Predicting and managing extreme weather events

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Predicting and managing *extreme weather events*

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Earth's climate is warming, and destructive weather is growing more prevalent. Coping with the changes will require collaborative science, forward-thinking policy, and an informed public.

This is a challenging time for the US and for US science. The economy, though it is beginning to show some positive signs, is still in bad shape. Extraordinary numbers of Americans are without jobs. The public holds a record-low opinion of government. The integrity of the scientific process is being questioned, and pressure to reduce federal spending is fierce.

The irony is that the demand for services provided by agencies such as the National Oceanic and Atmospheric Administration is at an all-time high and growing. Our ability to deliver those services depends in part on our scientific enterprise. One significant reason why demand for services is growing is the increased frequency and intensity of extreme weather events. Last year, new records were set in the US for tornadoes, drought, wind, floods, and wildfires. Heat records were set in every state. At one time last summer, nearly half of the country's population was under a heat advisory or heat warning. In late November, hurricane-force winds hit parts of Wyoming, Utah, Nevada, Arizona, New Mexico, and California, with winds reaching 97 mph in Pasadena.[1]

We at NOAA were able to predict most of the weather- and climate-related extreme events, but our capacity to continue to do so is seriously threatened by downward pressure on our budgets. Budgets and politics threaten NOAA's ability to observe and model weather and climate events and to deliver information to the public. NOAA's abilities to fund and conduct research aimed at understanding the causes of extreme weather and to improve the effectiveness of response to our warnings are all at great risk.

This article focuses on the unusual weather and climate patterns we've documented in 2011 and in previous decades and identifies several actions that would help us to better predict and manage them. Succeeding in this tough environment will take innovative new approaches, a collaborative effort from the scientific community, and a broader appreciation for what is at risk.

Going to extremes

The number of events that produced on the order of $1 billion or more in damages in 2011 is the largest since tracking of that statistic began in 1980, even after damages are adjusted for inflation. NOAA estimates that there were at least 14 such events in 2011. (The previous record was nine, set in 2008; an average year would see three or four.) Collectively, the 14 events resulted in approximately $55 billion in damage.[2] Furthermore, many events produced less than $1 billion in damage, but are not included in the tally, although they collectively represent additional significant financial losses. Why did we see such expensive damage last year? There are likely a number of contributing factors, including upward trends in population and infrastructure, migration to vulnerable areas, and climate change. The contribution of each of these factors remains an important research issue.

Of course, the economic losses are far from the full picture. Weather- and climate-related disasters in the US claimed more than 1000 lives in 2011, almost double the yearly average. For the victims, each of the events was a huge tragedy. For our country, as for all countries, the events are an unprecedented challenge to the safety of our citizens, the bottom line for our businesses, and the smooth functioning of our society. Timely, accurate, and reliable weather warnings and forecasts are essential to our nation's ability to plan for, respond to, recover from, and prosper in the aftermath of disaster. Short-term forecasts are critical, but so are forecasts of slowly evolving events like prolonged droughts, snow- and ice-melt flooding, and heat waves.

We've emphasized how unusual 2011 was, but was it an anomaly or part of a broader change? Should we expect more of the same in the future? Globally, according to the insurance company Munich Re, the number of extreme meteorological and hydrological events, defined in terms of economic and human impacts, has more than doubled over the past 20 years.[3]

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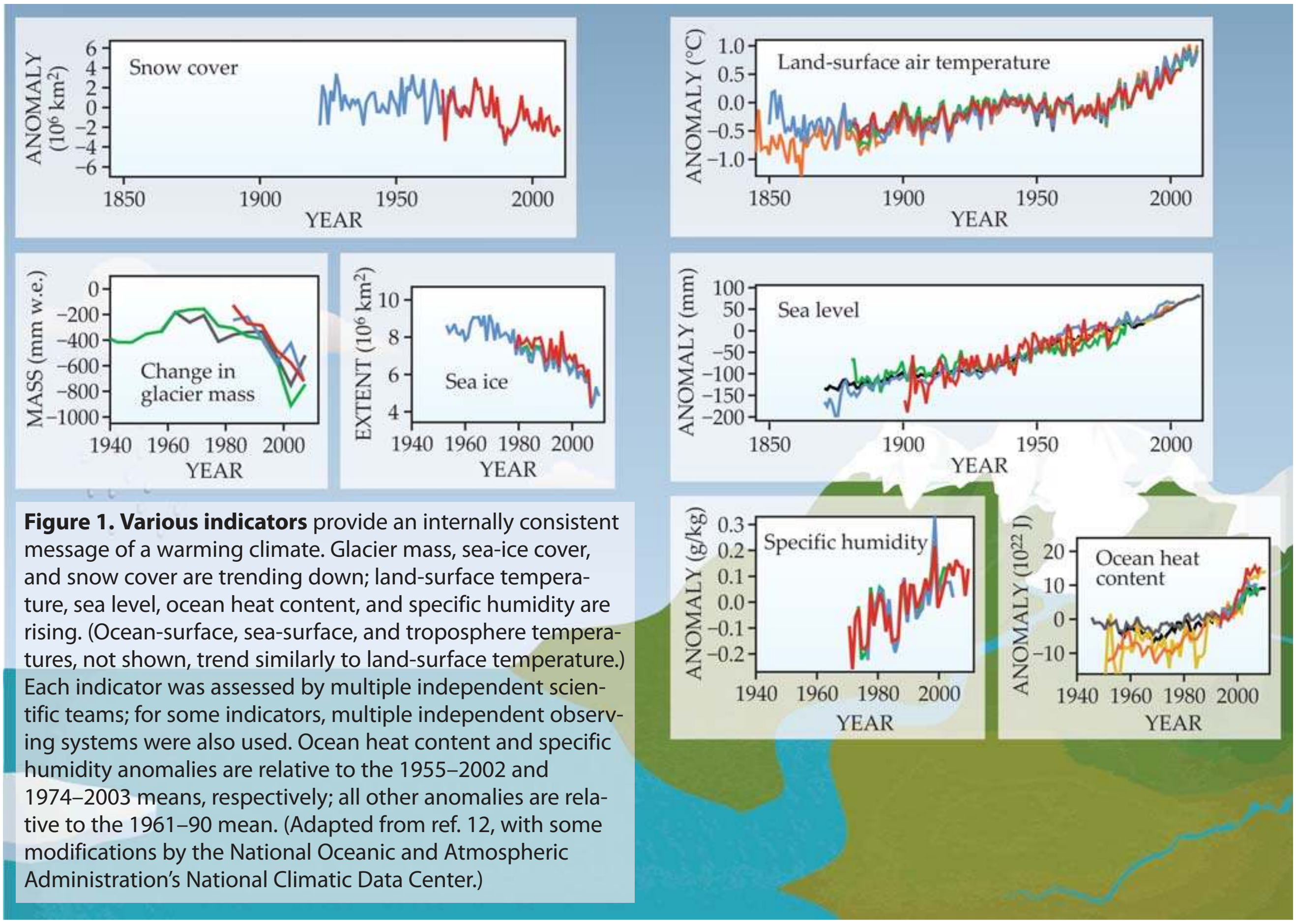

Figure 1. Various indicators provide an internally consistent message of a warming climate. Glacier mass, sea-ice cover, and snow cover are trending down; land-surface temperature, sea level, ocean heat content, and specific humidity are rising. (Ocean-surface, sea-surface, and troposphere temperatures, not shown, trend similarly to land-surface temperature.) Each indicator was assessed by multiple independent scientific teams; for some indicators, multiple independent observing systems were also used. Ocean heat content and specific humidity anomalies are relative to the 1955–2002 and 1974–2003 means, respectively; all other anomalies are relative to the 1961–90 mean. (Adapted from ref. 12, with some modifications by the National Oceanic and Atmospheric Administration's National Climatic Data Center.)

The Intergovernmental Panel on Climate Change recently released a special report, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*.[4] In short, it says that we can expect more of many kinds of extreme events. Here's what the report concludes about five kinds in particular, in order of the certainty of their prediction:

▶ "It is virtually certain that increases in the frequency and magnitude of warm daily temperature extremes and decreases in [the frequency and severity of] cold extremes will occur in the 21st century on a global scale."

▶ "It is very likely that heat waves will increase in length, frequency, and/or intensity over most land areas."

▶ "It is very likely that mean sea-level rise will contribute to upward trends in extreme coastal high-water levels in the future."

▶ "It is likely that the average maximum wind speed of tropical cyclones will increase throughout the coming century, although possibly not in every ocean basin. It is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged."

▶ "It is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st century over many areas of the globe."

Multiple studies and assessments[5] have found links between changes in global climate and changes in regional events such as heavy rainfall,[6] heat waves,[7] and flooding.[8] Global climate change is also likely to influence local phenomena, including severe thunderstorms and tornadoes, but the nature and degree of the influence are uncertain, particularly for tornadoes.[9] The trend toward more frequent extreme weather events only underscores how important it is that we enhance our ability to predict and manage them.

Environmental intelligence

In 2011, extreme events ran the gamut from highly localized and brief weather events such as tornadoes; to regional-scale events like hurricanes, snow, and flooding, for which there is more time to prepare; to climate-scale events such as drought, which we can watch develop over many weeks.

Extreme events within any one type of phenomenon—tornado outbreaks, seasonal blizzards, or severe thunderstorms, for example—are initiated and enhanced by a common set of weather and climate factors. But there are profound differences between the various types of phenomena. Observing, monitoring, and predicting extreme events and managing their impacts requires an extraordinary amount of information about the physical state of Earth and how it changes from moment to moment and decade to decade. One needs to understand phenomena ranging from local vertical wind pro-

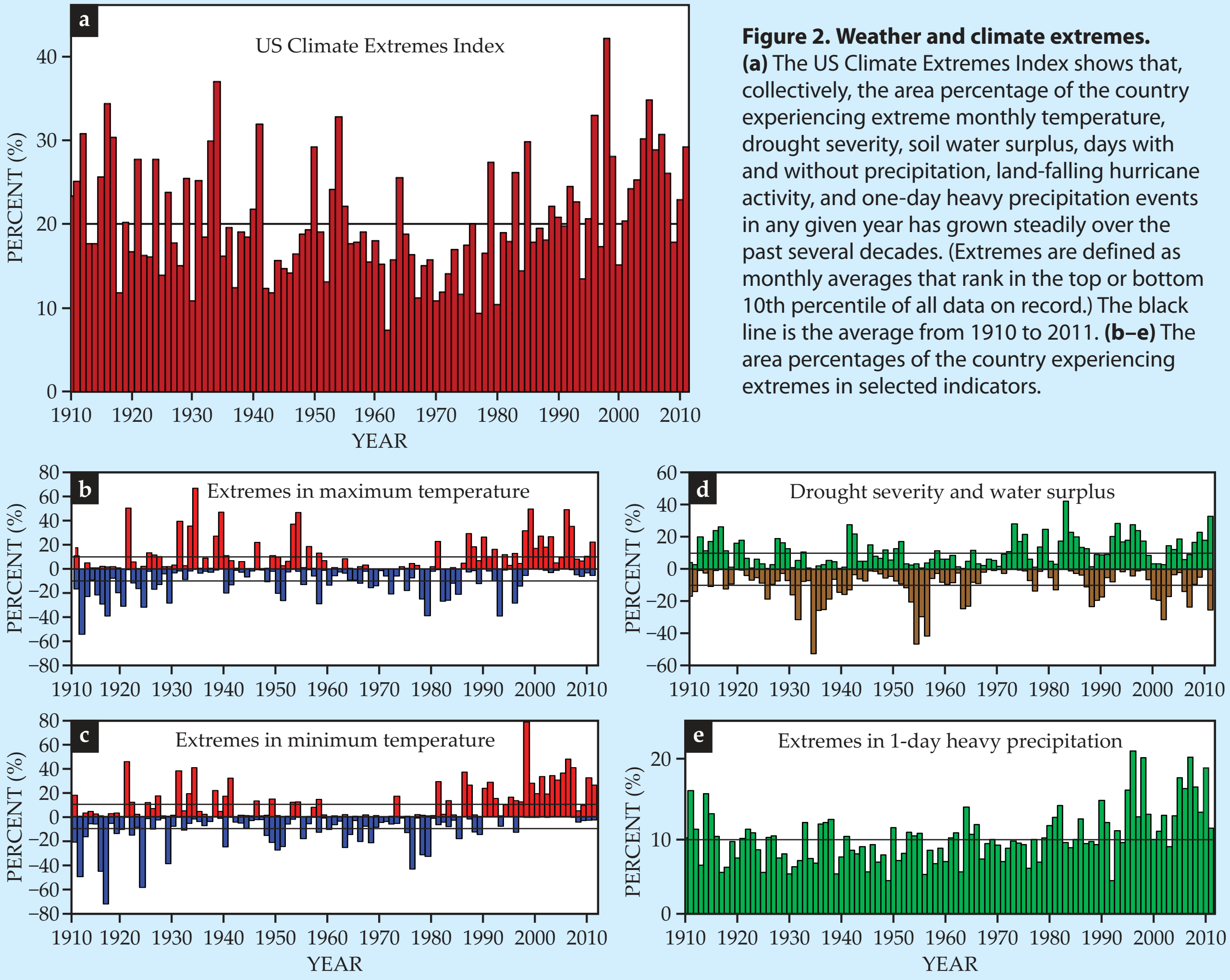

Figure 2. Weather and climate extremes. **(a)** The US Climate Extremes Index shows that, collectively, the area percentage of the country experiencing extreme monthly temperature, drought severity, soil water surplus, days with and without precipitation, land-falling hurricane activity, and one-day heavy precipitation events in any given year has grown steadily over the past several decades. (Extremes are defined as monthly averages that rank in the top or bottom 10th percentile of all data on record.) The black line is the average from 1910 to 2011. **(b–e)** The area percentages of the country experiencing extremes in selected indicators.

files for predicting tornadoes, to globe-spanning weather patterns for predicting heat waves, cold waves, and drought. Doing so calls for diverse observations from networks of weather balloons, radars, satellites, soil moisture sensors, ocean temperature sensors, and other monitoring devices.

The scientific community relies on the observing networks already established on Earth and in space to meet those demanding observational requirements. Major challenges for the nation include prioritization of both observations and observing systems, and the implementation of new systems that seamlessly link with the established ones. The latter is necessary to understand and predict longer-term changes.

We think that one essential key to meeting those challenges is critical environmental intelligence. Just like the intelligence of the security world, intelligence in the environmental arena combines data, analysis, modeling, and assessment.

Environmental intelligence is needed on every temporal and spatial scale at which decisions are made. To that end, NOAA provides data and forecasts on temporal scales ranging from minutes to decades and on spatial scales ranging from neighborhoods to the planet. Here are a few examples.

We provide forecasts for so-called short-fuse events, which include tornadoes, heavy rains, heat waves, and solar storms. Tornado warnings, for example, are issued just minutes ahead of time and often for specific neighborhoods. In our current sunspot cycle, solar storms are becoming more frequent and have the potential to affect global positioning systems, air travel, and electric-power distribution.

We also track slower-developing events such as the maturation of a tropical depression into a full-blown hurricane or the transformation of cold fronts in, say, Colorado into lines of severe tornadic thunderstorms along the Gulf Coast. We issue volcanic ash advisories to ensure safe air travel during volcanic eruptions.

Moving to longer time scales, we generate forecasts for droughts, floods, and other climate-scale events from weeks to months in advance. For example, NOAA helps produce the US Drought Monitor,[10] which issues weekly reports of the current state of drought across the country. Our scientists contribute extensively to the National Climate Assessment[11] and other national and international assessments of the state of the science regarding extreme events. They consider spatial scales from regional to global and project climate out to the end of this century and beyond.

How do we continue to improve our environmental intelligence? By improving our observations, research, and modeling of the environment. That means enhancing Earth observations from

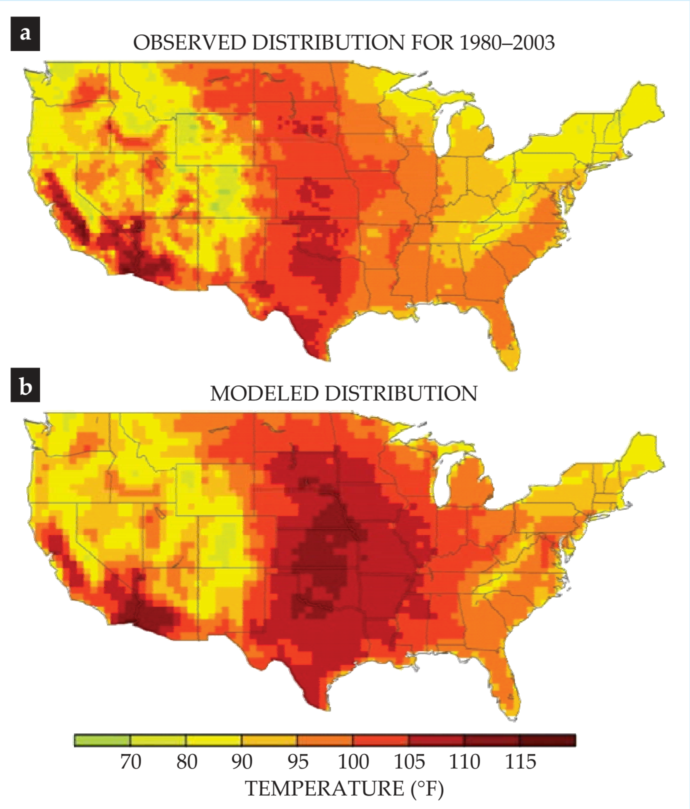

Figure 3. Climate models are increasingly able to capture region-scale features. The observed temperature distributions **(a)** during US heat waves, averaged over the span 1980–2003, are qualitatively similar to those **(b)** predicted by model simulations run with 50-km grid spacing at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory. (Adapted from ref. 14.)

satellites and other platforms, bolstering computational capacity, improving the resolution of numerical models and the underlying science, and strengthening research to detect and understand changing patterns in weather and climate extremes.

Intelligence, however, is only as valuable as society's capacity to use it. Improving response to forecasts will require a weather-ready nation whose citizens, emergency managers, and businesses understand and value the forecast and warning services provided and use them to make informed decisions. Improving response will rely on social science research aimed at understanding how best to deliver timely, useable, credible information. Can people access and understand the information that NOAA provides? Do they respond in ways that protect themselves and their property whenever possible? With those questions in mind, let's now focus on the key strategies and challenges for improving and more effectively using critical environmental intelligence.

Sustaining and integrating observations

Environmental intelligence starts with observations. Our ability to withstand and recover from extreme events depends on many factors but most certainly on our ability to monitor changes in the frequency and intensity of extreme events. Overarching challenges are to detect extreme conditions more reliably, maintain continuity of observations, and improve the interconnectedness of observing systems.

For example, many of our existing observation networks were not built to withstand extremes of weather and climate. Furthermore, it's often difficult to get consistent, accurate measurements under extreme conditions. That is especially true for measuring, say, the ice accumulated during an ice storm, the wind speeds of a tornado or severe thunderstorm, or the size and frequency of hailstorms. We need new, cost-effective technologies that can monitor such peak conditions globally and nationally 24 hours a day, 7 days a week.

Satellites must have a sufficiently long overlapping period of record with their predecessors to properly calibrate their data. Given satellites' expense, achieving that overlap becomes increasingly challenging as budgets become tighter (see PHYSICS TODAY, November 2011, page 28).

To inform our strategies for investing in observation networks, we need to understand, first, how the predictive value of each system varies with investment and, second, the comparative value of alternate investments. For example, how much better are the predictions if there are twice as many observing points? How much worse are they if there are half as many?

To get that information, we need to link observing systems with modeling experiments. One way to do so is via observing-system model simulation experiments, a powerful tool used to assess the impact that variations in data have on forecasts in model systems. To ensure that modelers get the data they need, modeling requirements must be better communicated to the designers of observing systems.

Monitoring climate trends

Beyond having good observations, scientific analysis is critical. One strategy for improving data analysis is to make better use of multiple independent data sets.

Figure 1 shows the yearly averages of climate variables that the United Nations has deemed essential for characterizing Earth's climate. Of them, ocean heat content, sea level, specific humidity, and surface temperatures are all going up. Snow cover, glacial mass, and sea ice are trending down. All of those trends are consistent with a warming climate.[12]

Each indicator comprises multiple independent data sets, which helps increase the confidence in the data and mitigate the effect of structural or statistical error. Some data sets are from separate observing networks and some are from independent institutions that use common data but different approaches to develop long-term records. Looking at a suite of indicators lends additional confidence to the measurements and ultimately helps us better understand and predict Earth's vast and complex weather–climate system. Since the physical properties that the indicators are measuring are connected, it's not surprising that the measurements themselves are consistent with one another.

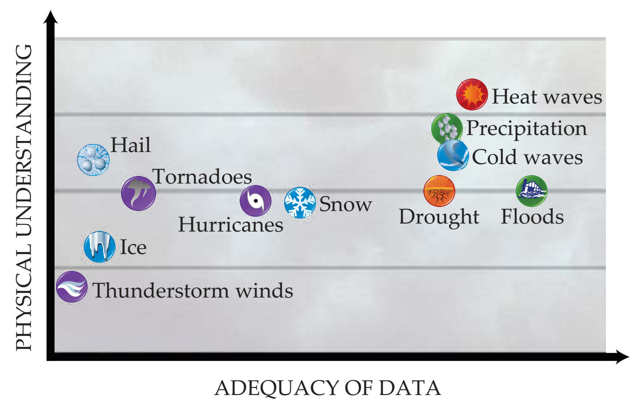

Figure 4. Experts' level of physical understanding of the factors responsible for long-term changes in frequency and intensity of extremes within each phenomenon versus their ability to detect changes and trends in those extremes. This chart was compiled from a series of workshops convened by the National Oceanic and Atmospheric Administration.

Changes in average values offer one lens for viewing climate and weather trends; changes in extreme values offer another. Whereas figure 1 depicts trends in annual averages, the US Climate Extremes Index[13] shown in figure 2a reflects unique aspects of weather and climate extremes. It shows that overall, the percentage of the country affected by extreme heat, cold, rainfall, soil moisture, or soil dryness in a given year has trended upward in recent decades. The index has been high in the past, but the increase from about 1970 to the present day is steady and pronounced.

What's driving the increase in the Climate Extremes Index? Plots of individual components of the index suggest that extremely high temperatures, extremely high or low soil moisture, and heavy one-day precipitation events all have contributed (see figures 2b-e).

Since the 1970s more of the country has experienced unusually high daytime temperatures and less of the country has experienced unusually low daytime temperatures. But more striking is the fact that more of the country has seen unusually warm nights, and less of the country has seen unusually cool nights. During summer months, warm overnight lows contribute to heat stress in humans, and in plants and animals, which never get a chance to cool off. Information about differences in trends of nighttime and daytime temperature extremes is important for effective emergency response planning.

The patterns for soil moisture are worth examining more closely. Although the country has had periods of more severe drought in the past—for example, the Dust Bowl years of the 1930s—we've never simultaneously recorded such extreme dry and extreme wet conditions as we have recently. In addition, days of heavy precipitation have become more prevalent—which is important information for hydrological engineers, water resource managers, and emergency managers in flood-prone areas.

A variety of observations, taken over time, can improve understanding and management of extremes. The Climate Extremes Index helps NOAA answer questions from industry representatives, emergency managers, infrastructure planners, and the public, all of whom have strong continuing interest in the state of extremes. The index and the broad suite of satellite and in situ data are vital input to models that predict and project the future state of the Earth system.

Right-scaled modeling

Extreme events occur on multiple scales in space and time. The output of global climate models is often at scales too coarse for practical decisions. For example, the total rainfall predicted by a weather and climate model for a grid cell covering hundreds of square kilometers may not be immediately relevant to a decision maker who is concerned about the probability of a flash flood at a local drainage basin.

To solve that problem, modelers historically had to either nest a regional climate model into a global one or use statistical techniques to interpolate between grid points. New models running on supercomputers, however, can resolve much finer detail. Combined with established downscaling techniques, the new models allow researchers to forecast climate-driven phenomena at scales of interest for practical applications. Climate models like the one run by NOAA's Geophysical Fluid Dynamics Laboratory, for example, are capturing increasingly fine spatial features of heat waves and other regional-scale events[14] (see figure 3).

An overarching challenge is to focus modeling efforts on extreme events and other phenomena of particular societal interest and to model those phenomena at the time scales most relevant to decision making. For example, the seasonal time scale is particularly important to agricultural and water managers, who need to plan the allocation of their resources months ahead of time. The decadal time scale is critical for infrastructure planners, construction managers, and some insurance adjusters. All of those decision makers need accurate estimates of climate 10–30 years in advance.

Information needs

Many sectors of society are vulnerable to changes in weather and climate—particularly the destructive effects of extremes. To make sound decisions, people need to know about observed changes in the frequency and intensity of extreme weather and climate events and the extent to which human activity or other factors may be affecting those changes. The current state of the science for detection and attribution of changes in extremes varies greatly by type of event.

We have a relatively good understanding of what can lead to changes in heat waves, and our data are fairly adequate to detect those changes over time. However, with ice storms, both our physical understanding of what factors influence their prevalence and our data on their frequency and intensity are inadequate. For most other phenomena—tornadoes, snow, drought, and so forth—our level of under-

Figure 5. Visualizations from the Digital Coast Sea Level Rise and Coastal Flooding Impacts Viewer depict Galveston, Texas, after a 6-ft rise in sea level. The bottom images show downtown Galveston as it currently appears, and as it would appear after the sea-level rise. The viewer allows users to see the potential physical, ecological, and socioeconomic impacts of sea-level rise in order to inform the planning efforts of community officials and coastal managers.

WWW.CSC.NOAA.GOV/DIGITALCOAST

standing and robustness of data collection fall between those two extremes (see figure 4).

Among the public services provided by NOAA are several tools that communicate the uncertainties and risks associated with long-range changes in weather and climate. Our flood forecasts allowed us to warn officials in Minot, North Dakota, as early as November 2010 of the intense winter and spring floods they would experience in 2011. State fire managers in Texas, warned of their 2011 drought months in advance, were able to pre-position firefighting resources so that first responders could act quickly when fire season arrived. The Digital Coast tool shown in figure 5 allows community officials and coastal managers to visualize the potential physical, ecological, and socioeconomic impacts of rises in sea level.

We know that more and more communities are using NOAA's tools to plan for a climate-influenced future. Data from NOAA are being used by New York City officials to plan and prepare for sea-level rise and flooding caused by coastal storms: The city's environmental protection department is repositioning pumps at the Rockaway wastewater treatment plant to account for an anticipated increase in sea level. Officials in Boulder, Colorado, are using NOAA data and climate models to manage their water future. Based on climate data and services, Boulder fast-tracked the rehabilitation of a key dam to buffer earlier-melting snowpack and prioritized a water pipeline project for increased flexibility in the presence of increased climate variability.

Businesses also use climate forecasts and data. For example, frost-protected shallow foundation design and construction, aided by a NOAA-inspired air-freezing index, has been demonstrated to save in both energy and construction costs. The US home-building industry estimates that more than $300 million per year can be saved in construction costs alone by using just one of NOAA's climate tools.[15] Frost-protected shallow foundations are now regularly used to effectively meet building codes in colder climates.[16]

The path forward

What's likely down the road on the weather–climate front? By all measures, we can expect more warming, an amplified cycle of evaporation and precipitation, more extreme weather, and more wild swings in weather. Preparing our country to deal with that future will require two things: critical environmental intelligence and a nation of informed citizens, communities, businesses, and emergency managers who know how to use that intelligence.

One way NOAA is working to improve the delivery of critical environmental intelligence is through a new initiative called Weather-Ready Nation.[17] We're launching a series of pilot projects, each geared toward a specific type of severe weather and its associated societal and environmental impacts. The NOAA weather forecast office leading each pilot will work hand in glove with physical and social scientists, officials from all levels of government, media representatives, and private-sector weather companies. Together, they'll identify ways to effectively develop and deliver critical environmental intelligence. The first Weather-Ready Nation pilot project, launched at NOAA's New Orleans/Baton Rouge Weather Forecast Office on 21 January 2012, will focus on developing decision support for coastal-region weather-related hazards.

As the nation's need for environmental intelligence continues to grow, we can take some comfort in the fact that our society is amassing more and more data, improving its technical communications, and enhancing its computational power—all of which can facilitate more effective use of NOAA's information and forecasts. As the number of people capable of using that environmental intelligence grows, new markets will be created, opening up opportunities for commercial companies to add value to the products that NOAA provides. But those opportunities are contingent on NOAA maintaining its ability to provide core environmental intelligence.

Our recent budget experiences are probably a harbinger of challenging times ahead for sustaining and improving NOAA's ability to predict extreme events and to provide information and tools to manage them. The road ahead is paved with uncertainty. Observation systems, research, and high-performance computing are absolute prerequisites for producing reliable weather and climate forecasts—and all are at risk.

We are concerned that the current economic and political landscape may erode our ability to provide basic information, products, and timely and reliable forecasts that can be used generally and can be tailored by others to meet more specific needs. We will continue to seek every opportunity to improve efficiency and to form partnerships. The need to understand, predict, and manage our response to weather and climate extremes exceeds the scope of any individual organization or government agency. Collaboration is vital. NOAA's partnerships with academia, industry, other federal agencies, and the international community will be the cornerstones for successfully securing the environmental intelligence we need in the future.

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