago, Illinois, and Boston, Massachusetts. Landsat collects surface temperature and vegetative change information that pinpoints urban heat islands. This information supports urban authorities' actions to mitigate heat stresses for residents. This work is growing in scope and urgency as urban and exurban landscapes throughout the world are growing at a rapid pace, with the total area of urban land cover estimated to triple between 2000 and 2030 and as global average temperatures continue to rise.

Continuing urbanization has numerous impacts on social and ecological systems. These impacts include expansion into critical protected areas, loss of croplands, changes in local hydrology, and changes to local climate. All these factors can contribute to residents' increased heat-borne mortality rates. Monitoring these landscape changes is critical for urban planners, resource managers, and decision makers seeking sustainable and equitable growth. Landsat is well-suited to this task, due to its multi-decade imagery archive, landscape-scale spatial resolution, and range of spectral imaging capabilities.

Descartes Labs, a New Mexico-based startup, has mapped urban growth and heating by using Landsat data combined with machine learning algorithms and Geographic Information Systems. The company produced a map of urban heat islands in the greater Boston area by generating a mosaic of Landsat's thermal bands over several months. Its results show the stark difference between urban green spaces, major transportation corridors, and built-up areas. The team was also able to detect local patterns on the landscape resulting from large climate-controlled warehouses or brick buildings. Through Descartes Labs' platform, it is possible to model seasonal changes in urban land-surface temperature over the course of more than thirty years, with significant implications for the study of climate and its effects on cities.

A September 2019 report featured on National Public Radio also used Landsat thermal-imaging capabilities to determine whether urban areas of lower income are correlated with higher daytime temperatures. The report found a strong, negative correlation between heat and income in many cities, indicating that the urban poor are often more susceptible to heat-related illnesses than their wealthier counterparts.

RESPONSE TO WRITTEN QUESTION SUBMITTED BY HON. JOHN HICKENLOOPER TO KEVIN GALLAGHER

Earth Observation Mission Architectures: The USGS and NASA collaborated on the Sustainable Land Imaging Architecture Study to examine novel concepts for next generation Earth observing missions, including the use of satellite constellations. They also gathered user feedback to establish data requirements and maximize scientific impact of future Landsat missions.

Question. Can you discuss how the findings of this study will impact the Landsat Next mission?

Answer. The USGS participated in two separate efforts to quantify the requirements and determine the architecture of the Landsat Next mission. First, the USGS National Land Imaging Program sought to understand and document user needs as-

sociated with Earth observation in general, and moderate-resolution space-based Earth observation in particular. The Program utilized a peer-reviewed process consisting of hundreds of expert interviews to understand user applications and observation needs. These findings were compared to existing and future observing systems to identify gaps in planned Earth observation capabilities.

These findings were a direct input into our second effort, a mission architecture study. Along with NASA, our Sustainable Land Imaging partner, the USGS commissioned an Architecture Study Team to examine candidate architectures which would maintain the Congressionally mandated Landsat data continuity record while also addressing the gaps identified by our user needs analysis. The Team developed scores of architecture options and evaluated them against mission capabilities, required technologies, and relative costs. It presented its methodology, driving requirements, leading candidate architectures, and its recommended architecture to NASA and DO1/USGS leadership. Recommendations were guided by the need to execute a cost effective solution that would meet the user needs within the schedule and risk constraints of an operational Landsat mission. The architecture proposed by the study team, and eventually accepted by the agency partners and administration, is known as "hybrid triplets". The triplets are a simultaneously operating constellation of three observatories in a repeating ground track Sun-synchronous orbit. The selected architecture achieves an aggregate six-day revisit over the Earth's land surface and more than doubles Landsat's spectral and spatial resolution.

For Landsat Next, NASA and the USGS determined that this hybrid triplets architecture will be the most cost-effective option to meet user needs for emerging science and applications while assuring continuity—an enduring connection—to the historical land record started by Landsat back in 1972.

The new architecture will enhance users' ability to perform land use and urban development planning, observe soil moisture, accurately estimate agricultural water use, assess crop health, understand wildfire risk and forest recovery processes, and respond to natural disasters including flooding, drought, and wildfire, while also supporting many other societal applications.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. RAPHAEL WARNOCK TO KEVIN GALLAGHER

Coastal Erosion: Georgia's coast is home to numerous barrier islands that support thousands of residents and significant biodiversity. These islands play a crucial role in not only tourism and shipping, but also protecting the mainland from powerful winds, tides, currents, storms and hurricanes.

Question 1. Your testimony references Landsat images showing the effects of Hurricane Ian on the coastlines of Georgia and Florida. How does the United States Geological Survey (USGS) use Landsat data such as this to work with local governments to address coastal erosion?

Answer. Landsat's consistent, reliable, repeated observations of Earth's landscapes keep an objective record of their conditions before and after disasters. This information serves as an essential tool for inventorying land resources, assessing the risks of hurricanes, mapping the extent of hurricane damage, and planning post-disaster recovery in states such as Georgia.

Landsat images are among the remote sensing images that feed into the USGS's Hazards Data Distribution System. This system is used by local responders across the Nation to support citizens affected by hurricanes, typhoons, volcanoes, earthquakes, widespread flooding, and other hazards.

During the recent Hurricane Ian, Landsat 8 passed directly over the storm's eye on Sept 28 as the hurricane approached southwest Florida, enabling scientists to scrutinize the images and analyze the forces that made it so catastrophic. In the hours after the storm passed, millions lost power.

Landsat helped capture the extent of the power outage, as well as post-storm sediment runoff from rivers and streams on Florida's southwest coast. Authorities used Landsat to generate the first high-resolution, broad scale land disturbance map detailing damage wrought by the hurricane's wind and storm surge. This map was released just days after the storm to aid teams on the ground in their search and recovery work.

Landsat measures coastal change not only after storms but continuously through time. This capability enables scientists and coastal managers to calculate erosion trends, evaluate processes that shape coastal landscapes, and predict how coastlines will respond to future storms.

Agriculture: As you may know, Georgia is a proud agricultural state. However, changes in weather patterns and climate can threaten the success of Georgia's agricultural sector.

Question 2. Your testimony discusses the importance of Landsat in agriculture. Please elaborate on how USGS partners with the agricultural sector to identify challenges and implement solutions based on Landsat data. How can an agricultural state such as Georgia strengthen its partnership with the USGS to better support farmers?

Answer. Freely and easily accessible Landsat data has long benefited the agricultural sector. The USGS would be glad to work with the USDA and your staff to discuss how Landsat can further benefit Georgia's farmers.

Millions of farmers and consumers already benefit from Landsat data that improve crop and water management decisions. Food and farming organizations rely on Landsat's unbiased, accurate, and timely information. It enables Federal and state agencies, local authorities, businesses, and farmers to analyze the health and vigor of crops they mature over the growing season; to understand needs of specific fields for fertilizer, irrigation, and rotation; to monitor planted acreage to forecast crop production and fight crop insurance fraud; to decide how much water is used in irrigation; and to forecast the impacts of drought on particular crops.

Farmers once had to walk their entire farm, which could be hundreds of acres, on a regular basis to witness the same crop conditions that can now be readily detected by Landsat. The USDA uses Landsat data as a key input into several reports during the growing season that forecast crop production. In turn, the multimillion-dollar U.S. agricultural commodities market relies on these forecasts when conducting futures trading.

Nearly two-thirds of U.S. surface-freshwater withdrawals are for crop irrigation. Keeping track of just how much water gets used—and making sure it gets used efficiently and legally, where and when it's needed across millions of acres of crop land—is no easy task. Landsat images can map evapotranspiration—water evaporating from the ground or transpiring from the plants—to estimate how much water crops are using.

As rising temperatures, more widespread droughts, and intensifying weather events threaten food security and farmers livelihoods, farmers can use Landsat as a tool for effective action before, during, and after the growing season.

Response to Written Question Submitted by Hon. Maria Cantwell to Dr. Waleed Abdalati

Observation Gaps: As one of the co-chairs of the 2017 Earth Science Decadal Survey, Director of NOAA's Cooperative Institute for Research in Environmental Science (CIRES) and a former NASA Chief Scientist, you are uniquely positioned to talk about the Nation's current Earth observations, continuity of those observations, and what may be missing from the portfolio.

Question. On January 5, 2023, it will be 5 years since the release of the last Earth Science Decadal Survey. Given that you are approaching the mid-term assessment, which measurements do you believe are critical to be sustained and which new measurements should be added to the portfolio to improve our understanding of Earth's changing climate? What are the tangible benefits of these measurements (or the consequences of not obtaining these measurements)?

Answer. The *Earth Science and Applications from Space 2017* (ESAS) Decadal Survey was a two-year effort that drew on the input from many hundreds of scientists. The panels and committee that wrote the report numbered approximately 100. The priorities that have been put forward were robustly developed, and they still remain priorities today. As such, my interest is in seeing the recommendations of the Decadal Survey implemented as soon as is practical. There have been some delays, and little has changed in terms of scientific and applications needs, so what were priorities at the time of release remain priorities today. As such, NASA's Earth System Observatory (ESO), which seeks to implement the recommendations of the Decadal Survey in the "Designated Observable" category, should remain the primary focus of NASA's mission development efforts. The ESAS committee also recommended several Earth Explorer mission (missions on the order of $350M each) opportunities to explore several areas among a list identified in the Decadal Survey that spanned atmosphere, ice, ecosystems, ocean and atmospheric winds, snow depth, and trace gases. The discriminator among these would be the feasibility/likelihood of successfully achieving their science objectives within the $350M cost caps. These priorities remain.

Where there is an additional need, however, which was referred to in the Decadal Survey, but for which a path has yet to emerge, is in continuity of some critical measurements that do not quite fit into the NASA Earth process and discovery domains or the NOAA operational domain. These are sustained routine monitoring observations of important environmental parameters that are necessary for us to understand the evolution of our planet, particularly in the face of climate change. We addressed this to some extent in the Decadal Survey, by calling for an Earth Venture Continuity opportunity, which seeks to develop low-cost capabilities for conducting some critical Earth observations in a sustained way to provide this important information. To date, the continuity of observations that don't fall into the NASA or NOAA buckets remains a challenge, and they remain an important need.

The benefits of executing the Decadal Survey recommended missions have been articulated in the Decadal Survey. In short they are an improved understanding of environmental processes that affect the way we live, such that we can be in a position to thrive on our changing planet. The benefits of identifying ways to conduct sustained observations in critical areas are that we will gain a better understanding of the rate of change on our planet and the underlying consequences, which will empower us to meet the associated challenges. Acquiring that understanding—beyond the research and operational domains—is also fundamental to our success as a nation and society in the face of our changing environment. The consequences of not doing both the missions outlined in the Decadal Survey and the additional continuity missions will be a compromised ability to manage environmental changes (natural and human-induced). This compromised ability will be a result of (a) not fully understanding the processes driving those changes and their likely behavior in the future and (b) not understanding the rate at which those changes are occurring and the magnitude and implications of those changes. The absence of such knowledge and information will significantly impede our ability to manage and navigate those changes, resulting in sub-optimal, and in some cases very costly and harmful, responses to those changes.

We as a nation have been very fortunate in the fact that many of our Earth observing instruments (such as those on the Terra, Aqua, and Aura satellites) have surpassed their design lives by decades, and in the fact that many of our international partners have taken on the task, in a number of cases, of sustained observations. However, understanding these variables and processes are too important to leave to good fortune. A well-considered strategy is needed for prioritizing the range of variables needing continuity of measurements and subsequently prioritizing those needs against those associated with operational and discovery capabilities that are the subject of NOAA and NASA investments.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. JOHN HICKENLOOPER TO DR. WALEED ABDALATI

Drought Forecasting: Droughts threaten the livelihood and security of communities across the country. Water resource research is one of the primary focus areas at the Cooperative Institute for Research in Environmental Science (CIRES). CIRES researchers monitor changes in water supply and demand in order to inform policies for adaptation, resilience, and protection of this critical natural resource.

Question 1. What data could next-generation satellites collect to improve our ability to forecast, mitigate, and recover from droughts? Could ground-penetrating radar data aid our research on–and response to–droughts? Are there any current or planned missions flying radar instruments?

Answer. The ability to forecast, mitigate, and recover from droughts has several elements, some of which satellite observations can contribute to through the understanding of drought conditions, their evolution, and the associated processes. Our ability to understand and forecast droughts depends on our ability to assess the state of and changes in: subsurface water storage, near surface wetness of land/soil, rainfall rates, water stored as snow in the snowpack, and the rate at which this rain and snowfall runoff at the surface vs. penetrate into the ground and/or replenish aquifers.

For comprehensive subsurface water mass, the key space-based observational tool we have at the moment is the GRACE Follow-on (GRACE–FO) mission, which determines changes in large scale water storage by measuring perturbations in the Earth's gravity field. An assessment of changes in the water storage from such measurements is shown in Figure 1 for the period 2002–2016. NASA plans to fly a follow-on to the GRACE–FO mission known as the Mass Change (MC) mission, currently planned for launch later this decade. It is expected to have the same capabilities as GRACE–FO. The resolution of this capability is on the order of 100 km,

but technological advances can allow for improvement in the future. Such advances include increased precision and accuracy of the ranging between satellites (the gravity measurements of GRACE and GRACE–FO rely on accurately measuring distance between two satellites in orbit) and flying multiple satellite pairs, with the latter providing the greatest opportunity for improvement and more detailed analyses. Currently there is no plan in place for extended gravity measurements after the Mass Change mission (beyond the early 2030s), leaving a critical measurement capability for drought assessment in question.

For near surface wetness (soil moisture), long wavelength microwave sensors, both active (radar) and passive (radiometers), provide the ability observe soil water content. This is made possible by the fact that soil moisture affects both the emission of microwave energy from within the surface, and the penetration of radar into the soil and associated backscatter. While each provides some capability of assessing soil moisture, when combined (as was the case with the design of the Soil Moisture Active and Passive (SMAP) Mission), the complementary capabilities make for a more robust set of measurements. Currently, our ability to resolve soil moisture is on the order of 10 km, which is useful for homogeneous terrain (such as expansive farmland) but poses challenges on heterogeneous terrain that varies within the footprint. Synthetic aperture radar (SAR) has been shown to provide insight into variability of soil moisture on small scales, but its accuracy is limited by surface roughness and structure. None-the-less, it has the potential to provide information on relative variations in soil moisture. There is a range of synthetic aperture radar missions in operation and planned by international partners, but the U.S. has no current mission on orbit. The U.S. does have one in development, however, NISAR, which is a joint mission with the Indian Space Research Organisation (ISRO).

Another key measure of drought in the form of river and reservoir storage can be ascertained from visible and infra-red imagery, as in the case of the historic Landsat records, showing the drying out of lakes and reservoirs throughout the world. An example is shown in Figure 2 which provides a multi-decadal history of the health and stages of the Colorado River. In addition, surface dryness and its implications for vegetation and health can be inferred from visible and near-infrared imagery, a capability that has existed for decades in a number of forms, and is expected to continue into the foreseeable on commercial, operational, and research instruments.

Finally, the ability to measure and quantify rain and snowfall are key to understanding the sustainment and replenishment of water supplies. Precipitation can be measured using active radar and passive radiometers as is the case for the Global Precipitation Measurement (GPM) Mission, led by NASA and the Japanese Space Agency, JAXA. The resolution of such measurements is about 10 km x 10 km. The spatial character of snowfall deposited on the ground can be measured with visible imagery, since the reflectivity of snow is far greater than the reflectivity of background land surfaces, but the more important parameter is the snow water equivalent (SWE), which is a function of snow depth and density. One tool for measuring snow depth is the laser instrument on NASA's Ice Cloud and Land Elevation Satellite-2 (ICESat-2), since laser scattering characteristics vary as a function of snow depth (Lu *et al.,* 2022). Such measurements provide some insight into snow water equivalent stored in the pack, but without knowledge of the snow density, the information is not complete. One of the missions called for in the Decadal Survey in the Earth Explorer category is a mission to measure snow water equivalent, which would likely be a microwave sensor that "sees" into the snow and can provide information not just on snow depth, but the associated snow water equivalent.

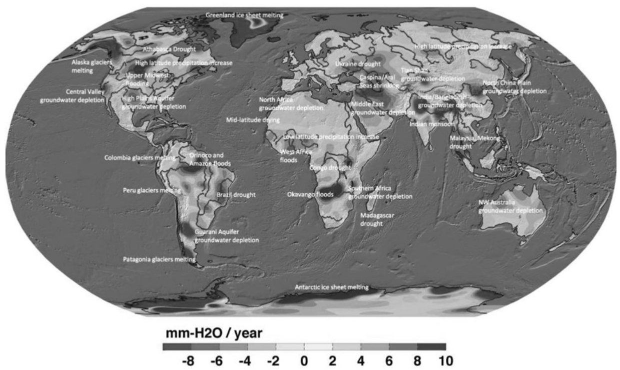

Figure 4: Regional distribution of trends in water mass from 2002-2016, derived from the Gravity Recovery and Climate Experiment (GRACE) satellite mission and its follow-on. While the effects are variable with gains and losses occurring in different locations, the trends show a drying out of the continents and significant mass loss on Greenland and much of Antarctica, and an increase in ocean mass (and subsequently sea level rise) as water flows from land to the ocean. (Rodell et al, 2018, https://www.nature.com/articles/s41586-018-0123-1)

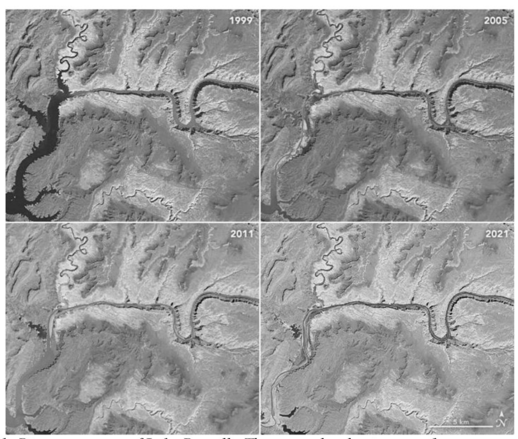

Figure 2: Colorado River upstream of Lake Powell. The natural-color images above were acquired in March 1999, April 2005, May 2011, and April 2021 by the Landsat 5, 7, and 8 satellites. Springtime typically marks the lowest water levels before mountaintop snow starts to melt and run down into the watershed. The images capture years with the two highest and lowest levels over the past 22 years. (https://landsat.visibleearth.nasa.gov/view.php?id=148861)

While the visible imagery, such as Landsat has a robust history, and the outlook is good for sustained observations, the other capabilities are limited going forward. The GRACE and GRACE Follow-on missions will be succeeded by NASA's Mass Change mission, extending gravity measurements into the next decade, however the SMAP mission suffered a failure of its active sensor, and there is no successor planned. Therefore the benefits of radar subsurface measurements will likely not be realized, except through some of the international and U.S. SAR missions, which have their own challenges in retrieving snow water equivalent. The passive microwave sensors are expected to continue through the coming decade, but their future beyond that is uncertain. The likelihood of a mission to directly measure snow water equivalent is not known, because it will depend on how successfully such a mission competes in NASA's Earth Explorer budget line. Our vision on the decadal survey was for there to be three Earth Explorer missions in the 2017–2027 decade to address three of the seven priority areas identified in the Decadal Survey:

- Greenhouse gases
- Ice elevation

- Ocean surface winds and currents
- Ozone and trace gases
- *Snow depth and snow water equivalent*
- Terrestrial Ecosystem Structure
- Atmospheric Winds

Unfortunately, there will likely be only one or two, rather than three. The future of snow depth and snow water equivalent measurements will depend on the success of such a proposal in the limited Earth Explorer competition(s).

All of these on-orbit or planned sensors provide the capability to observe the movement and evolution of water on and within the Earth's surface and in the atmosphere, however, predicting water resource availability and the associated implications, requires the integration of these observations with meteorological and hydrological models. Moreover, managing the challenges associated with changes in water resource availability requires policies that are targeted toward ensuring that whatever the effects of natural and human-caused climate change are, society can adapt. The satellite observations are a fundamental tool for informing those choices, but in the end, managing the challenges depends on a combination of observations, modeling, policies adopted, and choices made.

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Decadal Survey Recommendations on Commercial Data Use: NASA's Decadal survey provides a forum for members of the scientific community to help guide the agency's objectives and future missions. You recently served as the Co-Chair of the Earth Decadal Survey, which discussed the utility of commercial Earth Observing datasets.

Question 2. Can you share more about why the Earth Science Decadal Survey focused on the importance of commercial data sources in its recommendations?

Answer. The Earth Science Decadal Survey explicitly pointed to the importance of commercial data sources primarily because the need for space-based observations in meeting critical societal goals is such that NASA's budget cannot accommodate them all. It was also done because commercial capabilities have evolved considerably in the last decade to the point where they can be a more cost-effective tool for some Earth observations. Because of limits in Federal resources, and because NASA does not have the budget to carry out all the work that is needed, the adoption of more cost-effective ways of observing the Earth is a necessary part of the space-based Earth observation portfolio. There are some cases in which the commercial sector can provide Earth observing capabilities of sufficient quality at a significantly lower cost than Federal agencies can develop them. These tend to be in areas in which a commercial business model can be profitable, such as with visible and infrared sensors. As a result, the science community sent a clear message that when these cost-effective methods can be used to provide sufficient critical Earth observations of high priority parameters, they should be used so that more could be done with the resources available. The commercial sector is by no means a substitute for the science capabilities that NASA missions enable or many of the operational capabilities that NOAA missions provide, but they are an important complement for providing cost-effective measurements that have become more routine and don't require significant technology development in order to provide useful data for scientific and societal purposes.

NASA & NOAA: Roles and Missions: You have a great deal of experience working with both NASA and NOAA. CU-Boulder now has a research partnership with NOAA through the Cooperative Institute for Research in Environmental Sciences (CIRES).

Question 3. Can you discuss the importance of interagency coordination to federally-funded Earth Observation missions? Do you have any suggestions for improvements to prevent unnecessary duplication or uncertainty over responsibilities?

Answer. Interagency coordination is absolutely critical for an effective Earth observing program. Were there to be overlap in observing capabilities, there would be

an inefficient use of resources. Where there are gaps between the agencies' combined portfolios, there is an absence of knowledge and information fundamental to societal success. Both agency missions are clear, and I don't see significant overlap in capabilities, but there are important gaps, and going forward it is crucial that all of the needs for space-based Earth observation be articulated, and an agreed-upon framework that involves all relevant agencies be adopted for meeting those needs.

These gaps arise from observations that are needed to understand and prepare for the Earth's changes and their implications for local, regional, national, and global populations but do not fit either into NOAA's operational mission or NASA's mission of discovery and process understanding. Examples include monitoring the evolution of Arctic sea ice, monitoring sea surface heights and sea level rise, assessing the changes in ice sheet mass balance and their implications for sea level rise, monitoring the Earth's radiation budget, etc. In each of these cases, I refer to monitoring. This is because climate variations and associated implications require observing for sustained periods of time for the purpose of understanding the evolution of the state of certain geophysical variables (such as sea surface height). Such observation strategies are not geared toward immediate operational (*e.g.,* weather forecasting) needs, and at the same time they do not fit well into the category of exploring and understanding Earth environmental processes.

Addressing the need to fill these gaps requires a well-considered strategy for prioritizing the range of variables in need of continuity of measurements and establishing a framework for implementing these observations. Doing so means that NASA's or NOAA's (or both) agency responsibilities would need to be expanded to address the need for this kind of monitoring, and resources would need to be allocated for this purpose. If additional resources were not to be allocated for this expansion of agency mission, then they would come at the expense of current agency priorities, which both agencies are having difficulty meeting in the current budget environment.

In such a scenario, judgements would need to be made on the relative value of these monitoring missions against the exploration and operational value of the missions currently in the portfolio. In the end, our success as a nation depends on robust capabilities in all three areas—research, operations, and monitoring.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. RAPHAEL WARNOCK TO DR. WALEED ABDALATI

Natural Disasters: Your testimony discusses how space-based observations can be used to track storm trajectories, vulnerability to storm surges, and other weather threats to people.

Question 1. How can these observations better help communities in states such as Georgia, which may be vulnerable to natural disasters such as tornadoes and storms, prepare and respond to natural disasters?

Answer. These observations are already used to help communities prepare for natural disasters in that they inform prediction and allow for short-term preparation for impending disasters such as tropical storms and coastal flooding. However, this is under conditions in which disasters are imminent, and the data and associated forecasts can inform evacuations, rescue, and other quick-response strategies. Ideally, preparation for natural disasters should occur long before they strike. As a result, in addition to forecasts, there is a need for assessments of disaster likelihood and vulnerability, so communities can prepare in advance. If we just consider one example, such as coastal flooding in Georgia, such assessments would include understanding coastal topography, an assessment of vulnerability to storm surge, the determination of coastal sea level rise, etc. In western states, such assessments would likely be along the lines of vulnerability to fire or drought. For the Georgia coastal flooding example, observations and data that support such assessments include:

- the history of meteorologic observations that show the evolution of tornadoes, hurricanes, and other severe weather,
- the time series of regional sea level rise,
- local topography,
- integrity and vulnerability of structures and infrastructure in coastal regions,
- rain rates to assess flooding risks.

NASA has made a concerted effort to work with the applications communities, the kind that would be doing these types of assessments, to better understand their

needs and to produce data in usable formats. At the same time, NOAA produces coastal topography maps, and forecasts that allow for the risk assessment in the near term. What is needed, however, involves a more integrated strategy of multiple agencies (NASA, NOAA, USGS, NSF, FEMA, etc.) to quantify risks that would inform building strategies and management approaches. A simple example is the reassessment of flood zones. What was a 100-year flood zone as little as 30 years ago, is often now subject to the recurrence of those "100-year-floods" in just a few decades, or in some cases, just a few years (Marsooli *et al.,* 2019). Space-based observations, provide the foundational data to inform such reassessments, by providing fundamental insights into the processes that produce such disasters and by tracking the history and evolution of change, thus informing assessments of the rate, magnitude, and likelihood of future change. Similar assessments should be made for the other types of risks, such as fires in the drying west, landslides in mountainous regions, and flooding near rivers, to name a few.

Question 2. What challenges, if any, have you observed in the ability of communities to effectively use these space-based observations to prepare for natural disasters?

Answer. In some ways this depends on the types of disasters. For those related to weather (which can include fires and flooding), the challenges have been limited, as a result of our Federal agencies being good at examining the data and model results and predicting the likelihood of natural disasters and where they will occur. The forecasts have improved significantly over the last two decades, and the location and magnitude of weather-and climate-related disasters are much better understood than they were even ten years ago. NOAA, as an agency with an operational focus has always had a history of delivering products (whether derived from observations or models) that are usable by the community.

The products primarily developed by NASA have been more in the domain of advancing research and advancing knowledge, and thus have been developed more for use by a particularly data savvy research community. More recently, however, it has become clear that NASA's Applied Sciences Program has made a robust and concerted effort to broaden the base of users of space-based observations for applications, including disaster preparedness and response, and ensure that their products are of such a nature that these communities can make effective use of them. NASA deserves great credit for their efforts to work from a user-needs perspective (which includes data formats, volumes, and other usability considerations) as a complement to its efforts to advance scientific knowledge and understanding. There are still some hurdles to overcome, as community management entities tend to stick with familiar types of data and systems, but the conversations between the expanding base of potential users and NASA will improve this aspect of disaster preparation. NASA's continuing efforts in this area should be supported and commended.

To summarize, the challenges have not been in the domain of forecasting and use of forecasts, which is familiar to many and has been very successful. The challenges are more in the domain of direct data use from observations, as not all potential users are familiar with or comfortable with these data products. The situation is improving, as NASA continues to strive to understand user needs and works to present data in forms that are most valuable to user communities, and as these user communities continue to become more comfortable and familiar with how to use these types of data sets.

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