REPORT TO THE PRESIDENT

Extreme Weather Risk in a Changing Climate: Enhancing prediction and protecting communities

Executive Office of the President

President's Council of Advisors on Science and Technology

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EXECUTIVE OFFICE OF THE PRESIDENT
PRESIDENT'S COUNCIL OF ADVISORS ON SCIENCE AND TECHNOLOGY
WASHINGTON, D.C. 20502

President Joseph R. Biden, Jr.
The White House
Washington, D.C.

Dear Mr. President,

Your administration has made unprecedented advances in addressing climate change. PCAST believes advances in climate science and computation can add to this record by creating an effective and accessible suite of tools that provide individuals, communities, and the federal government with the information they need to prepare for the risks of extreme weather in a changing climate.

The most immediate danger that Americans face from climate change is the worsening of extreme weather, including hurricanes, floods, droughts, heatwaves, and wildfires. Extreme weather disasters have caused over $1 trillion in damages over the last seven years, and in 2022 alone, displaced an estimated 3.4 million Americans from their homes. Recent scientific studies have found that the likelihood of certain weather patterns, such as extreme hurricane rainfall over the state of Texas, have multiplied due to climate change. This type of change makes historical models and long-term records unreliable guides to future probabilities. Reliable information is critical for American families choosing where to live, municipal leaders developing flood-control plans, or insurers selling wildfire coverage. And yet, when it comes to assessing the future risks from extreme weather, America is flying blind.

The good news is that climate modeling and computation are advancing rapidly. Capabilities exist within federal agencies to make significantly better predictions of the likelihoods of extreme weather – for example the chance that a category five hurricane will hit Miami in any one year, or the chance of another rainfall event like the one that caused catastrophic flooding in Kentucky in July 2022. By sharing resources and information, the federal government also can spur an ecosystem of academic research and private investment that improves and expands access to climate and weather risk information. This in turn can inform smart government policy and support the American people with information they can use to protect themselves.

The households at greatest risk from floods, fires, and heatwaves are often low-income families, and discriminatory historical practices such as redlining have contributed to minority populations living in risk-prone areas. A national effort to improve the quantification of extreme weather risk also would help to ensure that federal funds, including those designated under the Infrastructure Investment and Jobs Act (IIJA), are targeted to areas where their benefit will be highest.

This report recommends steps to dramatically improve our quantification of extreme weather risk, and to share this information with households, businesses, and government agencies. It also recommends the development of a national adaptation plan that would provide guidance that local communities need to tackle changing risks from extreme weather events. Taken together, PCAST believes that these actions can help protect the lives, livelihoods, and property of Americans for generations.

Sincerely,
The President's Council of Advisors on Science and Technology

The President's Council of Advisors on Science and Technology

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Executive Summary

Extreme weather has devastating impacts on the American people, our communities, and our economy. All of us have seen the damage wrought by catastrophic wildfires in western states, by floods, and tropical cyclones on the Gulf Coast, and by recent severe tornados in southern and eastern states. Extreme weather also reduces property values, raises the costs of insurance, and poses national and global economic risks from supply chain disruptions and forced migrations. Today, climate change is changing the patterns and risks of extreme weather, including the frequency and severity of many hazards.

The challenge of hurricanes and other severe storms, floods, and wildfires is gaining significant attention and the annual cost of climate and weather disasters has been rising. The National Oceanic and Atmospheric Administration (NOAA) has catalogued over $1 trillion of damages during the last seven years (2016-2022).[1] Industry reports caution that by mid-century, insurance premiums in certain markets could rise substantially, straining U.S. households.[2] Last year, the Office of Management and Budget (OMB) cited a potential federal revenue loss of $2 trillion per year from climate change at the end of the century, along with additional expenditures of $25 to $128 billion on selected insurance and disaster relief programs.[3] In addition, there are deeper costs from loss of life, negative health impacts, and the destruction of communities.[4] The Census Bureau recently estimated that in 2022 alone, 3.4 million Americans were displaced from their homes by extreme weather disasters.[5] Moreover, lower-income households are often those at greatest risk from floods, storms, and wildfires. These households have fewer resources to take actions that will offset a rising risk of extreme weather.

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[1] Smith, A. B. (2023, January 10). *2022 U.S. billion-dollar weather and climate disasters in historical context.* NOAA National Centers for Environmental Information. https://www.climate.gov/news-features/blogs/2022-us-billion-dollar-weather-and-climate-disasters-historical-context . The average disaster costs for 2017-21 are $148 billion per year; the data include only large (> $1bn) disasters.

[2] One specific example cited by McKinsey is that (inflation-adjusted) annual flood losses in Florida could rise by 50% by 2050, with corresponding premium increases if the costs are passed to policy-holders. Grimaldi, A., Javanmardian, K., Pinner, D., Samandari, H., & Strovink, K. (2020, November 18). *Climate change and P&C insurance: The threat and opportunity.* McKinsey & Company. https://www.mckinsey.com/industries/financial-services/our-insights/climate-change-and-p-and-c-insurance-the-threat-and-opportunity

[3] The revenue number is from an OMB blog post “Quantifying Risks to the Federal Budget from Climate Change” (April 4, 2022) that summarizes a set of OMB reports, including “Climate Risk Exposure: An Assessment of the Federal Government’s Financial Risks to Climate Change” which contains the specific estimates on program costs. Estimates of climate damages 75+ years out have a wide range of associated uncertainty, and OMB’s analysis of costs looks only at a small number of federal programs. Executive Office of the President (2022, April 4). Quantifying Risks to the Federal Budget from Climate Change. The White House. https://www.whitehouse.gov/omb/briefing-room/2022/04/04/quantifying-risks-to-the-federal-budget-from-climate-change/ ; U.S. Office of Management and Budget (2022, April). *Climate Risk Exposure: An Assessment of the Federal Government's Financial Risks to Climate Change.* https://www.whitehouse.gov/wp-content/uploads/2022/04/OMB_Climate_Risk_Exposure_2022.pdf

[4] Chapter 9 of the 2023 *Economic Report of the President* discusses evidence on a wide range of costs from climate change and extreme weather. https://www.whitehouse.gov/wp-content/uploads/2023/03/ERP-2023.pdf

[5] U.S. Census Bureau. (2023, January 15). *Week 53 Household Pulse Survey: January 4 - January 16.* https://census.gov. https://www.census.gov/data/tables/2023/demo/hhp/hhp53.html

This PCAST report investigates how recent scientific and technical advances could be used to provide more accurate and actionable information to guide decision-making and policy at all levels. PCAST recommends federal actions to better quantify and disseminate current and future risks of extreme weather, including risks of human and financial losses caused by flood, fire, storms, and drought. PCAST also recommends actions to bolster the emerging private ecosystem providing climate risk information. Finally, PCAST recommends the development of a national adaptation plan to assist communities in preparing for and adapting to changing risks from extreme weather events.

This report builds on the October 2021 White House report, *A Roadmap to Build a Climate-Resilient Economy,* outlining a multi-agency plan to implement Executive Order 14030 on climate-related financial risk.[6] That plan addresses both the rising *physical risks* from extreme weather, and *transition risks* in moving toward a low-carbon economy. PCAST's recommendations focus on how climate science and computing can provide significantly better information about the physical risks from extreme weather to empower households, communities, and companies and enable smart policy.

Recommendations

Recommendation 1: A National Effort to Quantify Extreme Weather Risk.

To prepare for dangerous weather, one needs to know how damaging it is likely to be and how frequently it will occur. A levee designed for a 100-year storm producing 15 inches of rain is not adequate if the 100-year storm now packs 25 inches. PCAST recommends a focused federal effort to provide estimates of the risk that a weather event of a given severity will occur in any location and year between now and midcentury. These include extremes of temperature, rainfall, and wind speed.

1.1. U.S. climate-modeling centers supported by the National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), Department of Energy (DOE), and National Aeronautics and Space Administration (NASA) should enhance their high-resolution modeling capabilities and state-of-the-art statistical methods **to quantify annual extreme weather risks from the present until mid-century** at a resolution of 10 km or finer. *This will require both agency prioritization and collaboration.*

The work of multiple agencies together with an effective leadership framework is critical because, as explained in Box 2 of the report, this activity does not fit within a single existing administrative unit within the federal government.

1.2. The White House should **designate a lead agency to maintain an extreme weather data portal** where observations and modeling products are regularly updated and widely accessible, using an analysis-ready format that enables downstream users and hazard models on smaller scales to assess the local risks of wildfire, flood, drought, and other weather-related hazards. The portal should also provide guidance and recommendations related to the reliability of modeling products.

[6] The White House. (2021, October 14). *A Roadmap to Build a Climate-Resilient Economy*. https://www.whitehouse.gov/wp-content/uploads/2021/10/Climate-Finance-Report.pdf

Here, we are not focused on predicting weather over the coming days and weeks, a problem adeptly handled by the National Weather Service, but on predicting the climate, that is the probability of weather events over years and decades. In particular, the recommendation directly addresses the lack of high-quality estimates of extreme weather probabilities for most locations and types of events. Current risk assessments are based on older models or historical weather records. Older climate models typically have a resolution of 25 to 100 km or coarser, limiting their predictive accuracy, while today's computational resources and downscaling techniques have the potential to provide resolutions of 10 km or finer. Historical weather records are generally too short to estimate the chance of once-in-a-lifetime events and are unreliable when there are changes in the climate. Recent advances in observations, modeling, and computation make it possible to create more accurate and operational assessment of evolving risks, provided that existing federal computational and human resources are deployed at the needed scale, and that information is made readily accessible for downstream uses. The aspiration is that just as Americans today have access to high-quality operational weather forecasts, the time has come to invest in an operational climate science that provides improved tools for risk assessment and management.

Recommendation 2: An Improved Ecosystem for Climate Risk Assessment.

To prepare for changing patterns of extreme weather, the nation will require information beyond the probabilities of extreme temperature, rainfall, and wind speed. One must be able to predict the severity of resulting weather hazards, (e.g., flood, fires and droughts) and the human and economic losses they will cause. PCAST recommends steps that will enable the development of high-quality private and public sector tools to better measure and evaluate extreme weather-related risks across the country.

2.1 Designate an interagency group to **inventory and release federal data that are useful to develop and test weather-hazard models**, which predict flood, fire and drought from extreme weather, and **hazard-loss models**, which predict human and financial losses from hazards or directly from extreme weather such as significant heat, cold, hail, or wind. This effort should include any relevant and available fine-scale elevation data and other physical information, as well as data on Federal disaster and insurance claims needed to validate risk models, with appropriate safeguards to protect privacy and security. The interagency group will require expertise about procedures and rules governing the release of federal data.

2.2 The National Oceanic and Atmospheric Administration (NOAA) and the Federal Emergency Management Agency (FEMA), and other federal agencies as the President deems necessary, should develop **guidelines for measuring the accuracy of weather-hazard and hazard-loss models** with skill scores and promote the use of skill-scoring among federal agencies that rely on assessments of climate and weather hazards including flood, drought, storm, and wildfire, and the human and economic damages they cause.

2.3 Fund research, potentially through multiple agencies, **on risk-assessment modeling systems** that use extreme weather probabilities, weather-hazard models, and hazard-loss models to quantify the likelihood and economic costs of extreme weather events. This effort should aim to foster improved quantification of weather-hazard risks in the public and private sector, through improved access to models and data, and a robust ecosystem of model evaluation and testing.

This recommendation addresses the fact that households, communities, companies, and government agencies do not have sufficiently reliable and geographically specific information about how they may be affected by extreme weather. While a burgeoning industry is beginning to provide climate risk information, much of this is of questionable quality, either because it has not been transparently skill-scored to show that it can predict past events, or because it relies on methods that have been shown by the academic literature to have significant bias.[7] Also, much of this information is too costly for most individuals or small municipalities to afford, although some is available at no cost. To improve the quality of the models, developers need support in overcoming two primary barriers: 1) the data required to improve models is often siloed or inaccessible, and 2) the field lacks sufficiently robust mechanisms to allow consumers of the information, including federal agencies, to assess model skill. Transparent and accessible skill-scoring would promote model improvement and help standardize nascent industry efforts, especially if federal agencies were to prioritize applications for funding that rely on relatively skillful models. Addressing these barriers will help foster a stronger academic and private sector ecosystem of climate risk assessment. This will also leverage prior investments, such as the DOE's HyperFACETS project or the World Climate Research Program's CORDEX project.

Recommendation 3: A National Adaptation Plan to Mitigate Extreme Weather Risk

To prepare for changing risks from extreme weather, the provision of information will not be enough, especially given uneven resources across local communities. The federal government can accelerate preparedness by creating a national plan that guides and supports investment at all levels, and by funding research that illuminates which policy responses are effective and equitable.

3.1 **The White House should develop and publish a National Adaptation Plan** to prepare for and mitigate increased risks from extreme weather. The Plan should include:

(a) A systematic approach to mapping near term and longer-term high-danger zones for each extreme weather hazard, updated as estimates of risk are improved.

(b) Decision frameworks to assist local communities in making plans to mitigate or adapt to extreme weather risk.

(c) Regulatory and legal options to reduce long-term risk exposure, for instance through land-use planning, zoning, and building code adoption.

(d) Comprehensive assessment of Federal and State programs in alleviating disaster risks, including the distribution of federal funds for disaster preparation with attention to whether these programs are accessible to low-income communities.

(e) Guidelines for equitable allocation of disaster relief. These guidelines should anticipate the potential for recurring extreme weather events, so that relief programs work to mitigate future dangers to a community.

[7] Condon, Madison (2023). Climate Services: The Business of Physical Risk. *Arizona State Law Journal, Forthcoming*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4396826#

3.2 **Fund research on the adaptation of households, real-estate and insurance markets, and local governments to changing climate and extreme weather risk.** This effort should aim to illuminate the behavior of households and firms in response to evolving climate and weather risks, and the benefits and costs of alternative policies aimed at mitigating and adapting to these risks. NSF may be best positioned to lead this effort, especially if coordinated with mission-oriented agencies such as NOAA, HUD, EPA, and others.

This final recommendation addresses the current lack of a national adaptation plan to guide federal and local investments to mitigate extreme weather risk and to improve the safety of lower-income and marginalized communities in greatest peril,[8] particularly Black, Latino, Indigenous and other communities of color. Relevant programs are distributed over a score of federal agencies, and in many cases, responsibility lies with communities and local governments who confront a disjointed array of federal programs and initiatives.[9] A coherent national plan should address issues of equity as well as economic efficiency and resilience, especially given the disproportionate risks faced by lower-income and marginalized communities. This adaptation plan also must incorporate current data and modeling that quantifies the changing climate, avoiding likely significant inaccuracies from exclusive reliance on the historical record.

[8] White House Environmental Justice Advisory Council. (2021, May 21). Final Recommendations: Justice 40 Climate and Economic Justice Screening Tool & Executive Order 12898 Revisions. https://www.epa.gov/sites/default/files/2021-05/documents/whiteh2.pdf

[9] A broad set of federal programs are relevant for disaster recovery. For instance, social-safety net programs (disability, unemployment, Medicare) play an important financial role in areas affected by disasters, although not specifically designed for this purpose (e.g. https://www.aeaweb.org/articles?id=10.1257/pol.20140296).

Extreme Weather Risk in a Changing Climate: Enhancing prediction and protecting communities

A Hypothetical Scenario: The Case of Franklinburg, Georgia

Franklinburg is a town of 30,000 people in northern Georgia. Franklinburg's mayor, Kimberley Wilson, is alarmed by the repeated hurricanes and tropical cyclones in recent years. She is also conscious of extreme rainfall throughout the Southeast not linked to tropical cyclones, including a 20-inch event in Baton Rouge in 2016, a 16-inch event in Kentucky in 2022, and a 24-inch event in Ft. Lauderdale in 2023. Franklinburg has never suffered a serious flood over 200 years, but also has not had a rainfall event of this severity. Mayor Wilson consults several publicly available assessment tools but they do not answer her questions. One informs her that the chance of a rainfall event greater than 3 inches might have increased by as much as 30-50% since 1975 or might not have increased at all. She also knows that Franklinburg has had multiple rainfall events of more than 3 inches without major flooding. Faced with vague fears but lacking actionable information, Mayor Wilson simply waits and hopes for the best.

A few years on, *Mayor Wilson hears of an ongoing federal effort to dramatically improve the prediction of extreme weather risk. She contacts the Climate Navigation Foundation (CNF), which is using data and standards released by the federal government to develop software that predicts flooding and damages, down to the level of individual homes and buildings. An assessment by CNF identifies a serious concern for Franklinburg. Brush Creek, which flows through a low-income neighborhood, is at risk of flooding from an 8-inch or greater rainfall, potentially depositing multiple feet of water into the heart of town, damaging the hospital, middle school, and the town hall, as well as many homes and offices. Following a series of public meetings that feature the alarming flood maps from CNF, the town undertakes a hydrological study. It recommends increasing the height of the natural barrier between Brush Creek and the surrounding neighborhood. The town applies successfully for a grant from FEMA's Flood Mitigation Assistance Grant program. Mayor Wilson also convinces the town council to invest in back-up electricity generation for the hospital and the town community center.*

Nearly 3 years after construction, *an extreme rain event deposits 14 inches of rain over three days. The town leadership prudently evacuates the neighborhoods in danger. The community center provides refuge to the ill, elderly, and other vulnerable people. As designed, the additions to the Brush Creek barrier keep the water contained, though Mayor Wilson knows that the town would have been devastated if they had not had the knowledge and resources to prepare. The event never crosses the President's desk because a disaster has been prevented.*

Introduction

Extreme weather has devastating impacts on the American people, our communities, and our economy. Severe wildfires that have ravaged parts of the American West, and destructive tropical cyclones along the Gulf Coast, are salient examples. These types of climate and weather-related disasters also affect American households by reducing property values and raising the costs of insurance. Moreover, multiple events of different types are sometimes occurring in rapid succession and interact synergistically to strain infrastructure and budgets. Now, climate change is affecting the frequency and severity of extreme weather events, creating new uncertainty about the risks we face.[10]

Recent scientific studies have shown that the probability of certain extreme weather events, such as Hurricane Harvey which severely impacted Louisiana and Texas in 2017, or the heat wave that swept the Pacific Northwest in 2021, have increased dramatically over the last several decades because of climate change.[11] The risks of future extreme weather-related disasters are amplified both by climate change and by increased development in areas that are prone to floods, fires, and droughts.[12] Moreover, an extensive body of work documents that low-income communities are disproportionately impacted by extreme weather, often due to discriminatory historical practices such as redlining that have affected housing patterns.[13]

Insurance arrangements, both public and private, play a critical role in sharing the financial costs of climate and weather disasters. Swiss Re, a global reinsurer, forecasts that global property insurance premiums will rise by 5.3% annually to 2040, with climate change as the main driver.[14] Rising costs from extreme weather challenge communities, businesses, and states and local governments. The federal government often has significant liability because it provides disaster relief following major events. In the case of flooding, a failure of private insurance arrangements prompted Congress to create the National Flood Insurance Program in 1968. As we look ahead to higher costs of climate and weather disasters, American taxpayers, as well as American families, will benefit by preparing for and mitigating these risks.[15]

PCAST identified three obstacles to addressing risks from extreme weather and makes recommendations for federal action to address each of them.

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[10] The 2022 IPCC Report assigns high or very high confidence to higher flood/storm induced damages in coastal areas, damages to infrastructure, and damages to key economic sectors due to climate change, and a litany of global risks from climate events, especially in the period from 2040-2100. Intergovernmental Panel on Climate Change (2022). *Summary for Policymakers.* https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

[11] Columbia University (Climate Attribution. (2023). *Climate Attribution Database.* https://climateattribution.org/) maintains a large database of attribution studies that calculate the likelihood of specific weather patterns and weather-related events under alternative climate scenarios. For example, “Assessing the present and future probability of Hurricane Harvey’s rainfall” finds that due to climate change the probability of Harvey-magnitude rainfall may have increased by a multiple of six since the late 20th century. See Emanuel, K. (2017). Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National Academy of Sciences of the United States of America,* 114(48), 12681–12684. https://doi.org/10.1073/pnas.1716222114

[12] US Geological Service (2016, November 29). *Effects of urban development on floods [Fact sheet].* https://pubs.usgs.gov/fs/fs07603/

[13] For example, see Buchanan, M. K., Kulp, S., Cushing, L., Morello-Frosch, R., Nedwick, T., & Strauss, B. (2020). Sea level rise and coastal flooding threaten affordable housing. *Environmental Research Letters*, 15(12), 124020. https://doi.org/10.1088/1748-9326/abb266

[14] Holzheu, T., Lechner, R., Vischer, A., Bevere, L., Staib, D., Finucane, J., Belgibayeva, A., & Fan, I. (April 2021). *sigma 4/2021 - More risk: the changing nature of P&C insurance opportunities to 2040 | Swiss Re.* https://www.swissre.com/institute/research/sigma-research/sigma-2021-04.html

[15] U.S. Office of Management and Budget (2023). *Analytical Perspectives: Budget of the U.S. Government: Fiscal Year 2023.* https://www.govinfo.gov/content/pkg/BUDGET-2023-PER/pdf/BUDGET-2023-PER.pdf

- *First,* we lack high-quality estimates of extreme weather probabilities for most locations and types of events. Most current assessments are based on historical records of extreme weather and do not incorporate rapidly changing climate. Others rely on climate models that, for example, underestimate the risks of extreme rainfall that causes flooding, the severities of tropical cyclones, and other critical extremes.[16] However, recent advances in modeling and computation provide a far more accurate capability that could be deployed using existing human and computational resources within federal agencies. To prepare for the complex and geographically varying effects of climate change, it is critical that we have the best possible understanding of the frequency and severity of current and near future (to mid-century) extreme weather. The first set of recommendations outlines an effort to dramatically improve the quality of available estimates.

Box 1: Terms of Reference

- **Extreme Weather Model**: the LIKELIHOOD of extreme weather of X MAGNITUDE
- **Weather Hazard model**: The SEVERITY of a weather hazard, such as locations and depth of flooding, or the locations and intensity of wildfire caused by an X magnitude weather event.
- **Hazard Loss model**: ECONOMIC OR HUMAN LOSSES due to a magnitude X weather event or a severity Y weather hazard.

- *Second,* communities and households do not have reliable access to the information necessary to prepare for and mitigate risks from extreme weather-related disasters. While a burgeoning industry is beginning to provide climate risk information, details of the products are proprietary and there is little assurance as to their quality, the projected costs of damages vary widely, and the data required to improve models is often siloed or inaccessible. Moreover, we lack robust mechanisms to evaluate the quality of models and estimates being used by government agencies and the public. Our second set of recommendations therefore aims to stimulate and improve the public and private ecosystem that provides climate risk analysis.

- *Third,* there is currently no national adaptation plan that guides federal and local investments to mitigate extreme weather risk and secure the safety of communities, particularly those with the greatest risk and the least resources. Relevant programs are distributed over a score of federal agencies. In many cases, however, responsibility lies with communities and local governments who lack the personnel and know-how to navigate their options. There are significant issues of equity as well as economic efficiency with this process. Our final recommendations are aimed at developing a national plan to help guide decision-making and advise on steps to protect communities, especially those likely to experience the most harm.

The challenges are, of course, interconnected. High-quality estimates of the probability of extreme temperatures, and extreme precipitation and wind, are critical to assessing the risks from intense wildfires, floods, and drought. This information must be distributed widely because decisions about

[16] Intergovernmental Panel on Climate Change. (2021). *Working Group 1: The Physical Science Basis, Climate Change 2021: The Physical Science Basis.* https://www.ipcc.ch/report/ar6/wg1/

how to mitigate these risks are highly decentralized across households, corporations, and governments. Finally, federal guidance can both assist local communities in planning, and benefit from improved risk assessment.

A National Effort to Improve Estimates of Extreme Weather Risk

With recent advances in extreme weather modeling and computing power, it is now possible to focus a national effort on quantifying the *evolving likelihoods* of extreme weather events at a resolution of at least 10 km (Appendix B). Heat waves are the deadliest weather extremes and are becoming more intense and more frequent worldwide.[17,18]

Climate models have had some skill in predicting heat waves for more than a decade,[19] but until recently have systematically underestimated extreme precipitation and thus inland floods, which are the costliest weather-related hazards.[20] These models were also unable to accurately represent, for example, extra-tropical frontal systems or tropical cyclones.[21]

Recently developed models with 10-25 km resolution can now more accurately predict risks of extreme rainfall and other extreme weather events and how these have changed with the climate (Appendix B). High-resolution modeling could thus provide more accurate risk estimates of extreme weather than is possible by relying solely on historical records and older models. Statistical methods using machine learning techniques may also provide a useful complement to high-resolution climate models.[22]

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[17] NOAA National Weather Service. (2021). Weather Related Fatality and Injury Statistics. NOAA's National Weather Service. https://www.weather.gov/hazstat/

[18] The sixth report of the IPCC states (with confidence level *virtually certain*): "The intensity of hot extremes (including heatwaves) has increases and those of cold extremes have decreased on the global scale since 1950." Intergovernmental Panel on Climate Change. (2021). Chapter 11: Weather and Climate Extreme Events in a Changing Climate | *Climate Change 2021: The Physical Science Basis.* https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-11/

[19] National Academies of Sciences, Engineering, and Medicine. (2016*). Attribution of extreme weather events in the context of climate change.* The National Academies Press. https://nap.nationalacademies.org/catalog/21852/attribution-of-extreme-weather-events-in-the-context-of-climate-change ; https://doi.org/10.17226/21852

[20] NOAA & FEMA (2010, March). Flooding - Our Nation's Most Frequent and Costly Natural Disaster [Press release]. https://www.fbiic.gov/public/2010/mar/FloodingHistoryandCausesFS.PDF

[21] Srivastava, A., Grotjahn, R., & Ullrich, P. A. (2020). Evaluation of historical CMIP6 model simulations of extreme precipitation over contiguous US regions. *Weather and Climate Extremes, 29*, 100268. https://doi.org/10.1016/j.wace.2020.100268

[22] For example, it is possible to project future extreme weather probabilities by starting with high-resolution historical data (e.g., temperature and precipitation) jointly with models, to learn how to correct biases in models and scale output down to impact-relevant scales. See examples in Harris, L., McRae, A. T. T., Chantry, M., Dueben, P. D., & Palmer, T. N. (2022). A Generative Deep Learning Approach to Stochastic Downscaling of Precipitation Forecasts. *Journal of Advances in Modeling Earth Systems, 14*(10), e2022MS003120. https://doi.org/10.1029/2022MS003120 &
Ballard, T., & Erinjippurath, G. (2020, November 24). *Contrastive Learning for Climate Model Bias Correction and Super-Resolution*. https://s3.us-east-1.amazonaws.com/climate-change-ai/papers/aaaifss2022/10/paper.pdf

At least four federal agencies and institutions have the expertise and computer resources to contribute to a national effort to improve the quantification of extreme weather risk: the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the Department of Energy (DOE), and the National Aeronautics and Space Administration (NASA). Because robust estimates of risk require *ensembles* of many runs from multiple models, it makes sense that a national modeling effort would draw on the collective capabilities of agencies.

Recommendation 1.1

U.S. climate-modeling centers supported by NOAA, NSF, DOE, and NASA should enhance their high-resolution modeling capabilities and state-of-the-art statistical methods to quantify annual extreme weather risks from the present until mid-century at a resolution of 10 km or finer. *This will require both agency prioritization and collaboration.*

The work of multiple agencies together with an effective leadership framework are critical because, as explained in Box 2 of the report, this activity does not fit within a single existing administrative unit within the federal government.

Box 2: Agency partitioning of responsibilities – creating operational climatologies
Climate modeling does not fit neatly within any current branch of government. While NOAA has responsibility for operational weather forecasting, climate research is spread across multiple agencies and centers, including NOAA, NASA, DOE, and NSF. These groups each have the capacity to calculate *climatologies* – which are defined here as relationships between characteristics of a weather event such as temperature, wind speed, and rainfall, and its annual chance of occurrence - for every place on Earth in every year. Climatologies include severe and low-likelihood extreme weather, such as the chance of a Category 5 hurricane hitting Miami in any one year. But until recently, these so-called tail risks have not been estimated with enough accuracy to be used operationally. As a result, anything labeled "weather" or "operational" has been exclusively within NOAA's domain. The four climate modeling centers have long recognized that accurate extreme weather climatologies would be indispensable to plan for and manage the risks of extreme weather, especially the growing risks caused by climate change. Several have long-standing research programs to improve extreme weather climatologies and have anticipated the day when these could become operational. This research has recently surged ahead. PCAST has concluded that the most advanced climate models, when combined with historic weather data and advanced analytical techniques, could now produce far better and more accurate estimates of extreme weather risk than we have today, and also predict the changes in risk that will occur over the next several decades. Recommendation 1 would launch an operational wing of climate science, which will require many runs of high-resolution climate models that already exist within each of the four large climate modeling centers. Thus, the activity will not fit into the existing operational/nonoperational partitioning.

Ensembles from climate models provide evolving probability distributions of temperature and other atmospheric conditions (e.g., humidity, precipitation, wind) at different locations, as well as probabilities of near-future El Niño's and other natural climate events that contribute to extreme weather. Models may be *global* to capture planetary changes in climate, or *regional* to provide greater precision; PCAST envisions that efforts under recommendation 1.1 would use regional models and statistical methods to downscale the 10-25 km resolution of the global models to 1 km over the U.S. and its territories.

High-resolution climate modeling would improve the inputs to the downstream models (e.g., weather-hazard models and hazard-loss models) that provide estimates of economic and human risks from weather-related disasters. Weather-hazard models require both weather inputs (i.e., amount of precipitation for flooding) and other data to predict the severity of weather-related events such as urban flooding, droughts, and wildfires. These additional data include local topography for flood modeling, water holding capacity of soils for drought modeling, and forestland fuel conditions for wildfire modeling. Hazard-loss models then predict human and economic losses from the severity of weather-related hazards and information on local populations and infrastructure. Critical to achieving these benefits is to effectively disseminate the resulting improved, high-resolution climate estimates. Importantly, this is not a one-time action; equally critical is a process to update and disseminate estimates as climate, infrastructure, and modeling methods evolve.

Recommendation 1.2

The White House should designate a lead agency to maintain an extreme weather data portal where observations and modeling products are regularly updated and widely accessible, using an analysis-ready format that enables downstream users and hazard models on smaller scales to assess the local risks of wildfire, flood, drought, and other weather-related hazards. The portal should also provide guidance and recommendations related to the reliability of modeling products.

In addition to their value to the United States, the outputs of Recommendations 1.1 and 1.2 would create a valuable *global public good*. Indeed, most analyses find that climate-induced risks from extreme weather are even larger outside of the United States, for instance in countries such as India, China, Malaysia, and the Philippines, many of which also host significant U.S. interests (e.g., U.S. Navy installations, which are vulnerable to coastal flooding).[23] This is partly because other countries are at greater risk from sea-level rise or other compounding effects, and partly because their physical infrastructure and populations are highly vulnerable to floods, storms, and other weather-related risks.

An Improved Ecosystem for Climate Risk Assessment

Many of the methods to estimate human and economic risks from extreme weather were originally developed by the insurance industry (Appendix C) and companies that provide insurers and lenders with sophisticated catastrophe (CAT) modeling capabilities and/or results. However, with the growing attention paid to climate change, there is now a growing industry of climate risk assessment initiatives that include both for-profit companies and NGOs. Some organizations even provide

[23] Swiss Re Institute assesses climate risks across 48 countries, finding that the United State risk profile was 7th lowest amongst those assessed. Swiss Re Institute (2021, April). *The economics of climate change: no action is not an option*. https://www.swissre.com/dam/jcr:e73ee7c3-7f83-4c17-a2b8-8ef23a8d3312/swiss-re-institute-expertise-publication-economics-of-climate-change.pdf

estimates of the potential risks of wildfire, flood, and heat risk at the property level. The federal government is also taking steps to provide and freely share information, through the new Climate Mapping for Resilience and Adaptation (CMRA) data portal, the National Risk Index, and the HAZUS program.[24]

In principle, granular information about the impending risks from heat, flood, fire, and other hazards should allow homeowners, companies, and local governments to have risk information tailored to their situation. This information should be used to pinpoint areas at high risk, so local communities can engage in robust discussions about risk mitigation.

At this time, however, there is little assurance of the accuracy and reliability of available estimates. Moreover, the data required to improve and validate risk estimates is often inaccessible. For example, private insurers generally are reluctant to share historical claims data that would be valuable for quantifying risk, and there is no simple way to access both physical and financial data that resides in federal agencies. Our first recommendation for improving the ecosystem for climate risk assessment, therefore, is aimed at sharing federal data that would help to stimulate a more robust ecosystem of accurate, accessible, and reliable climate risk assessment.

Recommendation 2.1

Designate an interagency group to inventory and release federal data that are useful to develop and test weather-hazard models, which predict flood, fire and drought from extreme weather, and hazard-loss models, which predict human and financial losses from hazards or directly from extreme weather such as significant heat, cold, hail, or wind. This effort should include any relevant and available fine-scale elevation data and other physical information, as well as data on Federal disaster and insurance claims needed to validate risk models, with appropriate safeguards to protect privacy and security. The interagency group will require expertise about procedures and rules governing the release of federal data.

The proliferation of climate risk models raises a further challenge. In areas such as weather modeling there is a long tradition of skill-scoring, where models are assessed and validated relative to historical data. For instance, NOAA's Climate Prediction Center routinely scrutinizes the accuracy of short-term and medium-term weather forecasts. There is no analogous mechanism in place to assess climate risk models. PCAST repeatedly found it difficult to get a clear statement about the accuracy of a weather-hazard or hazard-loss model from its developer. Nonetheless, skill scoring of these

[24] The CMRA data portal aims to provide climate-related information to local communities. It was developed in 2022 as an interagency partnership overseen by the U.S. Global Change Research Program (USGCRP). The National Risk Index, which is the product of another interagency partnership, hosted by the Department of Homeland Security, provides county-level estimates of natural hazard risk. Hazus is a collection of hazard-loss models produced by the Federal Emergency Management Agency (FEMA).

models is both possible and increasingly prevalent in the academic literature.[25,26,27] Comparative shopping made possible by routine, transparent, and accessible skill-scoring would increase the pace of model improvement and help the nation to develop a rigorous climate risk assessment industry. The federal government could also require or prioritize the use of skillful models in applications for hazard-mitigation funding, which would indirectly incentivize model developers to skill score their models and publish the results.

Recommendation 2.2

NOAA, FEMA, and other federal agencies as the President deems necessary, should develop guidelines for measuring the accuracy of climate risk models with skill-scores and promote the use of skill-scoring among federal agencies that rely on assessments of climate and weather hazards including flood, drought, storm, and wildfire, and the human and economic damages they cause.

Finally, proprietary CAT models in the insurance industry estimate risks of losses by linking together extreme weather probabilities, weather-hazard models, and hazard-loss models. This industry needs to rapidly expand beyond its traditional borders to keep pace with the new risks caused by climate change, the rapid growth of the climate-risk assessment industry, and the diversification of its customer base to include every public and private entity that faces climate-related risk. For this reason, PCAST recommends a new federal investment in research and graduate training.

Recommendation 2.3

Fund research, potentially through multiple agencies, on risk-assessment modeling systems that use extreme weather probabilities, weather-hazard models, and hazard-loss models to quantify the likelihood and economic costs of extreme weather events. This effort should aim to foster improved quantification of weather-hazard risks in the public and private sector, through improved access to models and data, and a robust ecosystem of model evaluation and testing.

Taken together, the purpose of recommendations 2.1-2.3 is to stimulate the creation of a more vibrant ecosystem for climate risk assessment, so that communities, companies, and government agencies can have the accurate and reliable information they need to prepare for and mitigate rising extreme weather risks.

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[25] Johnson, J. M., Fang, S., Sankarasubramanian, A., Rad, A. M., da Cunha, L. K., Clarke, K. C., ... & Yeghiazarian, L. (2023). Comprehensive analysis of the NOAA National Water Model: A call for heterogeneous formulations and diagnostic model selection. 10.22541/essoar.167415214.45806648/v1

[26] Johnson, J. M., Munasinghe, D., Eyelade, D., & Cohen, S. (2019). An integrated evaluation of the National Water Model (NWM)–Height Above Nearest Drainage (HAND) flood mapping methodology. *Natural Hazards and Earth System Sciences, 19(*11), 2405–2420. https://doi.org/10.5194/nhess-19-2405-2019

[27] Wing, O. E. J., Smith, A. M., Marston, M. L., Porter, J. R., Amodeo, M. F., Sampson, C. C., & Bates, P. D. (2021). Simulating historical flood events at the continental scale: Observational validation of a large-scale hydrodynamic model. *Natural Hazards and Earth System Sciences*, *21*(2), 559–575. https://nhess.copernicus.org/articles/21/559/2021/

The components of recommendations 1 and 2 will both separately and synergistically improve the nation's capacity to manage risk. For example, a skillful flood model will accurately show how recent development exacerbates urban flooding caused by an historic 100-year rainstorm and suggest critical mitigation measures better than a less-skillful model (for example one that does not treat the impact of impermeable surfaces very well). Together with accurate estimates of the likelihoods of extreme rainfall both now and through midcentury, skillful flood and flood-loss models can provide the basis for better cost-benefit decisions when designing new or retrofitted climate resilient infrastructure.

A National Adaptation Plan to Mitigate Extreme Weather Risk

The final set of recommendations aim to provide communities with decision-making guidelines to help them mitigate and adapt to extreme weather risk. Here, we need to recognize that many important decisions about how to prepare for increased risks from extreme weather will not be made by federal agencies, but by households, businesses, and local, state, and tribal governments. In a recent analysis of weather risk, the Council of Economic Advisors noted this and, consistent with our recommendations, identified "producing and disseminating knowledge about climate risk," as the first of four pillars that should guide federal adaption efforts.[28]

However, providing information will not in itself equip at-risk communities to prepare for and adapt to new risks. Local communities have many concerns, of which disaster planning is only one, and many areas at high risk from extreme weather are lower-income.[29] Moreover, the decisions are complex: they may affect property values, or permitting decisions, or local development in ways that matter greatly to households and local businesses. Having access to common frameworks and decision-making tools can made it easier for communities to process newly available risk information and make appropriate planning decisions in response.

Any serious attempt to protect households and communities from rising extreme weather hazards must grapple with difficult trade-offs. For instance, in preparing this report, PCAST heard concerns that growing awareness and measurement of extreme weather risk would result in higher insurance prices and reduced property values, placing a disproportionate burden on lower-income and marginalized communities. While federal and state policies could subsidize insurance purchases or prop up home prices in high-risk areas, these policies can encourage people to live in harm's way. Relocating individuals and families away from high-risk areas is another way to save lives and reduce the future costs of disaster relief. However, relocation programs often are criticized for splintering

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[28] Council of Economic Advisors, (2023, February) "Opportunities for Better Managing Weather Risk in the Changing Climate," Chapter 9 of the 2023 *Economic Report of the President.*

[29] See examples: Burke, M., Heft-Neal, S., Li, J., Driscoll, A., Baylis, P., Stigler, M., Weill, J. A., Burney, J. A., Wen, J., Childs, M. L., & Gould, C. F. (2022). Exposures and behavioral responses to wildfire smoke. *Nature Human Behavior*, 6(10), 1351–1361. https://doi.org/10.1038/s41562-022-01396-6

Wing, O. E. J., Lehman, W., Bates, P. D., Sampson, C. C., Quinn, N., Smith, A. M., Neal, J. C., Porter, J. R., & Kousky, C. (2022). Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change, 12*(2), 156–162. https://doi.org/10.1038/s41558-021-01265-6. In addition, a sizeable literature documents historically how minority populations were pushed into high-risk areas, (e.g. Schell, C.J. Dyson, K., Fuentes, T.L., Des Roches, S., Harris, N.C., Miller, D.S., Woelfle-Erskine, C.-A., & Lambert, M.R. (2020) The ecological and evolutionary consequences of systemic racism in urban environments. *Science* (New York, N.Y.), 369(6510). https://doi.org/10.1126/science.aay4497) local communities, or leaving lower-income families with few options to move to nearby housing. Finally, programs that require or subsidize investments in "hardening" structures against fire or storms can protect property and lives. However, these programs take time to be effective, especially when they apply only to new construction, and they need careful design to ensure that investments are truly cost-effective.[30]

The federal government has a multitude of programs aimed at helping communities prepare for and respond to different extreme weather risks (see Box 3) and Appendix D.

BOX 3. Federal Programs and Interaction with Community Decisions[31]
• **Flooding:** FEMA operates the National Flood Insurance Program, which offers flood insurance in areas with significant flood risk and is involved in floodplain management. Local communities choose whether to participate in this program. • **Wildfires**: The Forest Service and Bureau of Land Management manage a vast acreage of forestland. However, much of the responsibility resides outside the federal government. For instance, property insurance for wildfires is a private market that is regulated at the state level. • **Hurricanes and Tropical Cyclones**: The federal government regularly steps in to fund recovery and rebuilding after a major disaster. However, local and state governments generally have responsibility for zoning decisions and building codes that affect the potential for storm damage. A variety of federal agencies, including FEMA and HUD, also have significant grant programs to assist communities in preparing for hazards and building resilience.[32] These programs have gained additional heft with the recent passage of the Infrastructure Investment and Jobs Act (IIJA). The IIJA designates $50 billion of investments in resilience and western water infrastructure,[33] including $6.8 billion in funding for FEMA to allocate toward climate mitigation programs.[34] Recently, FEMA revised its cost-benefit analysis framework for grant evaluation, with the goal of making grants more accessible for low income and marginalized communities.[35]

[30] Appendix D discusses and array of policies that have been used to protect communities from historical environmental risks, and that are potential responses to extreme weather risk.
[31] Programs include FEMA grant programs for preparedness, hazard mitigation, and resilience, Forest Service grant programs to support communities at wildfire risk, Bureau of Reclamation grants to support drought preparation, and many more.
[32] FEMA's grant program includes separate categories for Preparedness, Hazard Mitigation, and Resilience. https://www.fema.gov/grants
[33] The White House. (2021, August 2). Bipartisan Infrastructure Investment and Jobs Act. [Fact sheet] https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/02/updated-fact-sheet-bipartisan-infrastructure-investment-and-jobs-act/
[34] FEMA. (2021, November 15). *Infrastructure Deal Provides FEMA Billions for Community Mitigation Investments* [Press Released]. https://www.fema.gov/press-release/20211115/infrastructure-deal-provides-fema-billions-community-mitigation-investments
[35] The FEMA grant program has been criticized in the past for favoring higher-income communities better prepared to develop proposals and access funding – see especially its 2020 National Advisory Council report, and subsequent annual reports. The new methodology was released in October 2022.

However, despite the array of programs, our nation does not have a national adaptation plan that assesses climate and weather risks and provides guidelines for coordinating the complex and overlapping patchwork of federal, state, and local efforts. Such a plan would be a valuable step toward organizing existing programs, and it would build on the more than 20 climate adaption programs developed by federal agencies at the direction of the Biden-Harris Administration.[36]

Recommendation 3.1

The White House should develop and publish a National Adaptation Plan to prepare for and mitigate increased risks from extreme weather. The Plan should include:

- **(a) A systematic approach to mapping near term and longer-term high-danger zones for each extreme weather hazard, updated as estimates of risk are improved.**
- **(b) Decision frameworks to assist local communities in making plans to mitigate or adapt to extreme weather risk.**
- **(c) Regulatory and legal options to reduce long-term risk exposure, for instance through land-use planning, zoning, and building code adoption**
- **(d) Comprehensive assessment of Federal and State programs in alleviating disaster risks, including the distribution of federal funds for disaster preparation with attention to whether these programs are accessible to low-income communities.**
- **(e) Guidelines for equitable allocation of disaster relief. These guidelines should anticipate the potential for recurring extreme weather events, so that relief programs work to mitigate future dangers to a community.**

Subpart (a) would provide a federal categorization of risk levels that could be used by federal agencies allocating grant funding, or by states regulating insurance practices. There are several precedents. The National Flood Insurance Program is in the process of creating updated maps showing flood risks ("Risk Rating 2.0"). The National Risk Index published by FEMA and the Climate Mapping for Resilience and Adaption website developed by USGCRP both provide ratings of extreme weather risk for events at varying geographical granularities. These would be natural portals to share risk classifications based on updated estimates of the likelihood of heatwaves, hurricanes, floods, droughts, and wildfires as this information becomes available. Subparts (b), (c), and (d) envision guidelines that could help to improve and coordinate the decision-making of local communities and federal agencies. PCAST recommends developing a set of decision guidelines to assist local communities at risk from extreme weather, inventorying federal grant programs to ensure that funds are being delivered to areas at greatest risk, and working aggressively to ensure that the grant mechanisms do not disadvantage lower-income communities. After disasters occur, there is often a question of whether to rebuild in the affected area. These decisions ultimately are made locally, but a set of clear federal decision-making guidelines would benefit communities, especially as PCAST envisions that communities will be making these decisions more frequently in the coming decades.

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[36] White House (2021, October 7). *Biden Administration Releases Agency Climate Adaptation and Resilience Plans from Across Federal Government* [Fact Sheet] https://www.whitehouse.gov/briefing-room/statements-releases/2021/10/07/fact-sheet-biden-administration-releases-agency-climate-adaptation-and-resilience-plans-from-across-federal-government/

While the state of climate and extreme weather modeling is advancing rapidly, there has been less work on how increased risks from extreme weather affect housing prices, insurance and credit, household location choices, and investment, all of which are important for making policy at the state and local level. Our final recommendation is aimed at addressing this challenge.

Recommendation 3.2

Fund research on the adaptation of households, real-estate and insurance markets, and local governments to changing climate and extreme weather risk. This effort should aim to illuminate the behavior of households and firms in response to evolving climate and weather risks, and the benefits and costs of alternative policies aimed at mitigating and adapting to these risks. NSF may be best positioned to lead this effort, especially if coordinated with mission-oriented agencies such as NOAA, HUD, EPA, and others.

Research is urgently needed to understand how behavior changes in response to climate and weather risks. Today, we are just starting to understand how an increase in the frequency and severity of floods, hurricanes, or wildfires will affect housing and credit prices, insurance markets, business location decisions, or migration. These are important variables for federal, state, local, and tribal governments, and all organizations interested in facilitating climate adaptation.

In closing our report, PCAST also wants to highlight two ways in which a national effort to measure extreme weather risk more accurately would contribute to policies enacted during the Biden-Harris administration and to future policy.

Already in response to Executive Order 14030 on climate-related financial risk, more than twenty federal agencies have developed plans to address climate change, and there are interagency efforts to monitor climate risks to financial markets as well as to national security.[37] The Federal Insurance Office (FIO) has launched an effort to investigate the potential for major disruptions in insurance markets and to identify climate-related gaps in the supervision of insurers [38] Virtually all of these efforts can benefit from more accurate assessment of the risks of extreme weather events.

Second, it is important to consider the all too likely possibility that over time climate change may lead to increasingly more frequent and severe disasters. Some of the worst-case scenarios for the economic costs of climate change result from this possibility. Improving the quantification of extreme weather risk would not only inform decisions today, but enable risk mitigation decisions for likely impending catastrophes of greater scale and frequency in the future.

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[37] Two examples are the Climate-related Financial Risk Advisory Committee (CFRAC) established in October 2022 by the Financial Stability Oversight Council, and the Climate Working Group established by the Department of Defense in March 2021.
[38] U.S. Department of the Treasury. (2021, August 31). *U.S. Department of the Treasury Launches New Effort on Climate-Related Financial Risks in the Insurance Sector* [Fact sheet]. https://home.treasury.gov/news/press-releases/jy0337. It is important to recognize, however, that FIO has very limited regulatory authority, and in some cases can lack the ability to requisition or share data.

Conclusion

The Biden-Harris administration has made addressing climate change a central priority, including major investments in preparing for and mitigating extreme weather. We can make further advances by making it a national priority to improve our understanding and quantification of extreme weather risks, enabling effective policy decisions and providing Americans with the information they need to protect themselves.

Acknowledgments

The members of PCAST wish to thank the staff in the Office of Science and Technology Policy (OSTP) for their various contributions throughout the preparation of this report. PCAST would like to thank Alondra Nelson, Deputy Assistant to the President, formerly Performing the Duties of Director of the White House Office of Science and Technology Policy. PCAST also expresses its gratitude to Marc Aidinoff, Kei Koizumi, and Asad Ramzanali in OSTP. PCAST especially thanks the IDA Science and Technology Policy Institute (STPI) team, especially Emily Grumbling, Todd Ringler, and Margaret Murphy, and Xueying “Shirley” Han for assistance with analyses and the report. Additionally, PCAST would like to thank Eric Lander, former Director of OSTP and PCAST Co-Chair, for providing the initial impetus and energy that inspired pursuit of this topic. Finally, PCAST wishes to express a heartfelt thanks to the staff at the Department of Energy, particularly Karen Talamini, who have worked tirelessly in administering PCAST.

Appendix A. External Experts Consulted

PCAST sought input from a diverse group of additional experts and stakeholders. PCAST expresses its gratitude to those listed here who shared their expertise. They did not review drafts of the report, and their willingness to engage with PCAST on specific points does not imply endorsement of the views expressed herein. Responsibility for the opinions, findings, and recommendations in this report and for any errors of fact or interpretation rests solely with PCAST.

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Appendix B. Improved Estimates of Extreme Weather Probabilities

Current assessments of climate and weather risks are based predominantly on historical event statistics accumulated over the past 50 to 100 years.[39] But long-term losses are dominated by "tail risks" (i.e., rare, high-impact events, typically with recurrence intervals around 100 years). This poses a challenge for using historical records to assess important tail risks, because the weather records are generally much too short to provide accurate estimates. Moreover, climate change is increasing the probability of events that once were rare, such as the devastating rainfall during Hurricane Harvey in Texas.[40] Therefore, it is imperative in assessing current risks and risks in the coming decades to avoid exclusive reliance on the historical record and to take the changing climate into account.

High-resolution Climate Ensembles

A central opportunity to improve the assessment of extreme weather risks in a changing climate comes from exploiting the historical record jointly with advances in numerical modeling of weather and climate, enabled by the exponential increase in supercomputer performance. Models of the physics of the atmosphere, oceans, and the hydrological and biological processes on land underlie weather forecasts and are the most reliable sources of information about future changes in weather probabilities. As the climate system is nonlinear and chaotic, large ensembles of model simulations are needed to capture the probabilities of any event. Models have advanced to the point that ensembles of century-long simulations with resolutions around 10–25 km are now possible. Climate models divide the earth into three-dimensional grids, with finer grids permitting higher accuracy and precision. With a 15 km resolution, each cell is roughly the area of an average U.S. zip code.

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[39] Climate is the statistical distribution of weather, often characterized by summary statistics such as the mean temperature. Climate is analogous to the probabilities associated with numbers on a die (each has probability ⅙) while weather is analogous to the number that comes up in a single roll. A substantial fraction of R&D programs at NOAA are focused on prediction of individual weather events, with relevant timescales of days to at most a season. Here, we are interested in longer time scales – up to the multiple decades relevant for infrastructure planning – which means estimating the climate, i.e., the probabilities of different kinds of weather. Climate change complicates the picture by progressively changing the climate, which is analogous to progressively loading the dice.

[40] Emanuel, K. (2017). Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National Academy of Sciences of the United States of America, 114*(48), 12681–12684. https://doi.org/10.1073/pnas.1716222114

Risser, M. D., & Wehner, M. F. (2017). Attributable Human-Induced Changes in the Likelihood and Magnitude of the Observed Extreme Precipitation during Hurricane Harvey. *Geophysical Research Letters, 44*(24), 12,457-12,464. https://doi.org/10.1002/2017GL075888

van Oldenborgh, G. J., van der Wiel, K., Sebastian, A., Singh, R., Arrighi, J., Otto, F., Haustein, K., Li, S., Vecchi, G., & Cullen, H. (2017). Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, *12*(12), 124009. https://doi.org/10.1088/1748-9326/aa9ef2

Such simulations require the most advanced supercomputing facilities, such as those of the Department of Energy, which have consistently led the rankings of the world's fastest computers.[41] Leveraging newly developed AI tools and established methods for downscaling, the simulations can be combined with historical observations to correct biases that remain in even the most advanced simulations and to obtain information on geographically even more granular kilometer scales.

A coordinated modeling effort by the U.S. climate modeling centers can significantly improve current estimates of extreme weather probabilities based on the historical record. **As a recent review aptly stated, "calls for the integration of climate science into risk disclosure and decision-making across many levels of economic activity has leap-frogged the current capabilities of climate science and climate models by at least a decade."**[42]

At resolutions in the range of 10-25 km, extreme temperatures, extreme precipitation events, and severe storms are captured much more effectively than in existing climate simulations with courser scales.[43] For example, Figure 1, below, shows the improved performance of recent high-resolution modeling for extreme rainfall patterns in the U.S. Northeast.[44]

[41] In the 2022 Top500 list of the world's supercomputers, the Frontier system at Oak Ridge National Laboratory was judged to be the fastest, achieving over a quintillion operations per second.
[42] Fiedler, T., Pitman, A. J., Mackenzie, K., Wood, N., Jakob, C., & Perkins-Kirkpatrick, S. E. (2021). Business risk and the emergence of climate analytics. *Nature Climate Change, 11*(2), 87–94. https://doi.org/10.1038/s41558-020-00984-6
[43] Vecchi et al.Tropical cyclone sensitivities to CO2 doubling: roles of atmospheric resolution, synoptic variability and background climate changes. Clim Dyn 53, 5999–6033 (2019). https://doi.org/10.1007/s00382-019-04913-y
T. Delworth et al., SPEAR: The next generation GFDL modeling system for seasonal to multidecadal prediction and projection, Journal of Advances in Modeling Earth Systems,12, e2019MS00189. See also https://www.gfdl.noaa.gov/spear/
[44] T. Delworth personal communication using data from the large ensemble of NOAA's SPEAR model described in T. Delworth et al., SPEAR: The next generation GFDL modeling system for seasonal to multidecadal prediction and projection, Journal of Advances in Modeling Earth Systems,12, e2019MS00189. See also https://www.gfdl.noaa.gov/spear/

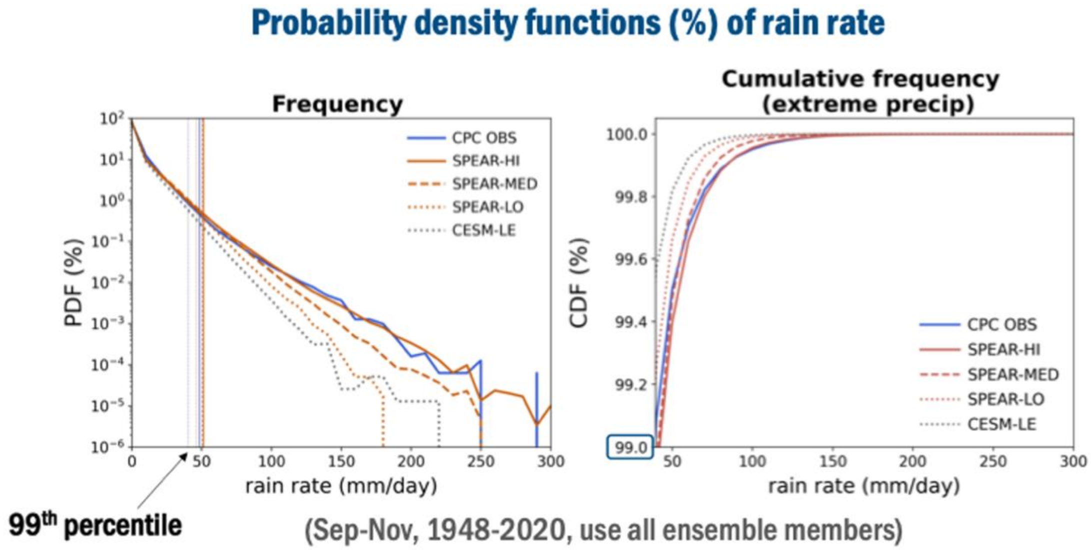

Figure 1. Probabilities of 24-hour rainfall produced by four models against observations for the Northeastern U.S. from 1948-2020. Ninety-nine percent of simulated or observed days have rainfall less than the value shown by the appropriate vertical line in the left graph. CPC-OBS shows the observations. CESM-LE is an NCAR model and SPEAR-LO is a NOAA model with horizontal atmospheric resolutions of 1 degree of latitude, which is about 100 km. SPEAR-MED has a resolution of one-half degree (~50 km), while SPEAR-HI has a resolution of 0.25 degrees (25 km).[42]

Extreme heat waves are the deadliest weather events, and floods from extreme rainfall and storm surge are associated with the highest financial damages.[45,46] Newer, higher-resolution climate models capture, for example, precipitation extremes better than previous models with roughly fourfold lower resolution (Figure 1).[47,48,49] Thus, the latest climate models provide a timely and unprecedented opportunity to estimate risks of the most deadly and costly extreme events, all of which have been impacted by climate change.

State-of-the-art climate models rely on ensembles of multiple models, each run multiple times to produce different possible realizations of the weather everywhere on the globe and for the duration

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[45] NOAA & FEMA (2010, March). Flooding - Our Nation's Most Frequent and Costly Natural Disaster [Fact sheet]. https://www.fbiic.gov/public/2010/mar/FloodingHistoryandCausesFS.PDF

[46] NOAA National Weather Service. (2021). Weather Related Fatality and Injury Statistics. NOAA's National Weather Service. https://www.weather.gov/hazstat/

[47] Harris, L., McRae, A. T. T., Chantry, M., Dueben, P. D., & Palmer, T. N. (2022). A Generative Deep Learning Approach to Stochastic Downscaling of Precipitation Forecasts. *Journal of Advances in Modeling Earth Systems, 14*(10), e2022MS003120. https://doi.org/10.1029/2022MS003120

[48] Maraun, D., & Widmann, M. (2018). *Statistical downscaling and bias correction for climate research.* Cambridge University Press. https://www.cambridge.org/core/books/statistical-downscaling-and-bias-correction-for-climate-research/4ED479BAA8309C7ECBE6136236E3960F https://doi.org/10.1017/9781107588783

[49] Groenke, B., Madaus, L., & Monteleoni, C. (2020, August 11). ClimAlign: Unsupervised statistical downscaling of climate variables via normalizing flows. *Climate Informatics 2020: 10th International Conference on Climate Infomatics.* https://arxiv.org/pdf/2008.04679

of the run. The data can be combined to generate estimated probabilities of any type of extreme weather in any location, for historical climate conditions (e.g. starting in 1950), the present, and the future. A coordinated effort to produce ensembles of climate simulations and evaluate them against historical observations will allow the field to close the gap between the climate information needs for risk disclosure and decision making and the information that is currently available.

Agency Coordination and Collaboration

Several federal agencies have the capacity to participate in such an ensemble modeling effort, including NASA, DOE, NOAA, and the National Center for Atmospheric Research (NCAR), which is supported by the National Science Foundation. Rather than restrict the modeling to a single agency or center, the report above recommends a multi-agency effort to improve estimates of extreme events.

Building on Recommendation 1.1 in the report, the primary agencies and institutions with climate-modeling expertise (NOAA, NCAR, DOE, and NASA) should enhance their high-resolution modeling capabilities and state-of-the-art statistical methods to quantify the current and near-future risks of extreme weather at 10km resolution or finer. Indeed, 1 km resolution could be possible in the US, given the current state of the art. To accomplish this, large multi-model ensembles (> 100 members) of climate simulations at 10-25 km resolution spanning the 20th century and extending through 2050, could be made by these four agencies. In this case each modeling center would use its own models, but all the centers would follow a common simulation protocol. Using the results of the ensemble runs, advanced statistical and machine-learning methods could then enable agencies and institutions with climate modeling expertise to estimate extreme weather probabilities from existing weather data and ensemble model projections.

Current operational federal efforts to predict weather rely on information about the current state of the atmosphere and planet's surface to forecast a short distance into the future (i.e. hours to days for a particular hurricane or a season for the expected number of named storms). This is the science of meteorology. In contrast, climatology is the longer-term probability distribution of the weather, such as the underlying likelihood of a hurricane of a given strength hitting Miami in any given decade. In technical terms, a climatology approach is dominated by boundary conditions such as the greenhouse gas concentrations in the atmosphere, rather than by the initial conditions that inform a shorter-term forecast. Also, a series of evolving climatologies is required to plan infrastructure and to adapt to climate change, while shorter-term forecasting is required to allocate disaster relief.

Recommendation 1.1 in the report above would add the first U.S. operational effort to produce evolving climatologies for extreme weather to the list of priorities of NOAA, NCAR, DOE, and NASA. The four organizations could carry out the ensemble simulations with their existing climate models, with funding for staff of around $10M plus supercomputer allocations, but only by re-allocating computer resources from other priorities, such as fundamental research.

PCAST notes that a steering body with authority over budget allocations would be needed to oversee the effort, to maintain coordinated activity, and to promote a genuine reprioritization. Existing efforts like the USGCRP are steered by agency leadership and may not provide the needed external push. An alternative would be a new steering body created by Congress or the White House.

Sampling and Downscaling Techniques

The large ensembles produced by this initiative will enable quantification of how often events such as the Western North America heat wave of 2021, which led to hundreds of excess deaths in Washington and Oregon, or Hurricane Ian, which devastated Florida in 2022, may occur as a result of natural atmospheric variability superimposed on climate change. These ensembles will also allow quantification of uncertainties in risk assessments due to two sources:

1. *Model uncertainty*, arising from imperfections in models (e.g., because not all clouds can be explicitly resolved, even at 10 km resolution, different models produce different cloud cover, with the differences affecting other aspects of climate such as precipitation).
2. *Internal variability of the chaotic climate system*, which can lead to different outcomes because of small changes in atmosphere or ocean conditions (e.g. the "butterfly effect").

These two types of uncertainty dominate uncertainties in outcomes for projections extending two to three decades into the future.[50] This is the most relevant timescale for incorporating extreme weather hazards into infrastructure planning, the analysis of financial system risks, and disaster preparedness. On longer time scales, an additional source of uncertainty, called *scenario uncertainty*, stemming from imperfect knowledge of how greenhouse gas emissions and land cover change will evolve, becomes relevant.[51] This scenario uncertainty is not captured by the recommended ensemble simulations, which focus on past greenhouse gas emissions and likely near-future emissions.

To sample the space of possible weather trajectories broadly, it will be important to explore broad variations of slowly varying ocean conditions. This can be done through sampling of ocean conditions from very long (thousands of years) coarser-resolution climate simulations or targeted variations of ocean initial conditions, such as those associated with El Niño. The modeling centers involved should develop a joint protocol for the ensemble simulations to produce the broadest possible sampling of weather extremes over the period of the simulations.

Producing ensembles of hundreds of simulations from the four modeling centers at resolutions of around 10-25 km will substantially improve the basis for quantitative assessments of climate and weather disaster risks. However, these simulations will not be free of systemic biases, for example, in the regional distribution of rainfall or the severity of extreme thunderstorms. Moreover, the scale on which impacts of extreme events manifest themselves is smaller yet (1 km or less). Additionally, even 300-400 carefully designed simulations may not suffice to sample and quantify, for example, the risks of hurricanes making landfall along the Gulf Coast: while the simulations will explore a much broader space of possible weather events than are available observationally, sufficiently rare events may still not be adequately sampled.

The shortcomings of relying on simulations alone in risk assessments can be mitigated by combining the simulations with available data, including data generated computationally in targeted high-

[50] Lehner, F., Deser, C., Maher, N., Marotzke, J., Fischer, E. M., Brunner, L., Knutti, R., and Hawkins, E.: Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6, Earth Syst. Dynam., 11, 491–508, https://doi.org/10.5194/esd-11-491-2020, 2020.
[51] Phenomena such as sea level rise also add uncertainty over longer (>50 year) time scales, because we do not know exactly how patterns of ice melt will respond to climate change.

resolution simulations (e.g., of hurricanes) and the large volume of Earth observations available from the ground and from space. Such additional data can be used to (a) downscale impacts such as wind and precipitation severity to scales of a few kilometers or less and (b) provide estimates of rare event risks, such as that of landfalling hurricanes, which extend beyond what can be directly obtained from the ensemble of climate simulations.

Downscaling has been done by dynamical and statistical means:

- *Dynamical downscaling* consists of embedding finer computational meshes in limited subdomains of a global model, driving the smaller, more finely resolved domains with boundary conditions supplied from a global model. For example, severe thunderstorms can be simulated today in computational domains that might span one or a few of the U.S. Plains States. The grids need not be fixed in space and can move with the hazard. For example, fine scale grids can automatically center themselves on hurricanes and follow them as they move. This is done routinely today in hurricane forecast models. Increasing computer performance will accelerate such dynamical downscaling and will enable ensembles of downscaled simulations.
- *Statistical downscaling* methods are computationally more efficient than dynamical downscaling methods and allow harnessing observational data. Traditionally, they have related the statistics of simulations from a global model to historical observations on finer scales.

As noted earlier, potential for advances in downscaling exist by using machine learning (ML) methods used in image processing and generation, and by combining dynamical downscaling and ML techniques. For example, it is possible to use ML to refine mappings from coarser-resolution climate simulations to local impact metrics, leveraging techniques similar to those that provide super-resolution in optical imaging. Moreover, generative ML models used in image generation can be trained on samples of dynamically downscaled events together with coarser-resolution ensemble simulations, providing computationally efficient and reliable statistical downscaling that can also correct some biases in climate simulations.[52,53,54]

To accomplish Recommendation 1.1, PCAST recommends that a downscaling and bias-correction research program be created to scale weather events from the 10-25 km resolution of the ensemble simulations to scales of 1 km over the U.S. and 10 km globally, with a focus on tail risks of extreme events.

The downscaling program should consider a call for proposals by NOAA and the NSF**,** open to the public and private sector, to deploy recent advances in the mathematical and computational sciences

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[52] Harris, L., McRae, A. T. T., Chantry, M., Dueben, P. D., & Palmer, T. N. (2022). A Generative Deep Learning Approach to Stochastic Downscaling of Precipitation Forecasts. *Journal of Advances in Modeling Earth Systems, 14*(10), e2022MS003120. https://doi.org/10.1029/2022MS003120

[53] Groenke, B., Madaus, L., & Monteleoni, C. (2020, August 11). ClimAlign: Unsupervised statistical downscaling of climate variables via normalizing flows*. Climate Informatics 2020: 10th International Conference on Climate Infomatics.* https://arxiv.org/pdf/2008.04679

[54] Maraun, D., & Widmann, M. (2018). Statistical downscaling and bias correction for climate research. Cambridge University Press. https://www.cambridge.org/core/books/statistical-downscaling-and-bias-correction-for-climate-research/4ED479BAA8309C7ECBE6136236E3960F https://doi.org/10.1017/9781107588783

and machine learning to generate physics-constrained granular weather events from the large ensemble of high-resolution climate simulations.

Finally, it is critical that the data generated by Recommendations 1.1, 2.1, and 2.2 be easily findable, accessible, and analyzable by a broad range of stakeholders. PCAST envisions these data serving as an input for weather-hazard and catastrophe-loss models and for a wide range of private and public sector planning decisions. Indeed, their use will extend outside the U.S. because the extreme weather estimates in Recommendation 2.1 will be global.

Large ensembles of high-resolution climate simulations generate data at volumes that are not easily transferable via Internet downloads. A more effective approach is to store the data on the cloud and make them accessible and analyzable through an application programming interface (API) and web-based interactive user interfaces for exploration. These interfaces will allow data analysis on the cloud and the effective integration into ML workflows, for example, for downscaling climate model output. The climate data products made easily and freely available under Recommendation 1.2 should include metadata with information from the model ensembles. Data distribution efforts as large as these are currently handled within the private sector, but not within the government. To facilitate effective action on these data efforts, OSTP could convene a panel of experts to plan and budget the needed effort before the end of 2023, including its administrative structure.

Appendix C. Weather-Hazard and Catastrophe-Loss Models

Weather-Hazard Models

Weather-hazard models combine information about weather with information about topography and surface conditions to predict weather-related hazards including:

1. Inland flooding that occurs when extreme rainfall causes rivers and streams to overflow their banks.
2. Coastal flooding due to storm surge and sea level rise.
3. Fire that occurs when an ignition source finds sufficient fuel in dry, hot, and windy conditions.
4. Drought caused by low rainfall, high temperatures, low humidity, insufficient water holding capacity of soils (for agricultural drought), and insufficient water storage in lakes, reservoirs, and rivers (for the low streamflow that prevents industrial cooling).

Weather-hazard models are used for two different purposes: (1) predicting the real-time behavior of an individual event to help manage emergency response, and (2) predicting the probabilities of hazards to help manage risk. Usually, a model is tailored to one purpose or the other, but some are designed to address both. This report focuses only on models targeting the second purpose, which allows one to compute the likelihood that a hazard of a given severity will occur, for all possible severities, *given the evolving probabilities of extreme weather conditions now and in the future*.

Agencies throughout the federal government, academia, and the private sector have operational flood, fire, and drought models that are constantly being updated. A selection of these is listed in Table 2.1. The table contains 4 flood models, 5 wildfire models, and 3 drought models that are used by federal agencies. These models play an essential role in the federal programs identified in the climate resilience *Roadmap,*[55] and in supporting private and public sector decision making. They are often geographically granular, sometimes at the scale of individual buildings.

[55] The White House. (2021, October 14). *A Roadmap to Build a Climate-Resilient Economy*. https://www.whitehouse.gov/wp-content/uploads/2021/10/Climate-Finance-Report.pdf

Extreme Weather Type	Models Used or Developed by One or More Federal Agencies	Model Description
Flood	RASPLOT	A computer program, created by FEMA, that allows the user to create flood profiles through the automatic extraction of data from the U.S. Army Corps of Engineers' Hydraulic Engineering Centers River Analysis System (HEC-RAS) hydraulic modeling files.
	National Streamflow Statistics	Provides regression equations to estimate the frequency of floods and other streamflow statistics.
	ADCIRC	A system of computer programs for solving time dependent, free surface circulation and transport problems in two and three dimensions.
	HEC-RAS	A computer program used in the preparation of studies and restudies for the National Flood Insurance Program.
Wildfire	FlamMap	A quasi-empirical fire spread model, widely used among forest and fire managers in operational settings
	FSim-Wildfire Risk Simulation Software	The FSim simulation process involves assembly of geospatial landscape and terrain data, assembly and processing of historical fire occurrence data, and assembly and processing of historical weather observations.
	Wildfire Hazard Potential Map	A raster geospatial product that can help to inform evaluations of wildfire hazard or prioritization of fuels management needs across very large landscapes.

Extreme Weather Type	Models Used or Developed by One or More Federal Agencies	Model Description
	Wildfire Risk to Communities	A model designed to help community leaders such as elected officials, community planners, and fire managers understand how risk varies across a state, region, or county and prioritize actions to mitigate risk.
	Rothermel Fire Surface Spread Model	This model has been used in fire and fuels management systems since 1972. It is generally used with other models including fireline intensity and flame length.
Drought	Standardized Precipitation Indices (SPI)	A universal meteorological drought index for effective drought monitoring and climate risk management.
	National Multi-Model Ensemble Experiment (NMME)	The NMME Experiment seeks further improvements in intraseasonal to seasonal climate and drought prediction. The NMME project uses an ensemble of leading national climate models to provide climate forecasts for research purposes.

In general, weather-hazard modeling is an active area of academic, private, and governmental research and development. Most weather-hazard models are publicly accessible, unlike most catastrophe-loss models (see below). The historic record contains many examples of severe weather hazards that can be used to develop and evaluate weather hazard models. These models remain valid despite climate change in the frequency of the severe weather that causes them, although unprecedented weather will obviously be beyond any data set used to develop a weather-hazard model. Despite these advantages, PCAST repeatedly heard concerns from experts from multiple sectors regarding needed improvements in hazard modeling.

Meteorology and climatology have a well-established methodology for discarding obsolete models and evaluating if a new model represents a useful advance. A collection of widely used *skill scores* measure how well each model would have predicted historical data (called *hindcasting)*.[56,57,58] Models without skill are simply not used, and new versions of models are typically not released until they demonstrate competitive skill.

In contrast, PCAST repeatedly heard that there is not a sufficiently healthy tradition of skill scoring for weather-hazard modeling. As a result, it is very difficult to obtain a simple clear answer to the question: "How well does your model work?" Without clear metrics that cause underperforming models to be discarded, the number of models in current use by the federal government and others continues to increase, and at an accelerating pace because of the growth of private firms selling climate-related risk analysis. Moreover, quantitative analysis of predictive power is required to produce quantitative estimates of prediction uncertainty. This is vital in risk analyses, which must account for all known risks, including modeling error risks. Recommendations 2.1 and 2.2 in the main text of the report aim to correct this problem through the development of data sets that can be used to skill-score weather-hazard models and to promote skill-scoring within federal agencies, including when evaluating proposals for funding and private climate risk disclosures. Although few publicly available hazard-loss (described below) models exist today, these should also be skill-scored, along with any proprietary models used within the federal government, or in applications for government funding.

As systematic quantitative assessment of model skill becomes common, researchers who work on weather-hazard models will inevitably uncover critical shortcomings in both existing models and test data. This will provide an opportunity to refocus priorities for federal research funding so as to reduce or eliminate the shortcomings. In the meantime, it is critical that federal funding of basic research aimed at improving weather-hazard modeling be given high priority. PCAST spoke with many researchers who were particularly concerned about the research needs summarized in Box 4, *precisely because weather-hazard models are already in common operational use, despite their shortcomings*.

Box 4 – Priority Areas for Research and Development of Weather Hazard Models

There is a critical need to address inadequacies in current generation weather-hazard models to improve their reliability and skill. These needs motivated Recommendation 2.3 in the main text and include:

1) Fire[59]

[56] Hargreaves, J. C. (2010). Skill and uncertainty in climate models. *Wiley Interdisciplinary Reviews: Climate Change, 1(*4), 556–564. https://doi.org/10.1002/wcc.58
[57] Hausfather, Z., Drake, H. F., Abbott, T., & Schmidt, G. A. (2020). Evaluating the Performance of Past Climate Model Projections. *Geophysical Research Letters, 47*(1). https://doi.org/10.1029/2019GL085378
[58] NOAA National Weather Service Climate Prediction Center. (December 2005). *CPC Verification Summary*. https://www.cpc.ncep.noaa.gov/products/verification/summary/index.php?page=tutorial
[59] Shuman, J. K., Balch, J. K., Barnes, R. T., Higuera, P. E., Roos, C. I., Schwilk, D. W., Stavros, E. N., Banerjee, T., Bela, M. M., Bendix, J., Bertolino, S., Bililign, S., Bladon, K. D., Brando, P., Breidenthal, R. E., Buma, B., Calhoun, D., Carvalho, L. M. V., Cattau, M. E., . . . Zhang, X. (2022). Reimagine fire science for the anthropocene. *PNAS Nexus,* 1(3), pgac115. https://doi.org/10.1093/pnasnexus/pgac115

- Investment in laboratory and field infrastructure to produce long-term, open-access, and multi-disciplinary datasets for improved understanding and modeling.
- Development of models that capture fuel heterogeneity, including the physiological dynamics that influence vegetation fuel loading, fuel, and the flammability of live and dead vegetation.
- Development of fire models within land surface models that integrate fire behavior and effects representative of the social and ecological environment within which humans interact with fires and subsequently influence impacts to terrestrial energy, water, and carbon cycles.
- Development of models that predict and quantify the air pollution hazard from wildfire.

2) Flood[60]

- Application of the latest high-performance computing techniques to inundation modeling for efficient high-resolution numerical solutions with sub-grid scale river channels.
- Improved understanding of soil infiltration in complex landscapes (highly variable terrain, soil structures, and land cover).
- Improved fine-scale models of urban flooding, including realistic representations of impermeable surfaces and water control measures.
- Improved input data on flood defenses, flood control structures and channel bathymetry. Accelerate and extend access to LiDAR data, and routinely update its coverage. Continue support of NOAA and the USGS to collect data from high quality measuring sites to accurately determine non-stationary probability-magnitude relationships.
- Model validation data: better observations of flood extent and water level through time during floods, particularly on floodplains and in urban areas. The forthcoming NASA Surface Water Ocean Topography[61] satellite mission may help with this.
- Improved weather inputs to the flood models for present-day and future climate modeling.

3) Drought[62]

- Reduce modeling uncertainties in precipitation projections, including extremes and intermittency.
- Improve understanding of land-vegetation coupling, including soil moisture, evaporation, and plant physiological responses to heat and water stress. This is an urgent need, motivated by the finding that no existing model (CMIP5 or CMIP6) reproduces the magnitude of the observed downward trend in atmospheric humidity (water vapor deficit) over arid regions of the U.S. and elsewhere.

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[60] Bates, P. D., Quinn, N., Sampson, C., Smith, A., Wing, O., Sosa, J., Savage, J., Olcese, G., Neal, J., Schumann, G., Giustarini, L., Coxon, G., Porter, J. R., Amodeo, M. F., Chu, Z., Lewis-Gruss, S., Freeman, N. B., Houser, T., Delgado, M., . . . Krajewski, W. F. (2021). Combined Modeling of U.S. Fluvial, Pluvial, and Coastal Flood Hazard Under Current and Future Climates. *Water Resources Research, 57*(2), e2020WR028673. https://doi.org/10.1029/2020WR028673

[61] NASA – Jet Propulsion Laboratory (2023) *Surface Water and Ocean Topography*. https://swot.jpl.nasa.gov/

[62] Simpson, I.R., K. A. McKinnon, D. Kennedy, D. M. Lawrence, F. Lehner and R. Seager, 2023: Humidity trends in dry regions are inconsistent with climate models and theoretical expectations. PNAS, Submitted Feb 16, 2023.

Hazard-Loss and Weather Catastrophe Models

The most advanced models that predict financial and human losses from the severity of a weather hazard are catastrophe (CAT) models produced by a small number of firms servicing mostly the insurance and reinsurance industries (e.g., AIR and RMS). A CAT model for estimating the risks of extreme weather has three components: the probabilities of extreme weather as a function of severity, weather-hazard models, and hazard-loss models that predict financial and human losses from the severity of a weather hazard or caused directly by weather (heat, cold, hail or wind). Hazard-loss models are typically based on engineering equations and fine-scale information about buildings and infrastructure and are calibrated with a large body of insurance claims data.

Private CAT models suffer important drawbacks, including:

- Lack of transparency (the models are largely proprietary and closed source), which reduces the usefulness of model outputs in a variety of dimensions.[63]
- Reliance on historical hazard records that are usually too short to define the all-important tail risks that dominate long-term losses and which are based on a climate state that has already changed appreciably, particularly in the tails.
- Current approach to quantifying risk uncertainty, which is often ignores methodological uncertainty.
- Lack of focus on assessing health and mortality risks (existing CAT models are largely focused on predicting losses to private and commercial property).
- High cost, which is prohibitive for many users, such as municipalities interested in assessing their current and future weather risks.

In addition to CAT modeling efforts in the private sector, FEMA, through its development of "Risk Rating 2.0," has invested in capabilities to better estimate economic damages from flooding. FEMA's Hazus program is building a portfolio of hazard-loss models and aspires to estimate human impacts such as health effects, lost wages, and productivity declines caused by weather hazards. Models estimating these human impacts are now primarily in the academic literature.[64,65] Finally, in recent years, a collection of open-source weather-hazard models, have also contributed transparent hazard-loss models that assess the risks of economic damage caused by flood and fire.

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[63] As an example, the National Association of Insurance Commissioners' "Catastrophe Computer Modeling Handbook" describes the challenges of using existing CAT modeling in the pricing of insurance:
Consumer representatives are skeptical about the application of computer models to property insurance rates and underwriting decisions. There has been a perception that the insurers are hiding behind a cloak of mystery that is held by the catastrophe modelers. The consumer representatives know that a great deal of public information goes into the models, yet the modelers claim the models are confidential and will not show consumer representatives how they work. This cloak of mystery and the varying results produced by catastrophe models tend to make consumer representatives wary. They often oppose including a catastrophe rate based on confidential models.

[64] Grant, E., & Runkle, J. D. (2022). Long-term health effects of wildfire exposure: a scoping review. *The Journal of Climate Change and Health*, *6*, 100110.

[65] Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., ... & Houser, T. (2017). Estimating economic damage from climate change in the United States. *Science*, *356*(6345), 1362-1369.

Data Needs

A key barrier to the development of reliable open-source models of damages from extreme weather is the availability of information on past financial and non-financial losses from extreme weather events. These data are essential to calibrate new models and to assess the reliability of legacy models.

Much of the loss data held by commercial insurance and CAT modeling firms from past insurance claims are proprietary and closely held, providing a strong barrier for new private-sector entrants as well as academic and other non-profit modeling efforts. The inaccessibility of these data also reduces the ability of outsiders, including regulators and consumer advocacy groups, to fully assess the quality of the industry models.

Fortunately, federal agencies hold a wealth of economic loss data from weather hazards, which, if made available to the modeling community, would support the development of more robust and diverse modeling capabilities by a wide range of entities. Perhaps most importantly, data held by FEMA on claims paid by the federal government after a Presidential Major Disaster Declaration contain information on property-level financial losses following a wide range of extreme weather events. Data from FEMA's National Flood Insurance Program also contain valuable information on financial damages from floods at the property level. Similarly, data from USDA's crop insurance program as well as loss data from damages to federal buildings and property would be helpful for estimating a range of financial losses from extreme weather. Data on health outcomes held within the Medicare system, public hospitals, and elsewhere might be similarly helpful for estimating a range of the health effects of extreme weather hazards.

PCAST believes that immediate efforts to make such data accessible in a privacy-preserving way would have substantial and immediate benefits by enhancing and enriching the nation's hazard-loss modeling capabilities. This motivated Recommendation 2.1 in the main text. Data released under Recommendation 2.1 would also facilitate the development and skill-scoring of weather-hazard models (previous section), but this need is less acute because substantial data on historic hazards and weather is already in the public domain.

Recommendation 2.1 will require that the government develops protocols to make these data widely accessible to the research, non-profit, and private-sector modeling communities. Loss data at the census block or census tract level are likely sufficiently aggregated to be shared widely without access restrictions (e.g., similar to the American Community Survey).

However, property-level loss data will also be important for estimating how financial damages vary with a range of features of the properties, such as efforts to mitigate climate damages from floods through raising foundations or reducing the hazards from wildfires through using flame retardant materials. As a result, PCAST also recommends that the government develop access protocols for property-level loss data available to the research community through existing Federal Statistical Research Data Centers (FSRDCs), which already allow qualified researchers to access restricted-use microdata from a variety of federal agencies to address important research questions.

Given its long and successful history of making privacy-protected data from a variety of agencies available to researchers, PCAST recommends that the U.S. Census Bureau be part of the InterAgency Working Group called for in Recommendation 2.1.

Research and Training Needs

The recommendations thus far would, if enacted, improve all of the components required to assess current and near-future risks of human and financial losses from extreme weather: extreme weather probabilities, weather-hazard, and hazard-loss models. Given the limitations of private models and the explosive growth in new efforts that offer climate risk assessments, PCAST also recommends that the federal government invest in expanded academic research and training in weather hazard and hazard-loss modeling, which is Recommendation 2.3 in the main text. Over time this would produce a critical mass of openly available information that would spur improvements in all the tools needed to plan for climate-related risk, foster a responsible private risk-assessment industry, and provide the skilled personnel needed by that industry.

Once this effort is underway, the interagency group that manages the research and training program should fund the cooperative development of an open-source climate and weather risk assessment system (a CAT model) that integrates the best available extreme weather probabilities, weather hazard models, and hazard loss models. An open-source system with these components would allow federal, state, and local agencies, private companies, and citizens to estimate and manage their own climate-related risks. However, to be useful, the system would have to be easy to tailor to the needs of a specific local region or group. This would not happen without oversight by the funder or an advisory body appointed by the funder, and would probably require the participation of for-profit companies able to produce a user-friendly interface. The University Corporation for Atmospheric Research (UCAR) has the experience required to manage this kind of multifaceted project.

PCAST notes that UCAR could coordinate the development of a public risk assessment system that allows for the estimation of monetary and health damages from extreme climate and weather events.

Such a public effort should have several features. Its products should:

1. Be made freely available to anyone, including insurance companies, regulators, states, municipalities, financial services firms, federal agencies, and commercial CAT modeling firms, which could use it as a baseline and benchmark for their own modeling efforts.
2. Be modular so that it can easily incorporate improved estimates of extreme weather hazards, exposure, damage, and health risks as they become available. This would also allow users to explore the sensitivity of estimates by using their own extreme weather models.
3. Be sufficiently transparent in its modeling assumptions that a wide range of end users may become comfortable in using the model itself as well as its outputs for a variety of applications.
4. Focus on estimating health and mortality risks in addition to economic damages from extreme weather and weather-related hazards. (As described above, those outcomes are not currently the focus of the private CAT modeling industry.)
5. Be developed in close coordination with the weather and hazard models proposed in previous sections of this report, to ensure that the output from the hazard models can be easily incorporated into exposure and economic loss modules. In doing so, the proposed

effort should lead to a new data standard that facilitates ongoing parallel development of these different modules by different teams.

6. Aim to propagate all the uncertainties inherent in risk modeling–from uncertainties in climate and hazard models to exposure and damage–right down to quantified uncertainty in financial and health damages, the latter of which are not handled by current industry CAT models.

The public system could be developed in partnership with both the commercial CAT modeling industry and non-profit risk modeling efforts. While a publicly available system could be viewed as competitive with existing industry CAT models, it will also serve as a valuable baseline for such models, freeing the private sector to focus on tailored risk estimates for paying clients, just as private weather forecasting enterprises profit from the free availability of global and regional numerical weather prediction output.

More generally, given the importance of modeling damages from extreme weather hazards, PCAST believes that having public, non-profit, and commercial models developed in parallel is central to building and supporting a broader and more diverse national modeling capability. Indeed, a public capability could also help catalyze research across the federal, academic, and private sectors and, in particular, would bring together the robust but largely non-overlapping research enterprises in (i) physical modeling of weather hazards, (ii) understanding economic and health risks of extreme weather, and (iii) forecasting the effect of federal, state, and local policies and policy changes on resilience and adaptation to climate and weather hazards (Recommendation 3.1 in the main text).

The development of a public climate and weather risk assessment capability would also be freely accessible to communities that cannot afford commercially developed models, and ensure the independence and continued availability of support from existing non-profit organizations. While a public capability would have the important benefits as described above, PCAST cautions against advancing it as the only or primary benchmark climate and weather risk assessment. Rather, an open source, public effort should work to encourage further model development in both the academic and private sectors. By rigorously and transparently testing the performance of different models, preferred models will naturally arise for different applications, and those preferred models may change over time as model performance evolves.

Appendix D. Federal Response to Environmental Hazards

As we identify areas at heightened risk from flood, fire, storms, or drought, how might the federal government respond? This question will become critically important if new analyses reveal that climate change has exacerbated extreme weather risk in ways that outpace response from current private insurance and government programs.

Historically, when the country has become aware of a significant environmental hazard, Congress has enacted legislation to address it, although often only after significant harms have accrued. This Appendix starts by reviewing six examples, as well as lessons learned, that may be applicable in crafting a national adaptation plan for extreme weather, as PCAST recommends, and future policy directions. The goal of the national adaptation plan should be to identify and avoid potential risks, especially to disadvantaged communities, in advance.

Historical Examples

- **Hazardous Waste.** The discovery of serious health problems from hazardous waste sites in Love Canal, near Niagara Falls, and other areas, spurred Congress to pass the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). Under the act, the EPA identifies priority hazardous waste sites ("Superfund sites") and manages both short-term removal and longer-term remediation actions.[66] As of February 2023, 453 Superfund sites had been completely remediated, and there were 1,335 sites on the national priority list.[67]

- **Drinking Water Quality.** Studies showing that many public water systems failed to meet public health standards led to the passage of the Safe Water Drinking Act in 1974 (SWDA).[68] Under the act, the EPA regulates drinking water in both privately and publicly owned water systems, other than those of very small size. The EPA sets standards for maximum contaminant levels and for treatment of drinking water. Today, more than 92% of the US population has access to drinking water meeting all relevant health standards.[69]

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[66] *U.S. EPA. (2022). Summary of the Comprehensive Environmental Response, Compensation, and Liability Act (Superfund).* https://www.epa.gov/laws-regulations/summary-comprehensive-environmental-response-compensation-and-liability-act

[67] U.S. EPA. (2023). Superfund: National Priorities List (NPL). https://www.epa.gov/superfund/superfund-national-priorities-list-npl

[68] Weinmeyer, R., Norling, A., Kawarski, M., & Higgins, E. (2017). The Safe Drinking Water Act of 1974 and Its Role in Providing Access to Safe Drinking Water in the United States. AMA Journal of Ethics, 19(10), 1018–1026. https://doi.org/10.1001/journalofethics.2017.19.10.hlaw1-1710
Harold M. Schmeck Jr. Special to The New York Times (1974, November 9). E.P.A. Orders a National Study of Chemical Contaminants in Drinking Water. The New York Times. https://www.nytimes.com/1974/11/09/archives/epa-orders-a-national-study-of-chemical-contaminants-in-drinking.html
U.S EPA. (December 1999). 25 Years of the Safe Drinking Water Act: History and Trends.

[69] U.S. EPA. (2022). Safe Drinking Water Act (SDWA). https://www.epa.gov/sdwa

- **Surface Water Quality**. A series of incidents in the 1960s, including rivers in Buffalo and Detroit catching fire, helped to spur the passage of the Clean Water Act in 1972 (CWA).[70] Under the act, the EPA creates regulatory requirements limiting effluent discharges that constrain the behavior of companies and municipalities. The CWA also authorizes federal assistance for municipal sewage plant construction.[71] Many US streams and wetlands are not protected by the CWA; however, studies have shown that the CWA prevents 700 billion pounds of toxic pollutants from entering US waterways.[72]

- **Air Quality.** Pervasive industrial smog in areas such as Los Angeles, and an incident in Donora, PA in 1948 where smog killed 20 people, helped to spur the Clean Air Act of 1970 (CAA).[73] Under the Act, the EPA sets National Ambient Air Quality Standards (NAAQS) for six pollutants: carbon monoxide, lead, ozone, nitrogen dioxide, sulfur dioxide, and particulate matter.[74] The EPA reports that amendments to the CAA have been responsible for preventing over 230,000 deaths and reducing the frequency of respiratory diseases.[75] However, the American Lung Association found in 2022 that more than 40% of Americans, a disproportionate number of whom are people of color, live in areas that have failing grades for particulate matter or ozone.[76]

- **Lead**. Concerns about lead poisoning from pipes, paint, and drinking water, and from gasoline fumes stretch back decades.[77] In 1970, the CAA required the development of standards for air quality.[78] In 1986, an amendment to the SWDA banned the use of lead pipes in new plumbing systems.[79] The Lead-Based Paint Poisoning Prevention Act of 1971 directed HUD

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70 Grant, M. (2022, October 18). The Clean Water Act At 50: How We Got Here and Where We Need to Go. Food & Water Watch. https://www.foodandwaterwatch.org/2022/10/18/clean-water-act-at-50-how-we-got-here-and-where-we-need-to-go/

71 Copeland, C. (2016, October). Clean Water Act: A Summary of the Law. https://sgp.fas.org/crs/misc/RL30030.pdf

72 National Wildlife Federation (2022). Five Decades of Clean Water: The Clean Water Act's Incredible Successes, its Current Limitations, and its Uncertain Future. https://www.nwf.org/-/media/Documents/PDFs/NWF-Reports/2022/Five-Decades-of-Clean-Water1

73 Jacobs, E. T., Burgess, J. L., & Abbott, M. B. (2018). The Donora Smog Revisited: 70 Years After the Event That Inspired the Clean Air Act. American Journal of Public Health, 108(S2), S85-S88. https://doi.org/10.2105/AJPH.2017.304219

74 U.S. EPA. (2022). Lead (Pb) Air Quality Standards. https://www.epa.gov/naaqs/lead-pb-air-quality-standards

75 UN Environment Programme (Tue, 2020, March 17). The United States Clean Air Act turns 50: is the air any better half a century later? United Nations Environment Programme. https://www.unep.org/news-and-stories/story/united-states-clean-air-act-turns-50-air-any-better-half-century-later

76 America Lung Association. (2022). State of the Air: Key Findings. https://www.lung.org/research/sota/key-findings

77 Dignam, T., Kaufmann, R. B., LeStourgeon, L., & Brown, M. J. (2019). Control of Lead Sources in the United States, 1970-2017: Public Health Progress and Current Challenges to Eliminating Lead Exposure. Journal of Public Health Management and Practice, 25(1), S13-S22. https://doi.org/10.1097/PHH.0000000000000889

78 U.S. EPA. (2022). National Ambient Air Quality Standards (NAAQS) for Lead (Pb). https://www.epa.gov/lead-air-pollution/national-ambient-air-quality-standards-naaqs-lead-pb

79 Congressional Research Service (2022, February). Controlling Lead in Public Drinking Water Supplies. https://crsreports.congress.gov/product/pdf/IF/IF11302

to eliminate lead-based paint hazards in all public housing and certain private housing.[80] Lead hazards continue to affect parts of the population: for example, around 20 million Americans live in homes where water is delivered at least partly through lead pipes.[81] However, levels of lead detected in the air decreased 97% between 1980 and 2010,[82] and blood lead levels in children have declined 94% since the 1970s.[83]

- **Asbestos**. A landmark 1964 study linked asbestos exposure to cancer (mesothelioma), showing that asbestos installation workers had a 7x higher death rate than expected in the general population.[84] Several pieces of legislation, including the Occupational Health and Safety Act of 1970 authorize aspects of asbestos regulation.[85] The EPA and OSHA set stringent limits on asbestos exposure, and the last asbestos mine in the U.S. closed in 2002.[86] However, asbestos is still imported and used in building materials and the number of mesothelioma deaths remains substantial according to the CDC.[87]

Lessons Learned

- In each of case, Congress acted to protect the American people as a response to accumulating evidence, although it often took several decades for the evidence to become sufficiently persuasive.
- The laws that were passed measurably improved health outcomes. Air quality, surface water, and drinking water quality have improved substantially. Exposure to lead, asbestos, and hazardous waste have decreased.
- Exposure to these six hazards persists today and disproportionately affects underserved communities. The hazardous waste sites that remain to be remediated are more likely to be located near vulnerable communities. Non-compliance with drinking water standards occurs more often in small communities. Air pollution disproportionately affects communities with lower-income or minority populations.
- The methods used to address the hazards included both *standards* (for air quality, drinking water, etc.) and *federal funding* (for hazardous waste cleanup, sewage treatment, etc.). The

[80] Yen, J. H. (2013, January). Lead-Based Paint Poisoning Prevention: Summary of Federal Mandates and Financial Assistance for Reducing Hazards in Housing. https://crsreports.congress.gov/product/pdf/RS/RS21688/20
[81] Olson, E., & Stubblefield, A. (2021, July 8). Lead Pipes Are Widespread and Used in Every State. National Resources Defense Council. https://www.nrdc.org/resources/lead-pipes-are-widespread-and-used-every-state
[82] U.S. EPA. (2022). Integrated Science Assessment (ISA) for Lead. https://www.epa.gov/isa/integrated-science-assessment-isa-lead
[83] Congressional Research Service (2022, February). Controlling Lead in Public Drinking Water Supplies. https://crsreports.congress.gov/product/pdf/IF/IF11302
[84] Zimmer, A. T., & Ha, H. (2017). People, planet and profit: Unintended consequences of legacy building materials. Journal of Environmental Management, 204(Pt 1), 472–485. https://doi.org/10.1016/j.jenvman.2017.09.026
[85] Ibid.
[86] Whitmer, M. (2023). Asbestos Mining and Exposure. https://www.asbestos.com/occupations/mining/
[87] U.S. Geological Survey (2021, January). Mineral Commodity Summaries: Asbestos. https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-asbestos.pdf

federal government also ensures *information sharing* – whether directly about air quality and water quality, or by mandating disclosure requirements for instance around the presence of lead paint.

Policies to Address Impacts of Extreme Weather

In writing this report, PCAST spoke to multiple experts to understand the range of policies that might be deployed to assist communities vulnerable to wildfires, floods, droughts, climate, and weather risk.

A frequent concern was that successfully quantifying climate risk across the country is likely to reveal communities that are at very high risk from extreme weather. If this risk was previously under-appreciated, the new information could lead to reductions in property value or breakdowns in insurance provision. This is not an argument *against* accurate risk assessment. PCAST's view is that if families and communities face a climate risk and they deserve to know about it so they can have an opportunity to reduce the risk and/or prepare for it. However, the potential to identify communities at risk means it will be important to understand, develop, and deploy policies that can help.

In the case of extreme weather, current federal programs largely focus on provision of federal funds supporting mitigation and disaster relief. Flooding is an exception because the federal government is directly involved in insurance provision under the National Flood Insurance Program (NFIP). The federal government also provides crop insurance through the USDA Risk Management Agency, protecting agricultural producers from drought, high rainfall, and freezes, as well as unexpected variation in agricultural prices. These programs, and the historical examples above, suggest a portfolio of approaches that might be considered over time to address heightened risks from extreme weather.

- **Insurance**: As noted above, the NFIP provides flood insurance to roughly 23,000 communities across the country, and the USDA provides crop insurance. Historically, the NFIP has lost money, suggesting that the premiums charged have been less than actuarily fair rates. Our working group heard suggestions that the federal government should provide insurance subsidies for other types of climate- and weather-related risk, such as wildfires, perhaps means-tested, in order to help vulnerable communities. While such an approach would assist property owners in high-risk areas, subsidizing insurance also creates incentives for households and businesses to remain in these areas, and indeed for further development. If subsidies are to be used, PCAST views it as preferable to condition premium reductions or premium support on requirements that property owners make investments or meet certain standards to reduce exposure or potential damage. This approach, which has been used in both the NFIP and in private insurance markets, has the benefit of reducing liability and ideally overall expected costs for insurers and taxpayers, as well as supporting property owners. It is also important to recognize that the federal government provides implicit insurance against major hazards through its disaster relief programs. This creates an incentive for property owners and communities to under-insure. Some countries, such as France and New Zealand, have mandatory national hazard insurance to address this.

- **Mitigation grants**: The federal government, especially through FEMA, administers a range of grant programs to help communities prepare for and mitigate climate disasters. IIJA includes substantial new funds for this purpose. Improved risk models, in conjunction with socio-economic data, can help target mitigation grants to ensure that federal funds flow to communities in greatest need. One concern however, is that lower-income communities may not have the resources to develop adaptation and mitigation plans or prepare compelling grant applications, giving these needy communities less access to the resulting federal funds. To this end, it would be beneficial to track grant allocations against the type of risk maps recommended in Recommendation 3.1(a), and if the evidence shows that lower-income communities are systematically missing out on grant funding, consider providing financial support to prepare applications, or to NGOs serving those communities. One lesson appears to be that relocation programs need careful design and execution, as well as extensive community engagement. A national adaption plan, as recommended in the report, will grapple with these sorts of difficult trade-offs, which may become increasingly important in coastal and flood-prone areas.

- **Relocation**. In recent years, both FEMA and HUD have initiated programs to relocate communities at high flood risk.[88,89] These programs follow an older tradition of buying and destroying homes that have been badly damaged by flooding. The new "managed retreat" programs have been criticized on the grounds of equity (for impacting lower-income areas disproportionately) and for destroying the fabric of existing communities. At the same time, relocation can move families or even whole communities out of harm's way, and be cost-effective because it reduces future federal liability under the NFIP.

- **Building standards**. In July 2022, the Biden-Harris launched the National Initiative to Advance Building Codes with the aim of helping state, local, tribal, and territorial governments "adopt the latest, current building codes and standards, enabling communities to be more resilient to hurricanes, flooding, wildfires, and other extreme events that are intensifying due to climate change."[90] The initiative builds on FEMA's Building Codes Strategy that was released in March 2022.[91] As documented in the FEMA and White House plans, building codes generally are set at the state and local level, but the federal government can provide assistance in a variety of ways to help ensure up-to-date codes. Improved risk quantification has clear value in helping to identify areas where current codes create vulnerabilities.

[88] FEMA fact sheet on support for Community Driven Relocation includes links to relevant grant programs: https://www.fema.gov/fact-sheet/fema-efforts-advancing-community-driven-relocation
[89] HUD Real Estate Acquisition and Relocation Program, https://www.hud.gov/program_offices/comm_planning/relocation
[90] Executive Office of the President (2022, June 1). Biden-Harris Administration Launches Initiative to Modernize Building Codes, Improve Climate Resilience, and Reduce Energy Costs [Fact Sheet] https://www.whitehouse.gov/briefing-room/statements-releases/2022/06/01/fact-sheet-biden-harris-administration-launches-initiative-to-modernize-building-codes-improve-climate-resilience-and-reduce-energy-costs/
[91] FEMA (2022, March). Building Codes Strategy. https://www.fema.gov/sites/default/files/documents/fema_building-codes-strategy.pdf

- **Planning assistance / guidance**. Historically, FEMA has played a large role in helping states and municipalities plan for disasters. For instance, FEMA provides a suite of risk modeling tools through its HAZUS program that are freely available. These tools continue to be widely used. However, both the underlying climate and risk data and the user interface are outdated. The types of quantification and data products recommended in our report would address this current challenge.

Consistent with this final point, our main report has proposed a comprehensive approach to promote the sharing of accurate risk information. PCAST views this as a crucial step to help households, businesses, and government agencies make sound decisions now, as well as to provide the necessary foundation for future policy.