Center for American Progress

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# Understanding Our Future

## Frontiers of Climate and Energy Data and Research

By Luke H. Bassett, Kristina Costa, Ryan Richards, and Dinu Krishnamoorthi September 2018

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# Introduction and summary

In the three months since the Center for American Progress published its initial assessment of budget cuts and political interference in U.S. federal climate and energy data and research programs, the effects of climate change have continued to wreak havoc on communities in the United States and around the world.[1] The Mendocino Complex Fire became California's largest wildfire in recorded history.[2] Smoke from that wildfire and others burning across the West have choked cities, and now the top five U.S. cities with the worst air quality are all in Washington and Oregon.[3] In 2018, the United States and Europe both experienced their hottest May through July periods in history; some areas, such as the Mid-Atlantic, have experienced record precipitation while others, such as New Mexico, have seen record dryness.[4] Washington, D.C., has received the eighth-highest amount of precipitation on record for the January through July period.[5] The first tropical cyclone since 1992 to strike Hawaii, Hurricane Lane, delivered a historic 52.02 inches of rainfall, a level surpassed only by one other cyclone in U.S. history.[6] But these alarming events have passed with essentially no notice from the White House or leaders in Congress; indeed, as the Mendocino Complex Fire burned, the Trump administration announced proposals to dramatically roll back both fuel economy standards for passenger vehicles and the first-ever limits on carbon pollution from the power sector.[7]

The United States has long led the global community's investment in and performance of the core scientific research needed to understand Earth's interconnected systems. From the atmosphere to the oceans, from energy systems to food and water flows, and from distant satellites to microbial studies, U.S. scientists have laid the groundwork and led collaborative efforts to better understand these systems from the smallest to the largest scales. This knowledge of the historic, current, and potential conditions on Earth has shaped policymaking, business decisions, public health outcomes, national defense, and even the ability to put bread on kitchen tables across the country.

The Trump administration has twice proposed unprecedented, draconian cuts to federal investments in climate science and data collection programs. The administration's budget requests would have yielded a $2.4 billion cut, or 16.8 percent, between FY 2017 and FY 2018, and a $1.89 billion cut, or 13.2 percent, between FY 2017 and FY 2019, according to a CAP analysis released earlier this year.[8] Congress has so far roundly rejected these proposals, restoring critical budgets the Trump administration proposed zeroing out and even increasing funding over Obama-era levels at times. In some cases, Congress has also provided guidance to the Trump administration to prohibit political appointees from scuttling long-planned Earth sciences missions. For instance, alongside a $150 million proposed cut to NASA's Earth Sciences programs, which observe and research the Earth and its natural systems, the Trump administration's FY 2018 budget request would have completely eliminated four major planned or ongoing satellite missions: the Plankton, Aerosols, Cloud, Ocean Ecosystem (PACE); the Orbiting Carbon Observatory-3 (OCO-3); the Deep Space Climate Observatory (DSCOVR); and the Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder. Congress ordered all four programs continued and appropriated funds to do so in its March 2018 omnibus spending package.[9]

However, the broad, bipartisan Congressional rejection of these proposed budget cuts does not mean that the federal climate science apparatus is safe from political interference. Federal agencies retain broad latitude to not obligate funds appropriated by Congress for research programs, reports, and other activities, so long as Congress did not provide explicit instruction to conduct the work. For instance, the Trump administration's FY 2018 budget request also proposed eliminating NASA's Carbon Monitoring System, a research program that enabled the remote monitoring of carbon emissions in the atmosphere and helped buttress international verification of whether countries are fulfilling their pledges to reduce tropical deforestation, among other initiatives. Congress failed to explicitly direct NASA to continue the program, leaving the Trump administration free to cancel it—which it did.[10] This ongoing budgetary uncertainty makes planning and conducting years-long scientific research initiatives increasingly difficult, whether inside federal agencies or at research institutions supported by federal grants.

At the same time, efforts to understand Earth's systems have never been riper with opportunities for scientific discovery. There is no doubt about the science of climate change: Carbon dioxide released by burning fossil fuels is driving CO2 concentrations in the atmosphere to levels not seen in all of human history, thereby increasing global average temperatures, causing the accelerated melting of glaciers and ice sheets, and increasing the severity of weather events—from droughts to wildfires to extreme downpours and floods. But beyond the basics, the severity and urgency of climate change presents an incredible set of challenges and important research questions for scientists and policymakers to address.

The United States needs to abandon President Trump's dismissal of Earth sciences and climate change and redouble its efforts to fund, perform, collect, and analyze the scientific data and research that remain integral to living on this planet and acting in its and our own best interests. To do this, the Center for American Progress proposes doubling federal investment in climate and energy data and scientific research over the next five years, over a FY 2016 baseline of $15.6 billion across the programs and activities of the 13 federal agencies that make up the U.S. Global Change Research Program.[11]

Going forward, several framing questions arise for the scientific and policy community regarding climate and energy data and research, including:

- What can we expect climate change to mean for Earth's natural systems on land, in the oceans, and in the Arctic?
- What will climate change mean for humanity and society—for our health, our economies, our cities, and the weather we experience day to day?
- What is required to pursue these and other important research questions, in terms of crosscutting programmatic, infrastructural, and organizational investments?

This report seeks to provide some initial answers to these questions. It identifies areas where opportunities and needs exist for continuing and expanding the U.S. federal government's investment in data collection, new capabilities for monitoring and analysis, and further research. By no means comprehensive, this report is intended to serve as a starting point for much-needed discussion to prevent data gaps in current programs and to look forward to the reestablishment and expansion of our efforts to understand our changing planet.

# What does the Earth's future look like?

Climate change has already profoundly reshaped ecosystems on land, in the oceans, and in the planet's polar regions, from earlier springs to longer wildfire seasons to rising temperatures on both land and sea. Even if carbon and methane pollution from human activity were to cease completely tomorrow, additional changes to the planet are already baked into the system as a result of past emissions.

## Polar regions

The Arctic is the canary in the coal mine of climate change. The Earth's remote polar regions are warming twice as fast as the rest of the world.[12] Sea ice covers 32 percent less of the Arctic at its lowest point in the annual sea ice cycle today compared to 1979, the first year in which complete satellite data were available.[13] A warming Arctic has real consequences for people far from the Arctic Circle: Not only do melting glaciers in Greenland and elsewhere increase sea levels, Arctic warming and the weakening of the polar vortex has sent unprecedented cold snaps and tumultuous weather into Europe and North America.[14]

Despite the importance of the Arctic to global climate change, the region's remoteness and historic challenges in collecting data mean there are significant gaps in our research programs that ultimately inhibit broader understanding of and planning for climate change.

For instance, the global Argo project has some 3,800 floats—small data collection devices that measure sea temperature and salinity—drifting freely in the global ocean.[15] In just 18 years since the first float was launched, Argo has transformed scientists' understanding of how climate change is affecting the global ocean. However, at any given time, the majority of the floats are clustered in the mid-latitudes, between 40 degrees North and 40 degrees South, with relatively few monitoring the far northern latitudes and the Arctic.[16] The first drifting buoy ever deployed north of the Bering Sea was released less than a decade ago, in 2009.[17] While the remoteness of the Arctic and the variability of sea ice extent creates logistical challenges for deploying additional floats, the current generation of Argo floats is equipped with two-way communication and ice-sensing algorithms.[18]

An ambitious next-generation Arctic Ocean-monitoring program could take advantage of new developments in artificial intelligence and drone technologies to build a fleet of remote-controlled, semiautonomous floats that could be deployed to conduct strategic sampling of the Arctic Ocean and build a more comprehensive data set for use in climate science modeling, weather research, and even commercial applications, such as predicting the availability of shipping lanes. In fact, the Danish shipping giant Maersk is planning to send its first container ship through the Arctic this month to test the viability of the route and to collect scientific data.[19]

Significantly more research is also needed to understand trends affecting permafrost, the thick layer of soil, rock, organic matter, and water that has remained frozen year-round for thousands of years, deep underneath some 25 percent of the Northern Hemisphere.[20] An estimated 1,400 gigatons of carbon is essentially locked up in the permafrost, in the form of frozen plant and animal matter.[21] The permafrost is covered by an "active layer" that freezes and thaws in the same kind of annual pattern experienced at lower latitudes and allows vegetation to grow in the tundra.

But now the permafrost is beginning to thaw—and that has huge implications not just for the Arctic, but for the global climate. Already, permafrost temperatures have risen by up to 2 degrees Celsius, according to the Arctic Council, and the southernmost extent of the permafrost is moving north, by as much as 80 kilometers over the past four decades.[22] Roads and runways in Alaska are buckling, and building foundations are shifting as a result of the permafrost thawing.[23] Thawing permafrost coupled with disappearing sea ice can also increase rates of coastal erosion in the Arctic, imperiling centuries-old native settlements.[24] Thawing permafrost is suspected to have released long-dormant anthrax microbes that killed at least one boy, sickened more than 70 people, and killed more than 2,000 reindeer in Russia in 2016.[25]

The 1,400 gigatons of plant and animal carbon currently locked in the permafrost is more than the amount of carbon currently in the atmosphere.[26] As the permafrost warms, microbes are able to access previously frozen plant and animal matter and cause decomposition, thereby releasing carbon dioxide or methane into the atmosphere, causing more warming and thawing more permafrost in a feedback loop.

Some recent studies and findings indicate that the permafrost may be thawing faster than expected. A recent NASA-funded study found that a little-known process called "abrupt thawing" may be accelerating the timeline for the greenhouse gas-permafrost feedback loop to begin.[27]

While scientists don't expect all 1,400 gigatons to be released, the question of how much decomposition will occur, how quickly, and whether the processes will release predominantly carbon dioxide or methane—the latter has a greater short-term effect on global warming than carbon dioxide—are all vital research questions.[28] A next-generation permafrost research program would need more support for field research and increased efforts to connect field research with satellite remote sensing and climate modeling.[29]

## Land

Beyond Earth's polar regions, trends in terrestrial ecosystems and agriculture are both critically important to the trajectory of the future climate and the well-being of billions of people. The changes are already evident in the United States, where the magnitude of wildfires is estimated to be growing in large part due to changes in the climate.[30] A consistent trend toward more arid conditions in the Southwest, along with more than 100 million dead trees in California's Sierra Nevada following a multiyear drought, are clear signs of the challenges that are rapidly approaching.[31] Governments, NGOs, and businesses have led a growing call for greater understanding of the possible effects on agriculture, biodiversity, and water, both in the United States and around the world.

Understanding how terrestrial systems function and how they will be affected by climate change is critically important to predicting climate scenarios and preparing society for the future. At present, federal efforts to understand these systems are diffuse, with significant gaps that could be addressed through an increase in funding toward specific priorities. Chief among these priorities is the collection of data on ecosystems and their interactions with regional and global components of the climate. Recent advances in computing—for example, processing capacity and machine learning—have extended our capacity to model complex systems, but good, fine-scale data are needed to ensure that these models are as precise and accurate as possible.

Increased monitoring efforts should be used to understand ecosystems at different scales. This is important both to minimize risks to communities and natural resources and to better inform the management of ecological systems in order to reduce future carbon emissions. Specifically, there is a need for more observation locations and more frequent measurement of how forests interact with the carbon cycle under different scenarios.

Forests in the United States are estimated to be able to store 14 percent to 19 percent of U.S. carbon needs, which is a wide band of uncertainty given carbon reduction commitments. In addition to varying by forest type and tree species, carbon uptake varies with precipitation and the age of a forest community—and many of these variables change every year. The U.S. Forest Service has a backlog of more than 800,000 acres of land where forests should be replanted, and states have also made their own commitments.[32] Better data will help these entities prioritize investments—as well as other forest management decisions—as part of their commitments to emissions reductions.

Similar investments in agricultural systems are important to both preparing food systems for change and investing in land uses that contribute to emissions reductions. Specifically, long-term data collection on soil carbon—and plant-soil carbon interactions—is important for mitigation and adaptation. While the Natural Resources Conservation Service within the U.S. Department of Agriculture conducts periodic assessments of specific resources,[33] data collection efforts should be increased to help refine models of environmental risks[34] and to inform outreach efforts to farmers as well as emerging policy tools such as environmental markets for carbon and other ecosystem services on agricultural lands.[35]

Ecological research should extend beyond soil and carbon as well. Monitoring of ecosystems through the National Science Foundation's Long-Term Ecological Research Network has had a significant influence on our understanding of ecosystem functions and development of environmental policy, but the coverage that these projects provide should be extended to refine our understanding of how the effects of climate change vary across ecosystems and regions.[36]

Other natural systems merit greater monitoring effort as well. The U.S. Geological Survey (USGS) conducts a water census every five years to track usage across different economic sectors throughout the country, and cooperates with other agencies to monitor river flows and precipitation patterns.[37] However, the current approach to data collection on water usage provides limited snapshots, and given the rapid changes in precipitation that may occur—such as the drought in California and the longer-term aridification patterns in the Southwest—there is a clear case for aggregating data more frequently to help the multitude of agencies and businesses responsible for managing water prepare for future scenarios.

## Oceans

The oceans are the lungs of the planet, with marine plankton responsible for generating as much as 70 percent of the oxygen in the atmosphere.[38] Oceans are also the planet's biggest carbon sink, absorbing a quarter of carbon pollution generated by human activity and 90 percent of the excess heat caused by climate change.[39] However, all of that additional carbon dioxide and heat energy has serious consequences for the health of marine ecosystems and the food chains and coastal economies that depend on them. Higher ocean temperatures increase thermal stress on the coral reefs that provide habitat to thousands of fish species worldwide, leading to bleaching events and mass coral die-offs.[40] In just the past two years, half of the corals in Australia's Great Barrier Reef have been "bleached to death."[41] In addition, when the carbon dioxide emitted from burning fossil fuels is absorbed into the ocean, it reacts with seawater and turns into carbonic acid, which in turn lowers the pH levels of the ocean.[42] This phenomenon, called ocean acidification, makes it harder for corals and shellfish to form the calcium carbonate shells they need to grow and thrive—further endangering the marine food web.

In general, however, scientists know less about the ocean than they do about land-based ecosystems. "More than 80 percent of our ocean is unmapped, unobserved, and unexplored," according to the National Oceanic and Atmospheric Administration (NOAA).[43] Even as this report was being prepared, scientists on a mission funded by NOAA, the Bureau of Ocean Energy Management, and the USGS found a previously undiscovered deep-sea coral formation, full of robust, healthy corals, stretching for at least 85 nautical miles off the South Carolina coast.[44] There are enormous opportunities for research to uncover, for instance, what makes some species of corals more resilient to climate change-related stressors and whether those genetic advantages can be passed on to future generations of corals to help replant and regrow reefs that have been damaged by rising ocean temperatures.[45]

A number of countries, including the United States, have in recent decades designated vast marine protected areas in their territorial waters—marine national monuments and parks where no fishing or other commercial activity is permitted. There is some evidence that fully protected marine areas may be better able to withstand the climate change-related stresses facing the entire ocean—for instance, the coral reefs contained in the Philippines' Tubbataha Reefs National Park appear "comparatively resilient," according to the Global Ocean Refuge System.[46] The George W. Bush and Obama administrations collectively designated more than 1.9 million square miles of ocean as marine national monuments; other nations that have designated robust marine protected areas include the United Kingdom, Chile, Ecuador, and Mexico.[47]

A next-generation ocean science program should increase monitoring and research in these areas to better understand how robust marine protected areas can serve as a cost-effective climate adaptation strategy for the global oceans.

In addition to causing oceans to grow warmer and more acidic, climate change is also causing sea levels to rise around the world due to a combination of thermal expansion—warmer water takes up more space than colder water—and the melting of land-based glaciers and ice sheets.[48] More research needs to be done both on the expected rate and extent of future sea level rise as well as how to make coastlines more resilient to sea level rise and storm surge.

The question of how rapidly the Antarctic ice sheets are going to melt is critical for predicting and adapting for future sea level rise. Most projections of future sea level rise, which predict at least a foot of sea level rise by midcentury, only accounted for thermal expansion and the melting of land-based glaciers and haven't considered the potential breakup of massive ice sheets in Greenland and Antarctica. A study published last year incorporating new Antarctic ice-sheet modeling for the first time concluded that sea levels would rise roughly twice as much between now and 2100 as previously believed, absent immediate action to sharply reduce greenhouse gas emissions.[49] While the National Science Foundation and NASA are both already supporting research into Antarctic ice-sheet dynamics, a next-generation ocean research program could include additional monitoring and observation resources for the Antarctic, including additional research trips.[50]

Forty percent of Americans live in coastal counties, and most of the world's biggest cities are located in coastal areas.[51] Coastal counties in the United States account for $7.9 trillion in gross domestic product and more than 50 million jobs, according to NOAA.[52] The difference between one foot, two feet, and four feet of sea level rise for the millions of Americans—and billions of people globally—living at or near sea level could determine the fate of coastal economies and countless livelihoods.[53]

However, all coastlines aren't created equal—some are rocky and elevated, as in much of the Northern California coast, whereas others are made up of fragile barrier islands, such as in the Carolinas, and still others are home to mangrove swamps and marshy wetlands that can absorb some seawater and deflect damaging storm surges. In a future administration, the federal government could consider a next-generation research program on climate risk to coastal communities that brings together climate scientists, experts in coastal geomorphology, municipal finance experts, and city planners to better understand the relationship between sea level rise, realistic coastal adaptation projects, and the viability of sustaining local economies.

# What will humans and society face in the future?

In the past several years, events such as the wildfires in the western United States, hurricanes, and severe drought and heat waves have illustrated the increasing need for tools and information that enable decision-makers and citizens to act quickly, plan ahead for multiple scenarios, and remain flexible in the face of ongoing changes in our environment. Although they stand out, these climate-related disaster events capture only one set of the factors where Earth systems shape or interact with human and societal systems. Climate and energy data and research need to be mainstreamed into policymaking around economic and labor force trends, public health risks, transportation and energy policies, and much more.

## Weather and precipitation

Most popular discussion of climate change centers on weather and precipitation. Time and again, the European Centre for Medium-Range Weather Forecasting has outperformed the U.S. weather model, called the Global Forecast System, most notably during hurricane seasons.[54] The Trump administration has announced that improving U.S. weather forecasting capabilities is a top priority, but it has simultaneously defunded climate research, repudiating the necessity to invest in both.[55] Improving the performance of weather modeling—and by extension that of climate modeling—depends on different spatial and temporal scales, feedback loops, and interdependence with inputs from other Earth systems. Weather forecasting occurs in four dimensions: across the latitude and longitude of Earth's surface, vertically through the atmosphere, and through time. Additionally, weather models must account for changes in complicated energy flows involving the sun, elements of the atmosphere from water vapor to ozone, and temperature and physical characteristics of the land, land cover, and oceans. When researchers improve the resolution of any one set of these data and analytical calculations, the forecasting or climate models improve.[56] Data collection, analytical capabilities, and scientific expertise also depend on the supercomputing capabilities to perform these complex calculations quickly, as discussed further below.

## Economics and labor productivity

The question of how changes in the climate affect the economy is one of the most complex and urgent in all of climate science. Efforts such as the Risky Business Project have provided national and regional analysis of the potential economic impacts of climate change to key sectors, such as agriculture and coastal property.[57] But climate change projections are not typically taken into account in projections of economic growth, even though rising extreme heat, severe weather disruptions, and sea level rise all have a direct effect on labor productivity, personal wealth, and the economy. A recent study from the Federal Reserve Bank of Richmond found that every 1-degree Fahrenheit increase in average summer temperatures decreases state-level economic output growth by 0.15 to 0.25 percent annually.[58] Much more work remains to be done to make such analyses usable to policymakers and to integrate climate change projections into economic decision-making—from where to build new developments to what worker protections will be needed in outdoor industries.

More thorough investigation is needed, as well, into how higher temperatures affect educational attainment, which is a key driver of economic growth and a global public policy priority. Some studies have indicated that test scores are lower in hotter years, and that better school infrastructure, including air conditioning, can mitigate the negative effects of higher temperatures on learning.[59]

One urgent issue that the federal government is not currently engaging with in a serious way is updating the social cost of carbon, which provides a measure of economic harm from climate change for use in cost-benefit analysis and rulemakings. During the Obama administration, a federal interagency working group devised the first federal social cost of carbon, which increased over time; the central 2020 value was $45 per ton.[60] The group also tasked the National Academies of Sciences, Engineering, and Medicine with formulating recommendations for updating the social cost of carbon to better reflect a fuller scope of economic damages from climate change; the National Academies released two thorough reports on how the federal government should go about building a robust, in-government research program to formulate this critical economic value.[61] Those recommendations appear to have gone unheeded by the current administration, which last year sharply revised the social cost of carbon downward to between $1 and $6 per ton.[62]

Economic activity also contributes to the United States' carbon emissions profile, and depending on the accuracy, geographic and temporal operation, and even simply the existence of data collection, the relationship between these activities, their growth or decline, and carbon emissions may be well or poorly understood. The U.S.

Environmental Protection Agency's (EPA) data collection on methane emissions from agriculture—particularly those from grazing animals—has relied on estimates that until recently may have been too conservative.[63] At the same time, due to the requirements under the Clean Air Act, the EPA continuously monitors the emission of carbon and conventional air pollution from power plants and certain other industrial sources, and pairing these data with Energy Information Administration data on energy use enables researchers to better understand the relationship between economic growth, energy demand, and carbon pollution.[64] Data collection and research regarding the connections among U.S. economic activity; natural resource use, including energy, land, water, and others; and air and carbon pollution is under attack from the Trump administration, and these analytical tasks must remain at the forefront of any agenda to address climate change going forward.

## Public health

The Fourth National Climate Assessment (NCA) illustrates the many connections between climate and energy systems and public health, ranging from direct effects such as air pollution and specific events such as wildfires to less obvious effects such as shifts in the range of disease-carrying vectors including ticks and increased incidence of respiratory diseases such as asthma due to changes in temperature and pollution.[65] The federal agencies involved in data collection and research relevant to these areas include the EPA; the National Institutes of Health, specifically the National Institute of Environmental Health and Science (NIEHS); and the Centers for Disease Control and Prevention (CDC). Scientists in these agencies—and those funded through grants overseen by the agencies and the National Science Foundation—conduct research that advances the ability of the United States and other countries to understand, plan for, and respond to health trends and emergencies large and small.

Although the Trump administration has targeted the EPA's scientific research and operations budget for cuts, the agency's scientists and facilities perform some of the most important data collection and analysis related to climate change and the public health trends it effects. In addition to continuous monitoring of individual sources of air and carbon pollution, from power plants to industrial sites, the EPA conducts extensive vehicle testing and coordinates with the Energy Information Administration on energy sector data and the USDA on land sector data, among others.[66] Despite this extensive data collection, analysis, and transparency, certain gaps exist where individual sources of emissions are especially challenging to monitor or estimate. For example, petroleum refineries and petrochemical plants are a major source of industrial emissions, but their complexity creates immense difficulty for monitoring and modeling air and carbon pollution sources. The inadequacy of current tools to monitor and model sources of air and carbon pollution from these facilities raises health risks for communities near them and impairs planning and mitigation efforts.[67]

Research conducted or funded by the NIEHS and the CDC has strengthened the United States' ability to understand interactions among changing climatic patterns, the range of disease-carrying vectors, and the environmental conditions that increase or decrease human exposure and susceptibility to infection and other health effects.[68] The incidence of diseases caused by mosquito, tick, and flea bites more than tripled in the United States between 2004 and 2016, in part due to those pests increasing in number and entering new areas.[69] For several decades, public health organizations, philanthropies, medical centers, and governments have coordinated efforts and increased funding to mitigate or fully eradicate several of the most serious diseases carried by these vectors, including, notably, malaria; the ability of climate change to multiply and intensify such threats both in new and existing ranges will require research and action.[70] In 2016, an estimated 216 million malaria cases and 445,000 deaths occurred globally, despite approximately $2.7 billion in investments in control and elimination, and this example illustrates only one set of potential public health threats exacerbated by the changing climate.[71] A new administration could increase funding for medical and ecological research for other less-well-understood diseases and associated vectors, including Lyme disease and waterborne diseases. Additionally, the federal government has a critical role in translating weather and climate data and trend analysis into actionable information for public health officials, particularly at state and local levels, so that health emergencies and trends are met with informed decision-making.

## Energy systems

With nearly half of U.S. greenhouse gas emissions caused by burning fossil fuels for energy and incredible growth in renewable energy in the past decade, the causes of and solutions to the most significant portions of the U.S. carbon budget hinge on obtaining and putting to use high-quality data and analysis on the energy sector.[72] The EPA and Energy Information Administration (EIA) collect the majority of energy sector data either through industry surveys or emissions-monitoring devices and testing.[73] The EIA's data collection and analysis sets a high standard for transparency and comprehensiveness, but even so, and in the advent of increased funding, the agency could expand the scope, granularity, and regularity of its data collection in the electric, industrial, and buildings sectors. For example, the EIA could expand its electricity data set to include more accurate information regarding distributed devices beyond the recent addition of estimates for distributed solar photovoltaic systems.[74] The EIA conducts its major end-use surveys for residential, commercial, and manufacturing sectors only on a multiyear basis, and with rapid changes occurring in energy consumption in each of these sectors, businesses, homeowners, and the public could use more detailed, accurate, and regular updates.[75] Much of these data inputs shape how the EIA models the energy sector overall, using its National Energy Modeling System, which subsequently aids policymakers and industry leaders in understanding energy market trends and outcomes.[76]

## Transportation

The rapidly changing U.S. transportation sector illustrates the challenges and opportunities facing policymakers and researchers at the nexus of climate change and societal systems. Given the increasing need to reduce carbon emissions from the transportation sector and policy and technological developments that continue transforming it—from ridesharing and autonomous vehicles to transit-oriented development and more—data collection and analysis present incredible opportunities for actionable research.

With decision-making authority largely held at the regional, state, or local level, the quality and granularity of data—in terms of both time and geography—remains lacking. As an example, the American Community Survey is administered on a yearly basis by the U.S. Census Bureau and collects data regarding commuting patterns, teleworking, and other aspects of the transportation system.[77] The survey does not paint a complete picture of how people use various modes of the transportation system, particularly when considering the vast quantities and higher-quality data acquired on a real-time basis by private applications such as Lyft, Uber, Apple, Waze, TomTom, or other GPS-based mapping software. Similarly, the National Household Travel Survey, published semiregularly, provides further information on vehicle miles of travel and other critical transportation data types, but more regular data collection and updating would improve its usefulness.[78] The shift from an annual survey with a relatively small sample size to nearly instantaneous data sets on point-to-point travel for millions of Americans illustrates a gigantic leap in data collection, but the analysis needed to turn these data into useful tools for transportation planning and resilience or to assess or reduce of carbon emissions and energy use may not yet exist.[79]

Data granularity and outright gaps in data contribute to an inability to plan or respond to common complaints such as traffic congestion as well as climate and energy-related challenges. Planners would benefit from greater understanding of vehicle occupancy across transportation modes. Despite recently publishing a framework for estimating vehicle occupancy, the U.S. Department of Transportation requirements may rely on innovative states, metropolitan planning organizations, and localities to identify the best practices for detailed data collection and analysis.[80] Additionally, seemingly minor information such as vehicle ages and tire pressure can affect transportation modeling integrity and the accuracy of calculating—and regulating—vehicle efficiency, respectively. The National Performance Management Research Dataset provides traffic data for the National Highway System, enabling planners to diagnose bottlenecks and other congestion problems. With a geographic scope covering only approximately 60 percent of all roads, the data set leaves a gap where private companies now provide drivers better—and proprietary—route prioritization data, leaving planners in the dust.[81] Data collection, modeling, and analysis varies across other modes of transportation, whether well-accounted for due to air traffic control requirements, tightly controlled and proprietary regarding shipping by freight rail, or less well-known regarding maritime emissions on the high seas.[82]

## Negative emissions

Without U.S. leadership, and due to the Trump administration's attempts to sabotage them, global efforts may fall short of reaching the Paris climate agreement's goals of keeping global temperatures less than 2 degrees Celsius higher than preindustrial levels, let alone the more ambitious 1.5 degrees Celsius.[83] This likelihood has driven increasing interest in negative emissions technologies to permanently remove carbon dioxide and potentially other greenhouse gases from the atmosphere, whether storing it underground, combining it with materials such as concrete, inducing photosynthesis, or using other techniques.[84] Ranging from reforestation to under-seabed storage, each of these fields varies greatly in terms of the maturity of the technologies it uses, but they all share a vital need for more extensive and more detailed data collection over a long period of time. A forward-looking research agenda in this area could research, develop, and utilize advanced sensors for underground storage activities, putting technologies developed largely in the oil and gas industry to use for carbon removal while also tying these new uses to long-term planning for the safe monitoring of the storage sites themselves.[85] To date, carbon storage demonstration projects in geological formations, such as saline domes, have indicated the safety of this method, although the scientific basis for maintaining and monitoring storage sites after injection has concluded requires further research, the development of protocols, and above-site land use or ocean planning guidelines.[86] Ensuring the efficacy of carbon capture and storage as a sound technology solution will require effective, long-term monitoring of geologic storage sites.

# What investments are needed in order to support next-generation climate science?

The United States and the international community depend on several factors to carry out the broad undertaking that is climate and energy data and research: infrastructure, including equipment, sites, and vessels; a trained and talented workforce; collaboration; and integrity. The preceding sections of this report have touched on many elements, but it remains important to highlight certain much-needed investments in infrastructure and scientists themselves, as well as actions that would strengthen or add to existing organizations, collaborative relationships, or standards of conduct and protections. U.S. citizens, scientists, policymakers, and other users of climate and energy data and research must consider how to navigate this era of doubt in and attacks on scientific institutions and the facilities, programs, and people that form their foundation. This section considers some of the fundamental challenges facing the overall U.S. scientific endeavor, focusing on climate and energy data and research but not limited to those fields.

In June 2018, the U.S. Department of Energy and Oak Ridge National Laboratory announced that the title of "world's fastest supercomputer" had returned from China to the United States—specifically, Tennessee—and Secretary of Energy Rick Perry has devoted words and funds to pursuing ever-faster computing capabilities there.[87] Perry's efforts belie the reality of the Trump administration's proposed funding for Earth system modeling capabilities, which depend on the same supercomputing infrastructure and saw funding cuts of between 63 percent and 70 percent proposed in FY 2018 and FY 2019.[88] Past investments in supercomputing and integrated Earth system models have enabled scientists to better understand and forecast potential climate impacts. For example, understanding the likelihood of glacier melting contributing to sea level rise shifted dramatically between the U.N. Intergovernmental Panel on Climate Change's Fourth Assessment Report in 2007 and its Fifth Assessment Report in 2014, due to enhanced modeling capabilities.[89] Even with the May 2018 launch of the Department of Energy's new Energy Exascale Earth System Model, a project begun in 2014, the need for ongoing investment in more detailed Earth system modeling across all spatial and temporal scales remains critical to advancing human understanding climate change.[90]

Another crosscutting and vital class of instrumentation exists in outer space: remote sensing equipment on satellites. Under the leadership of NASA, NOAA, the USDA, and the USGS, the portfolio of Earth observation satellites launched by the United States and the immense database they offer to the public at no cost have conveyed countless benefits across the fields of agriculture, water use, energy, environmental protection, land use planning, and more. In one estimate, USGS's Landsat satellite images alone contributed approximately $2 billion to the U.S. economy, far outweighing the program's $80 million budget.[91] The Trump administration has considered whether to charge for data from Landsat satellites and other Earth observation satellites, a move that may hinder the public's ability to prepare for storms, plant crops, or choose a commuting route.[92] Although new multi-instrument satellites may incur high costs—for example, Landsat 8 was estimated to cost $855 million—the use of private satellite launch companies, small satellites, and other measures are lowering the cost profile of Earth observation missions overall.[93] Most recently, the Environmental Defense Fund announced that it would launch a methane-monitoring satellite to fill a data gap in determining where and to what degree sources of the powerful greenhouse gas are contributing to climate change.[94] The question remains how to retain these valuable data as open resources for research and public use while also enhancing the coverage and quality of the data these satellites produce, including by launching new missions.

As referenced in the introduction of this report, the Trump administration's proposals to eliminate funding for certain satellite missions in NASA's Earth Sciences programs created uncertainty for the future of the data collection and science enabled by those missions. While Congress acted to restore funding for those existing and planned missions, huge swings in budgetary uncertainty complicate planning for critical future satellite investments, which are technically complicated and expensive undertakings involving multiyear preparations. In 2017, the National Academies of Sciences, Engineering, and Medicine published a comprehensive survey providing an overview of NASA's next decade of earth sciences research priorities. Instruments, missions, or satellites have been designated for five of the major Earth observation priorities outlined in that report, but an additional nine areas are still in earlier planning stages, including ones that are critical to the global understanding of and response to climate change, such as better quantification of point sources, sinks, and cycles for carbon and methane emissions and higher-resolution tracking of changes in forest ecosystems.[95] Planning for long-term investments like these, not only at NASA but also at NOAA and the USGS, can be set back considerably—and quietly—by political interference.

The interconnectedness of natural and human systems means that data needs are likely to emerge from agencies and departments that are not currently responsible for this type of research. Better coordination among agencies to share relevant data and shape research questions should therefore be a priority for the federal government. In some departments this is already occurring—the Landscape Conservation Cooperatives program administered by the U.S. Fish and Wildlife Service plays a coordinating role in 22 regions across the United States, and the LANDFIRE program links data on weather and vegetation from different agencies to help land managers make strategic decisions to reduce fire risk to communities.[96] Additional resources should be made available to organize federal agencies for the complex challenges that climate change poses and to help work between federal, state, and local levels to prepare communities for relevant future scenarios.

The Nobel Prize-winning research and science communication conducted by the Intergovernmental Panel on Climate Change (IPCC) sets a high standard for international collaboration, peer review, planning, and the synthesis of thousands of studies conducted on a voluntary basis by hundreds of scientists around the world. The IPCC's three working groups focus on the physical science of climate change; impacts, vulnerability, and adaptation; and the mitigation of carbon emissions and contributors to climate change.[97] The research that feeds into the IPCC assessment process is ongoing, and due to the rigorous collection, review, and publication process, it takes several years from determining the initial scope of each report to publish it.[98] The IPCC reports are vital resources for citizens, scientists, and decision-makers around the world, and funding the IPCC and protecting the integrity of its process should remain a high priority.

The international scientific community and global leaders would benefit from additional research and collaborative resources, particularly those that are actionable in near-term timeframes as climate change impacts become more severe. Since the Paris climate agreement in 2015, international work by climate scientists and policymakers has focused, in part, on increasing transparency in monitoring and verifying carbon emissions in an effort to help countries hold one another accountable on the pathway to reaching each country's nationally determined contribution.[99] Outside this mitigation-focused global stocktaking exercise, the international community could also benefit greatly from enhanced collaboration on climate and energy data collection, analysis, and communication resulting in actionable information, including by increasing data granularity as closely as possible—and as is useful—to local levels and in real-time intervals.

Machine learning and artificial intelligence also offer potentially powerful new tools for improving weather prediction and climate models alike. In 2016, researchers at Lawrence Berkeley National Laboratory reported that they were successfully able to use a machine learning system to identify key weather features, including weather fronts and tropical cyclones.[100] In the future, machine learning could help improve predictions of extreme weather events' frequency, severity, and location. Microsoft is investing $50 million over five years in its AI for Earth program to test artificial intelligence applications for researching climate change and environmental issues.[101] Developing a governmentwide program of exploring machine learning and artificial intelligence approaches to tackling climate science problems, including developing productive partnerships with the private sector, would be an ideal task for a future Office of Science and Technology Policy.

Whether siting a new bridge over a tidal estuary or responding to a wildfire, Americans increasingly need both foundational training on how—and how quickly—Earth systems are changing and more immediate, actionable information on which to base decisions. Much like the IPCC's assessment reports, the National Climate Assessment (NCA) has a long history and a scientifically rigorous process of study synthesis and peer review to report on the changing climate system and its effects on the United States.[102] Furthermore, similar to its internationally focused cousin, the NCA mirrors the IPCC assessment process in style and timing; both documents tend to catalogue observations and forecasts with conservative measurements of likelihood in a four-year-or-longer timeframe for publication. The Trump administration will publish the next NCA in the coming months, and that version and its successors may begin to take important steps toward offering ongoing, more detailed, and more actionable information to the public. By supporting the NCA process, funding its contributing agencies and research bodies appropriately, adding to the scientific infrastructure across the 13 federal agencies and even more facilities that support the NCA process, and building stronger independent institutions to safeguard its ongoing research and communication activities, the United States could enhance the NCA's usefulness. Transforming the NCA into a data repository and information clearinghouse, along with enhancing the spatial and temporal granularity of the data it translates for public use, could unlock an incredible tool for citizens, planners, and leaders across the country.

Collecting and subsequently translating such immense quantities and nuanced types of climate and energy data into actionable information relies on equally well-trained scientists and engineers. The nation's science, technology, engineering, and math (STEM) education pipeline is not thriving or growing to meet current or future needs in climate and energy research alone. Although STEM fields tend to pay higher wages and salaries, more than half of professionals with a STEM-related college degree work outside those fields.[103] Diversity in STEM fields remains another challenge, particularly in fields other than life sciences and health, as African Americans, Hispanic Americans, and women remain underrepresented.[104] The challenges facing training and education in climate and energy data and research fields extend into the energy industry as well, with several industrial sectors reporting difficulty in hiring due to applicants' lack of skills in areas from electrical engineering to nuclear physics.[105] To move forward on any aspect of climate and energy data and research, the United States should consider how to incentivize and retain scientists and engineers in these critical roles.[106]

Using science to understand the world and inform policy requires systemic supports for integrity and freedom of inquiry. Since the start of the Trump administration in 2017, proposed funding cuts and reorganizations have been accompanied by changes to advisory committees, staff reassignments, and new policy directives that aim to limit the ability of scientists to fulfill their responsibilities.[107] Making the most of the investments proposed in this report must also be accompanied by policies that preserve the processes needed to maintain scientific integrity, including protections from political interference, open channels to the public and its representatives in Congress, the opportunity to publish and engage in the broader scientific community, and the tools to disclose censorship and other potential abuses.[108] Although this report looks forward toward the frontiers of climate and energy data and research, it does so from a position rooted in protecting the field of science for the public good and retaining its unique ability to provide objective and factual insight to policy- and decision-makers.

# Conclusion

Laying out an agenda for next-generation research in the science of climate change and its effects may seem like a willfully optimistic exercise at a time when the Trump administration has repeatedly proposed slashing federal investments in science and is actively working to suppress the activities of climate scientists throughout the federal government. Just since the first report in this series was published in June, which catalogued the budgetary and non-budgetary attacks on climate science, reports have surfaced that research projects throughout the U.S. Department of the Interior are being subjected to a political review by an employee who was a high school football teammate of Interior Secretary Ryan Zinke and has no scientific qualifications.[109] Federal scientists with the U.S. Geological Survey are now operating under new restrictions barring them from speaking to reporters without approval from political personnel.[110]

Despite the current U.S. political landscape, it's vital to look to and prepare for a future in which the federal government is no longer shirking its responsibilities to promote robust, open research and data collection on climate change—and one need only consider the recent history of Canadian climate science to understand why.

The conservative Harper administration was in power in Canada for nearly a decade, and made headlines for, among other things, barring scientists from speaking to reporters and cutting budgets for environmental and climate research.[111] While the Trudeau government has reversed some of these policies, it has not yet taken steps to restart sustained funding for climate science. Beginning in 2000, the Canadian Foundation for Climate and Atmospheric Sciences disbursed $110 million in government funds to support climate science; in 2010, the Harper government announced plans to cease funding the program.[112] From 2013 to 2018, climate science was supported through the Climate Change and Atmospheric Research program; that program has since expired without any permanent replacement proposed by Trudeau.[113] The wind-down of the program endangered, among other things, one of the world's only scientific research stations in the high Arctic, the Polar Environment Atmospheric Research Laboratory (PEARL).[114] At the last minute, the Trudeau government provided $1.6 million for PEARL, which will keep the station operational through fall 2019—but the facility's fate is uncertain beyond that point, making it difficult for scientists to plan vital future research projects.[115]

The Canadian experience should serve as a cautionary tale for Americans of all political persuasions who are concerned about climate change. Prime Minister Justin Trudeau has made reversing the previous administration's head-in-the-sand approach to mitigating greenhouse gas emissions a central cause of his candidacy and government, telling the 2015 Paris climate summit that there is "no time to waste" in combating climate change.[116] But that posture has not yet translated into active measures to reverse cuts made to Canadian federal support for climate science.

Even as U.S. scientists, members of Congress, and citizens who want to see action to address climate change work to prevent the Trump administration from realizing its worst plans for reducing federal support for climate science, it is vital that researchers and policymakers begin laying the groundwork for the next generation of federal climate science to help answer the most pressing questions about what's in store for the planet, the economy, and the future of humanity.

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