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American Climate Prospectus

Economic Risks in the United States

Prepared as input to the Risky Business Project

October 2014 (v1.2)

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CHAPTER I

Introduction

Weather and climate – the overall distribution of weather over time – shape our economy. Temperature impacts everything from the amount of energy we consume to heat and cool our homes and offices to our ability to work outside. Precipitation levels not only determine how much water we have to drink, but also the performance of entire economic sectors, from agriculture to recreation and tourism. Extreme weather events, like hurricanes, droughts, and inland flooding can be particularly damaging, costing Americans more than $110 billion in 2012 (NOAA 2013).

Economic and technological development has made us less vulnerable to the elements. Lighting allows us to work and play after the sun goes down. Buildings protect us from wind and water. Heating and air conditioning allow us to enjoy temperate conditions at all times of the day and year. That economic growth, however, has begun to change the climate. Scientists are increasingly certain that carbon dioxide (CO_2) emissions from fossil fuel combustion and deforestation, along with other greenhouse gases (GHGs), are raising average temperatures, changing precipitation patterns, and increasing global sea levels. Weather is inherently variable, and no single hot day, drought, winter storm or hurricane can be exclusively attributed to climate change. A warmer climate, however, increases the frequency and/or severity of many extreme weather events.

ASSESSING CLIMATE RISK

The best available scientific evidence suggests that changes in the climate observed over the past few decades are likely to accelerate. The US National Academies of Science and the UK's Royal Society (2014) recently concluded that continued GHG emissions "will cause further climate change, including substantial increases in global average surface temperatures and important changes in regional climate." Given the importance of climate conditions to US economic performance, this presents meaningful risks to the financial security of American businesses and households alike.

Risk assessment is the first step in effective risk management, and there is a broad need for better information on the nature and magnitude of the climate-related risks we face. National policymakers must weigh the potential economic and social impacts of climate change against the costs of policies to reduce GHG emissions (mitigation) or make our economy more resilient (adaptation). State and city officials need to identify local vulnerabilities in order to make sound infrastructure investments. Utilities are already grappling with climate-driven changes in energy demand and water supply. Farmers and ranchers are concerned about the commercial risks of shifts in temperature and rainfall, and American families confront climate-related threats – whether storm surges or wildfires – to the safety and security of their homes.

While our understanding of climate change has improved dramatically in recent years, predicting the severity and timing of future impacts remains a challenge. Uncertainty surrounding the level of GHG emissions going forward and the sensitivity of the climate system to those emissions makes it difficult to know exactly how much warming will occur, and when. Tipping points, beyond which abrupt and irreversible changes to the climate occur, could exist. Due to the complexity of the Earth's climate system, we do not know exactly how changes in global average temperatures will manifest at a regional level. There is considerable uncertainty about how a given change in temperature, precipitation, or sea level will impact different sectors of the economy, and how these impacts will interact.

Uncertainty, of course, is not unique to climate change. The military plans for a wide range of possible conflict scenarios and public health officials prepare for pandemics of low or unknown probability. Households buy insurance to guard against myriad potential perils, and effective risk management is critical to business success and investment performance. In all these areas, decision-makers consider a range of possible futures in choosing a course of action. They work off the best information at hand and take advantage of new information as it becomes available. They cannot afford to make decisions based on conditions that were the norm ten or twenty years ago; they look ahead to what the world could be like tomorrow and in coming decades.

OUR APPROACH

A financial prospectus provides potential investors with the facts about the material risks and opportunities they need to make a sound investment decision. In this *American Climate Prospectus*, we aim to provide decision-makers in business and in government with the facts about the economic risks and opportunities climate change poses in the United States. We leverage recent advances in climate modeling, econometric research, private sector risk assessment, and scalable cloud computing (a system we call the Spatial Empirical Global-to-Local Assessment System, or SEAGLAS) to assessing the impact of potential changes in temperature, precipitation, sea level and extreme weather events on different sectors of the economy and regions of the country.

TIPPING POINTS

Even the best available climate models do not predict climate change that may result from reaching critical thresholds (often referred to as tipping points) beyond which abrupt and irreversible changes to the climate system may occur. The existence of several such mechanisms is known, but they are not adequately understood yet to simulate accurately at the global scale. Evidence for threshold behavior in certain aspects of the climate system have been identified based on observations of climate change in the distant past, including ocean circulation and ice sheets. Regional tipping points are also a possibility. In the Arctic, destabilization of methane trapped in ocean sediments and permafrost could potentially trigger a massive release, further destabilizing global climate. Dieback of tropical forests in the Amazon and northern boreal forests (which results in additional CO_2 emissions) may also exhibit critical thresholds, but there is significant uncertainty about where thresholds may be and of the likelihood their occurrence. Such high-risk tipping points are considered unlikely in this century, but are by definition hard to predict, and as warming increases, the possibilities of major abrupt change cannot be ruled out. Such tipping points could make our most extreme projections more likely than we estimate, though unexpected stabilizing feedbacks could also act in the opposite direction.

Physical climate projections

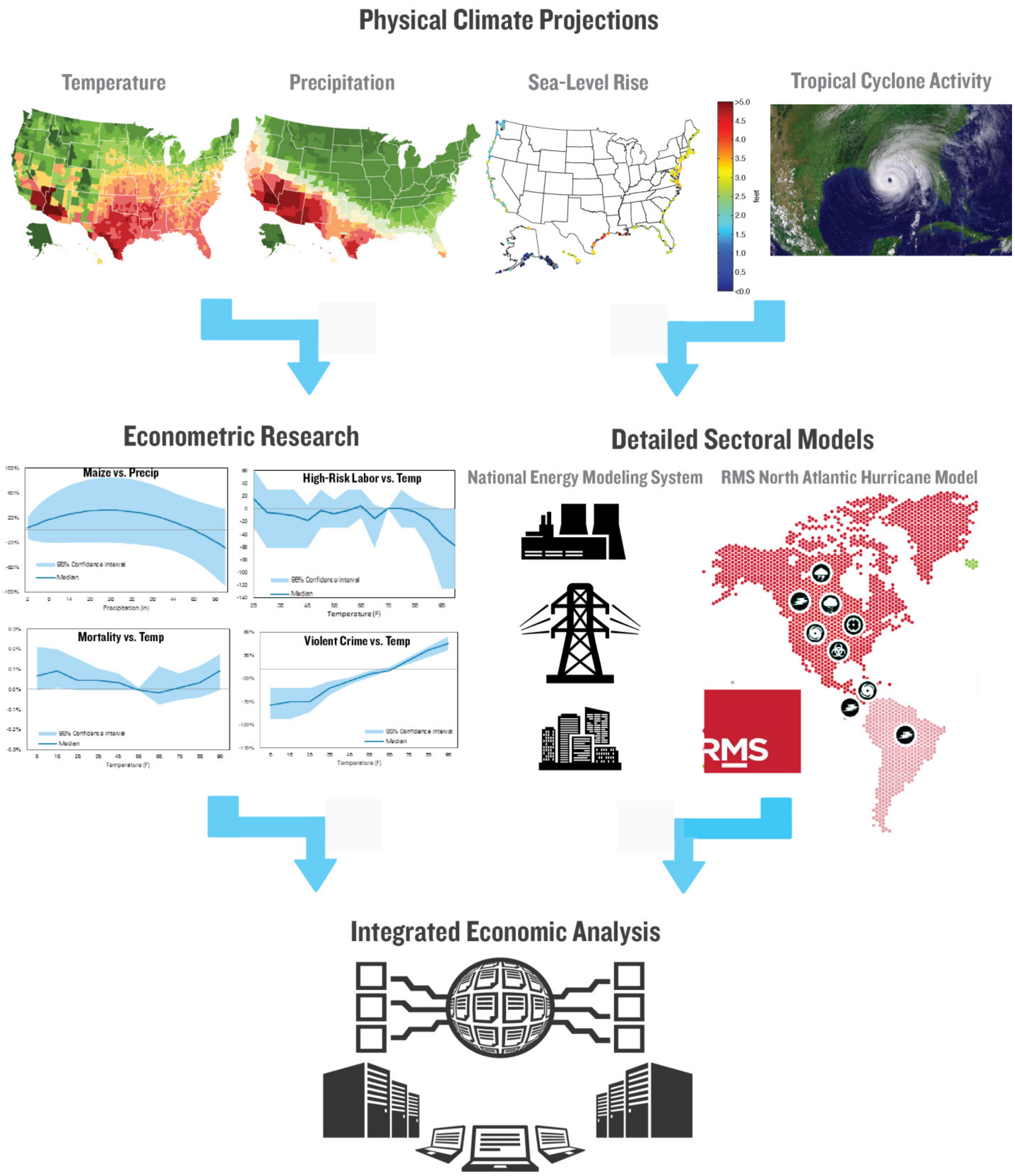
The scientific community has recently released two major assessments of the risks to human and natural systems from climate change. The Fifth Assessment Report (AR5) from the Intergovernmental Panel on Climate Change (IPCC) provides a global outlook, while the US government's Third National Climate Assessment (NCA) focuses on regional impacts within the US. These assessments consolidate the best information that science can provide about the effects of climate change to date and how the climate may change going forward.

Building on records of past weather patterns, probabilistic projections of future global temperature change, and the same suite of detailed global climate models (GCMs) that informed AR5 and the NCA, we explore a full range of potential changes in temperatures and precipitation at a daily, local level in the United States as a result of both past and future GHG emissions. As variability matters as much in shaping economic outcomes as averages, we assess potential changes in the number of hot and cold days each year in addition to changes in annual means. Using the observed, local relationships between temperature and humidity, we also project changes in the number of hot, humid summer days. Synthesizing model projections, formal expert elicitation, and expert assessment, we provide a complete probability distribution of potential sea-level rise at a local level in the US. While there is still considerable uncertainty surrounding the impact of climate change on hurricane and other storm activity, we explore potential changes, drawing on the work of leading tropical cyclone modelers at NOAA's Geophysical Fluid Dynamics Laboratory and MIT.

Econometric research

Economists have studied the impact of climate change on macroeconomic activity for nearly a quarter century, starting with the pioneering work of Yale professor William Nordhaus and Peterson Institute for International Economics fellow William Cline in the early 1990s (Cline, 1992; Nordhaus, 1991). Just as our scientific understanding of climate change has improved considerably, so has our ability to assess the impacts of climate change on particular sectors of the economy and, in particular, regions of the country. Such finer-scale assessments are necessary to provide useful information to individual decision-makers. For example, coastal property developers need to assess whether, when, and to what extent climate change increases the risk of flooding where they are looking to build. Farmers will want to understand the commercial risks of shifts in temperature and rainfall in their particular region, rather than the country as a whole. Electric utilities need to prepare for changing heating and cooling demand in their service territory, and the impact of climate change on labor productivity will vary by industry as well as geography. Natural variability in temperature and precipitation provides a rich dataset from which to derive insights about the potential economic impact of future climate changes. A wealth of new findings from micro-econometric research has become available in recent years, enabling us to evaluate the effects of climatic changes on certain segments of the economy using historically observed responses.

Figure I.1: Spatial Empirical Adaptive Global-to-Local Assessment System (SEAGLAS)



Detailed sectoral models

Complementing our meta-analysis of micro-econometric research, we employ detailed, empirically-based public and private sector models to assess the risk of climate change to key economic sectors or asset classes. These models are not traditionally used for climate change impact analysis, but offer powerful, and business- and policy-relevant insights. For example, to assess the impact of greater storm surge during hurricanes and nor'easters on coastal property as a result of climate-driven increases in local sea levels, we employ Risk Management Solutions' (RMS) North Atlantic Hurricane Model and building-level exposure dataset. More than 400 insurers, reinsurers, trading companies, and other financial institutions trust RMS models to better understand and manage the risks of natural and human-made catastrophes, including hurricanes, earthquakes, floods, terrorism, and pandemics. To model the impact of changes in temperature on energy demand, power generation, and electricity costs, we use RHG-NEMS, a version of the US Energy Information Administration's National Energy Modeling System (NEMS) maintained by the Rhodium Group. NEMS is used to produce the Annual Energy Outlook, the most detailed and widely used projection of US energy market dynamics.

Integrated economic analysis

We use geographically granular US economic data to put projected climate impacts in a local economic context. This is critical given how widely climate risk exposure varies across the country. We also integrate sectoral impact estimates into a state-level model of the US economy to measure the knock-on effects of climate-related impacts in one sector or region to other parts of the economy, and to assess their combined effect on long-term economic growth.

Cloud computing

Both the individual components of the analysis, and their integration to produce probabilistic, location-specific climate risk assessments is only possible thanks to the advent of scalable cloud computing. All told, producing this report required over 200,000 CPU-hours processing over 20 terabytes of data, a task that would have taken months, or even years, to complete not long ago. Cloud computing also enables us to make our methodology, models, and data available to the research community, which is critical given the iterative nature of climate risk assessment and the limited number of impacts we were able to quantify for this report.

USING THIS ASSESSMENT

In Part 1 of this report, we provide projections of the physical changes facing the United States. In Part 2, we assess the direct effects of these changes on six impact categories amenable to quantification: commodity agriculture, labor productivity, heat-related mortality, crime, energy demand, and storm-related coastal damages. In Part 3, we assess the economic costs of these impacts. Part 4 provides an overview of the many types of additional impacts that we have not attempted to quantify. Part 5 concludes by presenting principles for climate risk management.

This assessment does not attempt to provide a definitive answer to the question of what climate change will cost the US. Nor does it attempt to predict what *will* happen or to identify a single 'best estimate' of climate change impacts and costs. While great for making headlines, best guess economic cost estimates at a nationwide level are less helpful in supporting effective risk management. Instead, we attempt to provide American policymakers, investors, businesses, and households with as much information as possible about the probability, timing, and scope of a set of economically important climate impacts. We also identify areas of potential concern where the state of knowledge does not permit us to make quantitative estimates at this time. How decisions-makers chose to act upon this information will depend on where they live and work, their planning time-horizon, and their appetite for risk.

Probability

For many decision-makers, low-probability, high-impact climate events matter as much, if not more, than those futures most likely to occur. Nuclear safety officials, for example, must consider worst-case scenarios and design reactors to prevent the kind of catastrophic impacts that would result. National security planners, public health officials, and financial regulators are likewise concerned with "tail risks". Most decision-makers will not make day-to-day decisions with these catastrophic risks in mind, but for those with little appetite for risk and high potential for damage, the potential for catastrophic outcomes is a data point they cannot afford to ignore. Thus, in addition to presenting the most likely outcomes, we discuss those at each end of the probability distribution.

Throughout the report, we employ the same formal probability language as did the IPCC in AR5. We use the term '*more likely than not*' to indicate likelihoods greater than 50%, the term '*likely*' for likelihoods greater than

67%, and the term '*very likely*' for likelihoods greater than 90%. The formal use of these terms is indicated by italics. For example, where we present '*likely* ranges,' that means there is a 67% probability that the outcome will be in the specified range.

In some contexts, we also discuss 'tail risks,' which our probability estimates place at less than 1% probability. While we judge these outcomes as exceptionally unlikely to occur within the current century (though perhaps more likely thereafter with continued warming), we could plausibly be underestimating their probability. For example, carbon cycle feedbacks of the sort discussed in Chapter 3 could increase the temperature response of the planet, or the destabilization of West Antarctica might amplify sea-level rise. Though our formal probability calculation places low likelihood on these possibilities, the true probability of these scenarios is challenging to quantify.

As described in Chapter 4, our analyses include the four global concentration pathways generally used by the scientific community in climate change modeling.

Timing

Most of our analysis looks out over the next eighty-six years to 2100, extending just four years beyond the expected lifetime of a baby girl born the day this report was released. While climate change is already affecting the US, the most significant risks await us in the decades ahead. How much a decision-maker worries about these future impacts depends on their age, planning or investment time-horizon, and level of concern about long-term economic or financial liabilities. Individuals often care less about costs borne by future generations than those incurred in their own lifetimes. A small start-up does less long-term planning than a multi-generational family-owned company. Property and infrastructure developers have longer investment horizons than commodities or currency traders, and while some politicians are focused purely on the next election cycle, others are focused on the economy's health long after they leave office. We present results in three periods – 2020-2039, 2040-2059 and 2080-2099 – to allow individual decision-makers to focus on the time-horizon most relevant to their risk management needs. For a few physical changes, we also discuss effects beyond 2100 to highlight the potential challenges facing the future children of today's newborns.

Scope

Nationwide estimates of the economic cost of climate change average out important location- or industry-specific information. Climate risk is not evenly spread across regions, economic sectors, or demographic groups. Risks that appear manageable on an economy-wide basis can be catastrophic for the communities or businesses hardest hit. To ensure this risk assessment is useful to a wide range of decision-makers, we report and discuss sector-specific impacts as well as nationwide results. We also analyze economic risk by state and region.

A FRAMEWORK TO BUILD ON

Given the complexity of the Earth's climate system, uncertainty in how climatic changes affect the economy, and ongoing scientific and economic advances, no single report can provide a definitive assessment of the risks we face. Our work has a number of limitations, which are important to keep in mind when considering the findings presented in this report.

First, the universe of potential impacts Americans may face from climate change is large and complex. No study to date has adequately captured them all and this assessment is no different. We have necessarily been selective in choosing which economic risks to quantify – focusing on those where there is a solid basis for assessment and where sector-level impacts are of macroeconomic significance. This excludes well-known impacts that could be catastrophic for particular communities or industries, as well as poorly-understood impacts that pose risks for the economy as a whole. We describe these impacts to the extent possible, drawing on recent academic, government and private sector research, but they are not included in our economic cost estimates.

Second, this analysis is limited to the direct impact of climate change within the United States. Of course, climate change is a global phenomenon, and climate impacts elsewhere in the world will have consequences for the United States as well, whether through changes in international trade and investment patterns or new national security concerns. While we discuss some of these dynamics, we have not attempted to quantify their economic impact.

Third, individual climate impacts could very well interact in ways not captured in our analysis. For example, we assess the impact of changes in temperature on electricity demand and the impact of changes in precipitation on water supply, but not changes in water supply on the cost of electric power generation. These types of interactions can be limited in scope or pose systemic risks.

Figure I.2: Scope of this assessment

Finally, economic risk is a narrow measure of human welfare. Climate change could result in a significant decline in biodiversity, lead to the extinction of entire species of plants and animals, and permanently alter the appearance and utility of national parks and other natural treasures. Very little of this is captured in standard economic indicators like GDP. While understanding the economic risk of climate change is important, it is only one facet of the climate-related risks we face. A number of the economic risks we quantify have non-economic impacts as well, which we describe alongside the economic findings.

Figure 1.2 highlights the impacts we have included in our quantitative analysis of risks of climate change to the US, those we include in a limited or purely qualitative way, and those that are excluded from our assessment altogether.

Given these limitations, our goal is to provide a research framework rather than a definitive answer. Our climate is complex, and our understanding of how it is changing and what that means for our economy is constantly evolving. The US National Academies of Science have suggested that this kind of "iterative risk management" is also the right way to approach climate change (National Research Council, 2010), and we believe the approach we took in preparing this report provides a useful model for future climate risk assessments. Our team included climate scientists, econometricians, economic modelers, risk analysts, and issue experts, both from academia and the private sector. We found this interdisciplinary, intersectoral collaboration unique, enjoyable, and extremely helpful in better understanding such a complicated issue. While taking an integrated approach, our research is modular so that individual components can be updated, expanded, and improved as the science and economics evolves, whether that's the global climate models we use for local temperature and precipitation projections, our sectoral impact estimates, or the US macroeconomic model we employ. We provide a complete description of our methods and information sources in the technical appendices of this report, and will be making our data and tools available online at climateprospectus.rhg.com. We hope others build on and improve upon our work in the months and years ahead.

Part I

America's Climate Future

CHAPTER 2

What We Know

Over the nearly eight decades since the groundbreaking work of Guy Stewart Callendar (Callendar, 1938), scientists have become increasingly confident that humans are reshaping the Earth's climate. The combustion of fossil fuels, deforestation, and other human activities are increasing the concentration of carbon dioxide (CO_2) and other "greenhouse gases" in the planet's atmosphere. These gases create a "greenhouse effect," trapping some of the Sun's energy and warming the Earth's surface. The rise in their concentration is changing the planet's energy balance, leading to higher temperatures and sea levels and to shifts in global weather patterns. In this chapter, we provide an overview of what scientists currently know about climate change, and what remains uncertain. In the following two chapters, we discuss the factors that will shape our climate in the years ahead and the approach we take to modeling future climate outcomes in the United States. We present projections of changes in temperature, precipitation, humidity and sea level between now and the end of the century.

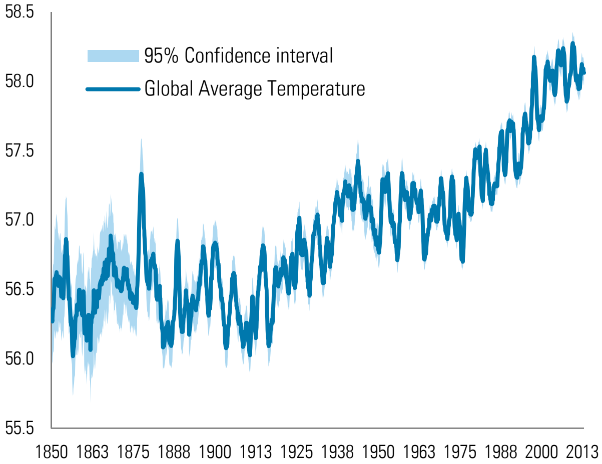
SEPARATING THE SIGNAL FROM THE NOISE

The climate is naturally variable. Temperature and precipitation change dramatically from day to day, month to month and year to year. Ocean circulation patterns result in climate variations on decadal and even multi-decadal timescales. Scientists have identified changes in the Earth's climate, however, that cannot be explained by these natural variations and are increasingly certain they are due to human activities (Molina et al., 2014; National Research Council, 2010).

Since the late nineteenth century, the Earth's average surface air temperature has increased by about 1.4 °F (Hartmann et al., 2013). At the global scale, each of the last three decades has been successively warmer than the decade before (Figure 2.1). Comparing thermometer records with indirect estimates of temperature, such as the isotopic composition of ice core samples, suggests that, at least in the Northern Hemisphere, the period between 1983 and 2012 was *very likely* the warmest 30-year period of the last 800 years and *likely* the warmest of the last 1400 years (Masson-Delmotte, Schulz, & et al., 2013). Other evidence supports these surface temperature measurements, including observed decrease in snow and ice cover (from glaciers to sea ice to the Greenland ice sheet), ocean warming and rising global sea levels.

Figure 2.1: Global average temperatures

Degrees Fahrenheit, 1850-2013



Source: Berkeley Earth (http://www.berkeleyearth.org)

Over the contiguous United States, average temperature has risen about 1.5°F over the past century, with more than 80% of the increase occurring in the last 30 years (Menne, Williams, & Palecki, 2010; Walsh et al., 2014). Glaciers are retreating, snowpack is melting earlier, and the growing season is lengthening. There have also been observed changes in some extreme weather events consistent with a warmer US, including increases in heavy precipitation and heat waves (Walsh et al., 2014).

The increase in both US and global temperatures over the past century transcend the regular annual, decadal or even multi-decadal climate variability. It is a disruption far beyond normal changes in the weather.

A HISTORY OF CLIMATE DISRUPTION

This is not the first time the Earth has experienced a climate disruption lasting more than a century. Indeed, over the past 800,000 years, variations in the Earth's orbit around the sun have triggered glacial cycles spanning roughly 100,000 years during which Antarctic temperatures (estimated using ice core samples) have fluctuated by 10°F to more than 20°F (Figure 2.2).

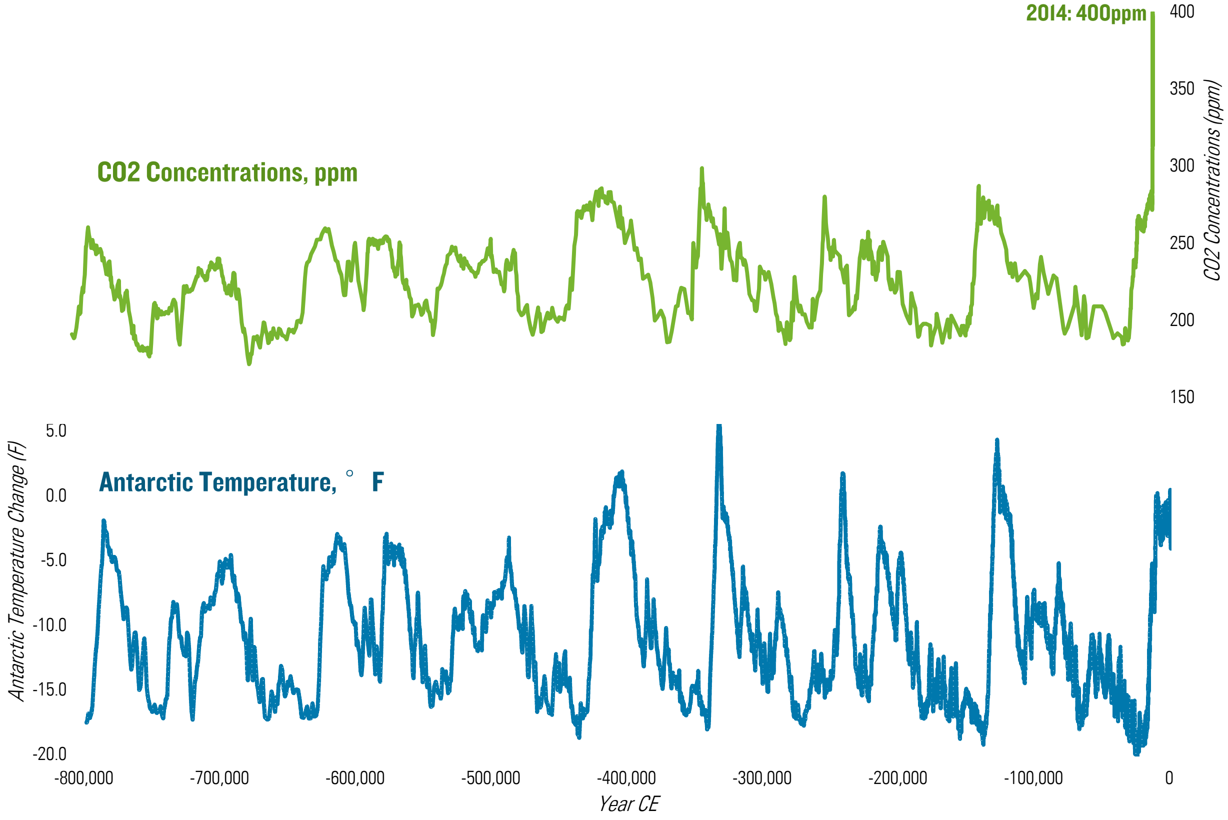
The amount of heat a body radiates increases as its temperature rises. For a planet to have a stable global average temperature, the heat it absorbs from the sun must equal the heat it radiates to space. If it is absorbing more than it is radiating, its surface and atmosphere will warm until energy balance is achieved. CO_2 and other gases in the atmosphere hinder the escape of heat from the Earth's surface to space. As the atmospheric concentrations of these gases rise, so too do average surface temperatures. This is known as the "greenhouse effect," and its fundamental physics have been well understood by scientists since the late nineteenth century (Arrhenius, 1896).

Variations in the Earth's orbit alter the way the heat the Earth receives from the Sun is distributed over the planet's surface and over the course of the year. These variations cause changes in surface temperatures that can increase or decrease natural emissions of CO_2 and methane (another greenhouse gas), amplifying the direct temperature impact (Figure 2.2). As the great ice sheets of the last ice age began to retreat about 18,000 years ago, atmospheric concentrations of CO_2 rose from a low of 188 parts per million (ppm), reaching 260 ppm over the following 7,000 years. Concentrations stayed in the 260 to 285 ppm range until the 1860s, when they started rising again. Today's CO_2 levels are near and have seasonally exceeded 400 ppm, far above the range experienced over the past 800,000 years (Luthi et al., 2008). Indeed, the last time CO_2 concentrations exceeded this level was likely over three million years ago (Seki et al., 2010), a period when global average temperature was about 5°F warmer than today (Lunt et al., 2010) and global average sea level may have been as much as 70 feet higher than today (Miller et al., 2012; Rovere et al., 2014).

The pace of the recent rise in atmospheric concentrations of CO_2 has also been far faster than occurs under normal glacial cycles – rising more over the last sixty years than during the 7,000 years following the last ice age (Figure 2.2).

Figure 2.2: Temperature and CO_2

Historical record



CHAPTER 3

What Comes Next

If past greenhouse gas emissions from fossil fuel combustion and other human activities have already changed our climate, what risks do we run if we continue on our current course? As discussed in the introduction, this report attempts to help answer that question. While our focus is the economic risks of climate change, the analysis necessarily starts with an assessment of ways in which the climate may change in the years ahead.

A growing body of evidence shows conclusively that continued emissions of CO_2 and other greenhouse gases will cause further warming, and affect all components of the Earth's climate system. While there have been significant advances in climate science in recent years, the Earth's climate system is complex, and predicting exactly how global or regional temperatures and other climate variables will change in the coming decades remains a challenge. It's important to be honest about the uncertainty involved in forecasting our climate future if we are to provide policymakers, businesses, and households with the information they need to effectively manage climate-related risks (Heal & Millner, 2013). Scientists face five major sources of uncertainty in predicting climate outcomes: (1) socio-economic uncertainty, (2) global physical uncertainty, (3) regional physical uncertainty, (4) natural variability, and (5) tipping points. We discuss each below and provide an overview of how they are addressed in our analysis.

SOCIO-ECONOMIC UNCERTAINTY

Future greenhouse gas emission levels will depend on the pace of global economic and population growth, technological developments, and policy decisions – all of which are challenging to predict over the course of a decade, let alone a century or more. As a consequence, the climate science community has generally preferred to explore a range of plausible, long-run socio-economic scenarios rather than relying on a single best guess (Bradfield, Wright, Burt, Cairns, & Van Der Heijden, 2005; Moss et al., 2010). Each scenario includes assumptions about economic development, energy sector evolution, and policy action – capturing potential futures that range from slow economic growth, to rapid economic growth powered primarily by fossil fuels, to vibrant economic development in a world transitioning to low-carbon energy sources. Each scenario results in an illustrative greenhouse gas emission and atmospheric concentration pathway.

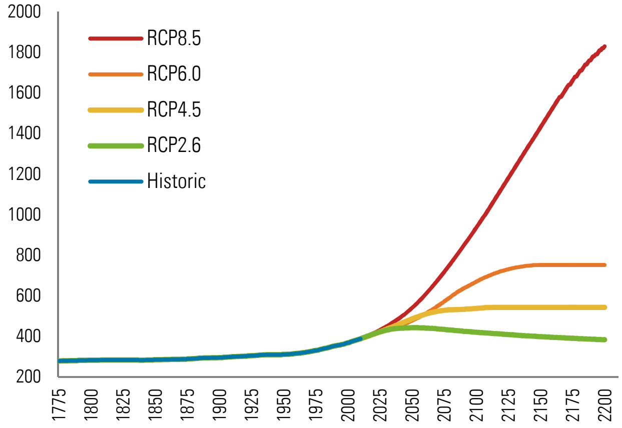
A broadly accepted set of global concentration pathways was recently developed by the Integrated Assessment Modeling Consortium (IAMC) and used in the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5). Termed "Representative Concentration Pathways" (RCPs), these four pathways span a plausible range of future atmospheric greenhouse gas concentrations. They are labeled based on their radiative forcing (in watts per square meter, a measure of greenhouse gas concentrations in terms of the amount of additional solar energy the gases retain) in the year 2100 (Meinshausen et al. 2011b). The pathways also include different assumptions about future changes in emissions of particulate pollution, which reflects some of the Sun's energy to space and thus dampens regional warming. The RCPs are the basis for most global climate modeling undertaken over the past few years.

At the high end of the range, RCP 8.5 represents a continuation of recent global emissions growth rates, with atmospheric concentrations of CO_2 reaching 940 ppm by 2100 (Figure 3.1) and 2000 ppm by 2200. These are not the highest possible emissions; rapid conventional economic growth could lead to a radiative forcing 10% higher than RCP 8.5 (Riahi, 2013). But RCP 8.5 is a reasonable representation of a world where fossil fuels continue to power relatively robust global economic growth, and is often considered closest to the most likely "business-as-usual" scenario absent new climate policy by major emitting countries.

At the low end of the range, RCP 2.6 reflects a future only achievable by aggressively reducing global emissions (even achieving net negative emissions by this century's end) through a rapid transition to low-carbon energy sources. Atmospheric CO_2 concentrations remain below 450 ppm in RCP 2.6, declining to 384 ppm by 2200. Two intermediate pathways (RCP 6.0 and RCP 4.5) are consistent with a modest slowdown in global economic growth and/or a shift away from fossil fuels more gradual than in RCP 2.6 (Riahi, 2013). In RCP 6.0, CO_2 concentrations stabilize around 750 ppm in the middle of the 22nd century. In RCP 4.5, CO_2 concentrations stabilize around 550 ppm by the end of the 21st century.

Figure 3.1: Representative concentration pathways

Atmospheric concentrations of CO_2 in ppm



Source: Meinshausen et al. 2011

We include all four RCPs in our analysis for two reasons. First, an individual RCP is not uniquely associated with any particular set of population, economic, technological, or policy assumptions; each could be attained through a variety of plausible combination of assumptions. For example, a rapid emissions decline in the United States combined with continued emissions growth in the rest of the world could result in a concentration pathway similar to RCP 8.5. Likewise, if emissions in the United States continue to grow but the rest of the world makes a rapid transition to a low-carbon economy, a concentration pathway similar to RCP 4.5 is still potentially possible. Given the uncertainty surrounding emissions pathways in other countries, American policymakers must assess the risks associated with a full range of possible concentration futures. This is especially true for local officials as well as American businesses and households who have little control over America's overall emission trajectory, let alone global concentration pathways.

The second reason is to identify the extent to which global efforts to reduce greenhouse gas emissions can reduce climate-related risks associated with the absence of deliberate mitigation policy (i.e., RCP 8.5 or, under a slower global economic growth scenario, RCP 6.0). This is not to recommend a particular emission reduction pathway, but to identify climate outcomes that are potentially avoidable versus those that are already locked in.

GLOBAL PHYSICAL UNCERTAINTY

Even if we knew future emissions growth rates with absolute certainty, we would still not be able to predict their impact precisely, due to the complexity of the Earth's climate system. At a global level, the largest source of physical uncertainty resides in the magnitude and timescale of the planet's response to a given change in radiative forcing, commonly represented by "equilibrium climate sensitivity" and "transient climate response." The former, typically reported as the response to a doubling of CO_2 concentrations, reflects the long-term response of global mean temperature to a change in forcing; the latter reflects how that response plays out over time.

The effect on global temperature of the heat absorbed and emitted by CO_2 alone is fairly well understood. If CO_2 concentrations doubled but nothing else in the Earth system changed, global average temperature would rise by about 2°F (Flato et al., 2013; Hansen et al., 1981). Across the entire climate system, however, there are several feedback mechanisms that either amplify or diminish this effect and respond on different timescales, complicating precise estimates of the overall sensitivity of the climate system. These feedbacks include an increase in atmospheric water vapor concentrations; a decrease in the planet's reflectivity due to reduction in ice and snow coverage; changes in the rate at which land, plants, and the ocean absorb carbon dioxide; and changes in cloud characteristics. Significant uncertainties remain regarding the magnitude of the relatively fast cloud feedbacks, as well as longer-term and/or abrupt feedbacks, such as high-latitude permafrost melt or release of methane hydrates, which would amplify projected warming (see discussion on "Tipping Points" below). Such longer-term feedbacks are not included in the "equilibrium climate sensitivity" as conventionally defined.

Uncertainty in the equilibrium climate sensitivity is a major contributor to overall uncertainty in projections of future climate change and its potential impacts. Scientists have high confidence, based on observed climate change, climate models, feedback analysis, and paleoclimate evidence that the long-term climate sensitivity (over hundreds to thousands of years) is *likely* in the range of 3°F to 8°F warming per CO_2 doubling, *extremely likely* (95% probability) greater than 2°F, and *very likely* (90% probability) less than 11°F (Collins et al., 2013). This warming is not realized instantaneously, as the ocean serves as a heat sink, slowing temperature rise. A more immediate measure, the "transient climate response," indicates that a doubling of CO_2 over 70 years is *likely* to cause a warming of between 2°F and 5°F over that period of time (Collins et al., 2013).

These ranges of climate sensitivity values are associated with significantly different projections of future climate change. Many past climate impact assessments have focused only on the "best estimates" of climate sensitivity. To capture a broader range of potential outcomes, we use MAGICC, a commonly-employed simple climate model (Meinshausen, Raper, and Wigley 2011) that can emulate the results of more complex models and can be run hundreds of times to capture the spread in estimates of climate sensitivity and other key climate parameters. MAGICC's model parameters are calibrated against historical observations (Meinshausen et al. 2009; Rogelj, Meinshausen, and Knutti 2012) and the IPCC's estimated distribution of climate sensitivity (Collins et al., 2013). A more detailed description of our approach is provided in Appendix 1.

REGIONAL PHYSICAL UNCERTAINTY

Since deliberate planetary-scale climate experiments are largely infeasible and would raise profound ethical questions, scientists must rely on computer models to conduct experiments on Earth's complex climate system, including projecting how climate will change at a regional scale in response to changes in greenhouse gases. Global climate models are descended from the first numerical weather prediction models developed after World War II (Edwards, 2011; Manabe & Wetherald, 1967; Phillips, 1956). Over time they have been expanded to include the dynamic effects of oceans and sea ice, atmospheric particulates, atmospheric-ocean carbon cycling, atmospheric chemistry, vegetation, and most recently land ice. Model projections of the central components of long-term, human-induced climate change have grown increasingly robust, and recent generations of increasingly complex models provide greater detail and spatial resolution than ever before.

There are dozens of global climate models, with a range of different model structures and parameter assumptions. Since the 1990s the global climate modeling research community has engaged in structured inter-model comparison exercises, allowing them to compare experiments run in different models to each other and to the observational record. The differences identified among the models allow estimates to be made of the uncertainties in projections of future climate change, and highlight which aspects are robust and where to focus future research efforts to improve results over time. By combining and averaging many models, clear trends emerge.

Analysis of the range of potential climate impacts to the US for this report is based on climate projections developed as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) with a suite of 35 different global climate models (Taylor, Stouffer, & Meehl, 2012). This suite of complex models has become the gold standard for use in global climate assessments (including by the IPCC in AR5) as well as for regional assessments (including the 3rd US National Climate Assessment released this year). Major US-based models participating in CMIP5 have been developed by teams led by the NASA Goddard Institute for Space Studies, the NOAA Geophysical Fluid Dynamics Laboratory, and the National Center for Atmospheric Research.

The global climate models that participated in CMIP5 typically have spatial resolutions of ~1 to 2° (about 70 to 150 miles at mid-latitudes). To produce projections at a finer spatial resolution, researchers have used a variety of downscaling approaches. The projections in this report build upon one particular downscaling technique, bias-corrected spatial disaggregation (BCSD) (Brekke, Thrasher, Maurer, & Pruitt, 2013; Wood, Maurer, Kumar, & Lettenmaier, 2002). We use a BCSD data set generated by the Bureau of Reclamation (2013) from the CMIP5 archive. In addition to the uncertainty in the global climate models themselves, further uncertainty is introduced by the downscaling step. Alternative downscaling approaches can give rise to different localized projections, particularly of extremes (Bürger, Murdock, Werner, Sobie, & Cannon, 2012).

It is important to recognize that the CMIP5 model projections are not a probability distribution, but instead an "ensemble of opportunity" (Tebaldi & Knutti, 2007). The models are not fully independent of one another, instead sharing overlapping lineages and a common intellectual milieu (Edwards, 2011). Moreover, every modeling team that participates in CMIP has striven to develop a model that captures a suite of important physical processes in the oceans and atmosphere, and has tuned some of the parameters of their model to reasonably reproduce historical behavior. Attempts to interpret the CMIP5 ensemble as a probability distribution will accordingly undersample the distribution tails and oversample "best estimates".

For this reason, we use estimates from MAGICC of the probability of different temperature outcomes at the end of the century to weight the projections of more complex global climate models. For those parts of the probability distribution for global temperature not covered by the CMIP5 models, primarily in the tails, we create "model surrogates" by scaling spatial patterns of temperature and precipitation change from the CMIP5 models using temperature projections from MAGICC. In the Appendix, we compare our key results to those we would estimate if we treated the CMIP5 projections as though they formed a probability distribution.

NATURAL CLIMATE VARIABILITY

As discussed above, natural climate variability can range in timescale from day-to-day temperature variations, to interannual patterns such as El Niño and longer-term patterns such as the Pacific Decadal Oscillation. In addition to the trends in climate associated with climate change, global climate models simultaneously simulate natural climate variability. The magnitude of such variability renders the differences in climatic response between plausible emissions pathways essentially undetectable at a global scale until about 2025. The relative magnitude of climate variability, physical uncertainty, and scenario uncertainty differs from place to place and for different variables. For example, in the British Isles internal variability in decadal mean surface air temperature dominates scenario uncertainty through the middle of the century (Hawkins, 2009). Internal variability, not fully captured by climate models, probably accounts for a significant fraction of the slow-down in global warming over the last decade (Trenberth & Fasullo, 2013) and for the absence of net warming in parts of the southeastern US over the last century (Kumar, Kinter, Dirmeyer, Pan, & Adams, 2013). While unprecedentedly warm years will occur with increasing frequency, climate variability means that the annual mean temperatures of cooler years in most of the US will be in the range of historical experience until at least the middle of the century (Mora et al., 2013).

Extreme weather events like heat waves, hurricanes, and droughts are examples of natural climate variability experienced on more compressed time scales. By nature the probability of these events occurring is low, putting them at the far "tails" of statistical weather distributions. There is increasing evidence, however, that climate change is altering the frequency and/or severity of many types of these events (Cubasch et al., 2013). Although most individual extreme events cannot be directly attributed to human-induced warming, there is relatively high confidence that heat waves and heavy rainfall events are generally becoming more frequent (Hartmann et al., 2013). As the climate continues to warm, certain types of storms such as hurricanes are expected to become more intense (though not necessarily more frequent), although less is known about how other types of storms (such as severe thunderstorms, hailstorms, and tornadoes) may respond (National Academy of Sciences & The Royal Society, 2014).

Due to the huge damages incurred by hurricanes in recent decades, there has been significant interest in understanding global and regional trends in cyclone activity and the causes of any observed changes. At a global level, the evidence for long-term changes and the influence of human-induced climate changes on hurricane activity over the past century is unclear (Knutson et al., 2010). That is not to say that human-induced warming played no role – due to limitations in the quality of historical records, it is possible that such influence is simply not yet detectable, or is not yet properly modeled given the uncertainty in quantifying natural variability and the effects of particulate pollution, among other factors (Christensen et al., 2013; Knutson et al., 2010; Seneviratne et al., 2012). Short-term and regional trends vary, however; hurricane activity has increased in the North Atlantic since the 1970s (Christensen et al., 2013).

Our confidence in projecting future changes in extremes (including the direction and magnitude of changes) varies with the type of extreme, based on confidence in observed changes, and is thus more robust for regions where there is sufficient and high quality observational data (Seneviratne et al., 2012). Temperature extremes, for example, are generally well simulated by current GCMs, though models have more difficulty simulating precipitation extremes (Randall et al., 2007). The ability to project changes in storms, including hurricane activity, is more mixed. There is a growing consensus that, around the world, the strongest hurricanes (Categories 4 and 5) and associated rainfall levels are *likely* to increase (Christensen et al., 2013; Knutson et al., 2010; Seneviratne et al., 2012). There is low confidence, however, in climate-induced changes in the origin and track of future North Atlantic hurricanes (Bender et al., 2010).

TIPPING POINTS

Many components of the Earth system exhibit critical thresholds (often referred to as tipping points) beyond which abrupt and/or irreversible changes to the climate or the biosphere may occur (Collins et al., 2013; Lenton et al., 2008; National Academy of Sciences, 2013). Many of these tipping points are poorly represented in the current generation of climate models. Some may have direct societal or economic impacts. Others affect the global carbon cycle and amplify climate change. Such feedbacks could increase the probability of our most extreme projections (although unexpected stabilizing feedbacks could also act in the opposite direction).

Summer Arctic sea-ice cover has fallen faster than most of the previous generation of climate models had projected (Stroeve et al. 2007), although the current generation of models appears to perform better (Stroeve et al. 2012). The Arctic appears on track for nearly ice-free Septembers in the coming decades. Reduced sea-ice coverage amplifies warming in the Arctic and may also lead to slower moving weather patterns at lower latitudes (Francis & Vavrus, 2012). Slow-moving weather patterns supported the long-lived cold winter experienced by much of North America in 2013-2014, which had a significant economic impact. However, the linkage with low summer Arctic sea-ice remains highly controversial (Barnes, 2013).

Past mass extinctions have been tied to global climate change (Blois, Zarnetske, Fitzpatrick, & Finnegan, 2013). Human activities, primarily land use changes, have increased the global species extinction rate by about two orders of magnitude above the background rate (Barnosky et al., 2011) and climate change is beginning to exacerbate extinction further (Barnosky et al., 2012). The economic impacts of mass extinction and the associated loss of ecosystem services are difficult to estimate, but they are likely to be substantial.

Past climate change has also driven rapid ecosystem shifts (Blois et al., 2013). Some research suggests that the Amazon rainforest and northern boreal forests may be vulnerable to a climatically-driven die-off, which would increase global CO_2 emissions, but there is significant uncertainty about the climatic threshold for such a die-off and its likelihood (Collins et al., 2013).

Destabilization of methane trapped in ocean sediments and permafrost may have played a major role in the geologically rapid 10°F global warming of the Paleocene-Eocene Thermal Maximum, 56 million years ago (McInerney & Wing, 2011). Global warming today may trigger a similar destabilization of methane reservoirs today, amplifying projected warming significantly, although such a methane release would be expected to play out over centuries (Collins et al., 2013).

Reconstructions of past sea level, as well as physical models of ice-sheet dynamics, suggest that the West Antarctic Ice Sheet can collapse and raise sea level by many feet over the course of a few centuries (Kopp, Simons, Mitrovica, Maloof, & Oppenheimer, 2009; Pollard & DeConto, 2009). Indeed, recent evidence suggests that such a collapse may be underway (Joughin, Smith, & Medley, 2014; Rignot, Mouginot, Morlighem, Seroussi, & Scheuchl, 2014). The possibility of a rapid collapse is included in the sea-level rise projections described below, which indicate a 1-in-1000 probability of eight feet of global mean sea-level rise by 2100 and 31 feet of global mean sea-level rise by 2200.

Other potential tipping points include drops in ocean oxygen content, changes to monsoons, and changes to patterns of climatic variability such as El Niño (National Academy of Sciences, 2013). There may be other critical thresholds not yet considered by science. High-impact tipping points with consequences realized primarily in this century are considered unlikely, but confidence in many of these projections is low (Collins et al., 2013). As warming increases, the possibility of major abrupt changes cannot be ruled out.

CHAPTER 4

US Climate Projections

This report seeks to assess how potential climate futures may differ from the conditions we know today. Results are provided for three future time periods: 2020-2039, mid-century (2040-2059) and late-century (2080-2099). We also report results for a historical reference period, in most cases the 1981-2010 used by the National Climate Data Center in defining the latest release of Climate Normals. Using multi-decadal averages, rather than a single year, ensures that results are not excessively influenced by natural interannual variability.

Under all scenarios average global and US temperatures rise over the course of the century. By mid-century global average temperature will *likely* (67% probability) be between 2.2 and 3.7°F warmer under the continued high global emissions pathway (RCP 8.5). The increase will be somewhat less under RCP 6.0 and RCP 4.5, with *likely* warming of 1.4 to 2.5°F and 1.5 to 2.8°F, respectively. Even under RCP 2.6, average temperatures continue to increase to a *likely* range of 1.1 to 2.2°F by mid-century. By the end of the century, the differences between future pathways are larger: the *very likely* (90% probability) warming is 4.7 to 8.8°F for RCP 8.5, 2.8 to 5.4°F for RCP 6.0, 2.1 to 4.5°F in RCP 4.5, and 0.9 to 2.6°F in RCP 2.6 (Figure 4.1).

The land warms faster than the oceans, and as a consequence the mean temperature increase in the United States over the 21st century will, *more likely than not*, be greater than the global average. (Note that these are average temperatures; just as they do today, individual years will vary by about 1-2°F around the average; see Figure 4.2.) Across the continental US, by mid-century the average temperature will *likely* be between 2.6 and 5.8°F warmer under RCP 8.5 and between 1.9 and 3.5°F warmer under RCP 2.6. By the end of the century, the differences between future pathways are larger, with *likely* warming of 6.1 to 12.5°F for RCP 8.5, 4.1 to 7.7°F for RCP 6.0, 2.9 to 6.9°F in RCP 4.5, and 1.1 to 3.7°F in RCP 2.6. These *likely* ranges, however, do not reflect the small, but not insignificant chance that average US temperatures may rise even further. Under RCP 8.5, by the end of the century there is a 1-in-20 chance that average temperatures could rise by more than 14°F, and a very small chance (which we estimate at 1% or less) of temperature increases above 19°F. In the continental US, RCP 6.0 is associated with cooler temperatures than the other three RCPs through mid-century because it projects greater emissions of particulate pollution from power plants and industrial sources, offsetting some of the warming that would otherwise have occurred.

Figure 4.1: Global average temperature projections

Degrees Fahrenheit relative to 1981-2010 averages, historical median projections (left side) and confidence intervals (right side)

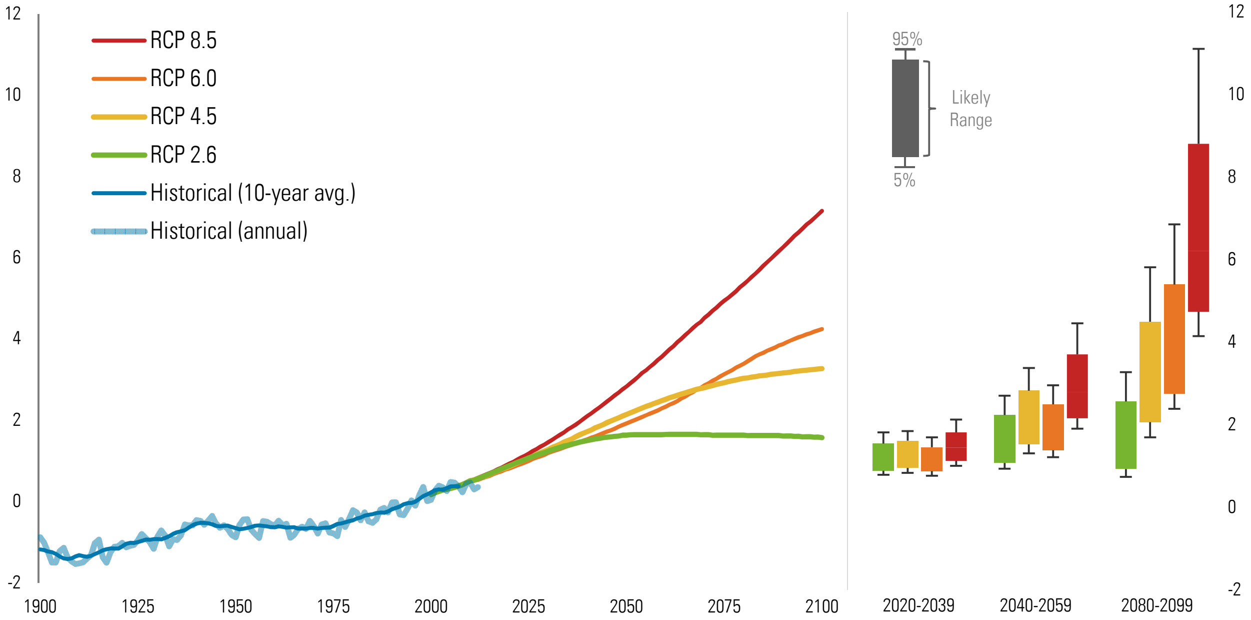
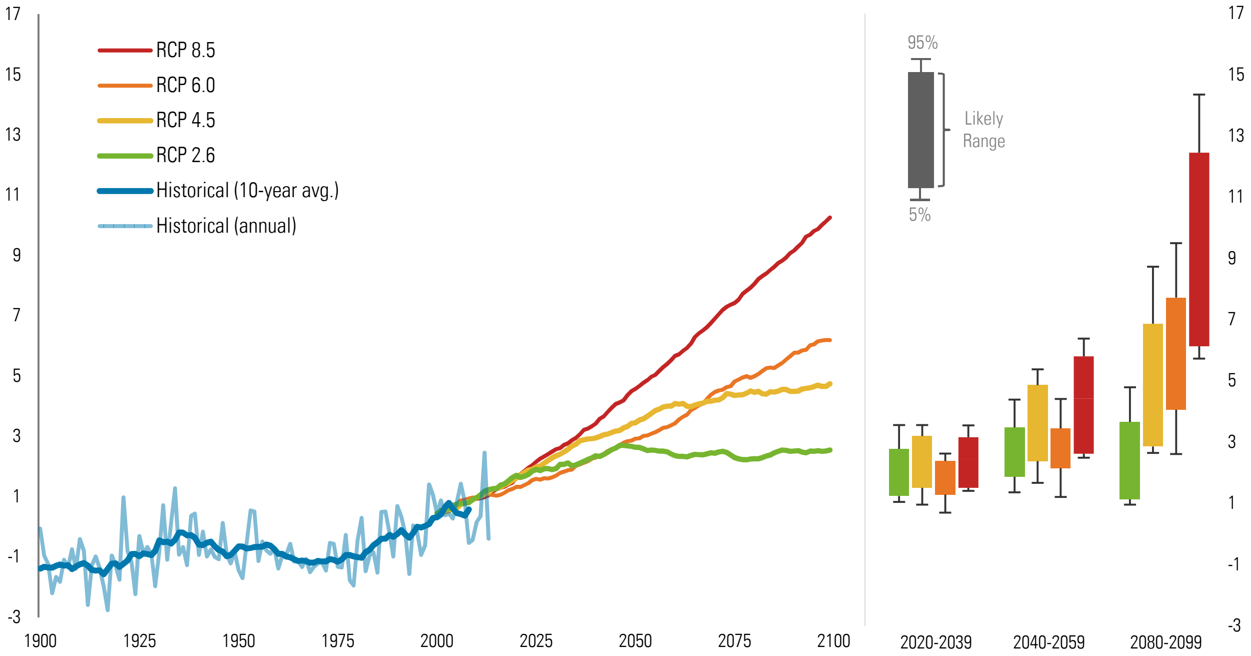


Figure 4.2: US average temperature projections

Degrees Fahrenheit relative to 1981-2010 averages, historical temperatures and median projections (left side) and confidence intervals (right)



The rise in global and US average will be reflected in increased daily high temperatures. Since 1950, global maximum and minimum air surface temperatures have increased by over 1.1°F, about 0.2°F per decade (Hartmann et al., 2013). Over the past 30 to 40 years, the ratio of record daily high temperatures to record daily low temperatures for the continental US has steadily increased (Walsh et al., 2014). The last decade experienced twice as many record highs as record lows, a larger difference than even the 1930s – a time of record heat and drought in much of the US (Blunden & Arndt, 2013). Extreme summer temperatures have also approached or exceeded those in the 1930s over much of the US.

One measure of changes in extreme temperatures is the number of days with temperatures reaching 95°F or more, a measure that is projected to increase dramatically across the contiguous United States as a result of climate change. Under RCP 8.5, by mid-century (assuming the geographic distribution of the population remains unchanged) the average American will *likely* experience an average of 27 to 50 days over 95°F each year. This represents a near doubling to more than tripling of the average 15 days per year over this threshold from 1981-2010. By late century the average American will *likely* see an average of 46 to 96 days per year over 95°F, or around 1.5 to 3 months out of the year. By the end of the century, the average Coloradan will *likely* experience more days above 95°F in a typical year than the average Texan does today (Figure 4.4).

There are similarly large projected changes in average winter temperatures (Figure 4.5) and number of extremely cold days (Figure 4.6). Again, northern states see the largest shift, with average winter temperatures *likely* rising by 2.9 to 6.5°F in the Northeast by mid-century under RCP 8.5 and by 6.9 to 13.2°F by the end of the century (Figure 4.5). Of the 25 states that currently have sub-freezing average winter temperatures, only six (Vermont, Maine, Wisconsin, Minnesota, North Dakota and Alaska) are still *likely* to do so under RCP 8.5 by the end of the century. In that scenario the average number of days with temperatures dropping below 32°F the average resident of New York state experiences will *likely* fall from 93 to less than 51. The number of days dipping below 32°F in Washington, DC will *likely* fall from 87 to less than 37.

Figure 4.3: Change in average summer temperatures

Daily average summer (June, July, August) temperature (°F) under RCP 8.5

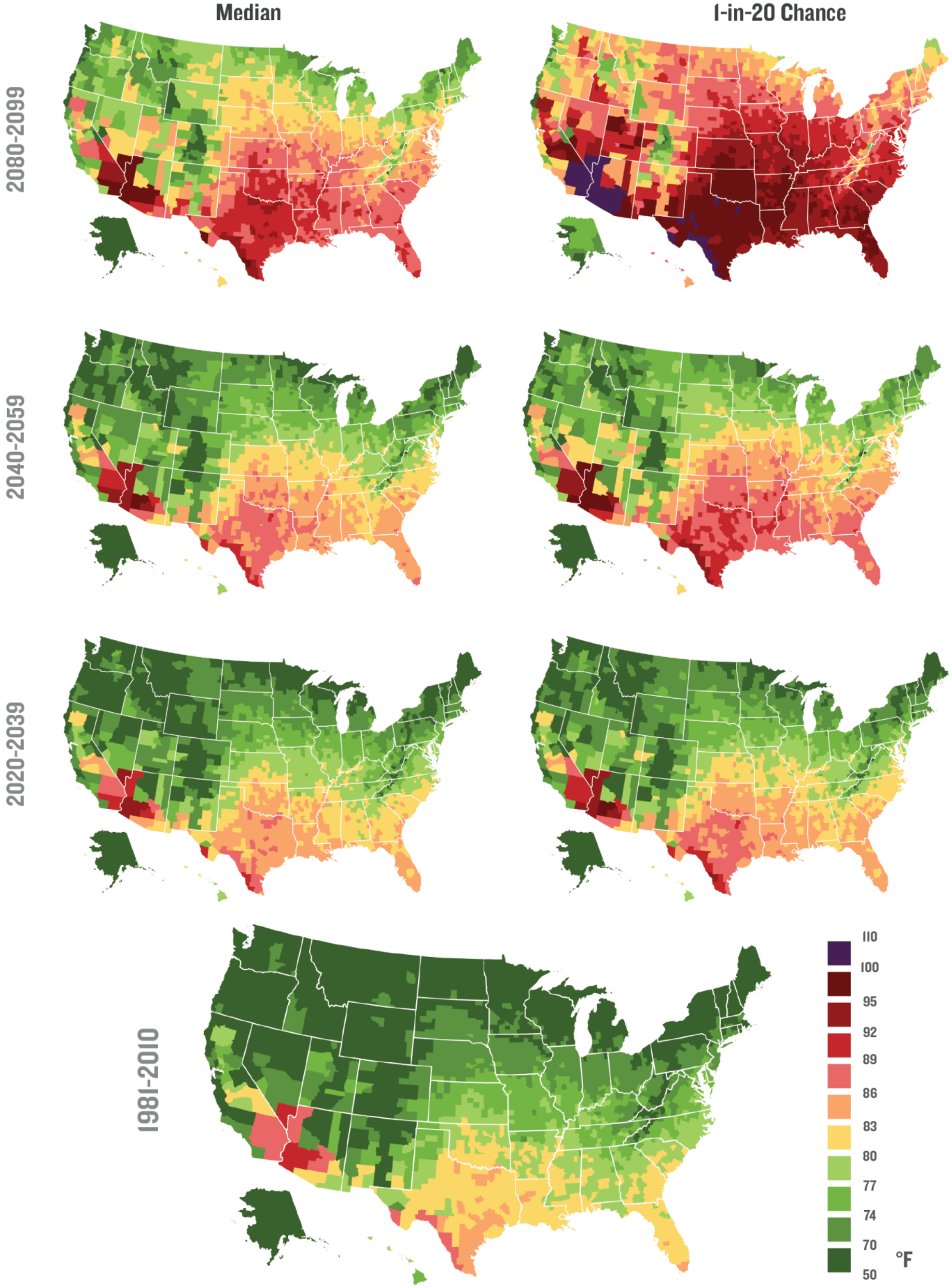


Figure 4.4: Change in number of extreme hot days

Number of days with maximum temperatures above 95°F, RCP 8.5

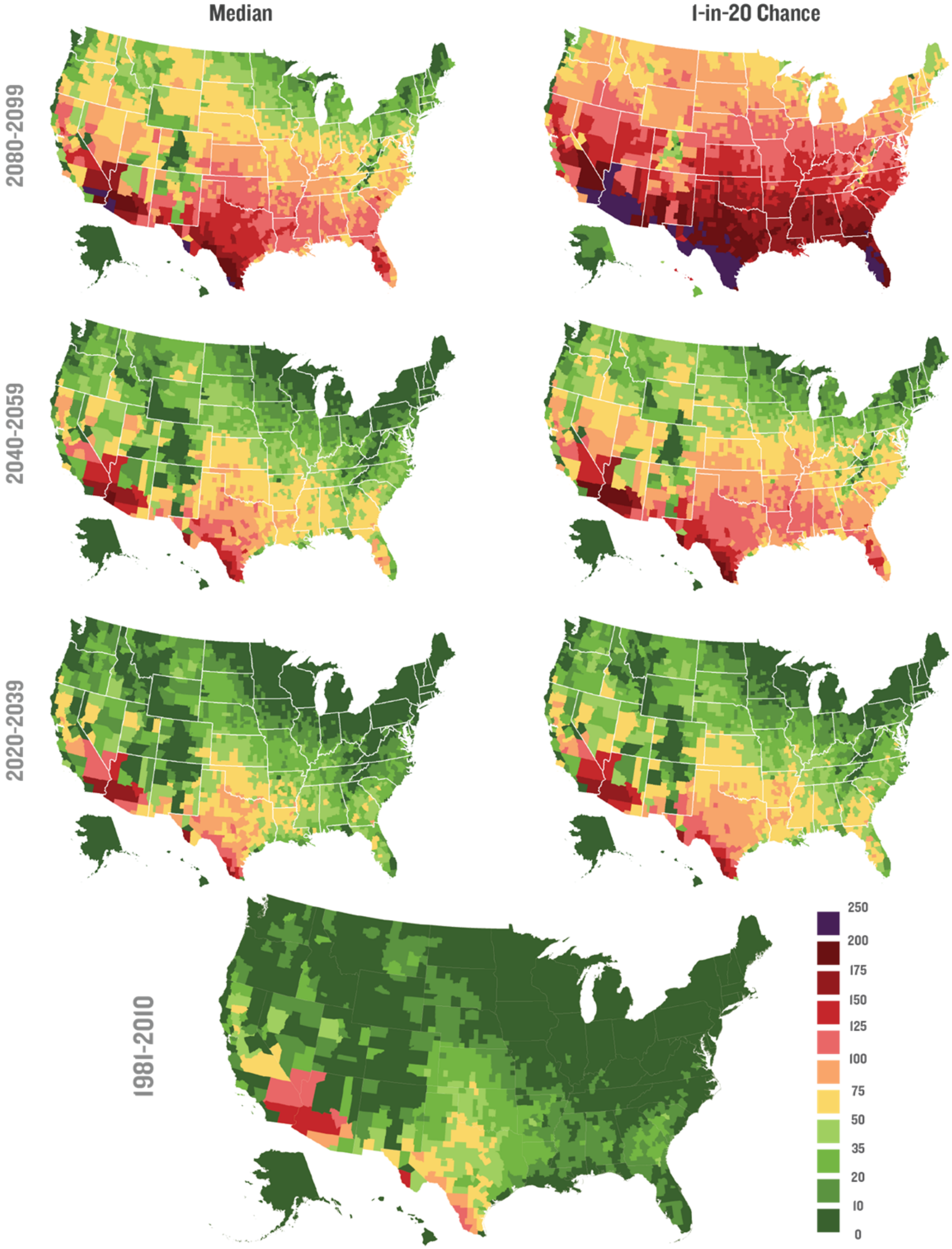


Figure 4.5: Change in average winter temperatures

Daily average winter (December, January, February) temperature (°F) under RCP 8.5

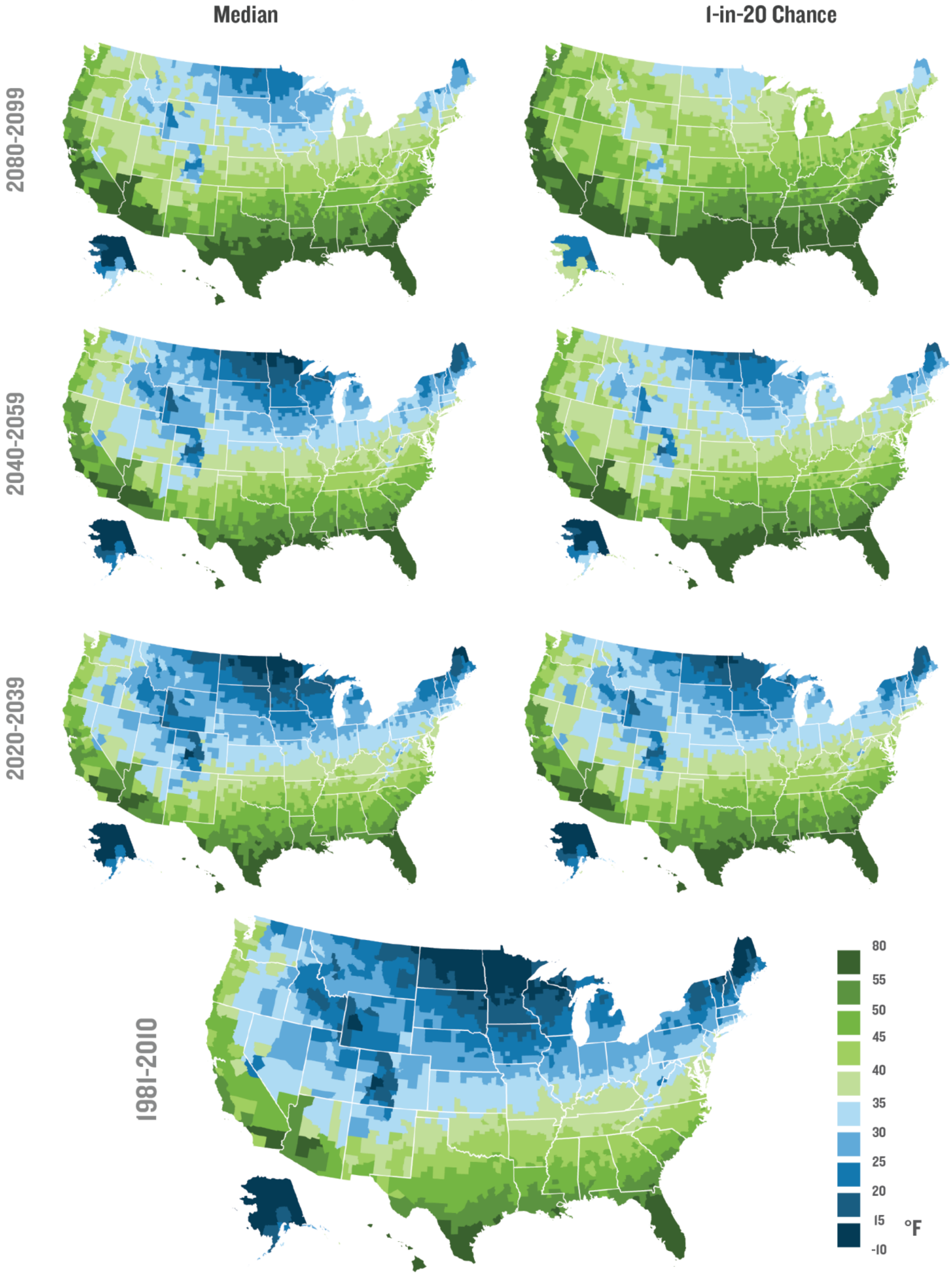
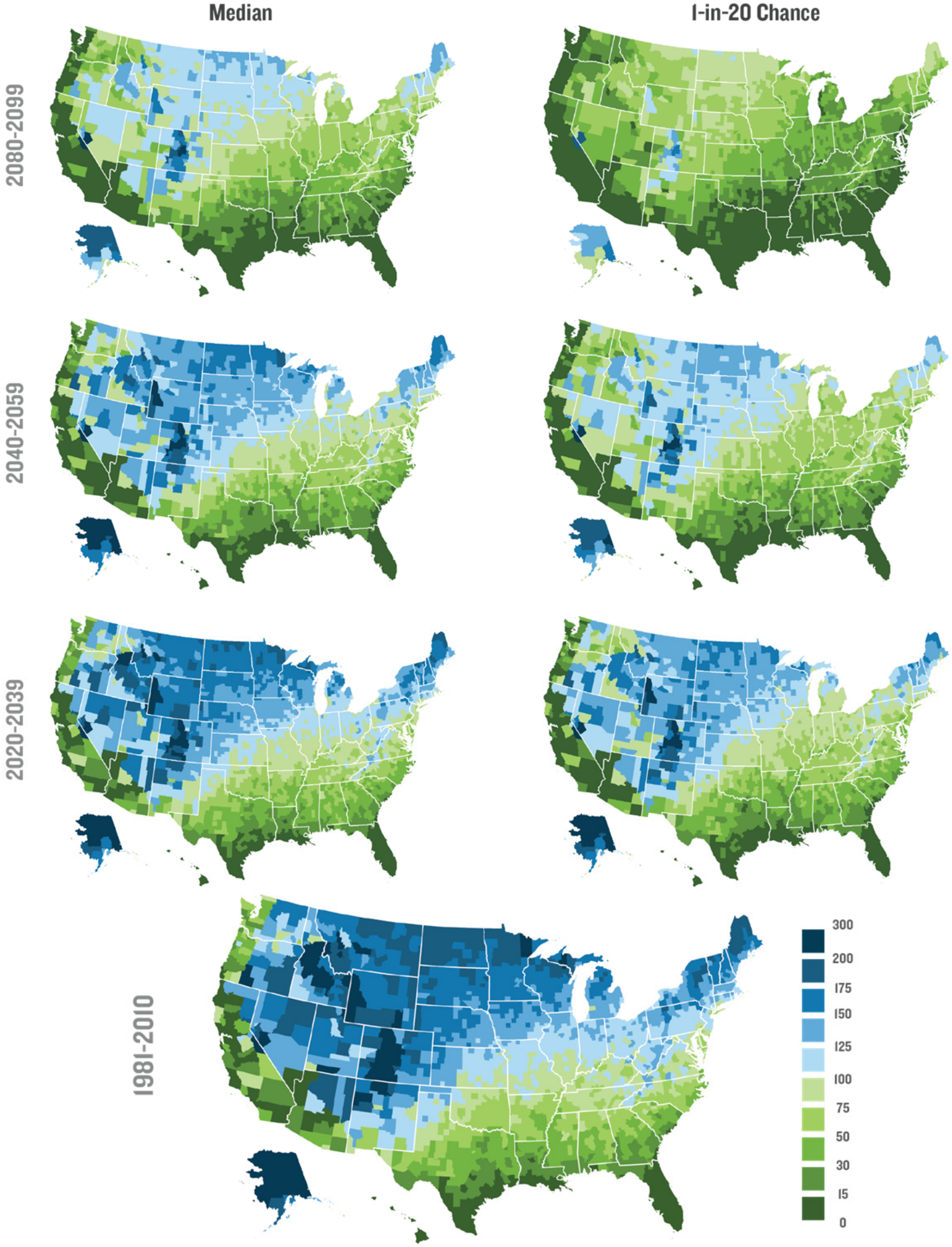


Figure 4.6: Change in number of extreme cold days

Number of days with minimum temperatures below 32°F, RCP 8.5



HUMIDITY

"It's not the heat; it's the humidity," the common saying goes. The combination of high temperatures with high humidity is significantly more uncomfortable, and potentially more dangerous, than high temperatures under drier conditions. Wet-bulb temperature is an important climatic and meteorological metric that reflects the combined effect of temperature and humidity (Buzan, 2013; Sherwood & Huber, 2010). Measured with a ventilated thermometer wrapped in a wet cloth, it reflects the ability of mammals to cool by sweating. In order for humans to maintain a stable body temperature around 98°F, skin temperature must be below 95°F, which for a well-ventilated individual at rest in the shade requires wet-bulb temperature of 95°F. Exposure to sunlight and exertion will increase body temperature. About an hour of vigorous, shaded activity at a wet-bulb temperature of 92°F leads to skin temperatures of 100°F and core body temperatures of 104°F (Liang et al., 2011; Nielsen, Strange, Christensen, Warberg, & Saltin, 1997). Higher core temperatures are associated with heat stroke, which can be fatal (Bouchama & Knochel, 2002).

Such high wet-bulb temperatures almost never occur on the planet today. The highest heat-humidity combinations in the US in the last thirty years occurred in the Midwest in July 1995, during the middle of that summer's heat wave. Wet-bulb temperatures then approached 90°F; one weather station in Appleton, Wisconsin recorded a temperature and dew point that correspond to a wet-bulb temperature of 92°F (Burt, 2011).

We developed the ACP Humid Heat Stroke Index, which divides daily peak wet-bulb temperature into four categories (Table 4.1). Category I reflects uncomfortable conditions typical of summer in much of the Southeast, while category II reflects dangerous conditions typical of the most humid days of summer in the Southeast, as far north as Chicago and Washington. Category III conditions are rare and extremely dangerous, occurring only a few times in the US between 1981-2010, including during the 1995 Midwest heat wave. The extraordinarily dangerous Category IV conditions exceed US historical experience.

Table 4.1 The ACP Humid Heat Stroke Index

ACP Humid Heat Stroke Index	Peak Wet-Bulb Temperature	Characteristics of the hottest part of day
I	74°F to 80°F	Uncomfortable. Typical of much of summer in the Southeast.
II	80°F to 86°F	Dangerous. Typical of the most humid parts of Texas and Louisiana in hottest summer month, and the most humid summer days in Washington and Chicago.
III	86°F to 92°F	Extremely dangerous. Comparable to Midwest during peak days of 1995 heat wave.
IV	>92°F	Extraordinarily dangerous. Exceeds all US historical records. Heat stroke likely for fit individuals undertaking less than one hour of moderate activity in the shade.

Projecting future increases in wet-bulb temperatures at the same resolution as the other analyses in this report is challenging. Indeed, assessing past wet-bulb temperatures precisely is tricky as well; differences between analytical methods and variations in humidity near weather stations can produce differences in historical estimates of up to about 4°F. Nonetheless, we can make some projections of future changes in wet-bulb temperature based upon the observed relationships between dry-bulb (conventional) temperature and wet-bulb temperature. Note that in the Midwest, humidity is enhanced by transpiration from crops (Changnon, Sandstrom, & Schaffer, 2003); changing agricultural practices and suitability, as well as the response of crops to higher CO_2 concentrations, may affect the likelihood of future extreme wet-bulb temperatures in this region in a way which we cannot account for in our projections.

Currently, the area expected to experience more than a month of dangerous Category II+ conditions in a typical year is confined to coastal Texas and Louisiana. Under RCP 8.5, by mid-century, it will expand to cover most of the Southeast up to Washington, DC, and much of the Midwest as far north as Chicago (Figure 4.7). A day or more of extremely dangerous Category III conditions is expected in a typical summer in counties currently

Figure 4.7: Change in wet-bulb temperatures

Expected number of Category II+ and Category III+ ACP Humid Heat Stroke Index days in a typical summer, RCP 8.5

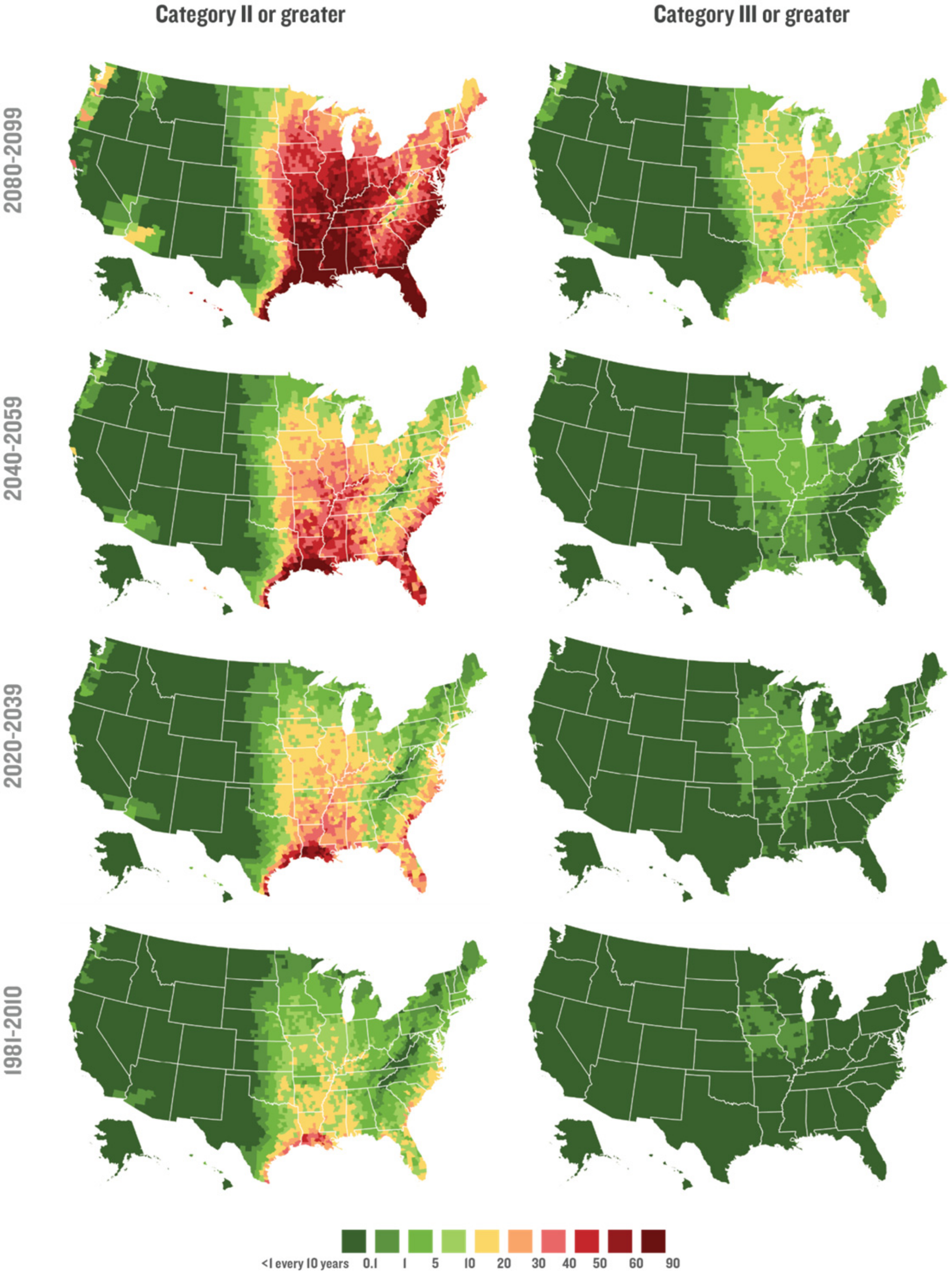
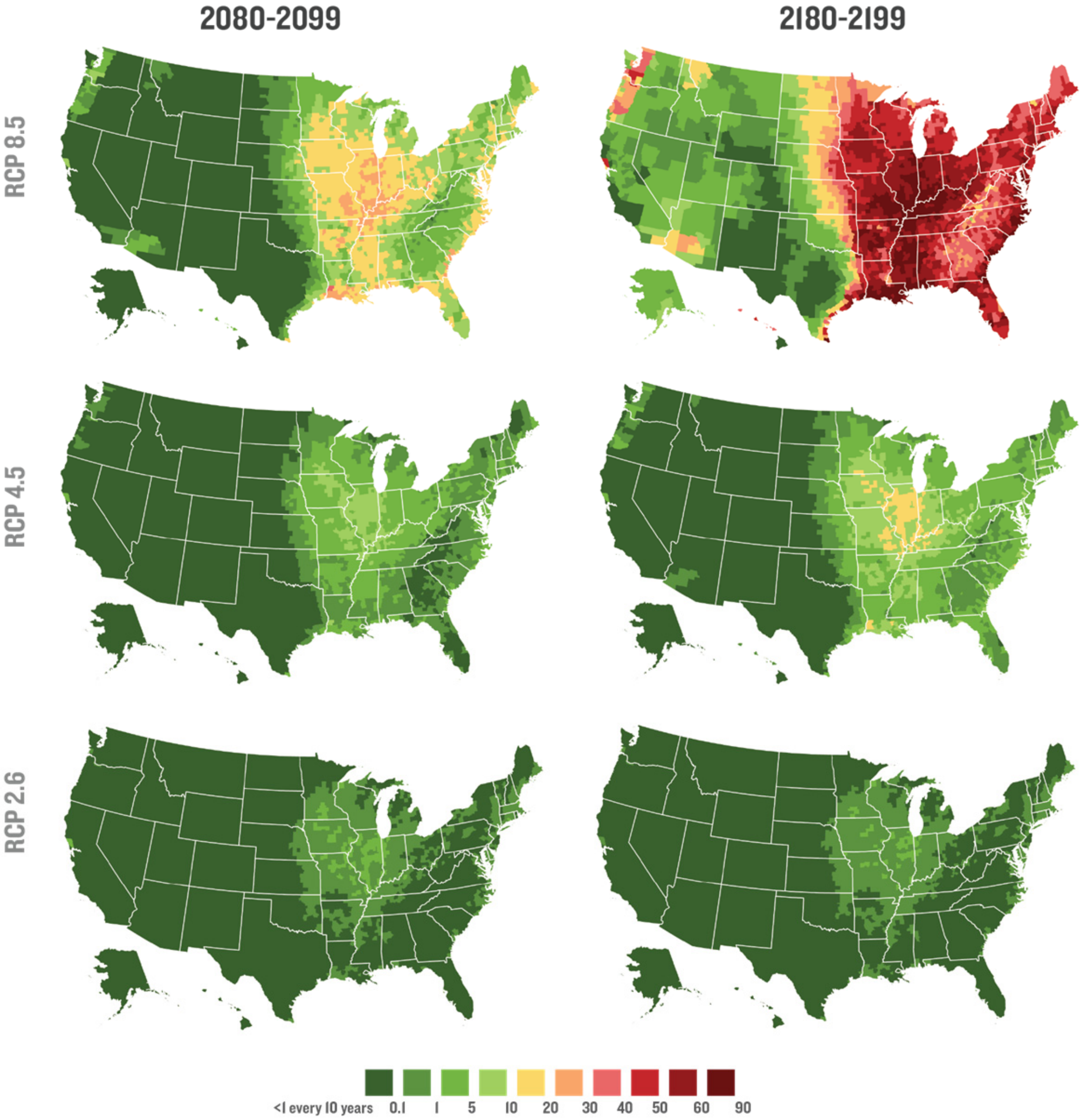


Figure 4.8: Increasing wet-bulb temperatures under different long-term emissions pathways

Expected number of Category III+ ACP Humid Heat Stroke Index days in a typical summer



home to a quarter of the US population. By the end of the century, dangerous Category II+ conditions are expected to characterize most of a typical summer in most of the eastern half of the country. A week or more of extremely dangerous Category III+ conditions are expected in counties currently home to half the US population, with a third of the population expected to experience a day or more of record-breaking, extraordinarily dangerous Category IV conditions in a typical year.

While projections for mid-century are similar across emissions scenarios, projections for the end of the century diverge significantly (Figure 4.8). Under RCP 4.5, only a third of the population would be expected to experience at least one extremely dangerous Category

Figure 4.9: Changing summer heat and humidity by state

Median summer temperature (F) and Category II+ ACP Humid Heat Stroke Index days per summer, 2080-2099

III+ day in a typical year; under RCP 2.6, only 1-in-25 Americans would thus be exposed. The expected number of extraordinarily dangerous Category IV days drops dramatically relative to RCP 8.5 under lower emission scenarios. Under RCP 4.5, only one-eighth of the population is expected to have at least a 1-in-10 chance of experiencing a Category IV day in a typical year. Under RCP 2.6, Category IV days remain rare for the entire population, with 97% of Americans having less than a 1% chance of experiencing such a day in a typical year.

Climate change does not stop in 2100, and under RCP 8.5 increasing numbers of Category III and IV days could transform the face of the eastern half of the country in the 22nd century. By the end of the next century, extremely dangerous Category III+ days are expected to characterize most of the summer in most of the eastern US, with extraordinarily dangerous Category IV days expected for about a month of a typical year. RCP 4.5 limits the expected number of Category III+ days to less than two weeks and the number of Category IV days to less than half a week for almost the entire country. Under RCP 2.6, conditions at the end of the next century resemble those at the end of this one.

The combination of projected summer temperatures and projected ACP Humid Heat Stroke Index days provides a sense of how the experience of future summers will change. By 2020-2039, for example, median projected average summer temperatures in Washington, DC match, and the expected number of hot, humid Category II+ days experienced by Washingtonians exceed, those in Mississippi today. By mid-century, median projected summer temperatures in Missouri under RCP 8.5 approach those in Florida today, while the expected number of hot, humid Category II+ days experienced by the average Missourian exceeds those of Louisiana today. By the end of the century under RCP 8.5, the Northeastern, Southeastern and Midwestern states south of the Mason-Dixon line have higher median projected summer temperatures than Louisiana today, and the residents of almost the entirety of those three regions – including the states north of the Mason-Dixon line – have more expected hot, humid Category II+ days than does Louisiana today (Figure 4.9).

While air conditioning can allow humans to cope with extreme wet bulb temperatures, habitability in the face of sustained extreme wet-bulb temperatures would require fail-safe technology and time-shifting of outdoor work to cooler (but likely still extremely unpleasant) parts of the day. Other species may not be as fortunate.

PRECIPITATION

Precipitation changes are more challenging to predict than temperature changes. Higher atmospheric temperatures will in general increase the absolute humidity of the atmosphere, making extreme precipitation events more likely. Higher temperatures will also increase evaporation, however, making extreme drought more likely. In general, wetter areas are expected to get wetter and drier areas drier, but much will depend upon changes in atmospheric circulation patterns, which could shift the dry subtropics poleward. High latitudes and wet mid-latitude regions are *likely* to experience an increase in annual mean precipitation by the end of this century under RCP 8.5, while many mid-latitude and subtropical dry regions will *likely* see decreases. Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will *very likely* become more intense and more frequent by the end of this century, as global mean surface temperature increases (Collins et al., 2013).

Across the contiguous US, average annual precipitation will *likely* increase over the course of the 21st century. The spatial distribution of median projected changes in seasonal precipitation under RCP 8.5 are shown in Figure 4.10. The Northeast, Midwest, and Upper Great Plains are *likely* to experience more winter precipitation. Wetter springs are *very likely* in the Northeast, Midwest, and Upper Great Plains, and *likely* in the Northwest and Southeast. An increase in fall precipitation is *likely* in the Northeast, Midwest, Upper Great Plains, and Southeast. The Southwest is *likely* to experience drier springs, while drier summers are *likely* in the Great Plains and the Northwest.

DROUGHT

Drought has multiple definitions. Meteorological droughts are defined by abnormally low precipitation, agricultural drought by abnormally low soil moisture, and hydrological drought by reductions in water supply through groundwater, reservoirs, or streams (Heim, 2002). Projected decreases in precipitation in some regions and seasons -- for example, the *likely* springtime decrease in the Southwest, and the *likely* summer decrease in the Great Plains and Northwest – make meteorological drought increasingly likely over the course of the century.

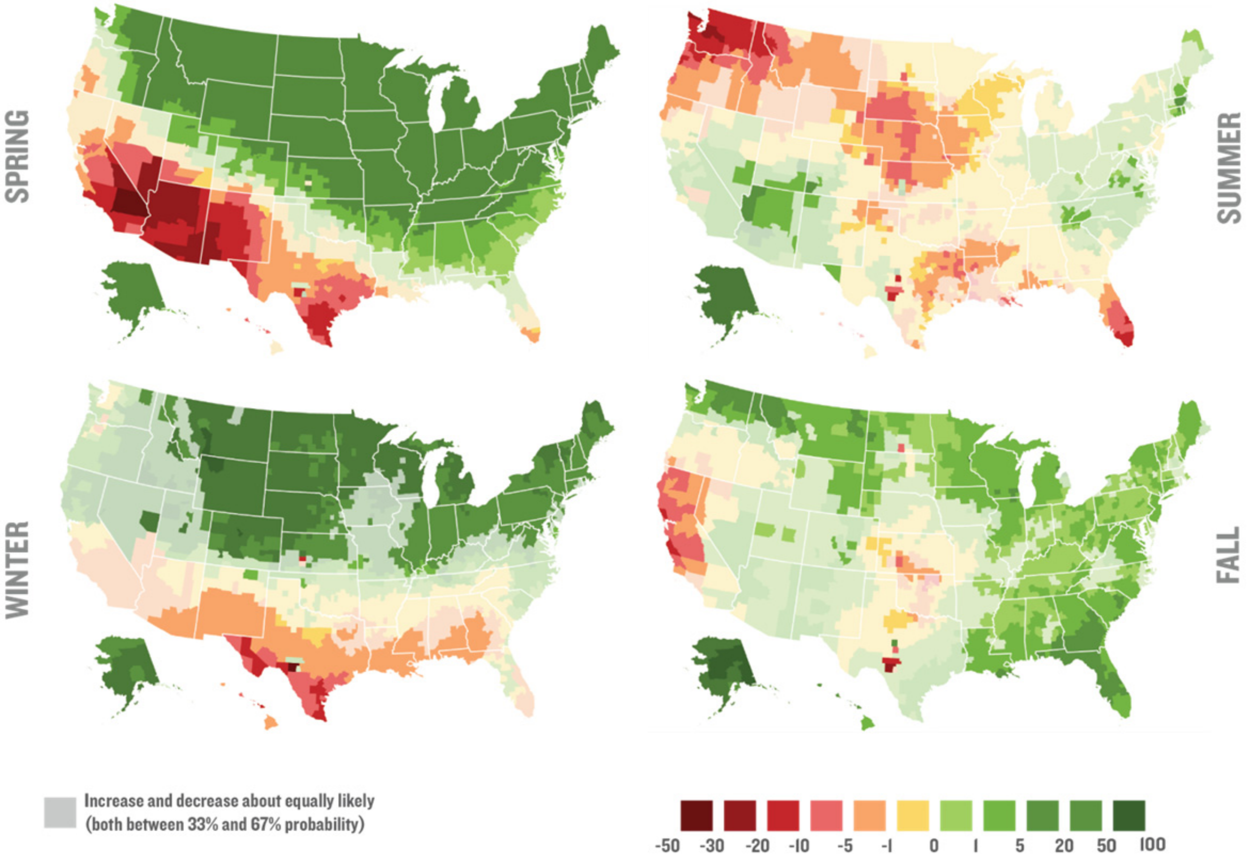
Projecting agricultural droughts is more challenging than simply projecting precipitation. Soil moisture is also affected by temperature -- which increases evaporation -- and from transpiration by plants, which may decrease in response to carbon fertilization (conserving soil moisture). Global climate models can explicitly model changes in soil moisture; of the models participating in CMIP5 and reporting soil moisture, more than 90% projected a decrease in annual mean soil moisture in the Southwest by late century in RCPs 4.5, 6.0 and 8.5. More than 90% also projected a decrease in soil moisture in the Northwest and Great Plains under RCP 8.5 (Collins et al., 2013). In the western half of the country as a whole, averaging model results together, drought extent by area in a typical year, defined as soil moisture below the 20th percentile, is projected to increase from about 25% to about 40% (Wuebbles et al., 2013). Summer droughts are projected to become more intense in most of the continental US due to longer dry periods, and more extreme heat that increases moisture loss from plants and soils (Georgakakos et al., 2014; Walsh et al., 2014).

Our agricultural projections (Chapter 6), which incorporate historical relationships between temperature, precipitation, and crop yield, as well as future responses to changing carbon dioxide concentrations, implicitly estimate agricultural droughts. The 2012 drought provides a benchmark for

Figure 4.10: Changing precipitation

Percentage change in average seasonal precipitation in 2080-2099 under RCP 8.5, relative to 1981-2010

Median values; in faded areas, an increase and decrease are about equally likely to occur (both between 33% and 67% probability)



assessment. That year saw drops in corn yield of 13% nationally, 16% in Nebraska, 20% in Iowa, and 34% in Illinois (US Department of Agriculture, 2013). The Department of Agriculture dubbed the drought the nation's "worst agricultural calamity since 1988." Chapter 6 projects a 1-in-3 chance that, nationwide, grain yields will decrease by more than 33% under RCP 8.5 by late century, with drops in production concentrated in the generally unirrigated eastern half of the country -- an indicator of the need to adapt to recurring agricultural shocks of the scale of the 2012 drought.

Hydrological droughts are even more challenging to project, as this involves tracing changes in precipitation and evaporation through to runoff and streamflow, and ultimately to implications for surface and groundwater supply. With continued high emissions of greenhouse gases, surface and groundwater supplies in the Southwest and parts of the Southeast and Southern Rockies are expected to be affected by runoff reductions and declines in groundwater recharge, increasing the risk of water shortages (Georgakakos et al., 2014; Seager et al., 2013). See Chapter 17 for more on changes in water resources.

SEA-LEVEL CHANGE

Sea-level change is an important physical consequence of global warming, one which will increase flood risk along American coastlines several fold over the course of the century (Kopp et al., 2014). At a global level, sea-level rise is driven primarily by thermal expansion (the increase in the volume of the ocean that occurs as it absorbs heat) and land ice melt, with an additional contribution from groundwater withdrawal that over the 20th century has been largely counterbalanced by dam construction. Both thermal expansion and land ice melt are expected to increase significantly over the course of the 21st century; indeed, observations indicate an ongoing acceleration of ice sheet melt in both Antarctica and Greenland (Church et al., 2013; Shepherd et al., 2012). However, there is considerable uncertainty regarding the future behavior of the ice sheets. This is particularly true for the West Antarctic Ice Sheet, much of which sits below sea level and may therefore be vulnerable to positive feedbacks that could lead to more than of three feet of global mean sea level rise over the century from this one source alone.

Under RCP 8.5, global mean sea level will *likely* rise by about 0.8 to 1.1 feet between 2000 and 2050, and by 2.0 to 3.3 feet between 2000 and 2100 (Figure 4.11) (Kopp et al., 2014). There is a 1-in-200 chance sea level could rise by 5.8 feet, and in a "worst-case" projection reflecting the maximum physically plausible sea level rise, global mean sea level could rise by as much as eight feet. It is important to note that the estimates of tail probabilities involve a particular set of assumptions about likely ice sheet behavior; feedbacks could render these extreme outcomes more likely than we project.

The uncertainty in ice sheet physics plays a larger role in sea-level projections than scenario uncertainty, but lower greenhouse gas emissions will lower projected sea-level rise, particularly in the second half of the century. Under RCP 2.6, global mean sea level will *likely* rise by about 0.7 to 0.9 feet by 2050 and by 1.2 to 2.1 feet by 2100. Under RCP 2.6, there is a 1-in-200 chance of a sea-level rise 4.6 feet, and the worst-case projection is reduced to seven feet.

Sea-level rise will not occur evenly across all regions of the globe. Understanding what global mean sea level rise will mean for US coasts requires consideration of several specific local factors (Kopp et al., 2014). First, ocean dynamics and the uneven distribution of ocean heat and salinity can cause unevenness in the height of the sea surface. The height of the sea surface off the coast of New York is about two feet lower than off the coast of Bermuda, for example (Yin & Goddard, 2013). Climate change can affect these factors, with some models suggesting that changes in them could cause more than a foot of sea-level rise off New York during the 21st century (Yin, Schlesinger, & Stouffer, 2009). Second, redistributing mass – including land ice mass – on the surface of the Earth affects the Earth's gravitational field, its rotation, and the way the Earth's crust bends underneath loads (Mitrovica et al., 2011). Due to changes in the Earth's gravitational field, sea level actually falls near a melting ice sheet: if the Greenland ice sheet melts, sea level will fall in Scotland, and the northeastern US will experience less than half the associated rise in global mean sea level. Third, in tectonically active regions such as the western United States, sea-level change can occur as a result of uplift or subsidence of the land driven by plate tectonics. Finally, in regions such as the mid-Atlantic and southeastern US coastal plain that rest on sand and other sediments rather than bedrock, regional sea-level rise can be driven by the compaction of these sediment. Such compaction can occur naturally, due to the weight of additional sediment deposited on the coastal plain, or artificially, due to the withdrawal of water or hydrocarbons from the sediments (Miller, Kopp, Horton, Browning, & Kemp, 2013).

As discussed in greater detail in the coastal impacts, sea-level change will vary around the country (Figure 4.12). Both the Atlantic and Pacific coasts of the continental US will experience greater-than-global sea-level rise in response to West Antarctic melt. The highest rates of projected sea-level rise occur in the western Gulf of Mexico, due to the effects of hydrocarbon withdrawal, groundwater withdrawal and sediment compaction. In the mid-Atlantic region, sea-level rise is heightened by the ongoing response to the end of the last ice age, potential changes in ocean dynamics, and – on the coastal plain sediments of the Jersey Shore and Delaware, Maryland and Virginia – groundwater withdrawal and sediment compaction. In Alaska and, to a lesser extent, in the Pacific Northwest, sea-level rise is reduced by the changes in the Earth's gravitational field associated with melting Alaskan glaciers. In Hawaii, far from all glaciers and ice sheets, sea-level rise associated with melting land ice will be greater than the global average.

EXTREME EVENTS

Projecting changes in the future occurrence of storms across the US is subject to much greater uncertainties than temperature or sea level rise. Relatively little is known about the influence of climate on the frequency and severity of winter storms and convective storms like tornados and severe thunderstorms. Since 1950, there has been no significant change in winter storm frequency and intensity across the US, though the northeast and northwest coasts have experienced an increase in winter storm activity in the period since 1979 (Vose, Applequist, Menne, Williams, & Thorne, 2012). The focus of most study to date has been on understanding the relationship between changes in climate and Atlantic hurricane activity including changes in frequency, intensity, and duration – and is an area that is only just beginning to be understood.

Figure 4.11: Global mean sea level rise

Feet

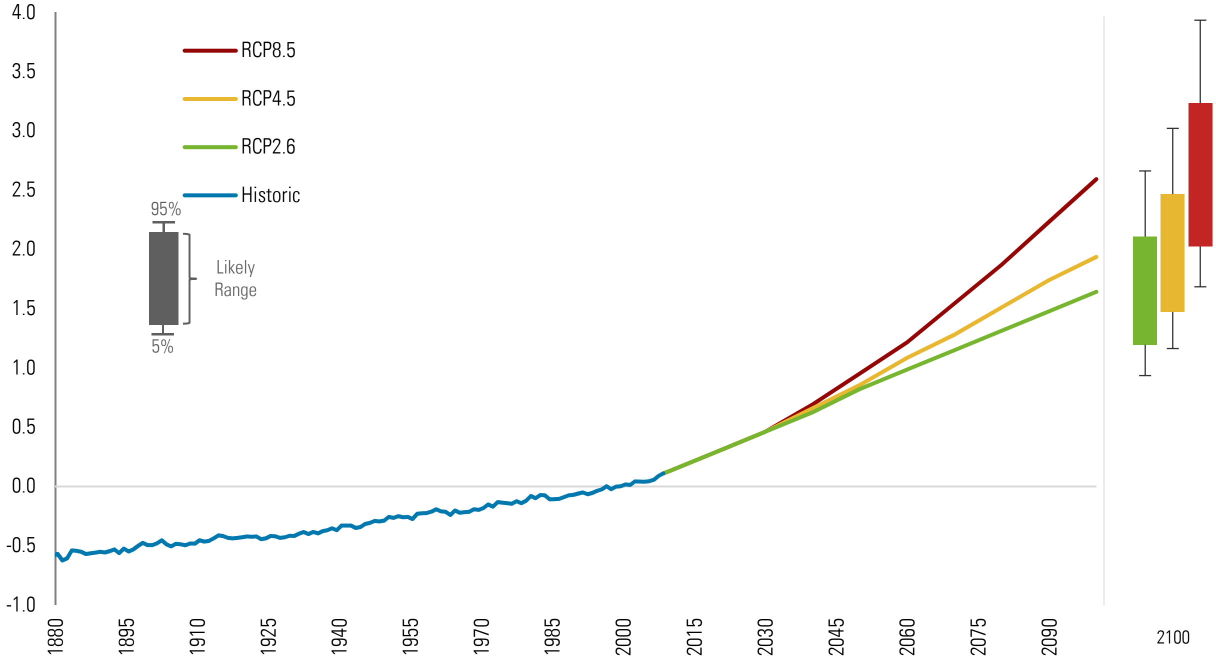
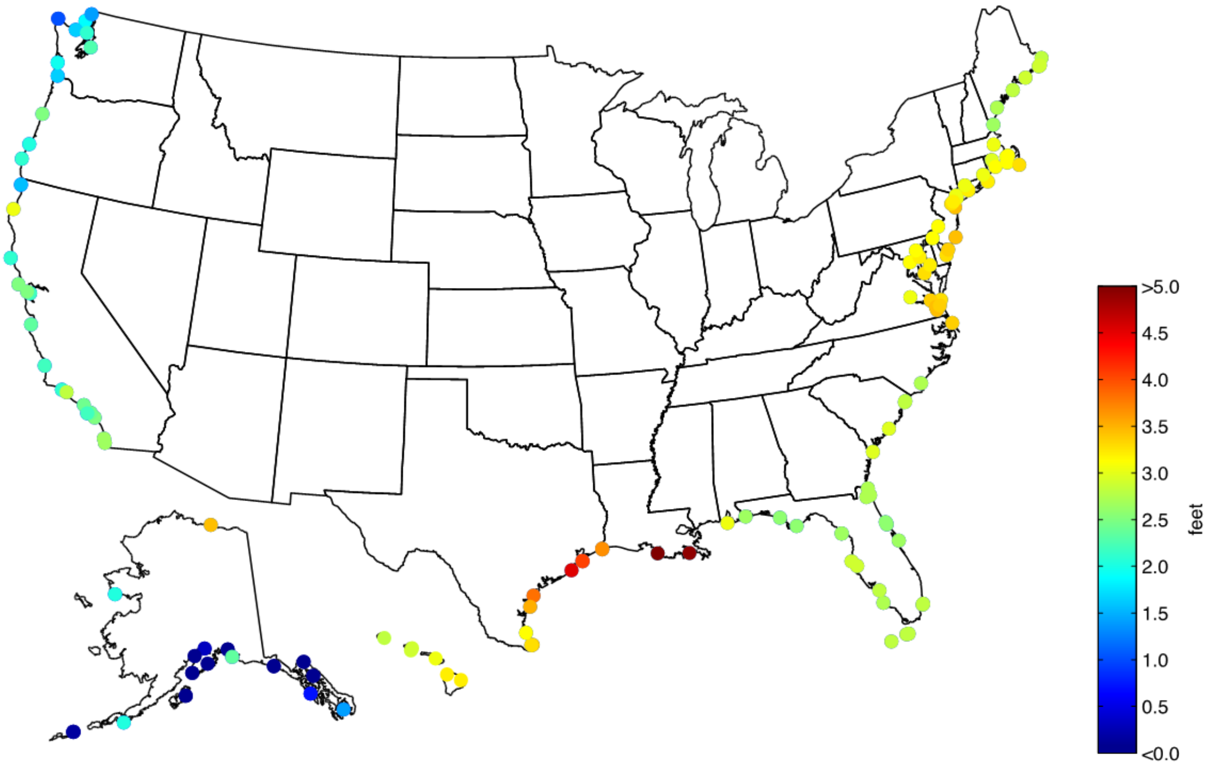


Figure 4.12: Local sea level rise in 2100

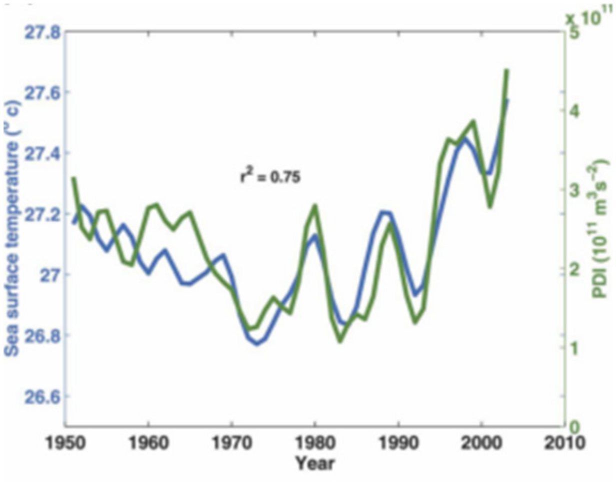
Median projected change (feet) from 2000 levels under RCP 8.5, after Kopp et al. (2014)



Observational data show a marked increase in hurricane activity in the Atlantic since the 1970s. As illustrated in Figure 4.13 below, there is a robust correlation between increases in hurricane activity, as measured by the Power Dissipation Index (PDI), and rising sea surface temperatures over that time (Emanuel, 2007). The statistical correlation suggests the possibility of an anthropogenic influence on Atlantic hurricanes over the past few decades; however, numerous factors influence local sea surface temperatures and hurricanes respond to more than just sea surface temperature. It remains difficult to attribute past changes in Atlantic hurricane activity to anthropogenic factors with any certainty. Although data going back to 1880 indicate a pronounced upward trend the number of tropical storms in the Atlantic, much of this increase may be due to improved monitoring, making it difficult to determine long-term trends (Vecchi and Knutson 2011; Villarini et al. 2011; Vecchi and Knutson 2008).

Figure 4.13: North Atlantic hurricane activity trends

Hurricane activity index (green) and sea surface temperature (blue)



Source: Emanuel 2007. Power dissipation index (PDI), shown in green, is an aggregate measure of Atlantic hurricane activity, combining frequency, intensity, and duration of hurricanes in a single index. Scaled Hadley Centre sea surface temperature (in blue) for the main cyclone development regions of the Atlantic.

Sea surface temperatures in the North Atlantic basin are expected to continue to rise over the next century, along with changes in wind shear and other climate variables that influence hurricane formation (Vecchi and Soden 2007). Incorporating the best understanding of the complex interaction among these factors, several studies project further increases in the frequency and intensity of the strongest Atlantic hurricanes (Emanuel, 2013; Knutson et al., 2013). One study, based on the RCP 4.5 pathway, found that although anthropogenic warming in the Atlantic basin over the 21st century will lead to a moderate reduction in tropical storms and hurricanes overall (of approximately 20%), the frequency of very intense hurricanes (categories 4 and 5) and the overall intensity of Atlantic hurricanes across the basin will *likely* increase (Knutson et al., 2013). While very intense hurricanes are relatively rare (accounting for only 15% of cyclones that make landfall in the US), the damage they inflict on coastal communities is considerable, contributing over half of historical US hurricane damage over the past century (Pielke et al., 2008). According to Knutson et al. (2013), tropical storms and hurricanes are also expected to have higher rainfall rates under future warming, with increases by late century of approximately 10% and even larger increases (approximately 20 to 30%) near the hurricane's core.

Given the large uncertainties in changes in hurricanes over the course of the 21st century, we do not assume any changes in storm distribution in our base case. We run two side cases, one using the six climate models downscaled for RCP 8.5 by Emanuel (2013), the other using the ensemble mean of the models downscaled for RCP 4.5 by Knutson et al. (2013).

Regardless of changes in storm activity, expected sea-level rise under all future concentration pathways will enhance flooding in coastal communities when storms do strike (Strauss, Ziemlinski, Weiss, & Overpeck, 2012). In the coming decades, even small changes in sea level may still impact low-lying coastal areas as they push water levels associated with past storm surge to progressively new levels. This will change the risk assessment of extreme storm events for the majority of US coastal areas as they see a substantially higher frequency of previously rare storm-driven water heights, pushing once-in-a-century level coastal floods (which currently have a 1% chance of happening in any given year) to once-in-a-decade levels (a 10% chance in any given year) in many areas by mid-century (Tebaldi, Strauss, & Zervas, 2012).

Part II

Assessing the Impact of America’s Changing Climate

CHAPTER 5

An Evidence-Based Approach

How do we assess the impact of the potential changes in temperature, precipitation, sea-level, and storm patterns described in the previous chapter on our homes, businesses, and communities? Anticipating climate impacts is in many ways even more analytically challenging than projecting climatic changes, as human systems are not constrained by laws as rigid as those of physics and chemistry that shape the natural world. Yet, by piecing together evidence from the distant and not-so-distant past, including what we have experienced in our own lifetimes, we can begin to identify common patterns in how populations respond to climatic conditions, and then use this information to assess the impact of climate change, both positive and negative, in the US in the years ahead.

PALEOCLIMATIC EVIDENCE

Hints of the physical effects of climate change and suggestions of their possible impact on humans and ecosystems can be found buried deep in the geological record. As discussed in Chapter 3, the greenhouse gas concentrations and temperatures projected for the 21st century have never before been experienced by human civilization, but they have occurred in our planet's past.

The last time global mean temperature was warmer than today was during the Last Interglacial stage, some 125 thousand years ago. Temperatures during that period may have been as much as 2.5°F warmer than at present (Turney and Jones 2010), comparable to levels expected by mid-century under all scenarios. The geological record shows that global mean sea-level during this interval was 20 to 30 feet higher than today (Dutton and Lambeck 2012; Kopp et al. 2009) – a magnitude of change that will not be realized in this century, but could occur over the coming centuries in response to warming. Such dramatic sea-level rise would swamp nearly all of Miami, Norfolk, New Orleans, Savannah, and Charleston.

The rate at which we are putting greenhouse gases into the atmosphere has no known precedent in the geological record before at least 56 million years ago. At that distant time, within a period that may have been as short as decade or as long as a few millennia, the Paleocene-Eocene Thermal Maximum (PETM) began with a massive release of carbon dioxide and methane that caused global mean temperatures to rise by 9 to 14°F, on top of a baseline already several degrees warmer than today (Wright and Schaller 2013; Zachos, Dickens, and Zeebe 2008; McInerney and Wing 2011). While there were no humans around to experience it, other animals did. The warming – comparable to that possible in the 22nd century under RCP 8.5 – lasted tens of thousands of years and led to dramatic ecological shifts, including the dwarfing of land mammals as a result of heat stress (Gingerich 2006; Sherwood and Huber 2010).

In more recent millennia, human populations have been subject to long-term climatic shifts lasting decades to centuries. By linking paleoclimatic reconstructions to archeological data, researchers have amassed a growing body of evidence that these historical shifts are systematically related to the migration, destabilization, or collapse of these pre-modern societies (Hsiang, Burke, and Miguel 2013). For example, abrupt drying or cooling events have been linked to the collapse of populations in ancient Mesopotamia, Saharan Africa, Norway, Peru, Iceland, and the United States (Ortloff and Kolata 1993; Cullen et al. 2000; Kuper and Kröpelin 2006; Patterson et al. 2010; D'Anjou et al. 2012; Kelly et al. 2013). The iconic collapse of the Mayan civilization has been linked to extreme droughts superimposed on sustained multi-century regional drying (Haug et al. 2003; Kennett et al. 2012), the fifteenth century collapse of the Angkor city-state in modern day Cambodia occurred during sustained megadroughts (Buckley et al. 2010) and the collapse of almost all Chinese dynasties coincided with periods of sustained regional drying (Zhang et al. 2006; Yancheva et al. 2007).

Economic development and technological advances (like air conditioning) have, of course, made humans of today more resilient to climatic changes than humans in the past, so we do not think it is appropriate to use paleoclimatic evidence in contemporary climate risk assessment. These historical examples demonstrate how ecologically and economically disruptive climatic change has been in the past, even though we have archeological evidence that these past societies attempted to adapt to the climatic changes they faced using innovative technologies. Thus these anecdotes, if nothing else, motivate us to carefully consider low-probability but high-cost outcomes.

EMPIRICAL ESTIMATES

Another strategy for understanding climate's potential impact on human and natural systems – what we'll call the empirical approach – is based on evidence of actual impacts and damages experienced in the not-so-distant past. Although this approach also uses the historic record to assess future risks, rather than rely on "proxy" data buried in the geological record, it draws on data recorded and analyzed during modern times. There has been an explosion of econometric research in recent years examining the relationship between temperature and precipitation, and current human and economic activity. When combined with the high-resolution output from global climate models, this research enables a granular assessment of the risks particular regions of the country or sectors of the economy face in the years ahead. The SEAGLAS approach employs these empirical findings for impact categories with a sufficiently robust body of econometric research. This includes:

1. **Agriculture:** The impact of projected changes in temperature and precipitation on maize, wheat, soy and cotton yields;
2. **Labor:** The change in number of hours employees in high-risk (construction, utilities, mining, and other) and low risk (indoor services) sectors of the economy work in response to projected temperature change;
3. **Health:** Changes in all-cause mortality for different age groups resulting from projected changes in temperature;
4. **Crime:** The sensitivity of violent and property crime rates to projected temperature and precipitation; and
5. **Energy:** The impact of temperature change on US electricity demand.

When trying to use data from the real world to understand the influence of climate on society, the key challenge is separating the influence of the climate from other factors. For example, if we tried to study the effect of warmth on mortality by comparing a warm location like Florida to cooler location like Minnesota, it might look like Florida had a higher mortality rate due to climate alone, but there are many other factors that make Florida different from Minnesota—such as the fact that the population of Florida tends to be older on average.

To get at these questions more reliably, we could imagine an ideal (but impossible) scientific experiment where we take two populations that are identical and assign one to be a "treatment" group that is exposed to climate change and one a "control" group that is exposed to a pre-industrial climate. If we then observed how outcomes, such as mortality or productivity, changed between these two groups, we could be confident that the change in the climate caused the change in these outcomes.

Because we cannot do this ideal experiment, econometricians have looked for situations where natural conditions approximate this experiment, i.e., "natural experiments". In these situations, individuals or populations that are extremely similar to one another are assigned to slightly different climates due to random circumstances, and we observe how those small changes in climate are then reflected in economically important outcomes. To ensure that "control" and "treatment" populations are extremely similar to one another, the strongest studies compare a single population to itself at different moments in time when it is exposed to different climatic conditions. In this way, we know that most or all other important factors, such as local geography, politics, demographics etc. are the same and that changes we observe are driven by the observed random changes in the climate. This approach allows researchers to construct "dose-response functions" (a term adopted from medicine) which describes a mathematical relationship between the "dose" of a climate variable that a population experiences and the corresponding "response" that they exhibit in terms of economic outcomes.

In developing empirically-based dose-response functions, we rely only on studies that account for temporal patterns that are often important factors in the outcomes we observe and might be correlated with small changes in the climate. For example, there is seasonality in crime rates and mortality, and these seasonal patterns may differ by locality, so it is critical that seasonality is accounted for because it will also be correlated with climatic conditions. Thus, the studies we rely on only compare how an outcome for a specific location, at a specific time of year, compares to that same outcome at that same location and time under slightly different climatic conditions. For example, a study might examine the number of minutes an average individual works on a Tuesday in May in Rockland County on a day that is 80°F compared to a day that is 70°F.

The climate of a location is neither the conditions on a specific day nor the average conditions throughout the year, but rather the distribution of conditions throughout the year. Two locations might have the same annual average temperature, but while one location may have very little daily or seasonal variation around that temperature (e.g., San Francisco), the other location may have tremendous daily and seasonal variation (e.g., New York). Therefore, we rely primarily on studies that measure responses to a complete distribution of daily temperature and rainfall measures. By decomposing outcomes as a response to the full distribution of daily temperatures that are experienced, we can more accurately characterize how populations will respond to changes in those distributions. For example, in the future some locations might see higher rainfall variance (more intense storms and more dry periods) but little shift in their average conditions.

Some critics suggest that considering the distribution of daily conditions conflates "weather" or "climate variability" with "climate." Often, these critics argue in favor of more simplistic approaches where outcomes are simply correlated with average conditions, but this alternative ignores the fact that individuals experience their local climate one day at a time, making decisions about their actions based on these daily events that they experience. Few individuals make choices about their daily activities based on what they expect annual mean temperature to be for the coming year, and in fact most individuals do not even know the average climatic conditions of the location they live in. Often individuals will adapt to their local climate based on what they perceive the distribution of daily conditions to be; for example, Chicagoans buy winter coats because they expect some days in the winter to be cold. It is therefore essential that we consider daily distributions to model these adaptive decisions. While it is true that Chicagoans may have less need of their coats if average Chicago temperatures increase, it is unlikely that winter coats will be discarded entirely so long as there is a reasonable likelihood that some days in a year will be below freezing. Thus, information on the distribution of daily outcomes is more informative for adaptive behavior than averages.

For additional reasons, understanding responses to daily climatic conditions is a particularly powerful approach for economic policy analysis. First, it enables us to carefully identify nonlinear responses that have proven to be critical in these sorts of analyses. In many cases, such as agricultural yields, variations in temperature or rainfall do not have a substantial effect on outcomes until sufficiently extreme conditions are reached, at which point outcomes may respond dramatically. Disentangling these nonlinearities is essential to our analysis, since many of the important changes in the climate will occur at these extremes.

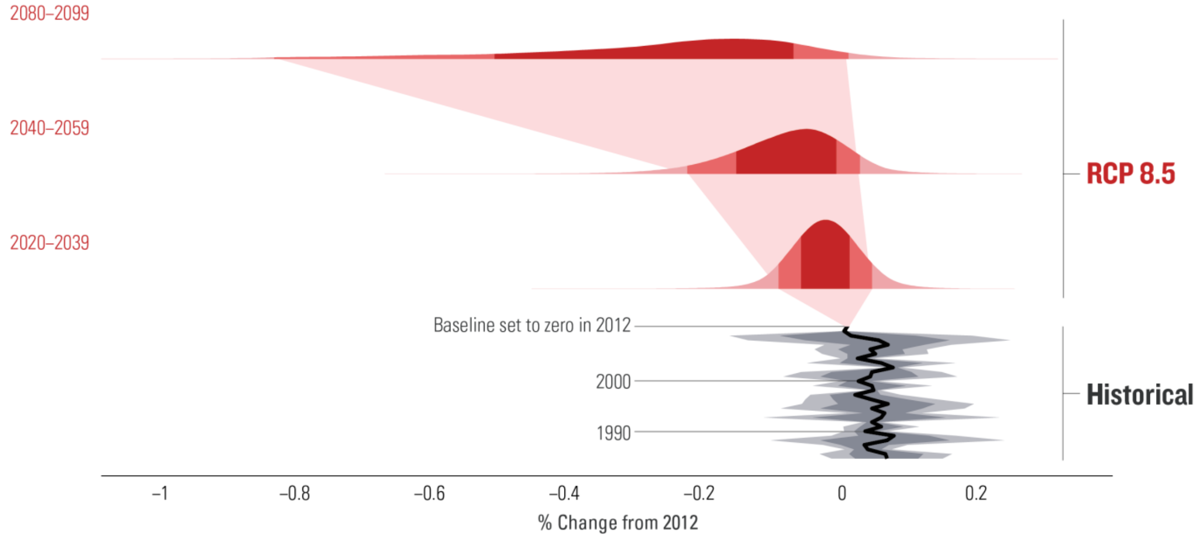
Second, by examining how different populations respond to the same daily conditions, we can begin to understand how populations adapt to climatic conditions in the long run. We often are able to recover how outcomes respond to hot days in regions that are usually hot and in regions that are usually cool. Because populations in hot regions may have adapted to their climate, for example, through infrastructure investments or behavior changes, we will be able to observe the effectiveness of this adaptation by comparing how the two populations respond to physically identical events, e.g. a 90°F day. In some cases, we are even able to study how populations at a single location change their response to the climate over time—allowing us to observe how outcomes might change (or fail to change) as new technology is developed and adopted (or not).

Finally, by identifying the effect of specific daily events on outcomes, we are able to naturally link empirically-derived responses to climate models that simulate future environmental conditions on a daily basis. Because we are able to compute the daily average, minimum, and maximum temperature, as well as rainfall, at each location throughout the country on a daily basis for each run of a suite of climate models, it is straightforward to estimate how outcomes at each location will be expected to respond to any of these future scenarios.

For each scenario that we model using empirical dose-response functions, we project changes in future outcomes relative to a future in which climate conditions are unchanged relative to those of 2012. Although it is common practice to compare future temperature changes to a pre-industrial baseline, climate change has been underway for many decades. We therefore focus our economic risk assessment on the ways in which future climate change may alter our economic future relative to the economic reality that we know today, which has already been partially influenced by the climate changes that have already occurred. This idea is illustrated in Figure 5.1, which shows how the probability distribution of potential future outcomes in an example sector (low-risk labor supply) changes in RCP 8.5 relative to historical impacts estimated using the same method. Throughout this report, we present impacts relative to recent conditions, when recent conditions may already be somewhat different from

Figure 5.1: Example of projected RCP 8.5 impacts relative to 2012 baseline estimates

Future probability distributions of 20-year average lost low-risk labor supply relative to impact estimates in 2012, with historical annual estimates also shown in black (likely range and 90% confidence interval based on statistical uncertainty shown in grey)



long-term historical patterns.

For each of the impacts we examine, we carefully scrutinize the existing literature to select those studies that we think most credibly identify the effect of climate on specific outcomes[1]. We restrict our analysis to studies that (1) are nationally comprehensive (or representative) in scope, (2) analyze recent history in the United States, (3) account for all unobserved non-climate factors that differ across locations (usually counties), and (4) break down the outcomes into responses to daily or weekly conditions. For this assessment, we have been especially conservative in the selection of empirical studies we rely on, although we expect that in the future additional studies will further improve our understanding of these relationships. To ensure that future assessments can build on our analysis, we have developed the Distributed Meta-Analysis System (accessible at http://dmas.berkeley.edu) (Rising and Hsiang 2014), which enables future researchers from around the world to seamlessly introduce new findings.

There are limits to what econometric research alone can tell us about the future, however. Some of the projected temperatures and precipitation patterns described in Chapter 2 are outside the range of empirical evidence, and we limit our econometrically-derived impact functions to historical experience. In a US that is on average 10°F warmer, most days will have past analogs that can be used for developing empirical models, but many will be record-breaking and have no such precedents. We have not experienced sea-level rise of three feet (our median projection for RCP 8.5 in 2100) or seen what that will do to Miami. Empirically-based sectoral models can help fill in some of these gaps.

DETAILED SECTORAL MODELS

There are a number of sector-specific models developed by academic researchers, government agencies, and private industry that can be useful in exploring the potential impact of future changes in climate. These models are calibrated using empirical estimates, but can also be used to explore temperature, precipitation, sea-level rise, or storm changes outside the range of historical experience or to analyze market interactions not captured in econometric research. We employ two such models in this assessment.

Energy

Existing econometric research on the relationship between temperature and energy demand is limited to electricity. To capture a broader range of fuels, as well as the impact of changes in demand on energy prices, we employ RHG-NEMS, a version of the US Energy Information Administration's National Energy Modeling System (NEMS) maintained by the Rhodium Group. NEMS is the most detailed publicly available model of the US energy system and is used to produce

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[1] We have engaged extensively with the original researchers of these studies to ensure an accurate representation of their results, and in several cases these authors provided additional analysis to help us better integrate their findings.

the Energy Information Administration's Annual Energy Outlook, the most commonly used forecast of US energy supply and demand. We model changes in regional residential and commercial electricity, natural gas, oil, and coal demand that would likely occur in potential climate futures (comparing modeled results to empirical estimates where possible), and what that implies for energy prices and the composition of energy supply.

Coastal communities

The insurance and finance industries use sophisticated and extremely detailed models of hurricanes and other storm activity, and their impact on coastal property and infrastructure. Risk Management Solutions, Inc. (RMS) is the world's leading developer of hurricane and other catastrophic risk models and a partner in this assessment. RMS's North Atlantic Hurricane Model combines extensive empirical evidence of past hurricane activity with a wind and surge model that simulate the wind and flooding damage likely to result from a given storm. We use RMS's building-level exposure database to identify property at risk from mean local sea-level rise, and the North Atlantic Hurricane Model to assess the increase in hurricane and nor'easter flood damage likely to occur as result of that sea-level rise. Using input from the leading cyclogenesis models, we also explore how changes in hurricane activity as a result of climate change could shape wind and flood damage in the future.

OTHER IMPACTS

There are many potential climate impacts, beyond those listed above, that are of profound importance to the functioning of the US economy and the lives of most Americans, among them impacts to national security, tourism, wildfires, water resources, and ecosystems. To date there is not yet a sufficient body of US-based econometric research from which to develop an econometrically-derived damage function or an empirically-based sectoral model capable of robustly analyzing potential climate impacts in these areas. That does not, however, mean these impacts should be ignored. Indeed, the impacts that are hardest to quantify could end up being the most costly. In Part 4 of this report, we describe the universe of potential climate impacts not captured in this assessment. More importantly, we provide a framework and a platform for quantifying these impacts in the future as research improves.

ADAPTATION

An important question in any climate impact assessment is the extent to which businesses, households, investors and policymakers will be able to adapt to potential changes in temperature, precipitation, sea-levels, and storm activity. Will coastal communities build walls to guard against rising seas? Will farmers develop and deploy heat and drought-resistant seeds? As a principal objective of our research is to give decision-makers the information they need to make those long-term adaptation investments, we exclude them from our baseline assessment. In Part V of this report, we explore the extent to which both adaptation investments and global greenhouse gas emission reductions can shield the US economy from future climate risks.

CHAPTER 6

Agriculture

Agriculture has long been an economic and cultural foundation for the United States. Known for its historical boom and bust cycles, agricultural productivity and incomes are often influenced by and in turn influence the US economy as a whole (Landon-Lane, Rockoff, and Steckel 2011; Feng, Oppenheimer, and Schlenker 2013; Hornbeck and Keskin 2012). In agriculture-dependent regions, the extreme drought and environmental mismanagement of the Dust Bowl in the early 1930s exacerbated the already dire economic conditions of the Great Depression (Egan 2006; Hornbeck 2012). Climate and weather variability have played roles to varying degrees in the cycles of US agriculture. Extremes in local and regional weather patterns and climate variability have disrupted agricultural production in the past. American farmers have developed production practices and strategies appropriate for their local conditions, taking into account long-term historical trends as well as the risks of short-term variability. Despite the flexibility of the US agricultural system, and advances in agricultural practices and technologies, US production and prices remain highly dependent on climate, making the sector particularly vulnerable to both gradual climate change and extreme climate events.

The agricultural sector's central role in rural and local economies, and the national economy, as well as its importance for human health and security, make understanding the economic risks posed by climate change important not only for agricultural states, but for farmer livelihoods, rural communities, and the US economy as a whole. The US produced over $470 billion in agricultural commodities in 2012. Although it has traditionally contributed less than 2% of US GDP, it is a much more significant source of income for many Midwestern and Great Plains states like North Dakota, South Dakota, Nebraska, and Iowa. Although a small share of California's overall economy, the state's agricultural contribution is significant, producing over 10% of the value of all US agricultural commodities last year, and nearly half of US-grown fruits, nuts, and vegetables.

American farmers, ranchers and the agriculture sector as a whole are familiar with making decisions in the face of uncertainty, which arise not just due to variability in weather patterns, but also from fluctuations in a whole host of other factors including trade dynamics, shifts in market demands and consumer preferences, evolution of agricultural technologies, and ever-changing state and federal policies. Risk-based decision-making must take each of these factors into account. Managing the risks associated with climate change will require the integration of the potential risks of climate on agricultural productivity and prices into decision-making by those involved in the full value chain of agricultural production.

In assessing the risks that climate change poses to agricultural productivity, there are a whole host of variables to consider including temperature; precipitation; availability of water resources for irrigation; CO_2 concentrations; ozone and other pollutant concentrations; and climate-driven changes in pests, weeds, and diseases. The relative importance of each of these variables will vary based on the region and the crop or livestock type. In this analysis we focus on the impact of changing temperatures and precipitation on commercial crop yields (including grains, cotton, and oilseeds) in areas where they are currently grown in the US. We discuss other impacts in more detail in the sections that follow.

BACKGROUND

On the whole, agricultural yields have increased across the US during the last quarter of a century due primarily to dramatic improvements in agricultural techniques and secondarily to increases in temperature and precipitation. Studies isolating climate-related impacts observed to date have shown that, on average, crops were more affected by changes in temperature than by precipitation, though temperature played a greater role in increased yields in central and northern regions, with higher precipitation contributing in the southern US (Sakurai, Iizumi, and Yokozawa 2011). However, in the past 15 years there has been a marked increase in crop losses attributed to climate events such as drought, extreme heat, and storms, with instability between years creating significant negative economic effects (Hatfield, Cruse, and Tomer 2013a). Understanding the potential risks to the highly varied agricultural regions across the US requires an assessment of both the changes in average climate variables, and also changes in the intensity and frequency of extremes.

Historical changes in temperature have varied both across regions of the US, with more significant changes in the Midwest and Southwest, and by season, with greater winter and spring warming. Overall, warming has lengthened the growing season by 4 to 16 days since 1970 (US EPA 2012a). Final spring frost is now occurring earlier than at any point since 1895, and the first fall frosts are arriving later (US EPA 2012b). Changes in the length of the growing season can have both positive and negative effects, as they may allow farmers to have multiple harvests from the same plot. However, they may preclude certain crops, lead to significant changes in water requirements, or disrupt normal ecosystem functions such as the timing of pollination and natural protections against weeds and invasive species.

Rising temperatures are expected to further lengthen growing season across most of the US (by as much as a month or two over the course of the century) and reduce the number of frost days, particularly in the West (Walthall et al. 2013). While longer growing seasons may be a boon to agriculture in some regions, the overall impact on yields will also be influenced by associated increases in exposure to warmer temperatures over greater time spans. While warmer average temperatures and increased precipitation over the past few decades have contributed to increased yields, this trend is unlikely to continue as temperatures rise across much of the US. Crop species display temperature thresholds that define the upper and lower boundaries for growth and the current distribution of crops across the US corresponds to temperatures that match their thresholds (Hatfield et al. 2014). The impacts on yield are non-linear as temperatures reach and then exceed a crop's threshold. When paired with declining precipitation and increased evaporation in areas like the Southwest and southern Great Plains, warmer temperatures result in even greater declines in yield. In most regions of the US, optimum temperatures have been reached for dominant crops, which means that continued warming would reverse historic gains from warmer temperatures and instead lead to reduced yields over time. As temperatures increase over this century, crop production areas may shift to follow the temperature range for optimal growth.

Rising temperatures and shifting precipitation patterns will also affect productivity through altered water requirements and water-use efficiency of most crops. The differential effect of these various factors will lead to regional production effects that alter regional competitiveness, potentially altering the agricultural landscape significantly by mid-century.

Changes in average conditions will be compounded by changes in extremes on a daily, monthly, and seasonal scale (Schlenker and Roberts 2009), as well as changing intensity and frequency of extreme weather events (IPCC SREX, 2012). Many extreme weather events of the past decade are outside of the realm of experience for recent generations, and as we've seen, these events can have devastating effects. The drought that plagued nearly two-thirds of the country for much of 2012 was the most extensive to affect the US since the 1930s, resulting in widespread crop failure and other impacts estimated at $30 billion, with states in the US heartland – Nebraska, Iowa, Kansas, South Dakota – experiencing the greatest impacts as maize and soybean yields were severely reduced, dealing a serious blow to the states' economies (NOAA 2013). Temperature fluctuations need not be long in duration to cause widespread destruction. In 2008, heavy rain and flooding, including up to 16 inches in parts of Iowa, caused significant agricultural losses and property damage in the Midwest totaling more than $16 billion (NOAA 2013).

Changing frequency, severity, and length of dry spells and sustained drought can significantly reduce crop yields. At their most extreme, crop death and reduced productivity due to drought can result in billions of dollars of damage; the 1988 drought that hit the central and eastern US resulted in severe losses to agriculture and related industries, totaling nearly $80 billion (NOAA 2013). As the IPCC notes, it is not possible to attribute historic changes in drought frequency to anthropogenic climate change (Romero-Lankao et al. 2014a). However, observations of emerging drought trends are consistent with projections of an increase in areas experiencing droughts in several regions of the US (Walthall et al. 2013). There has been no overall trend in the extent of drought conditions in the continental US, although more widespread drought conditions in the Southwest have been observed since the beginning of the 20th century (Georgakakos et al. 2014; M.P. Hoerling et al. 2012). Summer droughts are projected to become more intense in most of the continental US, with longer-term droughts projected to increase in the Southwest, southern Great Plains, and parts of the Southeast (Georgakakos et al. 2014; Walsh et al. 2014; Cayan et al. 2010; Dai 2012; Hoerling et al. 2012; Wehner et al. 2011).

Excess precipitation can be as damaging as too little precipitation, as it can contribute to flooding, erosion, and decreased soil quality. Surface runoff can deplete nutrients, degrading critical agricultural soils, and contribute to soil loss, which reduces crop yields and the long-term capacity of agricultural lands to support crops. In some critical producing states like Iowa, there have been large increases in days with extremely heavy rainfall even though total annual precipitation has remained steady (J. Hatfield et al. 2013). Greater spring precipitation in the past two decades has decreased the number of days for agricultural field operations by more than three days when compared to the previous two decades, putting pressure on spring planting operations and increasing the risk of planting on soils that are too wet, reducing crop yields, and threatening the ability of soils to support crops in the long-term (Hatfield, Cruse, and Tomer 2013b). Greater rainfall quantities and intensity across much of the northern US are expected to contribute to increased soil erosion (Pruski and Nearing 2002).

The projected higher incidence of heat, drought, and storms in some regions will influence agricultural productivity. The degree of vulnerability will vary by region and depend both on the severity of events as well as the adaptive capacity. Due to projected increases in extreme heat, drought, and storms, parts of the Northeast and Southeast have been identified as "vulnerability hotspots" for corn and wheat production by 2045, based on expected exposure and adaptive capacity, with increased vulnerability past mid-century (Romero-Lankao et al. 2014). Livestock production is also vulnerable to temperature stresses, as animals have limited ability to cope with temperature extremes and prolonged exposure can lead to reduced productivity and excessive mortality. These impacts increase the production cost associated with all animal products, including meat, eggs, and milk.

Extremes that last only short periods are still often critical to productivity because annual agricultural output may be driven largely by conditions during narrow windows of time when crops and livestock undergo important developments. The impact of variability in precipitation and water resource availability as well as temperature extremes will depend on the timing of such events in relation to these critical periods. Warmer spring temperatures within a specific range may accelerate crop development, but extremely high temperatures during the pollination or critical flowering period can reduce grain or seed production and even increase risk of total crop failure (Walthall et al. 2012). Warmer nighttime temperatures during the critical grain, fiber, or fruit production period will also result in lower productivity and reduced quality. Such effects were already noticeable in 2010 and 2012, as high nighttime temperatures across the Corn Belt were responsible for reduced maize yields. With projected increases in warm nights, yield reductions may become more prevalent (Walthall et al. 2012). Fewer days with cold temperatures can also have significant effects, reducing the frequency of injury from chilling in some cases, while in others yields may be negatively impacted as chilling requirements for some crops are not satisfied. Many fruit and nut tree types must be exposed winter chill to generate economically sufficient yields. The state of California is home to 1.2 million hectares of chill-dependent orchards, supporting an estimated $8.7 billion industry. With warmer temperatures expected by the middle to the end of this century, one study concludes that conditions will not be sufficient to support some of California's primary fruit and nut tree crops (Luedeling, Zhang, and Girvetz 2009).

Though the effect is less well understood than temperature- and precipitation-related impacts, rising CO_2 concentrations are expected to affect plant growth and therefore agricultural yields. Elevated atmospheric CO_2 concentrations stimulate photosynthesis and plant growth, with some plant species (e.g., C3 crops such as wheat, cotton, soybean) exhibiting a greater response than others (e.g., C4 crops including maize) (Leakey 2009). Increased atmospheric CO_2 since pre-industrial times has enhanced water use efficiency and yields, especially for C3 crops, although these benefits have contributed only minimally to overall yield trends (Amthor 2001; McGrath and Lobell 2013). Experiments and modeling indicate that the impact of CO_2 on yields depends highly on crop species, and even sub-species, as well as on variables like temperature, water supply, and nutrient supply. The interactions between CO_2 concentrations and these variables are non-linear and difficult to predict (Porter et al. 2014). Elevated CO_2 concentrations can also increase weed growth rates and alter species distribution, and there is some indication that elevated CO_2 may contribute to a reduction in the effectiveness of some herbicides (Archambault 2007).

An important consideration for determining the impacts of climate change on US agriculture is the degree to which farmers, ranchers, and the industry as a whole can adapt to changes over time. Agriculture is a complex system and has proved to be extremely adept at responding to changes over the last 150 years, though these adaptations were made during a period of relative climatic stability. Producers have continually adapted management practices in response to climate variability and change by using longer-maturing crop varieties, developing new cultivars, planting earlier, introducing irrigation, or changing the type of crop altogether (A. Olmstead and Rhode 1993; Olmstead and Rhode 2011).

However, the effectiveness of strategies used in the past may not be indicative for the types of changes expected in the future. Technological improvements, for example, improve yields under normal conditions but may not protect harvests from extremes expected in the future (Schlenker, Roberts, and Lobell 2013), such as increased drought in the Southwest and southern Great Plains, or increased flooding in the Midwest and Northeast. Catastrophic crop or livestock losses are likely to affect the financial viability of production enterprises in a fundamentally different way than moderate losses over longer periods of time. In addition, many adaptive actions may be costly (e.g., requiring increased energy consumption) or constrained by climate change (e.g., increasing groundwater use may not be an option in areas with declining precipitation) (Romero-Lankao et al. 2014b). Decisions about future adaptive action will need to take into account the potential risks of climate-related damages and the costs of adaptation, as well as complex changes in domestic and international markets and policies, all of which will determine the cost of doing business.

OUR APPROACH

To quantify the potential impacts of climate change on agricultural production, we rely on statistical studies that isolate the effect of temperature and rainfall on crop yields in the United States. Because there are strong cross-county patterns in crop yields, as well as strong trends over time (that may differ by location), we rely on studies that account for these patterns when measuring the effects of climate variables. Schlenker and Roberts (2009) provide nationally representative estimates that satisfy these criteria, which we use to construct quantitative projections. They examine county-level agricultural production during 1950-2005 and identify the incremental influence of temperature and rainfall variability on maize, soy, and cotton yields using data collected by the US Department of Agriculture's National Agricultural Statistical Service. While they focus their analysis on the eastern United States, they also provide parallel results for the western United States, which we also utilize. To estimate yield impacts on wheat, we apply a similar approach to yield data from the same source (see Technical Appendix II). We also consider how projections change when future adaptation is modeled explicitly by linking the results from Schlenker and Roberts to an analysis by Burke and Emerick (2013), who employ similar econometric strategies to measure rates of agricultural adaptation in the US (see Part V).

Figure 6.1 displays the temperature impact function for maize yield. In general, rising daily temperatures increase yields slightly until a breakpoint is reached, after which higher daily temperatures dramatically reduce yields. For maize, soy, and cotton these breakpoints occur respectively at 84°F, 86°F and 90°F.

Figure 6.1: Impact Function – Temperature and maize yields

Observed change in maize yields (%) vs. daily temperature (°F)

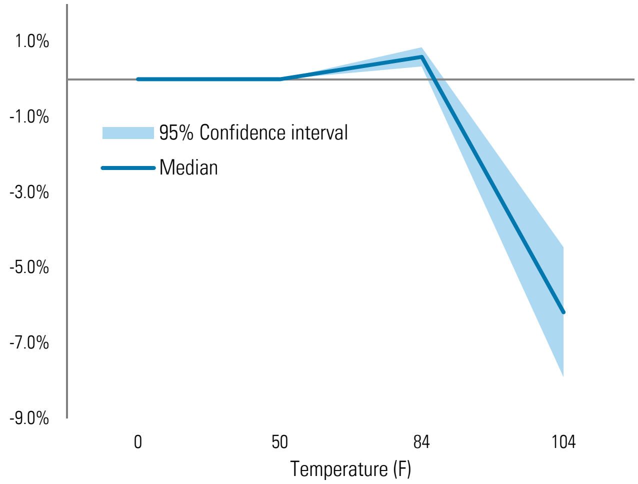
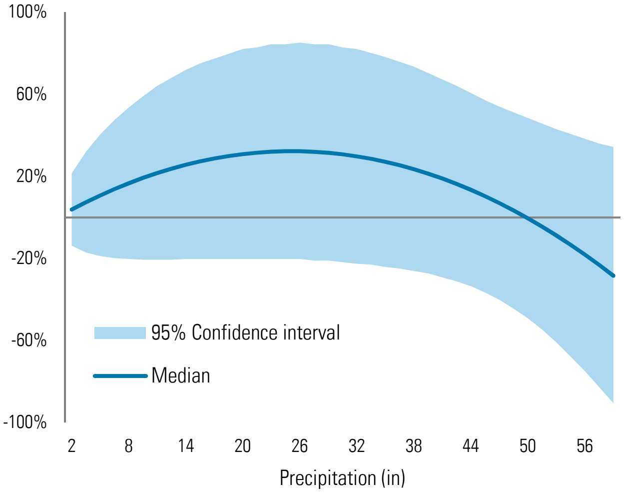


Figure 6.2: Impact Function – Precipitation and maize yields

Observed change in maize yields (%) vs. seasonal precipitation (in.)



This non-linear response has been broadly replicated in multiple studies that are more local in character and is consistent with quadratic temperature responses in studies that use seasonal mean temperature. Seasonal precipitation has a nonlinear inverse-U shaped relationship with yields (see Figure 6.2), again broadly consistent with local studies.

Schlenker and Roberts assess whether there is evidence that farmers adapt by examining whether there are changes in the sensitivity of crop yields to temperature over time. They find that the relationship between heat and yields has changed slightly since 1950, providing only weak evidence of adaptation. This finding is consistent with a more detailed analysis on the evolution of heat tolerance in maize in Indiana counties during 1901-2005 (Roberts and Schlenker 2011) and analysis of how yields in the eastern United States have responded to long-term trends in temperatures during 1950-2010 (Burke and Emerick 2013). Thus, while there is evidence that farmers are adapting over time, the evidence indicates that this process is extremely slow.

Schlenker and Roberts also look for evidence of adaptation by examining if counties that are hotter on average (in the Southeast) or drier and/or hotter on average (in the West) have a different sensitivity to climate. They find strong evidence that crop yields in counties in the South or in the West are less sensitive to temperature, suggesting that these locations have adapted somewhat to their local climatic conditions, probably through the adoption of heat-tolerant cultivars and/or irrigation (Butler & Huybers 2013). These adaptations come at a cost, such as lower average yields (Schlenker, Roberts and Lobell, 2013), but they might be more consistently adopted in the future in the Midwest and East if rising temperatures make them cost-effective strategies in these regions.

Table 6.1: Impacts of future climate change to US agricultural yields with CO_2 fertilization

Percentage change from 2012 production levels for maize, wheat, oilseeds, and cotton

Crop Type	RCP 8.5			RCP 4.5			RCP 2.6		
	1 in 20 less than %	Likely %	1 in 20 greater than %	1 in 20 less than %	Likely %	1 in 20 greater than %	1 in 20 less than %	Likely %	1 in 20 greater than %
Maize									
2080-2099	-84	-73 to -18	-8.1	-64	-44 to -2.8	1.9	-27	-19 to 0.4	2.8
2040-2059	-39	-30 to -2.3	2.8	-34	-25 to 0.1	3.6	-23	-18 to -1.0	1.3
2020-2039	-19	-15 to 4.3	12	-19	-15 to 5.2	9.7	-21	-14 to -3.1	0.4
Wheat									
2080-2099	8.6	19 to 42	50	-1.1	4.7 to 15	17	-2.6	-0.9 to 4.4	5.3
2040-2059	3.0	6.0 to 14	17	1.0	3.7 to 10	12	-0.8	0.6 to 5.1	6.2
2020-2039	0.6	1.8 to 5.6	8.3	-0.3	1.2 to 6.5	7.7	-0.9	0.2 to 4.4	5.3
Oilseeds									
2080-2099	-74	-56 to 18	29	-55	-30 to 8.6	16	-18	-13 to 6.3	8.4
2040-2059	-23	-16 to 11	17	-24	-15 to 7.6	14	-15	-8.8 to 5.8	9.9
2020-2039	-9.7	-6.6 to 9.9	15	-15	-10 to 6.9	13	-16	-7.4 to 3.8	6.8
Cotton									
2080-2099	-74	-52 to 16	31	-38	-18 to 9.8	18	-17	-9 to 3.0	5.7
2040-2059	-20	-12 to 13	18	-15	-7.3 to 8.0	13	-15	-7.3 to 4.9	8.6
2020-2039	-7.7	-3.6 to 5.6	7.8	-8.9	-4.8 to 5.8	9.2	-11	-5.4 to 4.3	6.3

Schlenker and Roberts are unable to account for the effect that rising CO_2 concentrations have on agricultural yields because gradual trends in CO_2 cannot be statistically distinguished from other trends (e.g. technological progress). Thus, to account for increasing CO_2, we must draw on a body of literature that combines field experiments in carbon dioxide enrichment with simple models. We obtain estimates for the incremental effect that CO_2 enrichment has on yields for different crops from McGrath and Lobell (2013), who collect results from multiple field experiments and use these results to construct estimates for the effect of CO_2 fertilization on US crops.

To assess potential future impacts of climate change on national agricultural production, we simulate changes in production of major crop varieties (maize, wheat, soybeans, and cotton) under different climate scenarios relative to a future in which the climate does not drive economic changes after 2012—although other social and economic trends are assumed to continue. Within each scenario we account for uncertainty in climate models, weather, and statistical results, causing our projection to be a probability distribution of potential outcomes at each moment in time.

When we consider the potential impact of changes in temperature, precipitation, and CO_2 fertilization on national yields, we find that the value of total production generally declines as early as 2020-2039 — even under RCP 2.6 — although the range of *likely* outcomes spans positive values through 2099 under all scenarios (Table 6.1). Under RCP 8.5, total production is *likely* to change by -14% to +7% by mid-century and -42% to +12% by late-century, with a 1-in-20 chance that late-century changes are below -56% or exceed +19% of production. Impacts on maize are generally negative throughout all periods because maize is strongly heat sensitive and benefits least from CO_2 fertilization, while impacts on wheat are overwhelmingly positive because wheat benefits more from CO_2 fertilization than it is harmed by heat. Impacts on cotton and soybeans are about as likely to be positive as negative until late-century in RCP 8.5, when they become generally negative. The *likely* ranges for all crops are shown in Table 6.1.

Projected changes are smaller in magnitude for RCP 4.5 and RCP 2.6, and the distribution of projected changes is more skewed towards negative yield changes relative to RCP 8.5. The *likely* range of late-century production changes for total production spans -25% to +6% for RCP 4.5 and -11% to +3% for RCP 2.6. The skewed distribution is most apparent when considering 1-in-20 outcomes: production changes below -43% or above 10% for RCP 4.5 and below -17% or above 5% for RCP 2.6. The skewed distribution of total production is mainly driven by maize and soy, which have especially skewed outcomes with a 1-in-20 chance that yields are below -64% and -55%, respectively, in RCP 4.5 by late-century. The skewness for total production in RCP 4.5 is sufficiently large that potential downside losses are similar in magnitude to downside losses in RCP 8.5; however, in RCP 4.5 there is a lower probability of ending up with the largest losses.

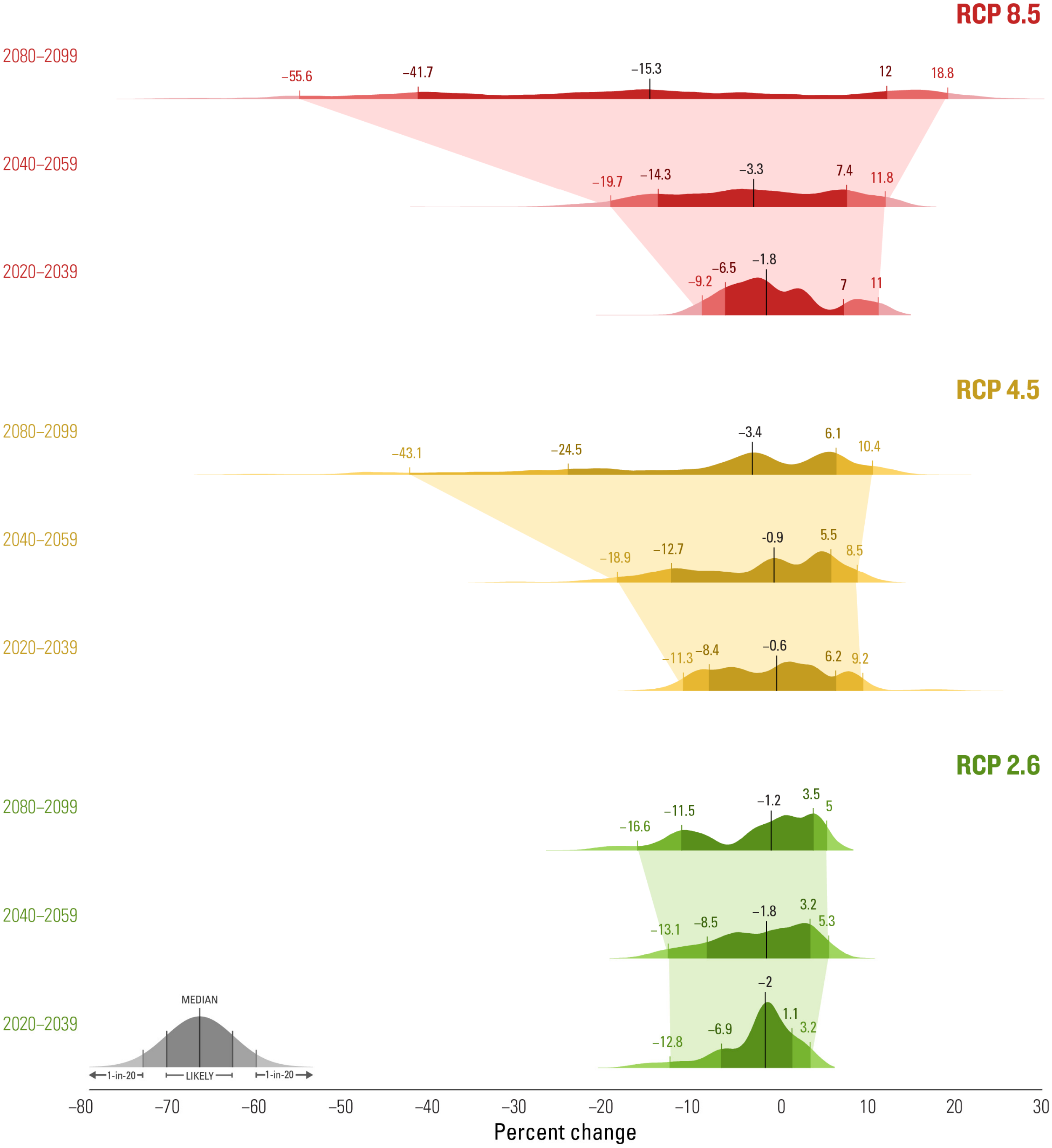
Across all RCPs, the distribution of potential yields broadens over time. The rate of spreading increases dramatically with increasing emissions. For total production, late-century *very likely* range spans 15 percentage points in RCP 2.6 and widens to span 31 and 54 percentage points in RCP 4.5 and 8.5 respectively (Figure 6.3). Climate change not only decreases expectations for national production, it also increases uncertainty regarding future national production in a warming world.

In percentage terms, the spatial distribution of projected impacts is uneven across the country, with the South and East regions suffering the largest projected yield losses while the Rockies, Northwest and northern Great Plains regions achieve yield gains in the median RCP 8.5 projection (Figure 6.4). The eastern US is hardest hit primarily because the dose-response function is more sensitive to extreme heat in the East, in part because irrigation infrastructure is not as widespread as in the West (Schlenker and Roberts, 2009). The Southeast suffers the largest percentage losses because the dose-response function is sensitive to extreme temperatures and because southern counties experience the highest number of additional extreme temperature days in future projections. Projected yields in the Rockies, Northwest and northern Great Plains benefit from both moderate warming and moderate wetting from a current climate that is both cool and dry. Projected changes in total national output are dominated by production losses in central Midwestern states that are not heavily irrigated, that warm substantially, and that currently have large land areas dedicated to high-yield production.

The impacts above are described in terms of average changes over 20 year intervals. These averages are useful for describing persistent economic changes in future periods, but they mask short-lived events that may only last a year or two but have substantial economic consequences. Within each 20 year window, the likelihood of extreme annual events, such as a very low-yield year, evolves with the climate. One way to describe how the likelihood of extreme events changes is to examine how frequently we expect to experience years that are as damaging as the worst year experienced during two decades of recent history, a so called "1-in-20 year event". In Figure 6.5 we plot the estimated number of years that will have yield losses larger than historically observed 1-in-20 year losses. For each year we plot the expected number of these extreme years that will be experienced in the 20 years that follow; i.e., we plot what the immediate future appears like to an individual in a given year. For a long-term investor with a 20 year time horizon, these are expected risks to take into account. By 2030, in all scenarios, production losses that used to occur only once every 20 years will be expected to occur roughly five times in the following 20 years. By 2080, these events will be occurring roughly eight times every 20 years in RCP 4.5 and 12 times every 20 years in RCP 8.5.

Figure 6.3: Change in national yield of grains, oilseeds, and cotton

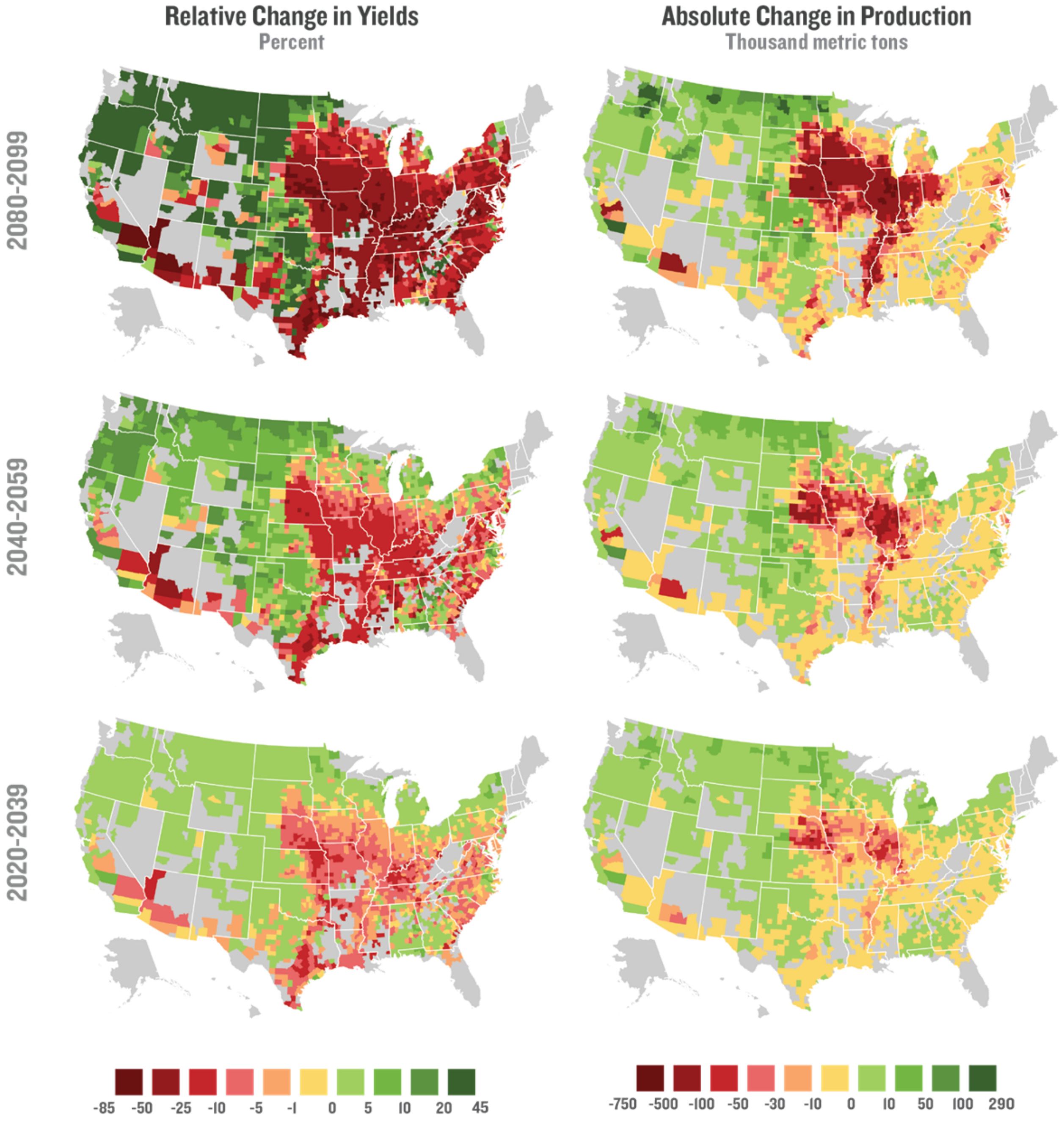
Percent, including CO_2 fertilization



These projections suggest there is a possibility that national yields will be higher in the future, with the benefits of CO_2 fertilization counterbalancing the adverse effects of extreme heat. We advise caution in interpreting these results, since the magnitude of carbon fertilization effects have not been measured empirically with the same level of consistency as temperature and rainfall effects (Long et al. 2006), and they have not been measured empirically in nationally representative samples (McGrath & Lobell, 2013). Thus, we also consider the distribution of potential yield changes due only to temperature and precipitation changes – not because the CO_2 fertilization effect is likely to be zero, but because separating the effect of CO_2

Figure 6.4: Projected change in grain, oilseed, and cotton yields by county

RCP 8.5 median projection, grey counties are those where no grain, oilseed, or cotton production currently occurs



fertilization allows evaluation of how large these uncertain effects must be to offset temperature and rainfall effects. When the effect of CO_2 fertilization is removed then agricultural output declines much more dramatically in projections that use only temperature and precipitation changes (see Table 6.2 and Figure 6.5). The likely range of late-century losses in RCP 8.5 are unambiguously negative and large, spanning 20 to 59% for total production. The effect of removing CO_2 fertilization has different effects for different crops, although in all cases removing CO_2 fertilization causes projected losses to be larger. It is unlikely that losses this large will occur since carbon fertilization will offset some of these losses, as it did in our main projections, so these estimates should be considered a "worst case scenario" for the situation where the benefits from carbon fertilization have been overestimated.

It is important to note that these estimates assume the national distribution of crop production remains fixed relative to 2000-2005. It is extremely likely that farmers' decisions regarding what they plant will change as they observe their climate changing, but this response could not be evaluated here because systematic analysis of this response is absent from the body of existing research. We hope that future analyses will incorporate this response and update our projections.

Prior analyses have not examined how planting decisions change in response to the climate, although recent work has examined how farmers who always plant the same crop adapt to changes in their local climate over time. We consider how these results can be incorporated into our analysis in Part V of this report.

Figure 6.5: Projected change in the frequency of national yield losses equal to or worse than historical 1-in-20 year losses

Expected frequencies across climate models and weather. Frequencies are plotted in the first year of each 20 year period.

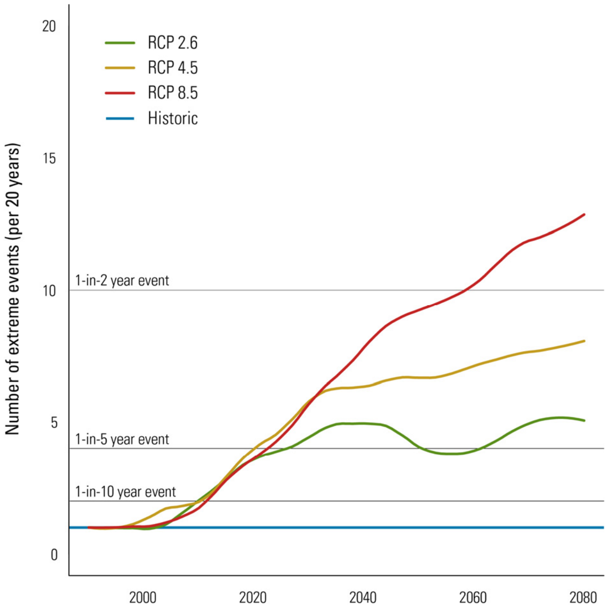


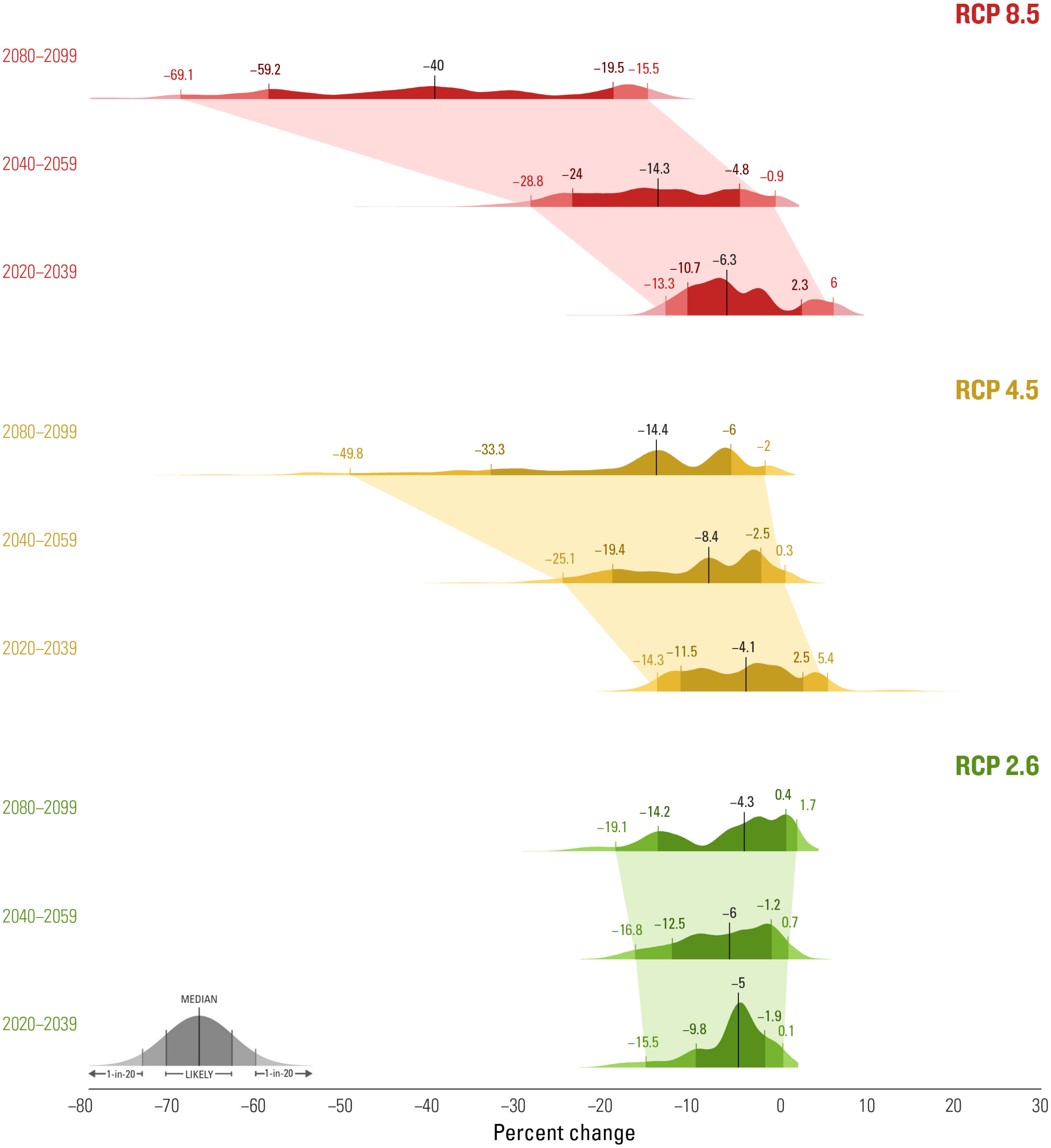
Table 6.2: Impacts of future climate change to US agricultural yields without CO2 fertilization

Percentage change from 2012 production levels for maize, wheat, oilseeds, and cotton

Crop Type	RCP 8.5			RCP 4.5			RCP 2.6		
	1 in 20 less than %	Likely %	1 in 20 greater than %	1 in 20 less than %	Likely %	1 in 20 greater than %	1 in 20 less than %	Likely %	1 in 20 greater than %
Maize									
2080-2099	-87	-76 to -29	-22	-66	-47 to -7.5	-3.6	-28	-20 to -0.8	1.5
2040-2059	-41	-33 to -7.1	-2.4	-36	-28 to -3.2	0.1	-25	-19 to -2.7	-0.5
2020-2039	-21	-16 to 2.5	9.4	-20	-16 to 3.7	8.0	-22	-15 to -4.3	-0.9
Wheat									
2080-2099	-27	-20 to -7.0	-4.0	-15	-9.8 to -1.5	-0.8	-6.2	-4.7 to 0.4	0.9
2040-2059	-11	-8.6 to -2.9	0.1	-8.2	-6.0 to 0.1	0.7	-6.0	-4.7 to -0.5	-0.2
2020-2039	-4.9	-3.9 to -0.9	2.0	-4.6	-3.3 to 1.9	2.5	-4.5	-3.7 to 0.4	0.9
Oilseeds									
2080-2099	-82	-70 to -20	-14	-61	-40 to -6.6	-0.3	-21	-16 to 2.2	4.2
2040-2059	-33	-27 to -4.0	0.7	-31	-23 to -2.5	3.2	-19	-14 to 0.0	3.9
2020-2039	-15	-12 to 4.0	8.5	-19	-14 to 2.4	8.3	-19	-11 to -0.1	2.6
Cotton									
2080-2099	-83	-68 to -24	-15	-47	-30 to -6.4	0.5	-21	-13 to -1.2	1.5
2040-2059	-31	-24 to -3.7	0.3	-23	-16 to -2.8	1.3	-19	-13 to -1.1	2.5
2020-2039	-13	-9.4 to -0.8	1.2	-13	-9.1 to 0.8	4.0	-14	-9.3 to 0.0	1.9

Figure 6.6: Change in national yield of grains, oilseeds, and cotton

Percent, Not including CO_2 fertilization



OTHER IMPACTS

There are a whole host of impacts that we were not able to include in this round of our analysis. We discuss some of them below.

Water resources

Changing climate – including shifting precipitation patterns, and greater frequency and intensity of precipitation extremes like heavy rainfall and drought in some regions – are likely to affect water resource availability with wide-ranging implications for the US agricultural sector and crop production in particular.

While irrigation reduces the risk from variable seasonal rainfall, producers that rely on irrigation to maintain yields may be at greater risk from volatility in cost and availability of water supplies. Climate change will have important implications for the extent and distribution of future US irrigated crop production. Although only 7.5% of all US cropland and pastureland are irrigated, farms that use irrigation accounted for 55% of the total value of crop sales in 2007, the last year for which USDA census data are available (USDA 2010). Irrigated agriculture accounts for over a third of the nation's freshwater withdrawals and approximately 80 to 90% of overall consumptive use (Kenny et al. 2009). Nearly three-quarters of irrigated acreage is in the western US, though in recent decades much of the expansion in irrigated acreage has occurred in the eastern areas.

Reduced water availability for agriculture may lead to contraction in irrigated acreage in some areas, particularly in the western US (Elliot et al., 2013). Warmer temperatures at the same time will also increase crop water needs and demand for irrigation, although increasing CO_2 concentrations can also increase water use efficiency of some crops (Wada et al. 2013; Elliott et al. 2013; Prudhomme et al. 2013; J. Hatfield et al. 2013). Irrigation, which has traditionally been relied on to offset the negative effect of high temperatures, has been particularly effective in areas with intensive cultivation and irrigation like the Corn Belt (Sakurai, Iizumi, and Yokozawa 2011). Such strategies may not be available, or will be much more costly, in regions with increased water scarcity where the cost of irrigation is likely to increase, as are energy costs associated with irrigation, including for water pumping.

Ozone pollution

Carbon dioxide is not the only ambient pollutant that affects plant growth. Emissions of nitrogen oxides (NOx) and volatile organic compounds (VOCs) from farm processes and industrial sources react to form ground-level ozone (O_3), which can damage vegetation by reducing photosynthesis and other important physiological functions resulting in stunted crops, decreased crop quality, and decreased yields (Mills et al. 2007). High temperatures increase ozone formation, especially during the warm “ozone season” of May to September (Bloomer et al. 2009). The impacts on a range of US agricultural crop yields is an area of emerging study; initial studies indicate that the impacts of elevated ozone concentrations are evident for soybean crops in the US Midwest, with annual yield losses in 2002-2006 estimated at 10% (Fishman et al. 2010). The interactions between elevated ozone and CO_2 concentrations have been found to dampen these effects, with ozone partially counteracting CO_2 fertilization. More study is necessary to understand the interactions between CO_2, ozone, and temperature on a variety of species.

Weeds, disease, and pests

Agriculture is a complex system, and the mechanisms through which climate can impact productivity are many. While changing climatic conditions affect crop yield directly, they also affect a whole array of other competing and complementary organisms that have varying effects on crop yields. Changes in temperature and precipitation patterns, combined with increasing atmospheric CO_2, change weed-infestation intensity, insect population levels, the incidence of pathogens, and potentially the geographic distribution of all three.

The relationship between climate change and agricultural crop yield losses due to increased competition from weeds, for example, is not fully understood due to the complex relationships between temperature, CO_2 concentration, and crop-weed interactions, as well as artificial factors such as herbicide use (Archambault 2007). Weeds are generally hearty species, and several weeds benefit more than crops from higher temperatures and CO_2 levels (Ziska 2010). The geographic distribution of native and invasive weeds will likely be extended northward as temperatures warm, exposing farms in northern latitudes to new or enhanced threats to crop productivity from weeds like privet and kudzu, already present in the South (Ziska 2010; Bradley, Wilcove, and Oppenheimer 2010). Weed control costs the US more than $11 billion a year, with most of that spent on herbicides. Use of herbicides is expected to increase as several of the most widely used herbicides in the US, including glyphosate (also known as RoundUp™), have been found to lose efficacy on weeds grown at CO_2 levels projected to occur in the coming decades (Ziska, Teasdale, and Bunce 1999).

Climate change is also expected to affect the geographic ranges of specific species of insects and diseases across regions of the US, potentially altering yield losses as a result. Changes in average temperature can result in gradual shifts in geographic distribution as earlier spring and warmer winters affect species overwintering and survival. In wet years, high humidity can help insects and diseases flourish, with negative indirect impacts on animal health and productivity (Garrett et al. 2006; Garrett et al. 2011). Climate affects microbial and

CLIMATE'S IMPACTS ON AGRICULTURE DOESN'T STOP AT US BORDERS

Although for the purposes of this report we isolate our analysis of climate impacts to those that occur within the US, the global nature of food production cannot be overlooked (B. M. J. Roberts and Schlenker 2013). The response of global agricultural systems to a changing climate may mean production shifts as some regions become more or less suitable for agriculture. The effects of climate on crop and food production are already evident in several key producing regions of the world, with recent periods of rapid food and cereal price increases following climate extremes (Porter et al. 2014). By the 2030s global average yields will *likely* be negatively impacted, with reductions *more likely than not* to be as much as 5% beyond 2050 and *likely* by the end of the century (Porter et al. 2014). The reductions will coincide with growing global demand, which is projected to increase by approximately 14% per decade until mid-century (Alexandratos and Bruinsma 2012; Porter et al. 2014).

These shifts will be reflected in changing global production and commodity prices, all of which will impact US producers, and, in turn, how they choose to respond. Due to the complexity of estimating the impacts of climate change on global agricultural production, price, and trade, we focus in this report on only those impacts that occur within the US in the absence of any changes to global trade or prices. In addition, we do not model how farmers will change which crops they grow, since we lack robust empirical evidence to quantify these changes. Historical anecdotes – such as the Dust Bowl – suggest this may be an important margin for future adjustments (Feng, Oppenheimer, and Schlenker 2013; Hornbeck 2012).

In an increasingly interconnected global market, the effects of climate change on global food production and prices will impact US farmers and other agricultural producers, as well as American consumers. Regional climatic changes may shift the distribution and costs of production across the globe over time, while extreme events may impact food security and price volatility. As a significant agricultural exporter, price and production shocks from extreme climate events in the US can have reverberations globally, though the globalized system can also act as a buffer to reduce the localized impacts of events in the US (Godfray et al. 2010).

The US imports about a fifth of all food consumed in the US, making food prices and supply vulnerable to climate variations in other parts of the world. Climate extremes in regions that supply the US with winter fruits and vegetables, and in particular tropical products such as coffee, tea, and bananas, can cause sharp reductions in production and increases in prices. Volatility in supplies and prices of internationally traded food commodities have a significant effect on decisions made by US agricultural producers and determine prices US consumers pay for such goods. Fluctuations and trends in food production are widely believed to have played a role in recent price spikes for wheat and maize, which followed climate extremes in 2008 and 2011. Between 2007 and 2008, the FAO food price index doubled; this was due to a confluence of factors, one of which was extreme weather conditions in major wheat and maize exporters including the US, Australia, and Russia (Food and Agriculture Organization of the United Nations 2011). Such extreme events have become more likely as a result of recent climate trends, and may be more frequent in the future, contributing additional volatility to an already complex global agricultural system.

The IPCC has reported that projected changes in temperature and precipitation by 2050 are expected to increase food prices, with estimates ranging from 3 to 84%. Projections of food prices that also account for the CO_2 fertilization effect (but not ozone and pest and disease impacts) range from -30% to +45% by 2050, with price increases about as likely as not. This does not take into account variations in regional effects or the effect of extremes, which can be a major contributor to variability in productivity and prices. Compound events where extremes have simultaneous impacts in different regions (as was witnessed in 2008 and 2011), driven by common external forcing (e.g. El Niño), climate system feedbacks, or causally unrelated events, may have additional negative impacts on food security and production, though there are very few projections of such compound extreme events and the interactions between multiple drivers are difficult to predict.

Quantifying these effects, in their agricultural and economic terms, is an extremely difficult task, requiring assumptions about the myriad climate and non-climate factors that interact to determine food security and prices, both at home and abroad. While all aspects of food security are potentially affected by climate change, including food access, utilization, and price stability, there is limited direct evidence that links climate change to food security impacts (Porter et al. 2014).

hotter summers to be offset by milder winter conditions (Adams et al. 1999).

The majority of American livestock raised in outdoor facilities, and therefore exposed to rising temperatures and increased heat stress, are ruminants (goats, sheep, beef and dairy cattle). Within limits, these animals can adapt to most gradual temperature changes, but are much more susceptible to extreme heat events (Mader 2003). Impacts are less acute for confined operations that employ temperature regulation, which house mostly poultry and pigs, though management and energy costs associated with increased temperature regulation will increase. Confined operations are not immune to the effect of rising temperatures, which can contribute to livestock heat stress. Despite modern heat-abatement strategies, heat-induced productivity declines during hot summers – including reduced performance and reproduction as well as mortality – cost the American swine industry, for example, nearly $300 million annually (St-Pierre, Cobanov, and Schnitkey 2003).

Current economic losses incurred by the US livestock industry from heat stress, most from impacts on dairy and beef cattle, have been valued at $1.7 to $2.4 billion annually. Nearly half of the losses are concentrated in a few states (Texas, California, Oklahoma, Nebraska, and North Carolina). Exposure to high temperature events can be extremely costly to producers, as was the case in 2011, when heat-related production losses exceeded $1 billion (NOAA 2013). Large-scale commercial dairy and beef cattle farmers are most vulnerable to climate change and the expected rise in high heat events, particularly since they are less likely to have diversified.

Other, less well-studied impacts to the livestock sector from expected climate change include indirect effects of warmer, more humid conditions on animal health and productivity through promotion of insect growth and spread of diseases. Warming is also expected to lengthen forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al. 2010; Izaurralde et al. 2011; J. Hatfield et al. 2014). One study identified significant expected declines in forage for ranching in California, even under more modest climate changes (Franco et al. 2011).

Studies of the potential effects of climate change have projected the resulting impacts to productivity through factors such as change in days to market and decrease in annual production. One study found that, given expected warming by 2040, days to market for swine and beef may increase 0.9 to 1.2%, with a 2.1 to 2.2% decrease in dairy milk production (Frank et al. 2001). By 2090, days to market increased 4.3 to 13.1% and 3.4 to 6.9% for swine and beef, respectively, with a 3.9 to 6.0% decrease in dairy production as a result of heat stress.

Relatively few economic impact studies have estimated the costs of climate-related impacts on productivity and management costs of the livestock and dairy sectors, as they involve accounting for the complex and interactive direct and indirect effects, such as lowered feed efficiency, reduced forage productivity, reduced reproduction rates, and assumptions about adaptive actions such as modifying livestock housing to reduce thermal stress. In the absence of such estimates, most system-wide economic impact assessments do not account for the potential direct costs and productivity effects of climate change on livestock, forage, and rangeland production (Izaurralde et al. 2011; Antle and Capalbo 2010).

CHAPTER 7

Labor

Labor is a critical component of our economy. Even slight changes in the productivity of the American workforce have a significant effect on overall economic output. Labor productivity improvements have been an important source of past GDP growth in the US and, as a result, is an area of extensive study. Of particular interest has been the identification of optimal working conditions in a variety of economic sectors, including workplace environment and exposure to a variety of climate-related factors (Seppanen, Fisk, and Lei 2006; Wyon 2000). Sub-optimal environmental conditions do more than simply make workers uncomfortable. They also affect workers' ability to perform tasks, and can influence work intensity and duration, all of which impact overall labor productivity. Thus the environmental sensitivity of individual workers represents a pathway through which climate change can influence all economic sectors, even those previously thought to be insensitive to climate (Hsiang 2010).

Climate change will affect workers, workplace environments, and ultimately worker productivity. Rising average and extreme temperatures will likely have the most direct effect on working conditions. Climate change may also affect the US labor force indirectly through increased storm damage, flooding, wildfires, and other climate-related changes, resulting in disruption of business and production in some areas. Health-related impacts, both negative and positive, will affect Americans' ability to work. While we provide an overview of the range of potential climate change impacts to US labor, our analysis focuses specifically on the effect of changing temperatures on labor supply.

BACKGROUND

Rising average temperatures, greater temperature variability, and more frequent and severe temperature extremes will make it harder to sustain optimal working conditions. Higher temperatures can change the amount of time allocated to various types of work as individuals spend more time indoors to beat the heat, or as outdoor laborers take more frequent breaks to cool off (Graff Zivin and Neidell 2014). Climate-related factors can also affect worker performance, affecting cognitive capacity and endurance (Mackworth 1948; Ramsey and Morrissey 1978). Increased use of air conditioning for indoor labor and schedule changes for outdoor labor can mitigate some, but not all, of the effects.

Not all American workers will be equally affected; the impact of climate differs across sectors of the economy. Workers in agriculture, construction, utilities, and manufacturing are among the most exposed (Graff Zivin and Neidell 2014). These "high-risk" sectors, which account for roughly 9% of the US labor force, are affected by changes both in average temperatures and temperature extremes. Workers in high-risk sectors are at particular risk of heat stress because of the internal body heat produced during physical labor. Higher temperatures and heat strain, however, can also impact workers in stores and offices (Kjellstrom and Crowe 2011). Thermal conditions inside commercial buildings are often not well-controlled, and can vary considerably over time as outdoor conditions change, making it difficult to ensure optimum temperatures for worker comfort and productivity (Seppanen, Fisk, and Lei 2006). The impact of projected temperature changes on these low-risk sectors is considerably lower than their high-risk peers.

The first empirical study of the impact of climate on labor productivity observed that performance in labor-intensive sectors declined nonlinearly at high temperature (Hsiang 2010), mirroring the response of subjects in laboratory experiments (Mackworth 1948; Ramsey and Morrissey 1978; Seppanen, Fisk, and Lei 2006; Wyon 2000) . Since then, studies have found that labor supply, measured in work hours, declines moderately at higher temperatures. This is true for a range of industrial sectors, though there are substantial differences in climate exposure among them. Temperature impacts endurance, fatigue, and cognitive performance, all of which can contribute to diminished "work capacity" and mental task ability, as well as increased accident risk (Kjellstrom and Crowe 2011). In order to cope with heat, workers often reduce the pace or intensity of their work, or take additional breaks, which reduces overall worker output. One study found that at temperatures above 85°F, workers in high-risk industries reduce daily output by as much as one hour, with much of the decline occurring at the end of the day when fatigue from prolonged heat exposure sets in (Graff Zivin and Neidell 2014).

Extreme heat stress, brought on by more intense or extended days of exposure to high temperatures, can induce heat exhaustion or heat stroke and can significantly reduce ability to carry out daily tasks. Estimates of the impact of higher average temperatures and heat stress on work capacity indicate that labor productivity in high-risk sectors is highly vulnerable to temperature extremes, despite our ability in many instances to mitigate these impacts. According to Center for Disease Control records, from 1992–2006 there were 423 worker deaths attributed to heat exposure in the US, nearly a quarter from the agriculture, forestry, fishing, and hunting industries (Luginbuhl et al. 2008).

Humidity can exacerbate these effects even further, particularly in mid-latitudes during summer months of peak heat stress. Occupational thresholds developed for industrial and US military labor standards provide guidelines for assessing labor capacity, or the ability to safely perform sustained labor under heat stress. Studies using these thresholds have found that the southeastern US is particularly vulnerable (Dunne, Stouffer, and John 2013). In our analysis, the Southeast is projected to continue to have the country's highest wet-bulb temperatures (the combination of heat and humidity) over the coming century, though the Midwest and Northeast will likely see larger increases.

OUR ANALYSIS

To quantify the potential impact of climate change on labor, we rely on statistical analyses that isolate the effect of temperature and other climatic variables on individuals' labor supply in the United States. Because there are strong cross-county patterns in labor markets, as well as strong trends over time (that may differ by location) and over seasons, we rely on the only analysis that accounts for these patterns when measuring the effect of temperature on labor supply.

Graff Zivin and Neidell (2014) provide nationally representative estimates that satisfy these criteria, which we use to construct quantitative projections. They examine how individuals around the country allocated their time on randomly selected days between 2003 and 2006, identifying the incremental influence of daily maximum temperature on the number of minutes individuals work, using data collected through the American Time Use Survey (Hofferth, Flood, and Sobek 2013). The individuals in the survey are considered nationally representative and each individual records the allocation of their time during a single 24-hour period.

Figure 7.1 and Figure 7.2 display the impact functions derived from Graff Zivin and Neidell for individuals working in high and low-risk industries, i.e. industries where individuals are likely and unlikely, respectively, to be strongly exposed to unregulated temperatures according to the National Institute for Occupational Safety and Health (Graff Zivin and Neidell 2014).

Figure 7.1: Temperature and High-risk Labor Productivity

Change in minutes worked for high-risk laborers as a function of daily maximum temperature (F)

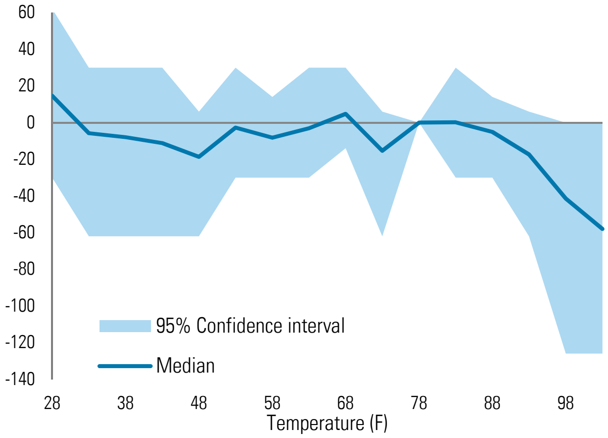
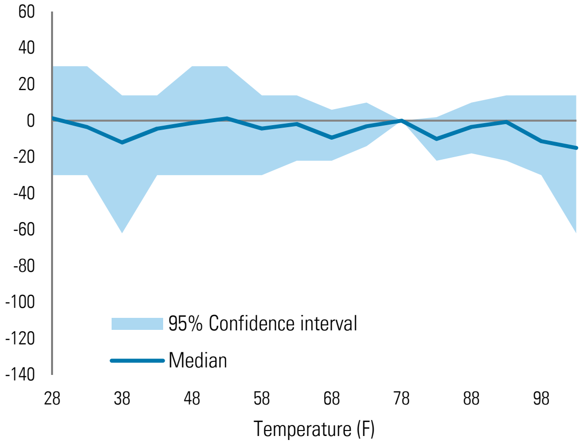


Figure 7.2: Temperature and Low-risk Labor Productivity

Change in minutes worked for low-risk laborers as a function of daily maximum temperature (F)



Temperature has little influence on labor supply in either category until very high daily maximum temperatures are reached, at which point individuals begin to supply less labor approximately linearly – the nonlinear structure of this response is broadly consistent with both laboratory studies (N. Mackworth 1947) and macroeconomic evidence (Hsiang, 2010). As one might expect, the response in high-risk industries is more negative at high temperatures, probably because the working environment of these individuals more closely reflects ambient outdoor temperatures. On average, increasing a county's daily maximum temperature from 76 to 80°F to greater than 96°F decreases high-risk labor supply by 41 to 58 minutes per day and low-risk labor supply by 11 to 15 minutes per day. Since baseline hours worked are 7.66 and 6.92 for these two groups of workers, these reductions represent roughly 9 to 13% and 3 to 4% of total labor supplied in these two classes of industries. Graff Zivin and Neidell consider whether decreased working hours caused by high temperatures cause workers to supply additional labor at other times (to make up for lost work). They find there is essentially no temporal displacement of labor across days. They also examine whether there is evidence that populations adapt by examining if the

Figure 7.3: Change in labor productivity in "high-risk" sectors

Percent

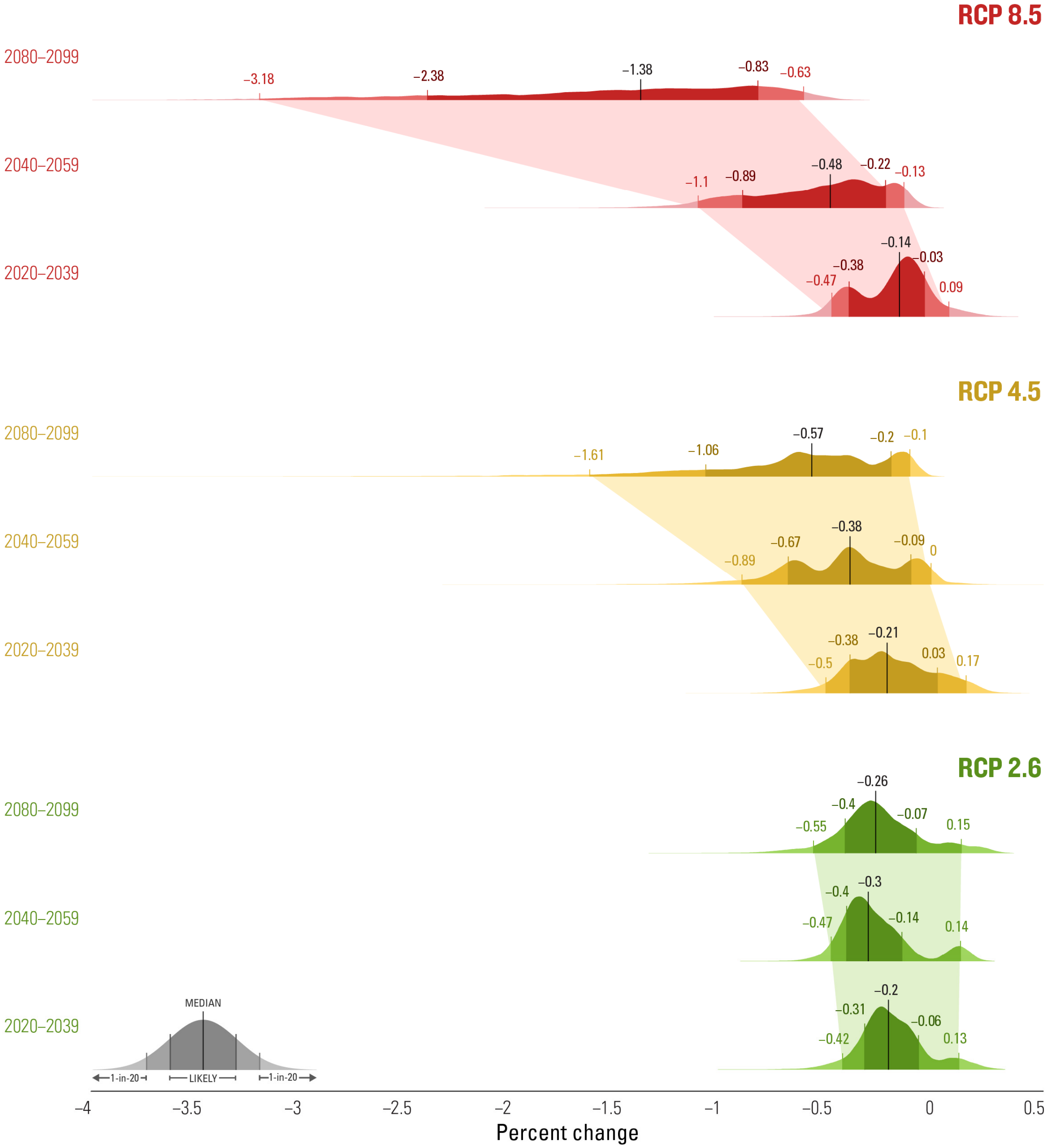
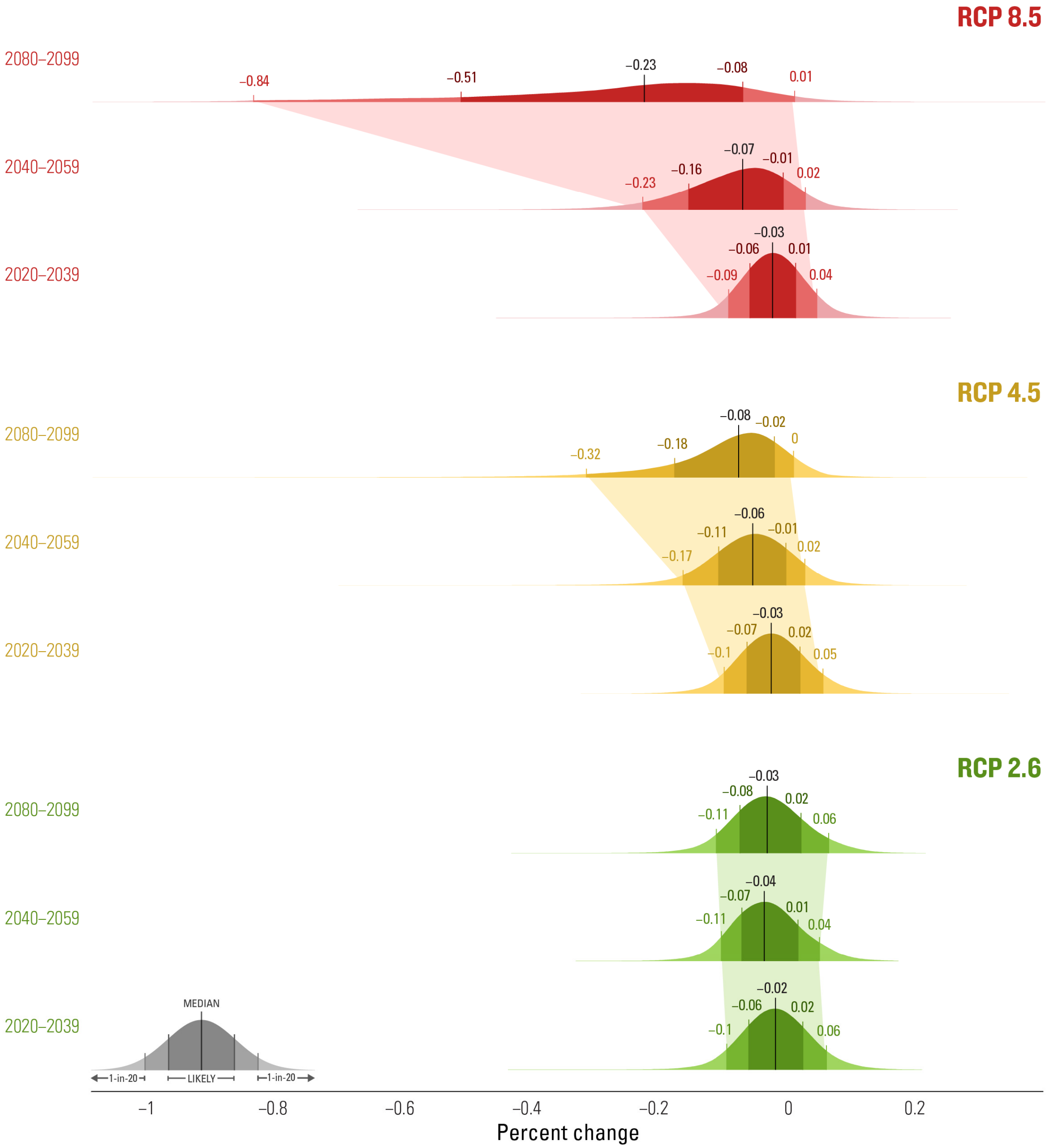


Figure 7.4: Change in labor productivity in "low-risk" sectors

Percent

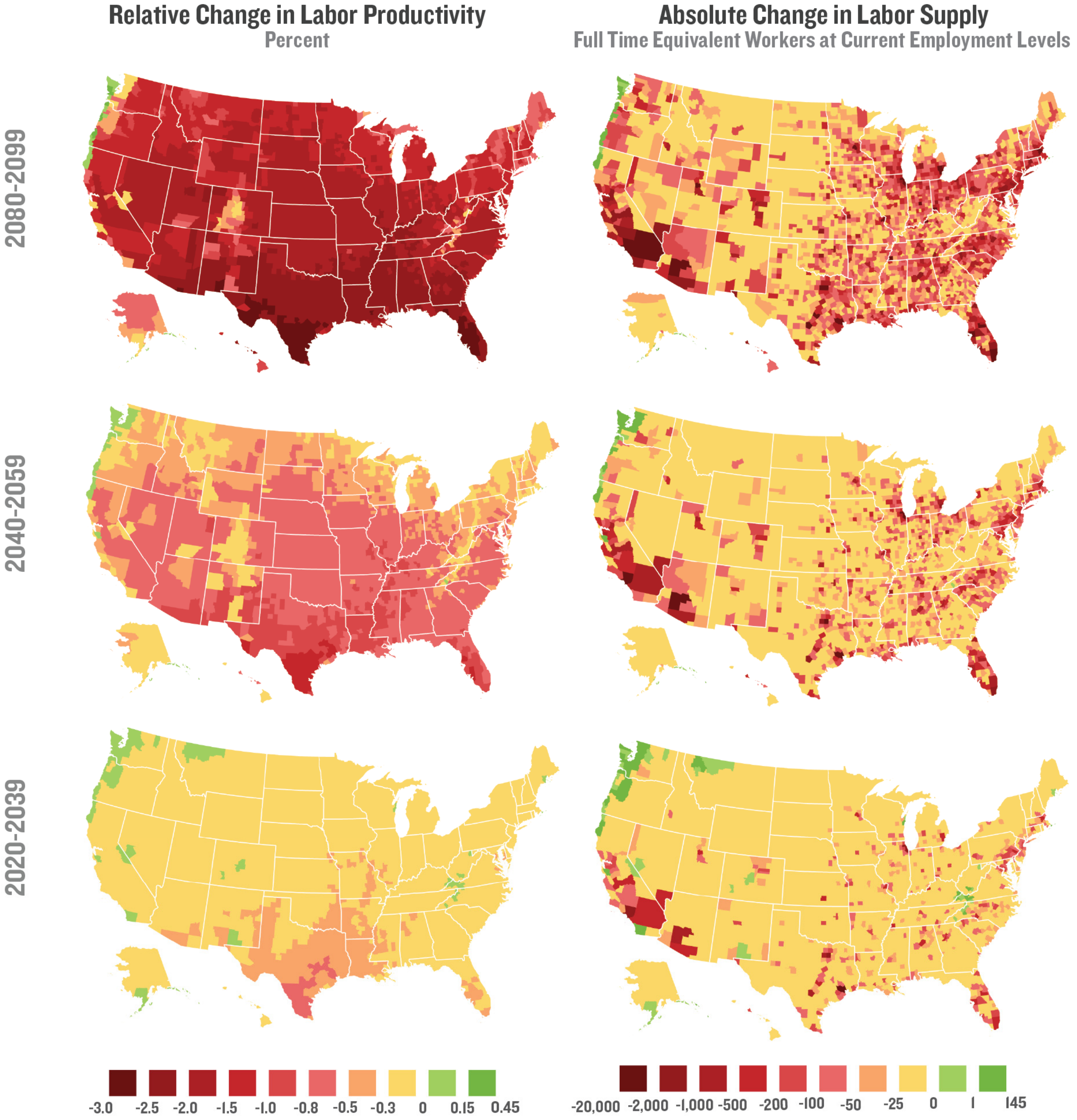


sensitivity of labor supply to temperature is lower in counties that are hotter on average. They find ambiguous evidence, due in part to statistical uncertainty. Taken at face value their estimates suggest warmer counties have a shallower response to temperature (consistent with adaptation), although adverse labor responses emerge at a lower temperature threshold in warmer counties (inconsistent with adaptation).

It is possible that these differences are spurious and due to sampling variability, since the statistical uncertainty of these estimates is large and the responses across hot and cool counties are not statistically distinguishable.

Figure 7.5: Change in labor productivity in “high-risk” sectors of the economy

RCP 8.5 median



As with other impacts, we explore possible adaptive responses in Part V.

Using the dose-response functions obtained by Graff Zivin and Neidell, we simulate changes in labor supply under different climate scenarios relative to a future in which the climate does not change after 2012. Importantly, within each scenario we separately account for uncertainty in climate models, weather, and statistical results, causing our future projection to be a probability distribution of potential outcomes at each moment in time.

To assess potential future impacts of climate change on labor productivity, we project changes in national labor supply, using the dose-response functions obtained by Graff Zivin and Neidell, under different climate scenarios relative to a future in which the climate does not drive economic changes after 2012—although other social and economic trends are assumed to continue. Within each scenario we account for uncertainty in climate models, weather, and statistical results, causing our projection to be a probability distribution of potential outcomes at each moment in time.

When we consider the potential impact of changes in temperature on labor supply, we find that high-risk labor supply generally declines by mid-century and the range of likely changes are unambiguously negative by late-century for all scenarios (Figure 7.3). In RCP 8.5, we find high-risk labor *likely* declines by 0.2% to 0.9% by mid-century and by 0.8% to 2.4% by late-century, with a 1-in-20 chance that late-century labor supply falls either by more than 3.2% or less than 0.6%. Examining low-risk labor supply, we find that losses are more modest, with *likely* late-century losses in RCP 8.5 of 0.1% to 0.5%, with a 1-in-20 chance that labor supply falls more than 0.8% or less than 0.01% (Figure 7.4).

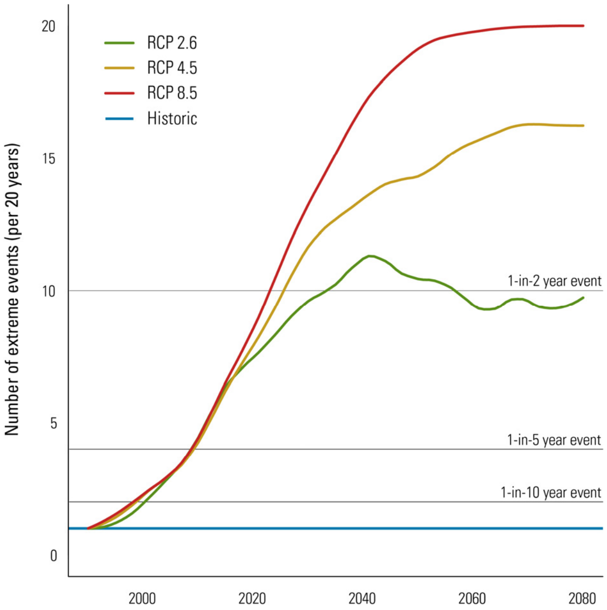
Projected changes are smaller in magnitude for RCP 4.5 and RCP 2.6, with the *likely* range for high-risk labor supply spanning -0.2% to -1.1% for RCP 4.5 and -0.1% to -0.4% for RCP 2.6 by late-century. The 1-in-20 outcomes span a narrower range than RCP 8.5, with high-risk labor having a 1-in-20 chance of falling by more than 1.6% or less than 0.1% for RCP 4.5 and more than 0.6% or increase by 0.1% for RCP 2.6. Projected changes for low-risk labor are very small in RCP 2.6 and are modest in RCP 4.5 where the *likely* range of changes span -0.02% to -0.18%.

For both classes of labor, the distribution of potential changes broadens moving forward in time for RCP 8.5 and 4.5, but modestly so for low-risk labor in RCP 4.5 (Figure 7.3). By late-century in RCP 8.5, changes in labor supply exhibit a 90% confidence interval spanning 2.5 percentage points for high-risk labor and 0.8 percentage points for low-risk labor. There is essentially no change in the spread of potential outcomes under RCP 2.6 for either type of labor.

In percentage terms, the spatial distribution of projected impacts is similar across the country in the median RCP 8.5 projection (Figure 7.5, left column), with only a slight reduction in productivity losses for northern and mountainous regions and small gains in productivity in a few coastal northwestern counties. For a sense of scale, we compute changes in total productivity losses assuming there is no growth in the labor force and then convert this lost productivity to "full time equivalent workers" (Figure 7.5, right column). These losses are more strongly influenced by the locations of urban centers (e.g. Dallas, Atlanta, and Chicago) than regional spatial patterns of climate change.

Figure 7.6: Projected change in the frequency of national labor supply losses due to temperature equal to or worse than historical 1-in-20 year losses

Expected frequencies across climate models and weather. Frequencies are plotted in the first year of each 20 year period.



The impacts above are described in terms of average changes over 20 year intervals. These averages are useful for describing persistent economic changes in future periods, but they mask short-lived events that may only last a year or two but have substantial economic consequences. Within each 20 year window the likelihood of extreme annual events, such as a very hot year, evolves with the climate. One way to describe how the likelihood of extreme events changes is to examine how frequently we expect to experience years that are as damaging as the worst year experienced during two decades of recent history, a so called "1-in-20 year event". In Figure 7.6 we plot the estimated number of years that will have high-risk labor supply losses larger than historically observed 1-in-20 year losses (due to temperature). For each year we plot the expected number of these extreme years that will be experienced in the 20 years that follow; i.e., we plot what the immediate future appears like to an individual in a given year. By 2030, labor supply losses that used to occur only once every 20 years will be expected to occur roughly ten times in the following 20 years under RCP 2.6, with even higher frequencies in RCP 4.5 and 8.5. By 2080, these events will be occurring roughly 16 times every 20 years in RCP 4.5 and every year in RCP 8.5. The relative frequency of analogous events in low-risk labor is essentially the same for all scenarios and time periods.

It is important to note that these estimates assume the national distribution of workers remains fixed relative to the average distribution from 2000-2005 and that air conditioning and other time-allocation behaviors remain fixed. It is likely that some amount of additional adaptation will occur in the presence of climate change, but existing research is currently insufficient to conduct a systematic evaluation of adaptive behaviors that affect labor supply.

We also note that our estimates only account for changes to labor supply, which reflects a change in the total quantity of hours that each individual works (the extensive margin). It is extremely likely that the intensity of each workers' effort (the intensive margin) will also change with warming, as has been observed in numerous laboratory experiments (Mackworth 1948; Ramsey and Morrissey 1978; Wyon 2000), although the magnitude of this effect has not been measured in nationally representative and ecologically valid samples, so it is not included in this analysis. The laboratory-derived dose-response function of labor intensity is similar in magnitude (in percentage terms) to the response of high-risk labor, so accounting for this effect would roughly double the size of the impacts that we present here.

OTHER IMPACTS

The US labor force is comprised of people, so any one of the number of climate-related impacts on the working population will ultimately affect the supply and quality of the US labor market. In the following chapter we report on the impacts to Americans' health, including increased respiratory illness due to increases in pollution, allergens, and pollens as a result of rising temperatures. Changes in the geographic ranges and seasonality of vector-borne infectious diseases will also affect health and productivity for some working populations. Outdoor workers are the most at risk of vector-borne infections because of their exposure to species that carry disease (Bennett and McMichael 2010). The risk of transmission may increase under climate change as warm, wet conditions contribute to greater number of vectors, a change in their habitat range, and as transmission becomes more efficient. Vector-borne diseases are already responsible for considerable losses in economic productivity every year, primarily in regions where a vector-borne disease is endemic. We have not captured losses due to illness in our analysis, but these will certainly affect labor supply and productivity.

Illness, injury, and even death from increased damages caused by hurricanes and other storms, flooding, wildfire, and other extreme weather will also affect the labor market, although quantifying their impact is not straightforward. In the months following an extreme storm, depending on the severity of the storm, there can be negative impacts on total employment and earnings, as well as disturbances across labor sectors (Deryugina 2011; Camargo and Hsiang 2012). Labor impacts are not limited to the areas hit by the storm; a study of 19 hurricanes that hit Florida between 1988 and 2005 found that labor markets in counties neighboring affected county became more competitive, with falling wages, due to the movement of skilled workers out from the affected county (Belasen and Polachek 2009). These effects were found to dissipate over time, though long-run impacts are not generally understood as they are more complex and more difficult to measure.

CHAPTER 8

Health

The American public health system has been designed to promote the health of American communities and residents, and to prevent disease, injury, and disability. Huge strides in public health have been made over the last century, thanks in part to greater wealth, scientific advances and innovation, increased education, and a more developed public health infrastructure (e.g., water treatment plants, sewers, and drinking water systems). Improvements in disaster planning and emergency response have also improved public health outcomes in response to disease outbreak and epidemics, as well as floods, heat waves, storms, and other disasters that can harm public health. These advances have relied on years of assessment of the evolving vulnerabilities and resilience of American communities and populations, the various factors that contribute to health impacts in those communities, and the potential risks, both likely and unlikely, that threaten public health.

Climate change is an emerging factor in the risk landscape for American public health. According to the US National Climate Assessment, there is very high confidence a wide range of health effects will be exacerbated by climate change in the US (Joyce et al. 2013). Human health and well-being are impacted by climate change both through gradual changes in average temperature and precipitation, and also through changing patterns of extreme events. Incremental effects of increasingly warmer summer temperatures will lead to increased rates of ozone formation and exacerbate respiratory problems. On the other hand, milder winters may reduce cold-related deaths. Such changes will also create conditions that can disrupt natural systems that affect public health. For example, altering the length and severity of allergy seasons and changing the patterns and spread of vector-borne diseases, such as Lyme disease. A changing frequency and intensity of extreme weather events, such as heat waves, floods, droughts, storms, and wildfires, create less predictable but potentially serious risk of disease, exposure to dangerous pollutants, injury, and even death.

Climate impacts will be wide ranging, and highly variable across regions and populations. There will be positive as well as negative impacts, depending on the local circumstances, but on the whole, net impacts are likely to be negative for most regions in the US. The cause and effect chain between climate and health impacts is complex, and climate change is one of many critical factors affecting public health outcomes. The magnitude and distribution of these effects will depend on the baseline vulnerability of populations over time, which are determined by a whole host of variables including population age, socioeconomic status, and race, as well as regional and local differences in critical public health infrastructure and investments. Evidence indicates that, absent changes that go beyond current prevention and adaptation activities and with increasing population susceptibilities (aging, limited economic resources, etc.), some existing health threats will intensify and new health threats will emerge (Joyce et al. 2013). While we provide an overview of a number of potential climate change impacts to health, our analysis focuses specifically on the temperature-related impacts to mortality.

BACKGROUND

One of the most well-studied impacts of climate on public health is the effect of temperature and, in particular, extreme hot and cold days. Impacts will be felt differently across the US, with some northern regions experiencing milder winters and reduced exposure to extreme cold and snow, while other regions will see longer and more frequent heat waves. The level of vulnerability of populations to these risks will depend on the severity of the extremes, as well as on society's adaptive response.

Across the US most regions are already experiencing the types of impacts that could be exacerbated by a changing climate. Many people remember the 1995 Chicago heat wave that brought nine consecutive days of record-setting daytime and nighttime temperatures, unprecedented in the preceding 120 years over which records have been kept. Nearly 800 people died from heat exposure, and thousands of excess emergency room and hospital visits were recorded as a result of the heat wave (Hayhoe et al. 2010). The 2006 heat wave that hit much of California was exceptional both for its intensity and duration, setting records for most consecutive days over 100°F, and resulted in 140 deaths, over 16,000 excess emergency room visits, and 1,180 excess hospitalizations (Knowlton et al. 2009). Children under the age of four and the elderly tend to be particularly vulnerable.

Heat stress can lead to increased hospitalizations due to heat exhaustion and heat stroke; dehydration and electrolyte disorders; acute renal failure, nephritis, and nephrotic syndrome; and other heat-related illnesses. (Knowlton et al. 2009; Kovats and Ebi 2006). Increased mortality during heat waves has been attributed mainly to cardiovascular illness and diseases of the cerebro-vascular and respiratory systems, especially among the elderly (Anderson and Bell 2011). Heat stress can rapidly become life threatening among those with limited access to immediate medical attention and often people with severe heat stroke symptoms have little time to seek treatment. These impacts have been most severe for people over 65 and those with pre-existing conditions (Zanobetti, O'Neill, Gronlund, & Schwartz, 2012).

Some of the most well documented effects of heat stress are in big cities, in part because large populations are simultaneously exposed to extreme heat events, generating large numbers of coincident cases. In addition, urban residents may be exposed to higher temperatures than residents of surrounding suburban and rural areas because of the "heat island effect" resulting from high thermal absorption by dark paved surfaces and buildings, heat emitted from vehicles and air conditioners, lack of vegetation and trees, and poor ventilation (O'Neill and Ebi 2009).

Heat stress on local populations can also stress the public health system. In 2009 and 2010, there were an estimated 8,251 emergency department visits for heat stroke in the United States, yielding an annual incidence rate of 1.34 visits per 100,000 population (Wu et al. 2014). In times of excessive heat, these figures can jump considerably. During the 1995 Chicago heat wave, for example, excess hospital admissions totaled 1,072 (up 11%) among all age groups for the days during and immediately after the event, including 838 among those 65 years of age and older (an increase of 35%), with dehydration, heat stroke, and heat exhaustion as the main causes (Semenza et al. 1999).

Extreme heat is increasing in parts of the US, and is expected to be more frequent and intense (Joyce et al. 2013). Changes in the intensity, duration, and seasonal timing will influence mortality and morbidity effects within communities. Under all future pathways, the number of days with temperatures reaching 95°F or higher across the continental US are expected to increase from the historic (1981-2010) baseline of 15 days per year. As described in Chapter 4, under RCP 8.5, by mid-century the average American will *likely* experience two to three times the number of days over 95°F than on average from 1980-2011 (an additional 12-35 days). By late-century, the average American will *likely* experience one and half to three months of days that reach 95°F each year on average (46 to 96 days). National averages, however, say little about regional and local effects, which may be more extreme in some areas. The average resident of the Southeast, for example, will *likely* see 56 to 123 days over 95°F on average by century's end, up from only nine per year on average from 1981-2010.

At the other end of the spectrum, milder winters may actually have a positive impact on public health. Deaths and injuries related to extreme winter weather, as well as respiratory and infectious disease related to extreme cold, are projected to decline due to climate change (Medina-Ramón and Schwartz 2007). Across the continental US, winter temperatures will *likely* be 2.5 to 6.2°F warmer on average by mid-century, and 5.4 to 11.8°F warmer by century's end under RCP 8.5. The number of average days with low temperatures below freezing for the average county in the contiguous US is also expected to decrease dramatically. Under RCP 8.5, the average number of days below freezing is *likely* to drop from the 1981-2010 average of 113 days per year to 81 to 100 days by mid-century, and 52 to 81 by late-century.

OUR APPROACH

Given what we know about observed climate impacts on health in the US over the past few decades, what can we predict in terms of likely future impacts? The most systematically documented relationship is the impact of rising temperatures on mortality, which can be estimated nationally because the Center for Disease Control (CDC) compiles and releases national mortality data. Morbidity impacts are more difficult to study because national data are not readily available.

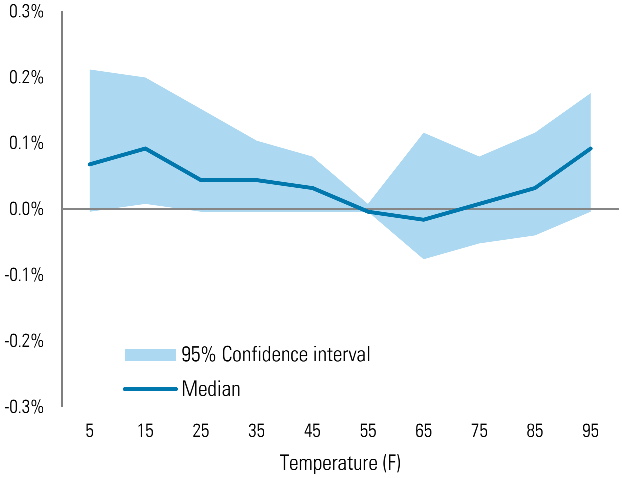
To quantify the potential impact of climate change on mortality, we rely on statistical studies that isolate the effect of temperature on mortality in the United States. Because there are strong cross-county patterns in mortality rates, as well as strong trends over time (that may differ by location) and over seasons, we rely on studies that account for these patterns when measuring the effect of climate variables on mortality rates. Two studies provide nationally representative estimates that satisfy these criteria, which we use to construct quantitative projections. Deschênes and Greenstone (2011) examine county-level annual mortality rates during 1968-2002, and Barreca et al. (2013) examine state-level monthly mortality rates during 1960-2004 (Deschênes and Greenstone 2011; Barreca et al. 2013).

Both studies identify the incremental influence on mortality for each additional day at a specified temperature level using data collected by the CDC on all recorded deaths in the United States. Deschênes and Greenstone provides greater spatial resolution, while Barreca et al. provides greater temporal resolution, thus the studies may be complimentary.

Figure 8.1 displays the impact function derived from Deschênes and Greenstone and Barreca et al. Both studies largely agree that both low and high daily average temperatures increase overall mortality rates relative to the lowest risk temperature range of 50 to 59°F, with annual mortality rates increasing roughly .08% for an additional single day with mean temperature exceeding 90°F. In both sets of results, low temperatures tend to pose a differentially high risk to middle-age (45 to 64 years) and older (>64 years) individuals. Deschênes and Greenstone estimate that high temperatures pose a differentially high risk to infant (<1 year) and older individuals, while Barreca et al. find that high temperatures pose a differential high risk to infants and younger (1 to 44 year old) individuals with modest proportional risks imposed on the elderly. Barreca et al. examine causes of mortality and find that high-temperature deaths are usually attributed to cardiovascular or respiratory disease, while low-temperature mortality is driven most strongly by respiratory disease as well as infectious and cardiovascular disease. These findings are generally consistent with studies of specific cities, regions, and sub-populations during extreme climatic events, (e.g., B. G. Anderson & Bell, 2009; Barnett, 2007; Frank C Curriero et al., 2002) and are nationally representative.

Figure 8.1: Temperature impact on mortality

Percentage change in mortality rate (deaths/100,000) vs. daily maximum temperature (F)



It is thought that one effect of high temperatures is to induce an acceleration or "forward displacement" of mortality that would have occurred in the near future anyway, even in the absence of a high temperature event (a phenomena sometimes known as "harvesting") (Deschenes and Moretti 2009). Deschênes and Greenstone and Barreca et al. do not extensively consider the extent to which increases in mortality rates caused by high and low temperatures cause forward displacement of mortality, although the authors attempt to account for possible temporal displacement by examining mortality over relatively long windows of time: a year for Deschênes and Greenstone and two months for Barreca et al. So long as temporal displacement occurs within these time frames, then these estimates will describe the net effect of a temperature event. Deschênes and Greenstone note that, since total mortality is fixed in the very long run, the welfare impact of climatic changes are best measured by changes in total life-years. However, for simplicity and clarity, we focus here on total premature mortality by age group.

Climate variables are not the only factor influencing mortality effects on US populations. Adaptation, primarily through increased use of air conditioning, mitigates the mortality risk of extreme temperatures. Barecca et al. study whether there is evidence that populations adapt by examining if the sensitivity of mortality to temperature declines over time or is lower in counties that are hotter on average. Barecca et al. find that the response of mortality to temperature has declined substantially since the early 20th century (1929-1959), with larger reductions in high-temperature mortality. Consistent with this evidence of adaptation over time, Barecca et al. find that modern high-temperature mortality is lowest in hot southern counties and modern low-temperature mortality is highest in these counties. They argue that these patterns of sensitivity inversely reflect patterns of air conditioning adoption, a likely mechanism through which populations adapt. Here we assume that the sensitivity of mortality to temperature does not change relative to the present and we explore the extent to which increased use of air conditioning and other adaptations can mitigate these deaths in the Part V of this report (Strategies of Climate Risk Management). However, it is important to note that air conditioning is unlikely to mitigate all temperature related deaths because only a portion of deaths occur due to inadequate air conditioning and the impact function we use here is similar to the response recovered when we examine only populations in the American South, where air conditioner penetration is roughly 100% (Barrecca et al., 2013).

To assess potential future impacts of climate change on mortality, we simulate changes in mortality rates under different climate scenarios relative to a future in which the climate does not drive changes in health after 2012—although other social and economic trends are assumed to continue. Within each scenario we account for uncertainty in climate models, weather, and statistical results, causing our projection to be a probability distribution of potential outcomes at each moment in time.

When we consider the potential impact of changes in temperature, we find that mortality rates do not generally increase until late-century except for populations aged 1 to 44 years old, which exhibit elevated mortality for all time periods (Table 8.1) because this age group does not benefit from reductions in in cold weather. In RCP 8.5, we find annual all-age mortality rates are *likely* to change by -0.5 to 6.6 deaths per 100,000 by mid-century and 3.7 to 21 deaths per 100,000 by late-century, with a 1-in-20 chance that late-century increases are below 0.6 deaths or exceed 36 deaths per 100,000 relative to baseline mortality rates. Results are roughly similar for all age groups (Table 8.1) except the over-65 age group where mortality rates are more responsive to both warming and cooling climate changes in all periods, with a *likely* range of changes spanning -23 to +18 additional deaths per 100,000 in 2020-2039, -24 to +22 by mid-century and -21 to +90 additional deaths per 100,000 by late-century.

Projected changes are modest in magnitude for RCP 4.5 and RCP 2.6, with the *likely* range of changes for all age annual mortality spanning a change of -2.5 to 5.9 deaths per 100,000 for RCP 4.5 and -2.3 to 3.2 deaths per 100,000 for RCP 2.6 by late-century. 1-in-20 outcomes span a narrower *likely* range than RCP 8.5, with a 1-in-20 chance mortality rates change by less than -4.5 deaths or more than 12 deaths per 100,000 for RCP 4.5 and less than -3.9 or more than 5.0 deaths per 100,000 for RCP 2.6. Projections for the over-65 age group are universally more extreme in magnitude, with a *likely* range of -38 to +16 deaths per 100,000 by late-century for RCP 4.5 and -25 to +17 deaths per 100,000 for RCP 2.6.

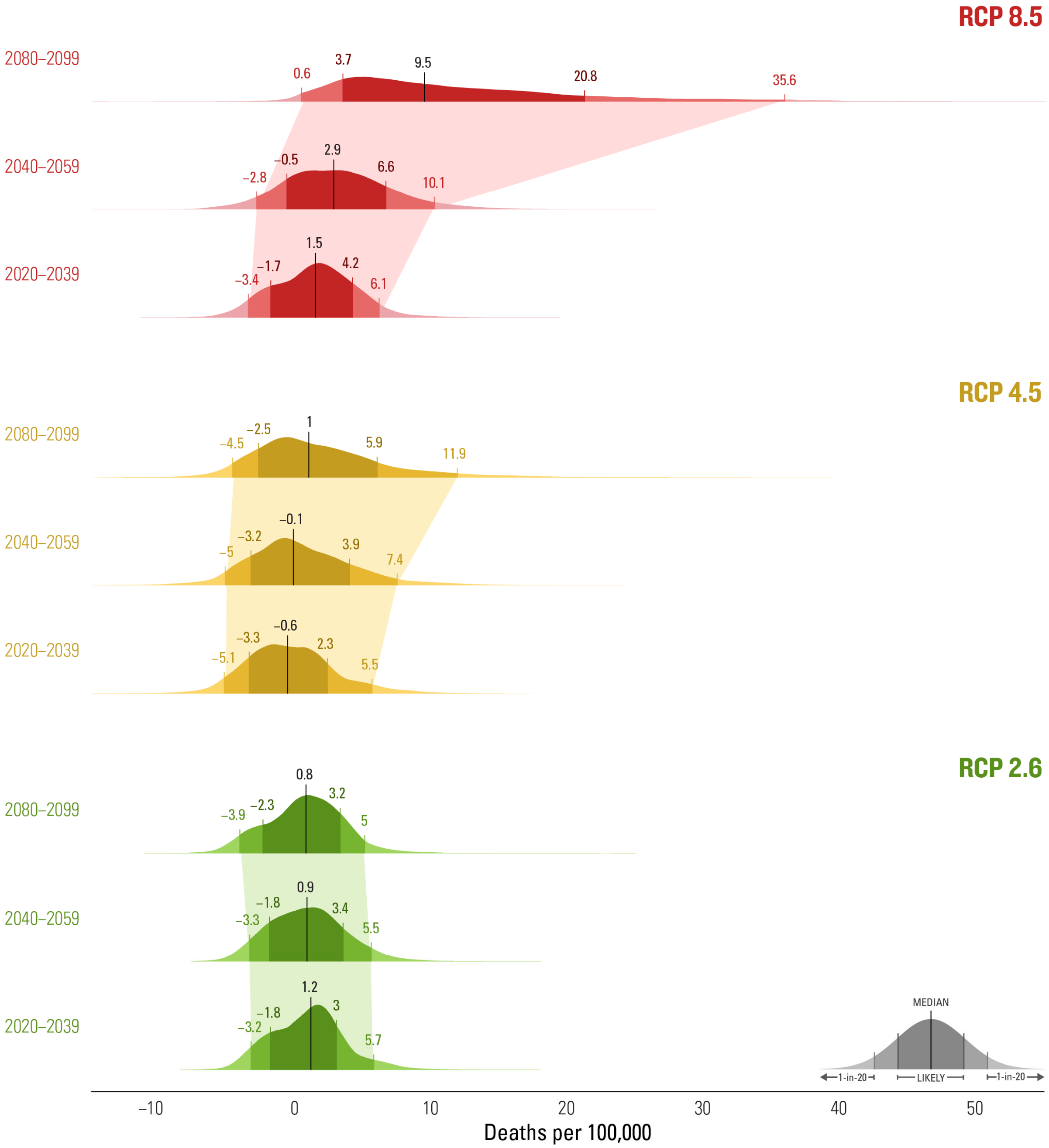
Table 8.1: Impact of future climate change to US mortality rate

Percentage change in net age-specific heat- and cold-related mortality from 2012 levels. Likely range represents 17-83% confidence band.

Mortality rate	RCP 8.5			RCP 4.5			RCP 2.6		
	1 in 20 less than	Likely	1 in 20 greater than	1 in 20 less than	Likely	1 in 20 greater than	1 in 20 less than	Likely	1 in 20 greater than
	Deaths per 100,000			Deaths per 100,000			Deaths per 100,000		
<1 year old									
2080-2099	0.7	3.2 to 17	29	-1.8	-0.4 to 4.9	9.2	-2.1	-1.1 to 2.5	3.5
2040-2059	-1.4	0.1 to 4.5	7.6	-1.9	-0.9 to 2.8	5.1	-2.2	-1.0 to 2.4	-3.6
2020-2039	-1.6	-0.9 to 2.4	3.7	-2.3	-1.4 to 1.7	3.3	-2.2	-1.0 to 2.3	-3.7
1-44 years old									
2080-2099	2.8	3.1 to 7.6	9.6	0.5	1.1 to 3.6	5.1	-0.1	0.2 to 1.5	1.9
2040-2059	0.9	1.0 to 3.0	3.5	0.3	0.5 to 2.3	2.8	-0.1	0.6 to 1.4	1.7
2020-2039	0.0	0.2 to 1.3	1.5	-0.3	0.1 to 1.2	1.5	-0.1	0.3 to 1.0	1.2
45-64 years old									
2080-2099	1.3	2.8 to 14	23	-2.4	-1.2 to 3.6	7.5	-2.2	-1.3 to 2.0	2.6
2040-2059	-1.1	0.2 to 3.6	5.3	-2.6	-1.8 to 2.3	4.3	-2.0	-1.2 to 2.0	3.1
2020-2039	-1.6	-0.9 to 2.1	3.4	-2.8	-1.7 to 1.5	3.1	-2.0	-1.9 to 1.8	3.4
65+ years old									
2080-2099	-51	-21 to 90	181	-55	-38 to 16	48	-41	-25 to 17	23
2040-2059	-43	-24 to 22	38	-48	-36 to 9.6	34	-41	-22 to 13	25
2020-2039	-35	-23 to 18	32	-41	-29 to 9.7	35	-33	-16 to 14	27

Figure 8.2: Change in national mortality rate

Net percentage change in all-age, heat- and cold-related mortality (deaths per 100,000)



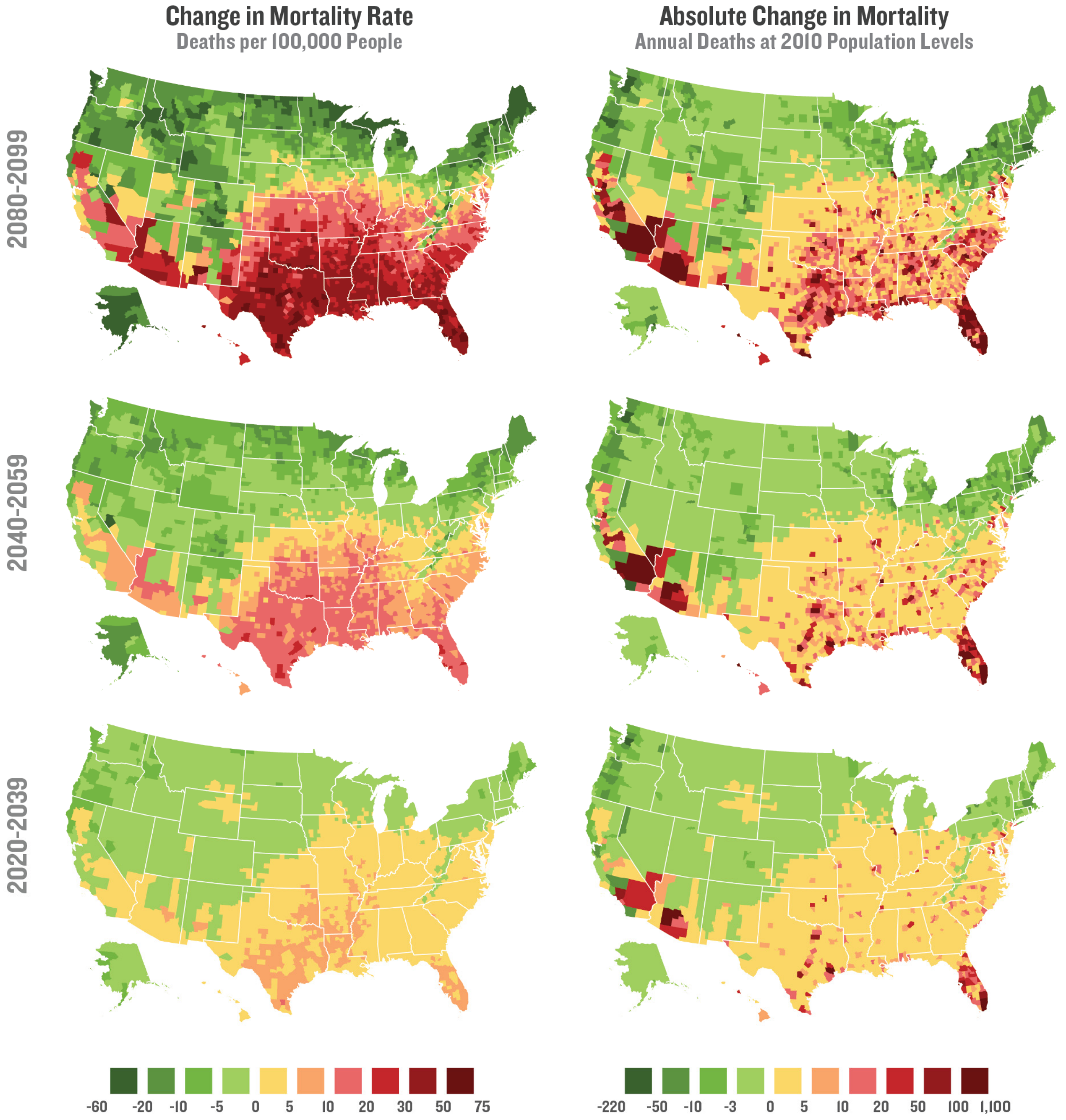
The distribution of potential changes broadens moving forward in time for RCP 4.5 and RCP 8.5, with almost no broadening for RCP 2.6 (see Figure 8.2). Changes in all-age mortality rates by late-century exhibit 90% confidence interval spanning 16.4 deaths per 100,000 in

RCP 4.5 and widens to span 35 deaths per 100,000 in RCP 8.5. Across age groups, the spread of potential outcomes is largest for ages 65+, with a 90% confidence interval that spans 232 deaths per 100,000 by end of century in RCP 8.5.

In percentage terms, the spatial distribution of projected impacts is uneven across the country (Figure 8.3), with the Southeast, Southwest, southern Great Plains, mid-Atlantic and central Midwest suffering the

Figure 8.3: Climate impact on heat and cold-related mortality

RCP 8.5 median



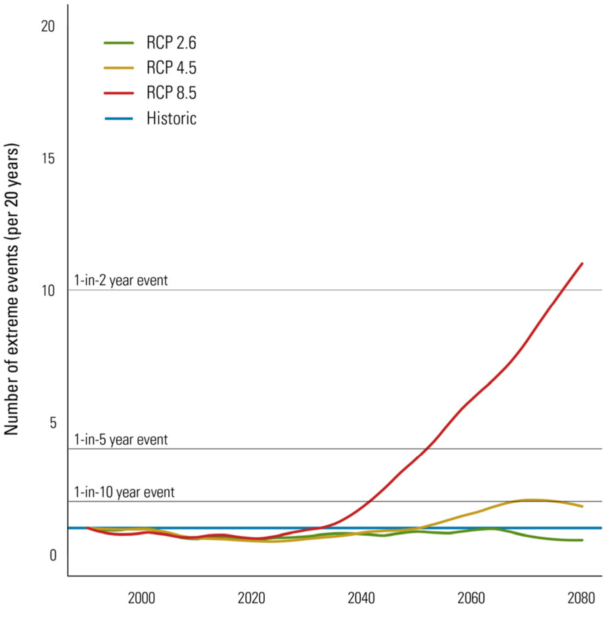
largest increases in mortality rates (deaths per 100,000 people) because the number of high temperature days in these regions increases substantially, but the baseline climate in these locations is too warm for them experience many lethally cold days initially, minimizing the gains from warming. In contrast, the Rockies, Appalachia, Northwest, northern Great Plains, northern Midwest and Northeast (except New York City and New Jersey) experience net reductions in mortality rates for the median RCP 8.5 projection because the gains from a smaller number of cold days outweigh the losses during additional hot days. For a sense of scale, we compute changes in total mortality assuming the no population growth from the 2010 Census and see how these gross national patterns translate into changes of national aggregate mortality (Figure 8.3, right column).

Because many of the regions that benefit from climate change have less dense populations (e.g. northern Great Plains) than many of the regions that see increasing mortality rates (e.g. Gulf States), the net change in national outcomes is for the risk of mortality to rise on average.

The impacts above are described in terms of average changes over 20 year intervals. These averages are useful for describing persistent economic changes in future periods, but they mask short-lived events that may only last a year or two but have substantial economic consequences. Within each 20 year window the likelihood of extreme annual events, such as a very high mortality year, evolves with the climate. One way to describe how the likelihood of extreme events changes is to examine how frequently we expect to experience years that are as damaging as the worst year experienced during two decades of recent history, a so called "1-in-20 year event". In Figure 8.4 we plot the estimated number of years that will have temperature-related mortality larger than historically observed 1-in-20 year mortality events. For each year we plot the expected number of these extreme years that will be experienced in the 20 years that follow, i.e., we plot what the immediate future appears like to an individual in a given year.

Figure 8.4: Projected change in frequency of temperature-related mortality events equal to or worse than historical 1-in-20 year events

Expected frequencies across climate models and weather. Frequencies are plotted in the first year of each 20-year period.



By 2030, mortality events that used to occur only once every 20 years will be expected to occur at roughly the same rate during the following 20 years for RCP 8.5, with the frequency falling slightly for RCP 4.5 and 2.6. The frequency of these extreme mortality events falls slightly in the first half of the century because reductions in cold related mortality more than offset increases in heat related mortality. However, after 2040 the effect of extreme heat events drive the likelihood of extreme mortality events steadily upward in RCP 8.5, causing these events to occur roughly 11 times every 20 years by the end of century. The frequency of extreme mortality events remains slightly depressed in RCP 2.6 throughout the century and rises to twice every 20 years by 2070 in RCP 4.5.

It is important to note that these estimates assume the national distribution of individuals remains fixed relative to 2010 (US Census estimates) and that other health factors that interact with heat-related mortality also remain fixed. If populations migrate for health-related reasons or invest in other protective investments, such as air-conditioning, then these projections will overstate future impacts. We explore the impact of some of these potential adaptations on our projections in Part V of this report.

OTHER IMPACTS

Air quality impacts (ozone, allergens, PM)

Climate change will affect air quality through several pathways, including temperature-related effects on regional ambient concentrations of ozone, fine particles, and dust. Air pollutants such as ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxide (NOx), volatile organic compounds (VOCs), and particulate matter (PM) have both acute and chronic effects on human health, including respiratory irritation, chronic respiratory and heart disease, lung cancer, acute respiratory infections in children and chronic bronchitis in adults, and aggravating pre-existing heart and lung disease, or asthmatic attacks (Kampa and Castanas 2008). Short- and long-term exposures have also been linked with premature mortality and reduced life expectancy.

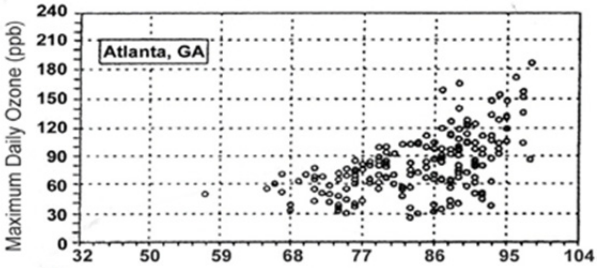
The public health impacts of ozone pollution are significant. A large body of evidence, summarized in EPA's most recent comprehensive assessment, provides clear evidence of the health impacts of exposure to ground-level ozone (US EPA 2013). The strongest evidence links ozone exposure to respiratory illness; as ozone has been found to irritate lung airways, diminish lung function, and exacerbate respiratory symptoms; and has been associated with increased hospital admissions and emergency room visits (US EPA 2013). Symptoms can arise quickly, sometimes within one hour of exposure, or may arise from cumulative exposure over several days or several days after exposure. Studies have found that nationwide ozone exposure from 2000-2002 resulted in not only nearly 800 deaths, but also over 4,500 hospitalizations and emergency room visits, and 365,000 outpatient visits, which resulted in costs of over $6.5 million dollars (Knowlton et al. 2011). One study of ozone pollution in Los Angeles from 1993-2000 found that a 0.01 ppm increase in the five day average ozone-level (the EPA National Ambient Air Quality Standard for eight hour daily maximum is 75 ppb, or equivalently 0.075 ppm) is associated with a 4.7% increase in hospitalizations for respiratory illness. Given ambient levels in Los Angeles during that period reached 0.05 ppm, the additional hospitalization costs from that ozone exposure amounted to $1.85 million per year (Moretti and Neidell 2009).

In some cases, ozone exposure can even lead to death. Mortality effects have been shown to be both short-term, happening within hours of exposure, and cumulative, having effects over long-term periods of exposure. Short-term exposure to a 0.01 ppm increase can lead to an increase in cardiovascular and respiratory mortality of 0.52% (M. Bell, McDermott, and Zeger 2004), and a 4% higher risk of death from increases in seasonal averages of 0.01 ppm (Jerrett et al. 2009). The mortality and morbidity effects are exacerbated for particularly susceptible populations, such as children, the elderly, and those with existing respiratory conditions like asthma.

Ground-level ozone is created in reactions between NOx and VOCs in the presence of sunlight. Consequently, studies find a direct correlation between temperature and ozone formation. During the summer of 1990 in Atlanta, maximum ozone concentrations were found to rise with maximum daily temperatures (Bernard et al. 2001), as shown in Figure 8.5 below. That same summer, hospitalizations for childhood asthma and other reactive airway diseases were found to increase nearly 40% following high ozone days (White et al. 1994).

With emissions at today's levels, warmer summer temperatures are expected to increase summertime ground-level ozone concentrations. One study estimated the potential future impact of climate change on ozone concentrations and public health for 50 eastern US cities (Bell et al. 2007). Using global and regional climate and regional air quality models, but keeping ozone precursor emissions flat at 1993-1997 levels, the study was able to isolate the effect of temperature on future ozone concentrations. It found that on average across the 50 cities, by mid-century the summertime daily one hour maximum was expected to increase by 4.8 parts per billion (ppb) from 1990 levels, with the largest increase, at 9.6 ppb, under a business-as-usual GHG emission scenario. The average number of days per summer exceeding the national regulatory standard was found to increase by 68% on average, and hospitalizations for asthma was found to increase by 2.1% as a result of temperature increases alone. A recent study by Pfister et al (2014), using downscaled climate projections (using RCP 8.5) and regional chemical-transport models, found similar results for mid-century. Without emission controls on ozone precursors, they found the number of high ozone events (with concentrations >75 ppb) show a clear increase from current levels (70%) over most of the contiguous US.

Figure 8.5: Ozone-Temperature relationship



Source: Bernard et al., 2001, Reproduced with permission from Environmental Health Perspectives.

Particulate matter — especially very fine particles such as those found in smoke or haze — can get deep into the lungs and cause serious health problems. While the potential impacts of temperature on particulate matter levels across the US are not well-understood (Tai, Mickley, and Jacob 2012; Tagaris et al. 2007), there is a clear relationship between particulate pollution and wildfires, which are expected to be more frequent in some areas of the US as temperatures rise and landscape become drier. Smoke produced by wildfires contains particulate matter, carbon monoxide, and several ozone precursors including nitrogen oxides, non-methane organic compounds, and volatile organic compounds which can significantly reduce air quality in local communities and areas downwind (Dennekamp and Abramson 2011). The respiratory health impacts of such exposures have been found to be significant, in line with exposures to similar levels of emissions in urban areas from vehicle tailpipes, power plants, and other industrial sources.

In many areas of the US, air pollution from wildfires and biomass burning represents a significant share of total exposure, especially as state programs have worked to reduce emissions from vehicles and other man-made sources. In California, criteria pollutant emissions from biomass burning were found to contribute emissions equivalent to 18% and 34% of man-made emissions of carbon monoxide and particulate matter (PM2.5), respectively. The same study found that under a medium-high future climate change scenario, end of century emissions from wildfires in California are projected to increase 19 to 101% above rates experienced in recent decades (Hurteau et al. 2014). They found the emissions increases to be most extreme in Northern California, an effect that was influenced very little by adjusting development patterns to control for impacts on population exposure. Emissions from wildfire in the Sierra Nevada will directly impact the San Joaquin Valley air basin, one of the most populous and fastest growing in the state, and one with a high probability of exceeding federal air quality standards for ground-level ozone. Under future climate scenarios, degraded air quality in the basin due to wildfires is expected to affect an additional 1.5 to 5.5 million people.

Allergies are the sixth most costly chronic disease category in the United States, and the direct medical costs of two of the main allergic diseases — asthma and hay fever — are estimated to be $12.5 and $6.2 billion per year, respectively (US EPA 2008). The production of plant-based allergens will also be affected by climate change. increased pollen concentrations and longer pollen seasons, resulting from warmer temperatures and higher ambient CO2 concentrations, which can generate allergic responses and exacerbate asthma episodes, diminish productive work and school days, and incur health care costs (L. H. Ziska 2008; Wayne et al. 2002). Studies have shown that between 1995 and 2001 the pollen season for ragweed, a significant cause of hay fever in the US, increased in as much as 13 to 27 days in the central US, with the largest increases observed in northern cities, including Minneapolis, Fargo, and Madison (L. Ziska et al. 2011).

Extreme weather, water- and vector-borne disease, and a whole host of other impacts

A whole host of other potential risks to health may result from changing climatic conditions. Whenever there is a negative impact on the built environment from extreme events, including storms, fires, and flooding, human health is at risk and loss of life may result. Changes in the frequency of extreme precipitation events will have consequences for health hazards associated with direct damages wrought by storms and floods (including injury and mortality), as well as ensuing exposures to waterborne diseases, toxins, sewage, and contamination from mold and other respiratory irritants (Joyce et al. 2013). Floods are the second deadliest of all weather-related hazards in the US, accounting for nearly 100 deaths each year, the highest portion of which occur as a result of flash floods and flooding associated with tropical storms (Ashley and Ashley 2008). Persistent heavy rains and thunderstorms in the summer of 1993 brought flooding across much of the central US, resulting in 48 deaths and $30 billion dollars of damages (NOAA 2013).

Heavy precipitation and runoff contribute to increased risk of waterborne disease from increased surface and groundwater contamination. Outbreaks of diseases like *Giardia*, *Escherichia coli*, and other acute gastrointestinal illnesses have been linked to heavy rainfall events, like the one in Milwaukee, Wisconsin in 1993, which led to 403,000 cases of intestinal illness and 54 deaths (Hoxie et al. 1997). More than half of the waterborne disease outbreaks in the US in the last half of the 20th century were preceded by extreme rainfall events, according to a study conducted at the Johns Hopkins Bloomberg School of Public Health (F C Curriero et al. 2001). In urban watersheds, more than 60% of the annual load of all contaminants is transported during storm events, increasing the risk to vulnerable urban populations exposed to dangerous contaminants.

Further impacts include changes in the distribution of diseases borne by insects, changes in crop yields and quality as well as global food security, changes in the frequency and range of harmful algal blooms, and risks resulting from population displacement (due to of sea-level rise and extreme weather events) (Joyce et al. 2013). Many of these impacts are difficult to study, and their causal processes and effects are less easily quantified (McMichael, Woodruff, and Hales 2006).

Vulnerable populations

It is important to take into account that climate-related risks are disproportionately higher for the most vulnerable sub-populations, including children and the elderly, low-income communities, and some people of color. Children in particular face increased impacts from heat waves (Basu and Samet 2002), air pollution, infectious disease, and impacts from extreme weather events (American Academy of Pediatrics 2007). The elderly and those with pre-existing health conditions face greater risk of death from heat waves, and suffer more severe consequences from air pollution and flood-related health risks (Balbus and Malina 2009). Low-income communities, already burdened by high incidence of chronic illness, inadequate access to health services, and limited resources to adapt to or avoid extreme weather, are also disproportionately impacted by climate-related events (Reid et al. 2009; Balbus and Malina 2009).

CHAPTER 9

Crime

Crime is an important social force in the United States. The incidence of both violent and non-violent crime impacts individuals, households, and communities at a very personal level. The threat of crime shapes how societies organize themselves to protect their fellow citizens, their families, and their neighborhoods from the potential consequences of crime. Victims of crime know firsthand its effects on quality of life.

Crime is also an important economic force in the US. In areas where crime is prevalent, residents notice direct effects on housing prices, education, and job availability. The opportunity costs are high, as crime removes both victims and perpetrators of crimes from the productive work force. Crime prevention and prosecution comes at significant costs to society, as public and private expenditures are redirected from other more productive uses. In 2010, public spending on police protection, legal and judicial services, and corrections totaled over $260 billion for all jurisdictions (Bureau of Justice Statistics 2010). Interpersonal violence each year amounts to tens of thousands of deaths across the US, with millions more the victims of assault and rape. Property crime, including burglary and larceny, affect nearly 10 million people each year (Federal Bureau of Investigation 2012). Given the magnitude of current losses due to criminal activity, even small changes in crime rates can affect communities at a very personal and economic level, and can ultimately have a substantial detrimental effect on the US economy as a whole.

According to the Federal Bureau of Investigation, many factors influence crime rates including population density, age, education, family cohesiveness, and divorce rates, effectiveness of law enforcement, and weather. Research efforts have long focused on understanding crime's causes and contributors in order to improve the effectiveness of crime prevention efforts. Because the human and economic stakes are so high, every potential cause has been seriously considered. These efforts have determined that weather and climate have a consistent and significant effect on human conflict, broadly defined, including both violent and non-violent crime. This relationship has been documented around the globe, across all types of conflict, levels of development, and all spatial scales, through all phases of human history to modern times (Hsiang, Burke, and Miguel, 2013).

Much attention has been given to climate's effect on war and civil conflict, especially in regions where the scale of conflict is large and where climate extremes are already evident. While it may be easy to imagine increased incidence of civil conflicts in hot, arid, resource-constrained countries, the empirical link to the climate applies just as readily to armed robbery in downtown Los Angeles. Findings from a growing body of rigorous quantitative research across multiple disciplines has found that weather, and in particular temperature, affects the incidence of most types of violent and non-violent crime in American cities and rural areas alike. Of course, climate is not the primary cause of crime, but studies find clear evidence that climate variations can have substantial effects (Card and Dahl, 2011; Jacob, Lefgren, and Moretti, 2007; Ranson, 2014).

Despite rising temperatures, the US is in the midst of a historic decline in crime rates. Nonetheless, the impact of climate on crime in American communities is real, and crime rates could increase — or decline more slowly than they otherwise would — as temperatures rise across the US in the coming century. With over 1.2 million incidents of violent crime and nearly nine million of property crime in the US last year, the potential for even a small increase relative to a world without climate change is significant enough — in both human and economic terms — to merit a serious assessment of the risk. As with all impacts in this assessment, social and economic factors may determine local or national trends in crime, but a changing climate may alter these trends substantially, imposing real costs on Americans. In this report we assess the temperature-related impacts on both violent and property crime in the US.

BACKGROUND

Studies across multiple disciplines – including criminology, economics, history, political science, and psychology – have found that climatic events have exerted considerable influence on crime and human conflict, even when controlling for all other possible explanations. This is true regardless of geography (whether Africa or the US), time period (as relevant in ancient times as last year), duration of climatic events (lasting hours, days, or months), or spatial scale (global down to neighborhood or even building level) (Hsiang and Burke 2013).

The evidence is particularly strong for one climate variable: temperature. Studies from across the US, drawn from extensive, high quality time-series data, provide compelling evidence of the heat-crime link. Studies have repeatedly found that individuals are more likely to exhibit aggressive or violent behavior toward others if temperatures are higher (Mares 2013; Kenrick and MacFarlane 1986a; Vrij, Van der Steen, and Koppelaar 1994). This has been documented for a whole range of aggressive behaviors: horn-honking by frustrated drivers; player violence during sporting events, and more serious criminal activity including domestic violence, assault, and murder (Kenrick and MacFarlane 1986; Mares 2013; Cohn and Rotton 1997; Rotton and Cohn 2000; Anderson, Bushman, and Groom 1997; Anderson et al. 2000; Jacob, Lefgren, and Moretti 2007; Larrick et al. 2011; Ranson 2014). The influence of higher temperatures on individuals has also been found to lead to increased retaliatory violence among groups. Studies have shown that police officers are more likely to use deadly force in a training simulation when confronted with threatening individuals in a hotter environment and hot days have contributed to more rapid escalation of retaliatory violence at sporting events (Larrick et al. 2011; Vrij, Van der Steen, and Koppelaar 1994). Temperature's role is evident even when you remove the confounding effects of normal seasonal or annual fluctuations in crime rates, economic and cultural factors, enhanced crime reporting of over time, and changes in law enforcement activity (Ranson 2014).

While there is substantial evidence to support the link between warmer temperatures and the incidence of crime, studies have not been able to determine the precise physiological mechanism(s) by which this occurs. There are several potential explanations. One suggests that individual criminal behavior is determined by rational decisions about the costs and benefits of certain actions, and that weather factors into the probability of committing a crime without getting caught (B. Jacob, Lefgren, and Moretti 2007). A second is based on consistent evidence that temperature affects aggression levels, affecting an individual's judgment in a way that causes loss of control and heightened propensity to commit criminal acts (C A Anderson et al., 1997; Card & Dahl, 2011). Another possible explanation is that that the frequency of criminal acts is determined in part by opportunity; in this case, certain climate conditions allow for increased social interaction, expanding opportunities for crime to occur (Rotton and Cohn 2003). Pleasant weather, for instance, brings victims and offenders in closer proximity as people flock outdoors, resulting in increased violence, particularly robberies and assaults (Cohn and Rotton 1997). No single explanation has been able to explain all of the observed patterns, indicating it is quite likely that several of these mechanisms are at play (Hsiang and Burke 2013).

OUR APPROACH

To understand what climate change may mean for US crime rates in the future, we rely on statistical studies that isolate the observed effect of temperature and rainfall on crime in the United States, and apply them to projected future conditions. Because there are strong cross-county patterns in crime, as well as strong trends over time (that may differ by location) and over seasons, we rely on studies that account for these patterns when measuring the effect of climate variables on crime rates. Two published studies provide nationally representative estimates that satisfy these criteria, which we use to construct quantitative projections. Ranson (2014) examines county-level monthly crime rates during 1960-2009, and Jacob et al. (B. Jacob, Lefgren, and Moretti 2007) examine jurisdiction-level weekly crime rates during 1995-2001. Both studies identify the incremental influence of temperature and rainfall changes on violent crimes and property crimes using data collected by the Federal Bureau of Investigation. Ranson's analysis provides greater coverage over years and across the country (the 2010 data covers 97.4% of the US population); however, the studies may be complimentary because their sample structure and statistical approaches differ somewhat, reflecting different modeling decisions.

Figures 9.1 and 9.2 display an optimally weighted average dose-response curve for both violent crime and property crime, drawn from Ranson (2014) and Jacob, Lefgren, and Moretti (2007). Both studies largely agree that higher daily maximum temperatures strongly and linearly influence violent crime, with a somewhat weaker and probably nonlinear influence on property crime. On average, increasing a county's temperature by 10°F for a single day increases the rate of violent crime linearly by roughly 0.2%. Jacob et al. assume that all types of crime respond linearly to temperature, but when Ranson examines nonlinearity, he finds that property crime increases linearly up to 40 to 50°F and then levels off (see Figure 9.1 and Figure 9.2). These findings are consistent with other work that finds aggressive behavior increases roughly linearly with temperature and that property crime is mainly constrained by opportunity (e.g., it is more difficult to steal cars and other property when it is extremely cold and snowy outdoors). Both papers find that the effects of rainfall are much smaller and less influential, with higher rainfall slightly increasing property crime and slightly decreasing violent crime.

Figure 9.1: Temperature and violent crime

Percentage change in incidence of violent crime vs. daily maximum temperature (F)

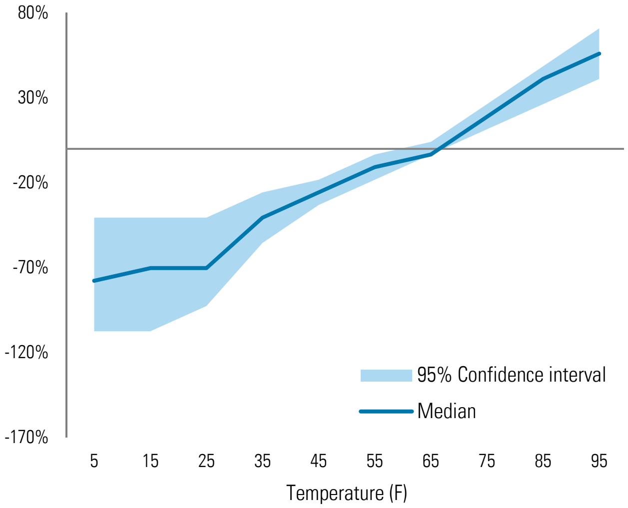
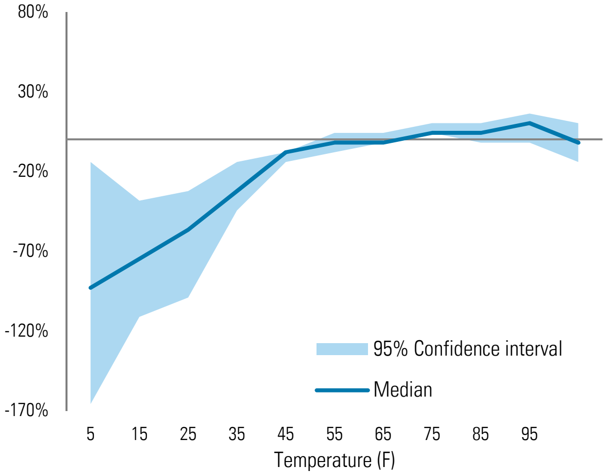


Figure 9.2: Impact temperature and property crime

Percentage change in incidence of property crime vs. daily maximum temperature (F)



Both studies consider whether increased crime rates caused by high temperatures induce forward displacement ("harvesting") of crimes or generate new crimes that would not otherwise occur. Jacob et al examine weekly crime rates and find that, when a hot week triggers additional crime, roughly half of the violent crimes and a third of the property crimes would have otherwise occurred in the following four weeks, with no evidence of displacement beyond the fourth week. Consistent with this finding, Ranson examines monthly crime rates and finds that, after an abnormally warm month, there is no evidence that crime in the following month is reduced. Thus, both studies find that temporal displacement beyond a one-month time-frame is minimal, although there is evidence of displacement within that month. To account for this temporal displacement in our analysis, we only consider temperature-induced crime that would not have occurred in later periods.

Ranson examines whether there is evidence that populations adapt by examining if the sensitivity of crime to temperature declines over time or is lower in counties that are hotter on average. Ranson finds that the response of crime to temperature has remained virtually unchanged since 1960, with only suggestive evidence that the sensitivity of violent crime has fallen very slightly over the half-century. Ranson finds no evidence that hotter counties are better adapted in this respect, since the response of hotter and colder counties are indistinguishable.

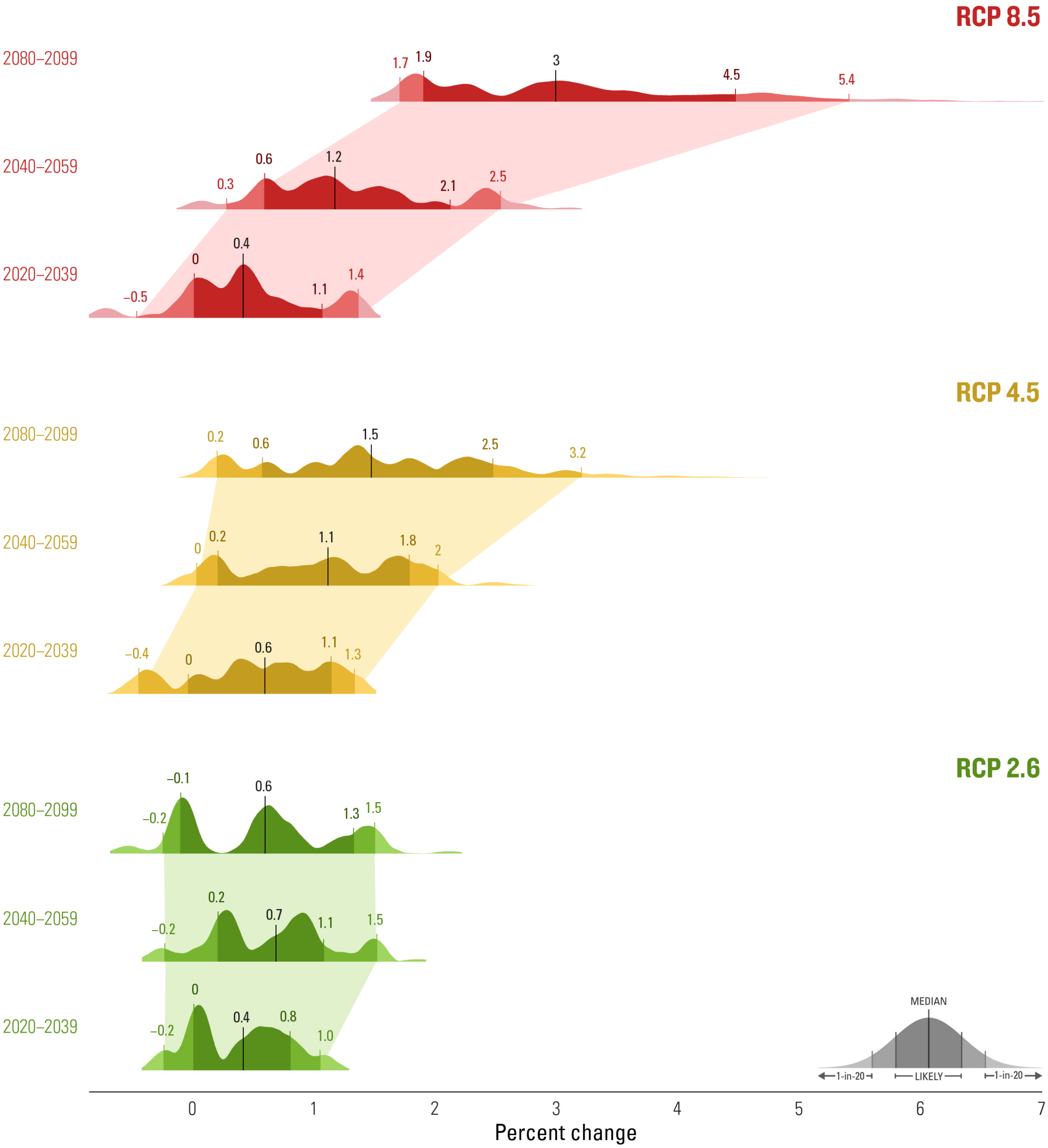
To assess potential future impacts of climate change on crime, we simulate changes in violent and property crime rates under different climate scenarios relative to a future in which the climate does not drive changes in crime after 2012—although other social and economic trends are assumed to continue. Within each scenario we account for uncertainty in climate models, weather, and statistical results, causing our projection to be a probability distribution of potential outcomes at each moment in time.

Considering the potential impact of changes in temperature and precipitation on crime, we find that crime generally increases as early as 2020-2039 and the range of likely changes are unambiguously positive by mid-century for all scenarios (see Figure 9.3). In RCP 8.5, we estimate violent crime is *likely* to increase 0.6% to 2.1% by mid-century and 1.9% to 4.5% by late-century, with a 1-in-20 chance that late-century increases are below 1.7% or exceed 5.4% relative to baseline crime rates. Examining property crime, we find that impacts tend to be substantially smaller in percentage terms for all cases, with late-century rates in RCP 8.5 *likely* rising 0.4% to 1.0%, with a 1-in-20 chance that the rise in property crime rates are less than 0.3% or more than 1.1%. Property crime does not increase as strongly as violent crime because the impact function for property crime is nonlinear and flattens at temperatures higher than 55°F (Figure 9.2), whereas the impact function for violent crime continues to increase even at high temperatures (Figure 9.1). Thus, future warming is likely to have a smaller percentage effect on property crime because much of the warming will increase temperatures on warm/hot days that are already above 55°F, a change that does not affect property crime but does affect violent crime.

Projected changes are smaller in magnitude for RCP 4.5 and RCP 2.6, with the *likely* range of changes for violent crime spanning an increase of 0.6% to 2.5% for RCP 4.5

Figure 9.3: Change in violent crime

Percent

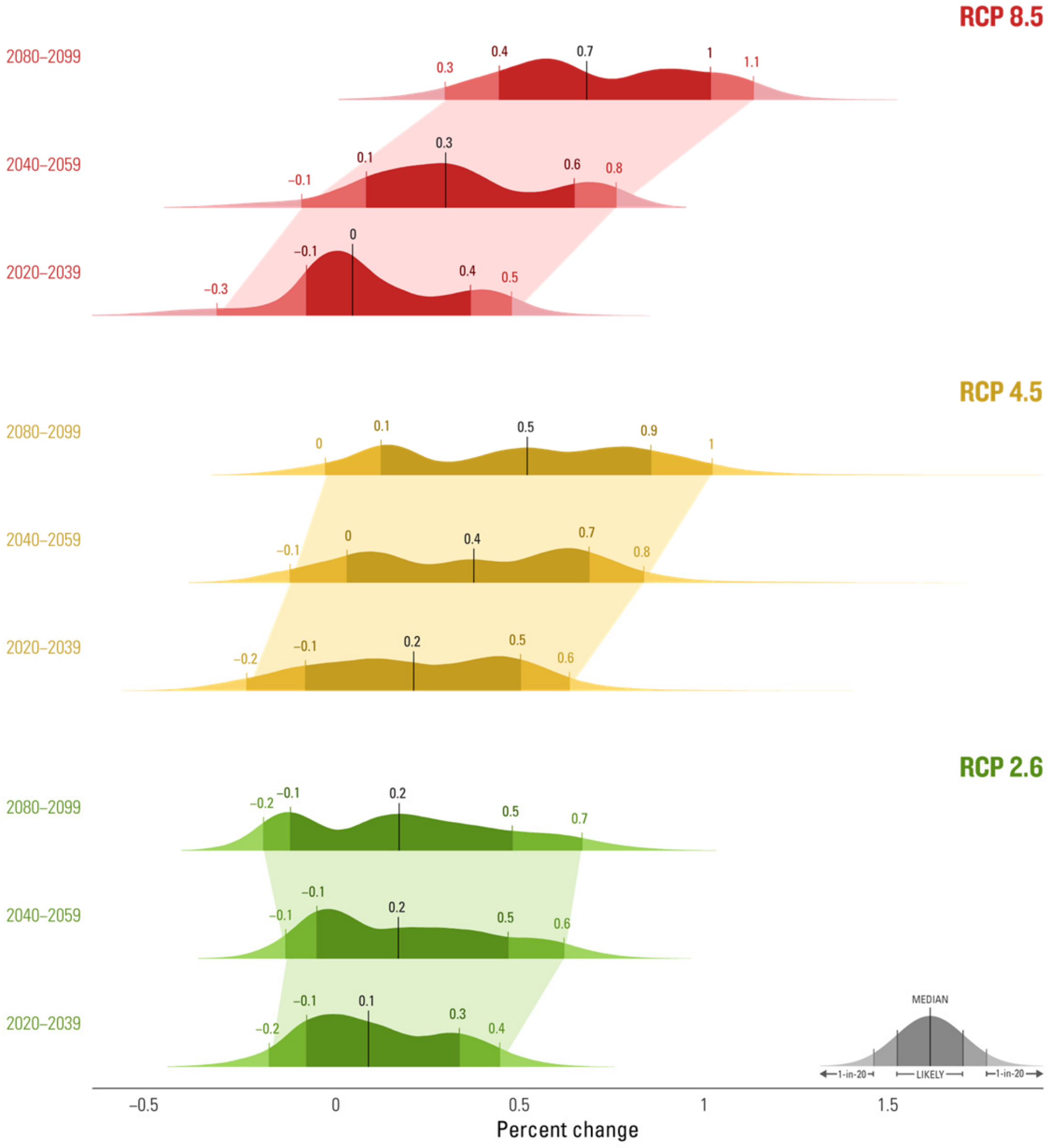


and -0.1% to 1.3% for RCP 2.6 by late-century. 1-in-20 outcomes span a narrower range than RCP 8.5, with a 1-in-20 chance of crime rates rising less than 0.2% or more than 3.2% for RCP 4.5 and a decrease larger than -0.2% or an increase above 1.5% for RCP 2.6. Projections for property crime are similar in structure but are roughly one-third the magnitude.

Across all RCPs, the distribution of potential changes broadens moving forward in time, and the rate of spreading increases moderately with increasing emissions for violent crime only (Figure 9.3). Changes in violent crime rates by late-century exhibit a 90%

Figure 9.4: Change in property crime

Percent

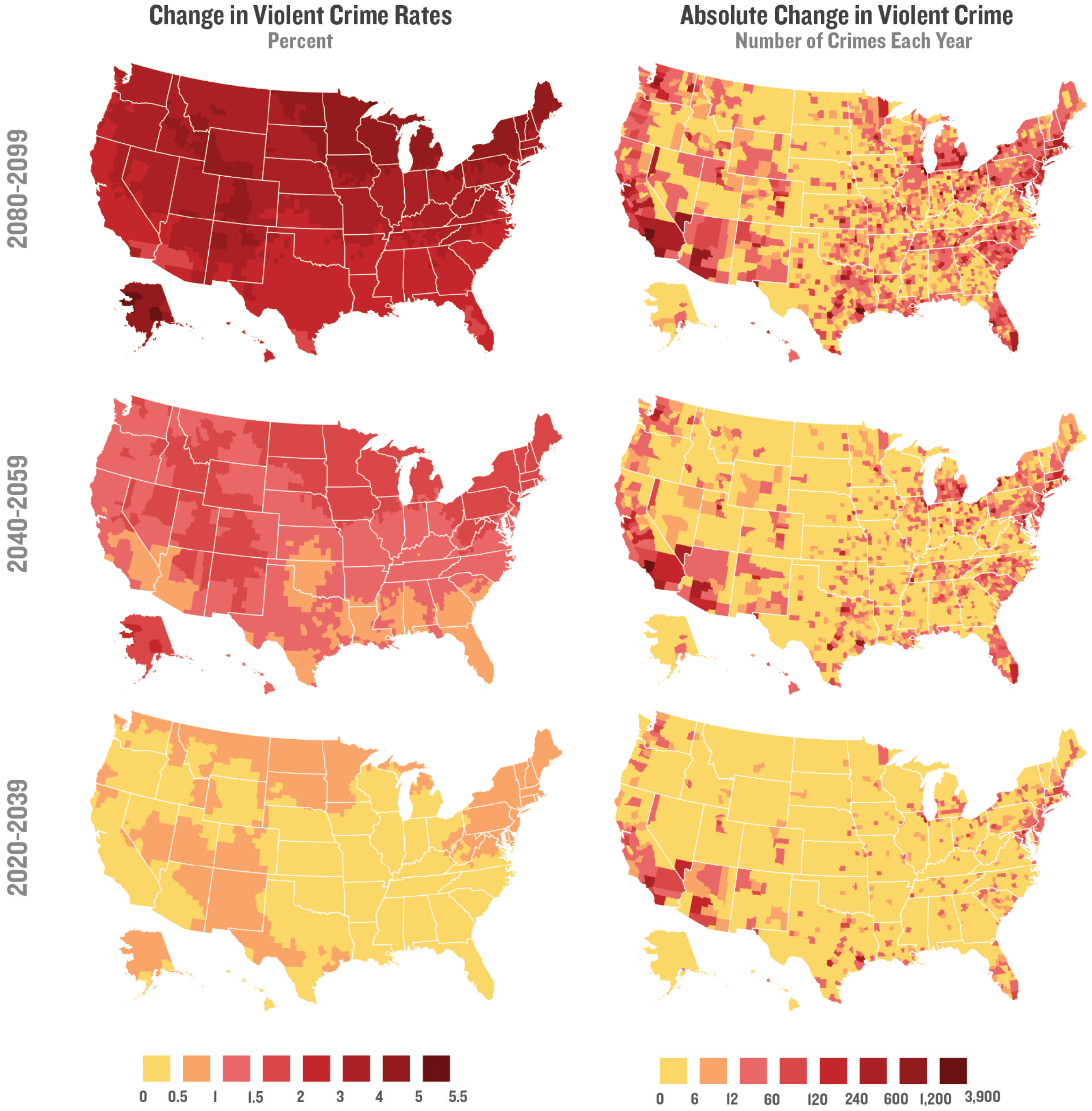


confidence interval spanning 1.7 percentage points in RCP 2.6 and widens to span 3.0 and 3.7 percentage points in RCP 4.5 and 8.5 respectively, indicating that future uncertainty over violent crime rates increases with warming.

The spread of potential outcomes is relatively more consistent across RCP scenarios for property crime, primarily because there is no response of property crime to variation in high temperatures that generate uncertainty for violent crime projections (Figure 9.4). The "lumpiness" (multi-modality) of the distributions in is because there is high statistical precision for the econometric results used to generate these projections. For other impacts, statistical uncertainty causes the climate-model-specific distributions to be broader and to overlap more, making them less well defined. Thus, the lumpiness of the crime distributions indicates that

Figure 9.5: Change in violent crime

RCP 8.5, median



between-climate-model uncertainty drives the bulk of uncertainty in these specific prjections.

In percentage terms, the spatial distribution of projected impacts is relatively similar across the country in the median RCP 8.5 projection, with increases in violent crime projected across all counties (Figure 9.5, left column) and increases in property crime projected across almost all counties (Figure 9.6, left column). There are somewhat smaller increases in property crime in the South, Southwest, and California because these locations have fewer cold days in their baseline climate, and warming during cold days drives the response of property crime. For a sense of scale, we compute changes in the total number of crimes committed assuming the baseline distribution of crimes remains fixed relative to 2000-2005, assuming no population growth, change in law enforcement, or additional social trends (Figures 9.5 and 9.6, right columns). The national distribution of additional crimes is strongly influenced by the locations of urban centers (e.g. New York, Chicago, Los Angeles) although it is also possible to discern the larger impact in northern counties for property crime.

The impacts above are described in terms of average changes over 20 year intervals. These averages are useful for describing persistent economic changes in future periods, but they mask short-lived events that may only last a year or two but have substantial consequences for well-being. Within each 20 year window the likelihood of extreme annual events, such as a very high crime year, evolves with the climate. One way to describe how the likelihood of extreme events changes is to examine how frequently we expect to experience years that are as damaging as the worst year over two decades of recent history, a so called "1-in-20 year event."

In Figures 9.7 and 9.8 we plot the estimated number of years that will have temperature-related crime anomalies larger than historically observed 1-in-20 year anomalies. For each year we plot the expected number of these extreme years that will be experienced in the 20 years that follow, i.e. we plot what the immediate future appears like to an individual in a given year. As early as 2020, climate-related violent crime anomalies that used to occur only once every 20 years will be expected to occur roughly seven times in the following 20 years for RCP 2.6 and 10 times in the following 20 years for RCP 4.5 and 8.5. Extreme property crime anomalies grow in frequency more slowly and do not reach as high values as violent crime. By 2080, violent crime extreme events will be occurring roughly ten times every 20 years in RCP 2.6, 16 times every 20 years in RCP 4.5 and every year in RCP 8.5. The frequency of extreme property crime anomalies are similar in RCP 8.5 by end of century, but only reach 10 events every 20 years in RCP 4.5 and seven events every 20 years in RCP 2.6.

Figure 9.7: Projected change in frequency of temperature-related violent crime anomalies equal to or worse than historical 1-in-20 year events

Expected frequencies across climate models and weather. Frequencies are plotted in the first year of each 20-year period.

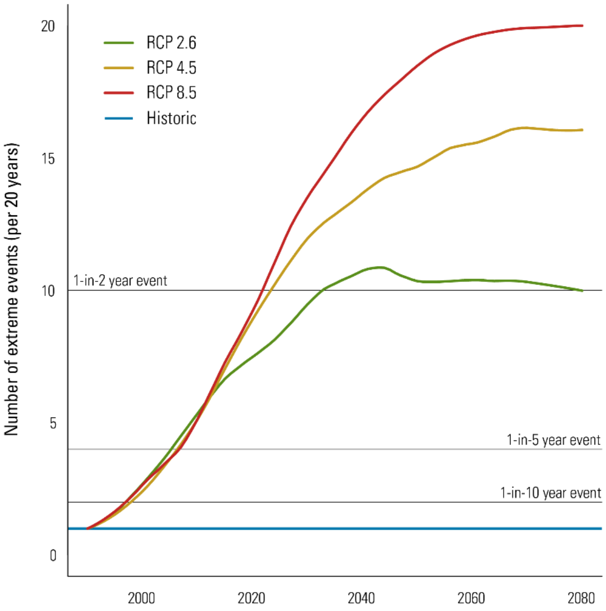
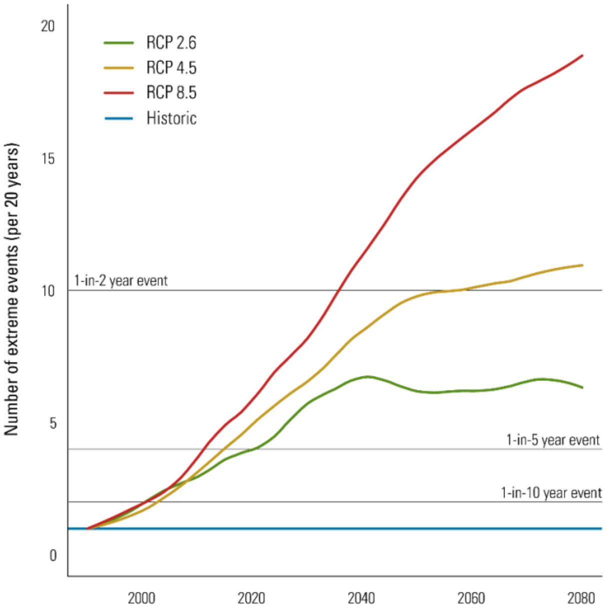


Figure 9.8: Projected change in frequency of temperature-related property crime anomalies equal to or worse than historical 1-in-20 year events

Expected frequencies across climate models and weather. Frequencies are plotted in the first year of each 20-year period.



It is important to note that these estimates assume the national distribution of crime remains fixed relative to the average crime rate during 2000-2005 and that geographic patterns in law enforcement remain unchanged. It is likely that if these changes in crime occur, communities will respond by expanding their law enforcement activities. One can roughly consider how much additional resource communities would need to invest in policing activity to offset these increases by using estimates for the effectiveness of policing activity in reducing crime. Observing that each 1% increase in the size of the police force reduces crime by roughly 0.1 to 0.6% (Chalfin and McCrary 2012), our results suggest that to fully offset the *likely* range of late-century violent crime changes in RCP 8.5, police forces would have to grow by 3 to 19% (lower end of likely range) to 8 to 45% (upper end of likely range). In Part V of this report (Principles for Climate Risk Management), we explore how our projections might change if future populations continue to adapt to climate-related crime at historically observed rates.

CHAPTER 10

Energy

Energy is a key ingredient in US economic growth. Ensuring a reliable supply of electricity and other sources of energy is critical to the financial security of American businesses and households, and to the national security of the country as a whole. While dynamic enough to respond to the climate conditions of the past, our energy system, as currently designed, is poorly prepared for future climatic changes. Rising temperatures, increased competition for water supply, and elevated storm surge risk will affect the cost and reliability of US energy supply. Climate change will also shape the amount and type of energy consumed. In this chapter we quantify the demand-side impacts of the projected changes in temperature discussed in Chapter 4, and discuss the range of supply-side risks the US energy sector faces as well.

BACKGROUND

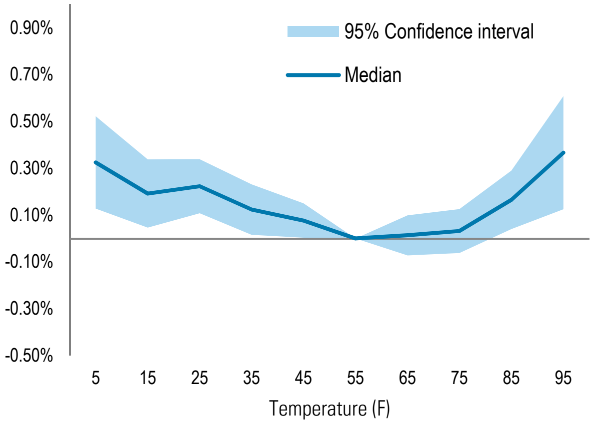
Energy demand is highly climate-sensitive in some sectors, and temperature in particular is a significant determinant of both the quantity and type of energy consumed. Demand for heating and cooling, which accounts for roughly half of residential and commercial energy use, fluctuates hourly, daily, and seasonally in response to outdoor ambient temperatures. Warmer winter temperatures as a result of climate change will reduce heating demand, particularly in northern states, which is currently met largely through the combustion of natural gas and fuel oil in boilers, furnaces, and water heaters. At the same time, hotter summer temperatures will increase demand for residential and commercial air conditioning run on electricity. Climate-driven changes in air conditioning can have an out-sized impact on the electric power sector, forcing utilities to build additional capacity to meet even higher peak temperatures.

OUR APPROACH

To assess the effect of the projected temperature changes discussed in Chapter 4 on US energy consumption, we turned first to the econometric literature. Because there are strong cross-location patterns in energy demand, as well as strong trends over time (that may differ by location) and over seasons, we focused on studies that account for these patterns when measuring the effect of climate variables on energy demand. Two studies provide estimates that satisfy these criteria, although only one is nationally representative. Deschenes and Greenstone (2011) examine state-level annual electricity demand for the country from 1968-2002 using data from the US Energy Information Administration (EIA), and Auffhammer and Aroonruengsawat (2011) study building-level electricity consumption for each billing cycle (roughly a month) for California households served by investor-owned utilities (Pacific Gas and Electric, San Diego Gas and Electric, and Southern California Edison). Both studies identify the incremental change in electricity consumed for each additional day at a specified temperature level. Deschenes and Greenstone provides national coverage, while Auffhammer and Aroonruengsawat provide greater temporal and spatial resolution across the full range of climate zones in California; thus, the studies may be complimentary.

Figure 10.1: Temperature and electricity demand

Observed change in electricity demand (%) vs. daily temperature (F)



Both studies find that electricity consumption increases during both hot days that exceed roughly 65°F and cold days that fall below roughly 50°F (Figure 10.1). Incremental increases in daily temperature cause electricity consumption to rise more rapidly than incremental decreases in temperature, although both changes have substantial impacts on overall demand. Auffhammer and Aroonruengsawat further examine how the shape of this dose-response function changes with the climate zone that each household inhabits, finding that in hotter locations that are more likely to have air conditioning widely installed, electricity demand increases more rapidly with temperature. This suggests that as populations adapt to hotter climates, they install more air conditioning infrastructure and use air conditioning more heavily for hot days at a fixed temperature.

Widening the lens

Unfortunately, the available econometric studies only capture part of the energy demand story. While residential and commercial electricity demand rises alongside temperature, as households and businesses increase their use of air conditioning, natural gas and oil demand in those two sectors falls. Many households and businesses use natural gas or oil-fired boilers and furnaces for heating, rather than electricity. The econometric studies mentioned above only cover changes in demand, not changes in price. To capture these fuel substitution and price effects, we employ RHG-NEMS, a version of the EIA's National Energy Modeling System (NEMS)[2] maintained by the Rhodium Group.

NEMS is the model used by the EIA to produce its *Annual Energy Outlook*, the most widely-used projection of future US energy supply and demand. NEMS is the most detailed publicly-available model of the US energy system, as it includes every power plant, coal mine and oil and gas field in the country. Individual consumer decisions regarding how much to heat or cool their homes, which appliance to buy and what car to drive are explicitly modeled, as are producer decisions regarding new electricity, oil, gas and coal production. Temperature is an input into NEMS, and impacts heating and cooling demand in the residential and commercial sectors. The appliances and equipment used to meet this demand influences the quantity of electricity, natural gas and oil supplied to household and business consumers.

We began by comparing the modeled impact of a given change in temperature on electricity demand in NEMS with the empirically-derived dose-response function above and found very similar results. We then modeled the impact of a range of regional temperature projections from Chapter 4 to capture the change in total energy demand, energy prices, and delivered energy costs. NEMS only runs to 2040, but is still useful in modeling the impact of longer-term temperature changes relative to the energy system we have today. As we are measuring the impact of climate-driven changes in energy demand relative to a baseline, the baseline itself matters less. Modeling long-term temperature changes in NEMS provides a reasonable estimate of the relative chance in demand, price, and costs given current economic and energy system structures.

RESULTS

Energy demand

Consistent with the econometric estimates, we find meaningful climate-driven increases in residential and commercial electricity demand. Under RCP 8.5, average nationwide electricity demand in the residential and commercial sectors *likely* increases by 0.7 to 2.2% by 2020-2039, 2.3 to 4.9% by 2040-2059, and 6.2 to 14% by 2080-2099 (Figure 10.2). The largest increases occur in the Southwest, the Southeast and southern Great Plains states (Figure 10.3). Texas, Arizona, and Florida see late century *likely* increases of 9.6 to 21%, 8.5 to 21% and 9.6 to 22% respectively. At the other end of the spectrum, most New England states and those in the Pacific Northwest see low single-digit *likely* increases, with declines possible in certain counties.

In RCP 4.5, we find a *likely* increase in average electricity demand of 0.2 to 1.9% by 2020-2039, 1.2 to 4.1% by 2040-2059, and 1.7 to 6.6% by 2080-2099. In RCP 2.6 we find a *likely* increase of 0.8 to 2.1% by 2020-2039, 1.1 to 2.7% by 2040-2059, and 0.7 and 2.7% by 2080-2099.

Offsetting this increase in cooling-driven electricity demand, we find a significant decline in heating-driven natural gas and fuel oil demand in the residential and commercial sectors under RCP 8.5. This decline is concentrated in the Northeast, upper Midwest, northern Great Plains, and Northwest, areas with the greatest heating needs today. Total natural gas demand does not fall because demand from the power sector increases, but the net effect of changes in heating and cooling demand is a very modest change in energy consumption overall.

Energy costs

While we find little climate-driven change in total energy demand, the switch from heating demand to cooling demand raises total energy costs. Climate-driven increases in cooling demand increase electricity consumption during the hottest times of the day and hottest periods of the year, when electricity demand is already at its peak. Higher peak demand requires the construction of additional power generation capacity to ensure reliable electricity supply. Under RCP 8.5, we find a *likely* increase in installed power generation capacity due to climate-driven changes in electricity

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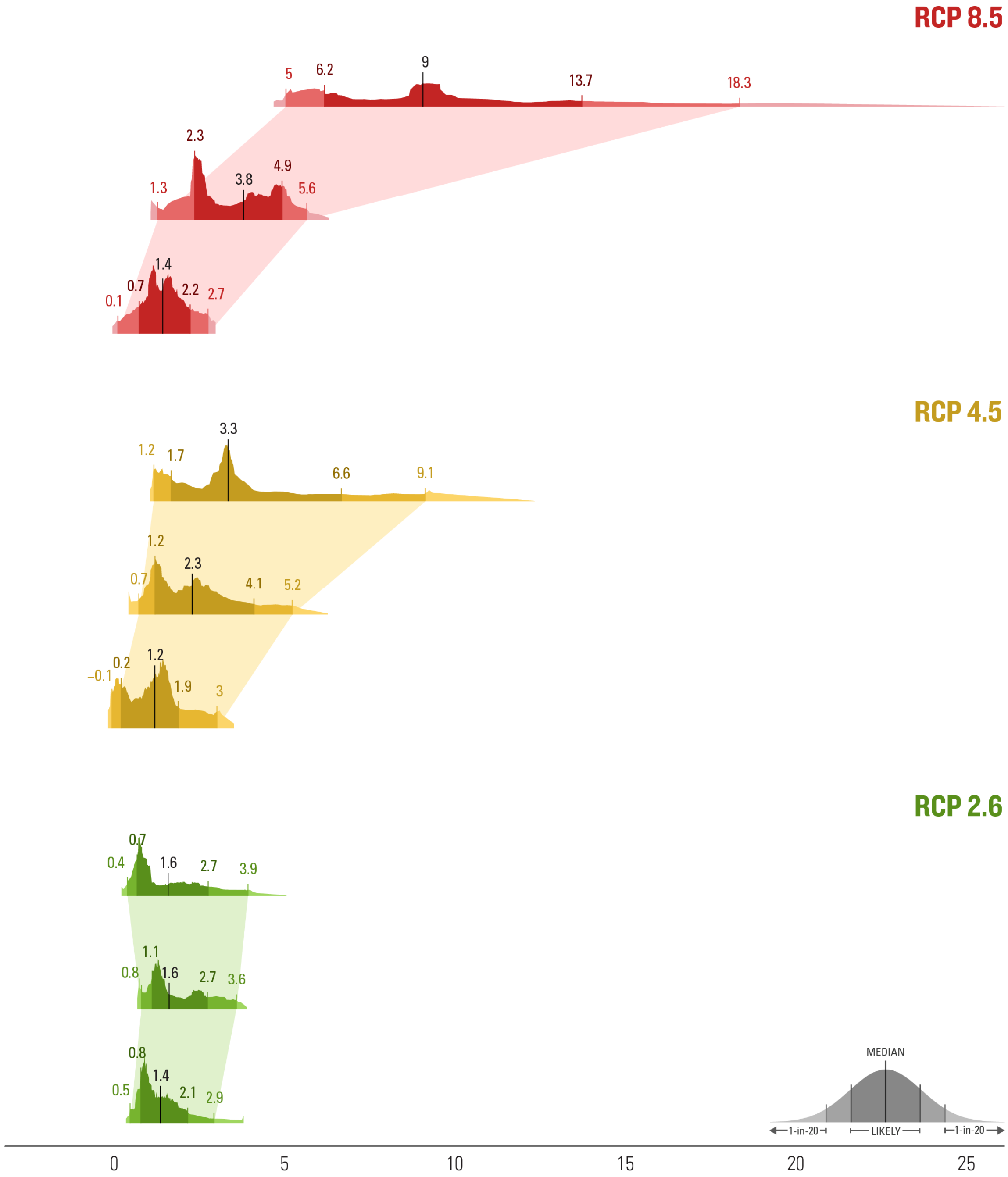
[2] More information on NEMS is available at http://www.eia.gov/oiaf/aeo/overview/

Figure 10.2: National Change in Electricity Demand

Percent

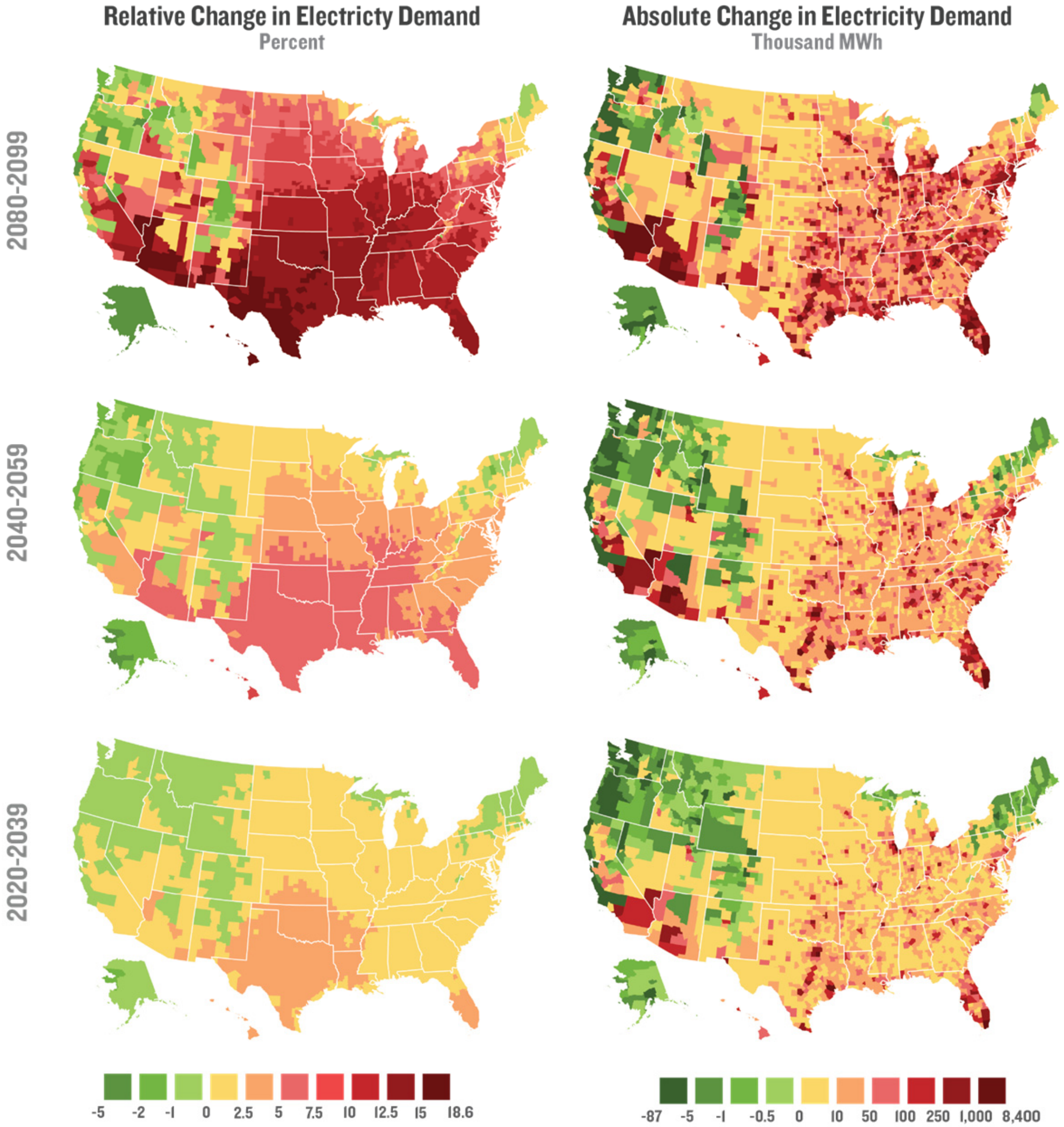


demand of 8 to 95 gigawatts (GW) by 2020-2030, 73 to 212 GW by 2040-2059 and 223 to 532 GW by 2080-2099.

While most of this capacity would only operate part of the time (during peak demand periods), the capital costs as well as operating costs are passed on to electricity consumers. The resulting electricity price increases lead to a *likely* 0.1 to 2.9% increase in total annual residential and commercial energy costs on average by 2020-2039, 2.1 to 7.3% by 2040-2059, and 8 to 22% by 2080-2099 (Figure 10.4). The greatest increases occur in the Southeast, Great Plains and Southwest, with a *likely* increase in 2080 -2099 of 12 to 28%, 9 to 30%, and 11 to

Figure 10.3: Local Changes in Electricity Demand

Median change in electricity demand from 2012 levels, RCP 8.5



Relative Change in Electricty Demand

Percent

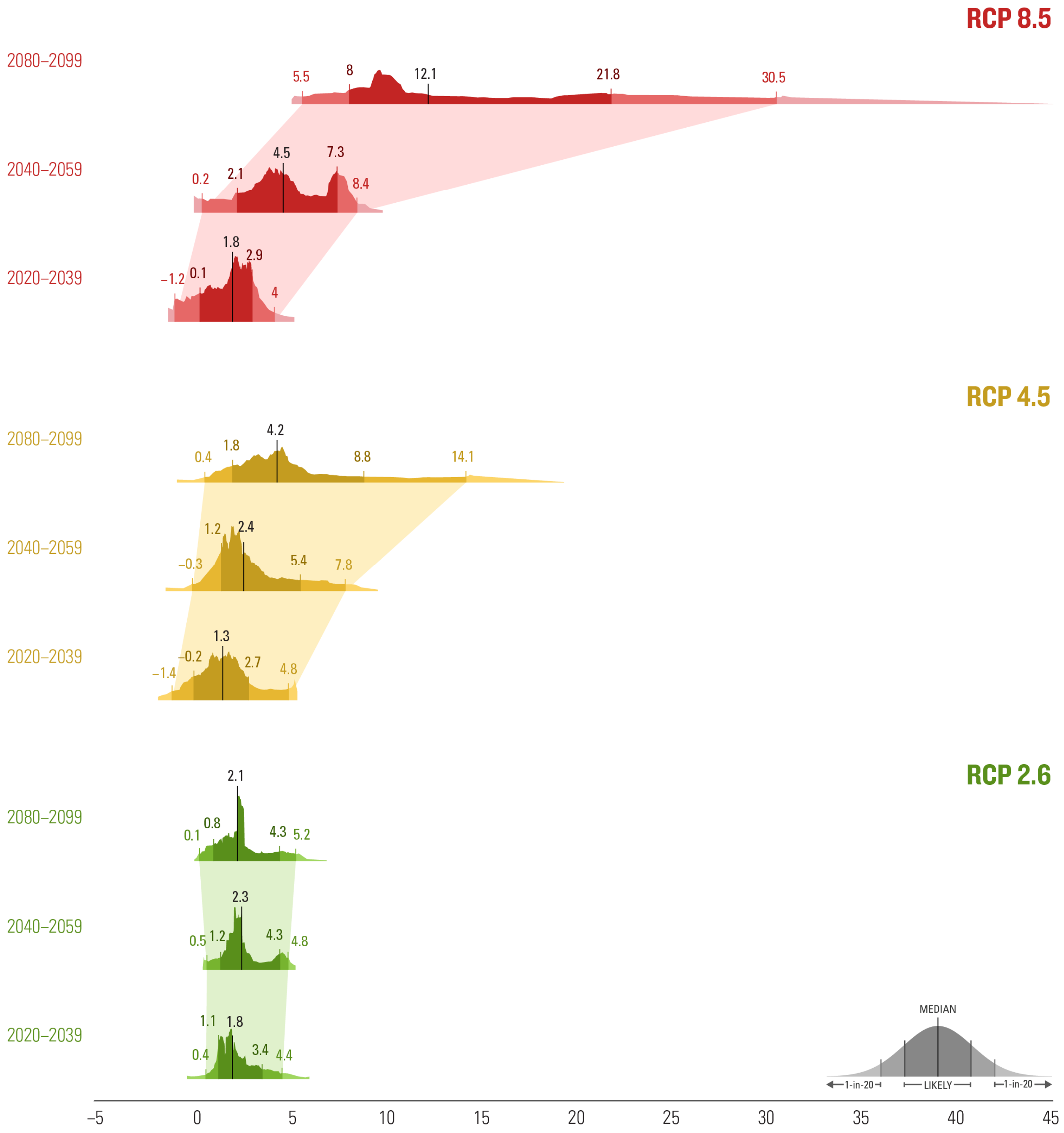
Absolute Change in Electricty Demand

Thousand MWh

25%, respectively. At the other end of the spectrum, the Northwest sees a *likely* change in energy expenditures of -4.5 to +3.7% late century, while the Northeast sees a 4.1 to 13.6% *likely* increase. In RCP 4.5 and 2.6, smaller increases in demand lead to less generation capacity construction and thus lower energy cost increases, though the RCP 4.5 and RCP 2.6 cost estimates do not include any increase in energy costs resulting from a change in US energy supply necessary to reduce GHG emissions consistent with either climate pathway. The cost estimates above also exclude the supply-side climate impacts discussed below.

Figure 10.4: Change in annual residential and commercial energy expenditures

Percent



OTHER IMPACTS

Climate change will impact energy supply as well as energy demand. The energy supply chain is long and complex. There are a number of points in that supply chain where climate-related disruptions could interrupt delivery of electricity, heating, or transport fuels.

Climate change will also have negative impacts on some sources of energy supply. For example, rising average temperatures and more frequent temperature extremes will reduce the efficiency of thermoelectric generation and transmission while reduced sea ice in the arctic will enable greater offshore oil and gas exploration. We describe some of the most significant supply-side climate impacts below.

Thermal generation efficiency

Coal, natural gas, oil, nuclear, and biomass power plants all produce electricity by boiling water and using steam to spin a turbine. This steam is then recycled by cooling it back into water. Higher ambient air temperatures as a result of climate change reduce the efficiency of this process. The magnitude of the impact depends on a number of plant- and site-specific factors. For most combined cycle plants, every 1.8°F (1°C) increase in air temperature will *likely* reduce electricity output by 0.3 to 0.5% (Maulbetsch and Difilippo 2006). For combined cycle plants with dry cooling, often more sensitive to warmer ambient temperatures, the reduction can be as large as 0.7% (Davcock, DesJardins, & Fennel, 2004). For natural gas-fired combustion turbines, which are often used for peaking, each 1.8°F increase in temperature will likely result in a 0.6 to 0.7% decline in electricity output, and for nuclear power output losses are estimated at approximately 0.5% (Linnerud, Mideksa, and Eskeland 2011). Combining these reductions with the projected increase in average summer temperatures under RCP 8.5 described in Chapter 4 suggests thermal efficiency declines could reduce total electricity generation by 2 to 3% by mid-century and 4 to 5% by late century, depending on energy technology mix.

Nearly all the electric power plants in the US use water for cooling, and the power sector accounts for nearly half of total US water withdrawals (Energy Information Administration 2011). Ambient temperatures affect surface water temperatures. Surface water temperatures in many US rivers have risen in recent years (Kaushal et al. 2010) and are projected to continue to warm due to climate change in the decades ahead (Cloern et al. 2011; Georgakakos et al. 2014; Michelle T H Van Vliet et al. 2012). Warmer water temperatures can degrade the efficiency of cooling processes and reduce electricity production as well (Van Vliet et al. 2012). In August 2012, record water temperatures in the Long Island Sound shut down one reactor at the Dominion Resources' Millstone Nuclear Power Station in Connecticut because the temperature of the intake cooling water exceeded technical specifications of the reactor. While no power outages were reported, the two-week shutdown resulted in the loss of 255,000 megawatt-hours of power, worth several million dollars (U.S. Nuclear Regulatory Commission 2012).

The majority of US thermal power plants currently use once-through cooling systems, which use water from a nearby lake, river, aquifer, or ocean to cool steam and then return it to the body of water from which it was withdrawn. Because of the elevated temperatures of discharged water, thermal discharge limits have been established to protect aquatic ecosystems. Increasing water temperatures put power plants at risk of exceeding these limits, with the potential for financial penalties or forced curtailments (Skaggs et al. 2012). Indeed, large coal and nuclear plants have, in several cases in recent history, been forced to restrict operations due to higher water temperatures (Averyt et al. 2011). A recent study projected a decrease in average summer capacity of thermoelectric plants with once-through cooling of 12 to 16% and those with recirculation cooling systems of 4.4 to 5.9% by mid-century, dependent on emissions scenario (Van Vliet et al. 2012). The study also found that the probability of extreme (greater than 90%) reductions in power production will on average increase by a factor of three.

Electricity transmission

Approximately 7% of generated electricity is lost during transmission and distribution (known as "line losses"), with the greatest losses occurring on hot days (Energy Information Administration 2012a). Increased average temperatures, as well as more frequent temperature extremes, will likely exacerbate these transmission and distribution losses (Wilbanks, Fernandez, et al. 2012; J. Sathaye et al. 2012; USGCRP 2009). Warmer temperatures are also linked to diminished substation efficiency and lifespan (Sathaye et al. 2012). Current line losses are valued at nearly $26 billion (Energy Information Administration 2012b), so even small increases in loss rates can have a significant impact on electricity producers and consumers. A recent study found that a 9°F increase in average summer temperatures in the Southwest (within our projected end of century range under RCP 8.5) would result in a 7 to 8% reduction in transmission carrying capacity (Sathaye et al. 2013). Extreme heat events could result in even higher losses. Depending on the duration and intensity of the event, extreme temperatures can lead to power outages, as happened in 2006 when power transformers failed in Missouri and New York during a heat wave, causing widespread electricity supply interruptions (USGCRP 2009).

Arctic oil and gas production

Climate change is already shaping the energy landscape in Arctic Alaska, which has warmed faster than any other region of the US to date, with both positive and negative impacts for US energy supply. Alaska currently accounts for over 10% of US crude oil production and is home to a large share of the national oil and gas resource base (US Energy Information Administration 2013). Warming temperatures have already resulted in permafrost thaw, which is beginning to threaten onshore infrastructure on which oil and gas exploration and production depends. Energy pipelines built on permafrost are at increasing risk of rupture and leakage, and warmer temperatures are already resulting in shorter winter road seasons. The number of days of allowable travel on Alaskan tundra have been cut in half over the past 30 years, limiting the time during which onshore oil and gas exploration and production equipment can be used (Alaska State Legislature 2008). In a changing and unstable Arctic, the cost of maintaining existing infrastructure will likely increase, as will design and construction costs for new onshore infrastructure. Climate change is opening up new sources of oil and gas development as well. Higher temperatures are reducing sea ice cover, which is improving access to substantial offshore oil and natural gas deposits in the Beaufort and Chukchi seas.

Water availability

Current US energy production is extremely water-intensive and climate change will impact US water supply in myriad ways (see Chapter 17). Increased evaporation rates or changes in snowpack may affect the volume and timing of water available for hydropower and power plant cooling, and changing precipitation patterns can affect bioenergy production. In regions where water is already scarce, competition for water between energy production and other uses may also increase. Regions that depend on water-intensive power generation and fuel extraction will be particularly vulnerable to changes in water availability over time.

At 40% of total freshwater withdrawals, thermal power generation is the largest water consumer in the US (Kenny et al. 2009). Seasonal and chronic water scarcity has resulted in electricity supply disruptions in the past, particularly during periods of low summer flow. For example, a drought in the southeastern US in 2007 forced nuclear and coal-fired power plants within the Tennessee Valley Authority system to shut down some reactors and reduce production at others (National Energy Technology Laboratory 2009). Similar water-driven shutdowns occurred in 2006 along the Mississippi River at the Exelon Quad Cities Illinois plant, as well as some plants in Minnesota. A recent assessment found that nearly 60% of coal-fired power plants in the US are located in areas subject to water stress from limited supply or competing demand from other sectors (National Energy Technology Laboratory 2010).

Although annual average precipitation will likely increase across the continental US over the next century, changes in seasonality of precipitation, timing of spring thaw, and climate-driven changes to surface runoff may affect surface and groundwater supplies in some regions. Potential future water scarcity increases the risk of electricity supply disruptions in some regions. In particular, surface and groundwater supplies in the Southwest, Southeast, and southern Rockies are expected to be affected by runoff reductions and declines in groundwater recharge, increasing the risk of water shortages (Georgakakos et al. 2014). According to the Electric Power Research Institute, approximately one-quarter of electricity generation in the US – 250 gigawatts (GW) – is located in counties projected to be at high or moderate water supply sustainability risk in 2030 (EPRI 2011). The study found that all generation types will be affected, with 29 GW of nuclear, 77 GW of coal, and 121 GW of natural-gas generation capacity in counties with "at risk" water supplies.

Hydroelectric generation accounts for 7% of total US electricity supply, roughly 20% of electricity generation in California and the Northeast, and up to 70% of electricity generation in the Pacific Northwest (Georgakakos et al. 2014; Energy Information Administration 2013). Projected climatic changes, including more precipitation falling as rain and less as snow, reduced snowpack, and earlier peak runoff, may decrease annual water storage and runoff. The resulting reductions in streamflow will decrease available hydropower generation capacity. The degree of impact will vary widely by region, with the western US expected to be at greatest risk.

Water also plays a vital role in oil and gas production. Large volumes of water are used throughout the production process, including enhanced oil recovery, hydraulic fracturing, well completion, and petroleum refining. As the share of US oil and gas production coming from unconventional sources, including coal bed methane, tight gas sands, and shale oil and gas, increases access to water will becoming increasingly important in sustaining US production growth (US DOE 2013a). In times of water stress, oil and gas operations must compete with other water users for access, limiting availability and driving up costs. During the severe drought of July 2012, oil and natural gas producers faced higher water costs or were denied access to water for six weeks or more in several states including Kansas, Texas, Pennsylvania, and North Dakota (Dittrick 2012; Ellis 2012; Hargreaves 2012).

Coastal storms and sea-level rise

The sea-level rise and coastal storm dynamics discussed in Chapter 4 threaten important energy assets as well as commercial and residential property. Superstorm Sandy demonstrated the extent to which coastal storms can disrupt energy supply. Storm surge and high winds downed power lines, flooded substations and underground distribution systems, and damaged or shut down ports and several power plants in the Northeast (US DOE 2013b). More than eight million customers in 21 states lost power, further threatening vulnerable populations reeling from the effects of the storm (US DOE 2012). Sandy also forced the closure of oil refineries, oil and gas pipelines, and oil and gas shipping terminals, impeding fuel supply in the region.

Over half of total US energy production and three quarters of electricity generation takes place in coastal states (US Energy Information Administration 2013). The concentration of critical facilities in vulnerable coastal areas creates systemic risk not only for the region, but the nation as a whole. The Gulf Coast is a prime example. The region is responsible for half of US crude oil and natural gas production and is home to nearly half the country's refining capacity, with nearly 4,000 active oil and gas platforms, more than 30 refineries, and 25,000 miles of pipeline (Entergy 2010; Wilbanks et al. 2012). It is also home to the US Strategic Petroleum Reserve (SPR), with approximately 700 million barrels of crude oil stored along the Gulf Coast for use in the event of an emergency (DOE 2012). With a substantial portion of US energy facilities located in the Gulf, isolated extreme weather events in the region can disrupt natural gas, oil, and electricity markets throughout the US (Wilbanks et al. 2012).

Outside of the Gulf Coast, other regional energy hubs are also at risk. The National Oceanic and Atmospheric Administration warns that outside of greater New Orleans, Hampton Roads near Norfolk, Virginia, is at greatest risk from sea-level rise and increased storm surge. The area is home to important regional energy facilities, including the Lamberts Point Coal Terminal, the Yorktown Refinery, and the Dominion Yorktown power plant (Wilbanks, Bilello, et al. 2012). On the other side of the country, many of California's power plants are vulnerable to sea-level rise and the more extensive coastal storm flooding that results, especially in the low-lying San Francisco Bay area. An assessment done for the California Energy Commission found that the combined threat of sea-level rise and the incidence of 100 year floods in California puts up to 25 thermoelectric power plants at risk of flooding by the end of the century, as well as scores of electricity substations and natural gas storage facilities (J. Sathaye et al. 2012).

Wildfires

Wildfires (see Chapter 18) also pose a risk to the nation's energy infrastructure. During the summer of 2011, severe drought and record wildfires in Arizona and New Mexico burned more than one million acres and threatened two high voltage lines transmitting electricity from Arizona to approximately 400,000 customers in New Mexico and Texas. In 2007, the California Independent System Operator declared an emergency due to wildfire damage to more than two dozen transmission lines and 35 miles of wire, with nearly 80,000 customers in San Diego losing power, some for several weeks (Vine 2008; SDGE 2007). More frequent and severe wildfires increase the risk of physical damage to electricity transmission infrastructure and could decrease available transmission capacity.

CHAPTER 11

Coastal Communities

Temperate climates, attractive scenery, ease of navigation, and access to ocean food supplies have put coastlines at the forefront of human development throughout history and around the world. The United States is no exception. Today, counties touching the coast account for 39% of total US population and 28% of national property by value. Coastal living carries risk, particularly on the East Coast and along the Gulf of Mexico, where hurricanes and other coastal storms inflict billions in property and infrastructure damage each year. Climate change elevates these risks. Rising sea levels will, over time, inundate low-lying property and increase the amount of flooding that occurs during coastal storms. Moreover, as discussed in Chapter 4, warmer sea surface temperatures may change the frequency and intensity of those storms.

BACKGROUND

A growing body of academic work assesses the potential impacts of sea-level rise (SLR) on coastal communities. Early studies focused on developing a methodology for site-specific estimates of damage from SLR that could be used as a model for nationwide assessments (Yohe 1990). Several compared the cost to coastal property of damages from mean sea-level rise with the cost of protecting that property with sea walls, structural enhancements, and other adaptive measures (Yohe et al. 1996; G. Yohe and Schlesinger 1998).

Subsequent work expanded to regional assessments. One of the first was conducted by the US Environmental Protection Agency (Titus and Richman 2001), which identified areas vulnerable to inundation from higher sea levels along the Atlantic and Gulf coasts. A subsequent US interagency assessment of the Mid-Atlantic simulated a one meter sea-level rise running from New York through Virginia and estimated the associated impacts on residential property and coastal residents (CCSP 2009). The first robust national estimate of potential inundation damage from SLR, as well as the cost of protective measures, was published in 2011 (Neumann et al. 2011) using the National Coastal Property Model (NCPM) developed by Industrial Economics, Inc. (IEc) for the US Environmental Protection Agency.

Permanent inundation from mean sea-level rise is only one of the risks climate change presents to coastal property and infrastructure. Higher average sea levels lead to higher storm surges and elevated flooding risks (Frumhoff et al. 2007), even if the intensity or frequency of storms remains unchanged (Frazier et al. 2010). Kemp and Horton (2013) found that, while the record 13.9 foot storm tide in New York Harbor during Superstorm Sandy was primarily due to the coincidence of the strongest winds with high tide, SLR driven by historical climate change added more than one foot to that 13.9 foot total.

A number of recent studies have assessed coastal communities' vulnerability to future SLR-driven increases in storm surge. At a local scale, following Superstorm Sandy, the New York City Panel on Climate Change analyzed the risk to the city's property and infrastructure from future climate-driven changes in sea levels and storm activity (NPCC 2013). California conducted an assessment of the impact of sea-level rise on the Bay Area's 100 year floodplains for coastal storms (Commission 2011; Heberger et al. 2012), and Harrington & Walton (2008) estimated impacts on coastal property for six coastal counties in Florida. Neumann et al. have incorporated projected increases in storm surge as a result of both mean SLR and potential changes in hurricane intensity and frequency into the NCPM for select cities (Neumann et al. 2014).

OUR APPROACH

Alongside the academic and policy-oriented work described above, private companies have developed sophisticated models to estimate potential losses from coastal storms. These models are used by the insurance industry in underwriting flood and wind insurance products, by the finance industry in pricing catastrophe bonds, and by local officials in coastal communities in preparing for and responding to hurricanes and other coastal storms. While not traditionally used in this way, they are also incredibly powerful tools for understanding how climate change will likely shape both industry and coastal community risk exposure in the years ahead.

Risk Management Solutions (RMS) is a leading provider of such tools, along with models for quantifying and managing other catastrophic risks, from earthquakes to terrorist attacks to infectious disease, and a partner in this assessment. To assess the value of property at risk from future sea-level rise, we mapped the probabilistic local SLR projections described in Chapter 4 against RMS's detailed exposure dataset, which covers buildings, their contents, and automobiles for all coastal counties in the US. To analyze the impact of local SLR on storm surge and flood damage during hurricanes and nor'easters, we employed RMS's North Atlantic Hurricane Model. This model combines state-of-the art wind and storm surge modeling, and a stochastic event set that represent more than 100,000 years of hurricane activity and spans the range of all possible storms that could occur in the coming years (see Appendix III).

The result of this analysis is the first comprehensive, nationwide assessment of the risk to coastal communities from mean SLR and SLR-driven increases in storm surge from hurricanes and nor'easters under a full range of climate futures, and at a very high level of geographic resolution. Taking this work one step further, we explore the impact of changes in hurricane frequency and intensity projected by Knutson et al. (2013) for RCP 4.5 and Emanuel (2013) for RCP 8.5 on both future storm surge and wind damage (see Chapter 4).[3]

There is considerable uncertainty surrounding future coastal development patterns, which makes accurate cost projections challenging. Over the past few decades, population and property values in coastal counties have grown faster than the national average, putting more people and assets at risk. It is unclear the extent to which this trend will continue going forward, given constraints to further development and expansion in many coastal areas. Rather than attempt to predict how the built environment will evolve in the decades ahead, we assess the impact of future changes in sea level and storm activity relative to the American coastline as it exists today. Damages are reported in current dollars against current property prices.

RESULTS

Inundation from mean sea-level rise

While all coastal states are at risk from rising sea levels, some are much more vulnerable than others. Under RCP 8.5, for example, between 4.1 and 5.5% of total insurable residential and commercial property in the state of Louisiana will *likely* be below MSL by 2050 (excluding that property already below MSL), growing to 15 to 20% by 2100 (Figure 11.1). Florida is the second most vulnerable state in percentage terms, with 0.4 to 0.6% of current statewide property *likely* below MSL by 2050, growing to 1 to 5% by 2100. In dollar terms, between $33 and $45 billion worth of current Louisiana property will *likely* be below MSL by 2050, growing to $122 to $164 billion by 2100. The total value of current Florida property at risk is similar, with between $15 and $23 billion *likely* below MSL by 2050, growing to $53 to $208 billion by 2100 (Figure 11.3).

Nationwide, we find that between $66 and $106 billion worth of current coastal property will *likely* be below mean sea level (MSL) by 2050 under RCP 8.5 unless protective measures are taken (Table 11.1), growing to $238 to $507 billion by 2100 (Table 11.2). The value of current property *likely* under MSL falls to $62 to $85 billion by 2050 in both RCP 4.5 and 2.6. By 2100, nationwide property *likely* below MSL is $175 to $339 billion in RCP 4.5 and $150 to $276 billion in RCP 2.6.

Two factors explain this relatively small difference in inundation between the RCPs. First, the expanding ocean and melting ice sheets respond both to the amount of warming and the length of exposure to elevated temperatures. Temperatures begin to diverge significantly between RCPs only in the second half of the century; sea level, which integrates temperature, diverges later. Second, the largest sources of uncertainty in sea level are potential positive feedbacks in the behavior of ice sheets, particularly the West Antarctic Ice Sheet (WAIS). For example, for parts of the sea floor that are appropriately sloped, it is possible that, as a warming ocean eats away at the base of the WAIS (which unlike most of the Greenland and East Antarctic Ice Sheets largely sits below sea level), it will expose more of the ice sheet to the ocean, which will accelerate melt, exposing still more ice, and so forth. Such feedbacks are poorly understood at present; the uncertainties arising from this low level of understanding are independent of emissions and therefore cause the projected ranges of sea level change for all the RCPs to overlap considerably.

At the tails of the sea-level rise probability distribution, inundation damages are considerably worse than the *likely* range. For example, there is a 1-in-20 chance more than $346 billion worth of current Florida property (8.7%) could be below MSL by the end of the century under RCP 8.5 (Figure 11.3), and a 1-in-100 chance that

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[3] While we capture projected change in frequency and intensity from the cyclogenesis models employed by Knutson et al. and Emanuel, we do not capture and projected change in landfall location. This could have a meaningful impact on the geographic distribution of hurricane-related losses and is worthy of considerable additional research.

Figure 11.1: Share of current property below MSL in 2100

RCP 8.5

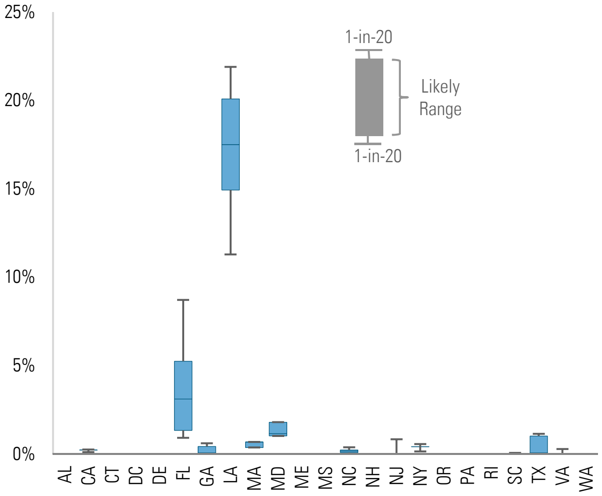


Figure 11.2: Share of current property below MHHW due to SLR by 2100

RCP 8.5

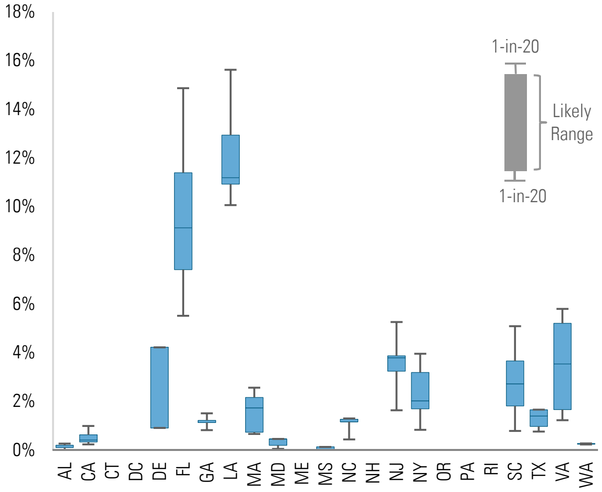


Figure 11.3: Value of current property below MSL by 2100

RCP 8.5, billion 2011 USD

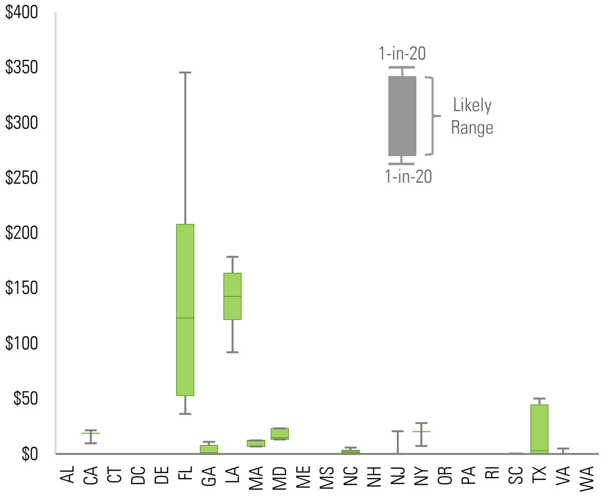
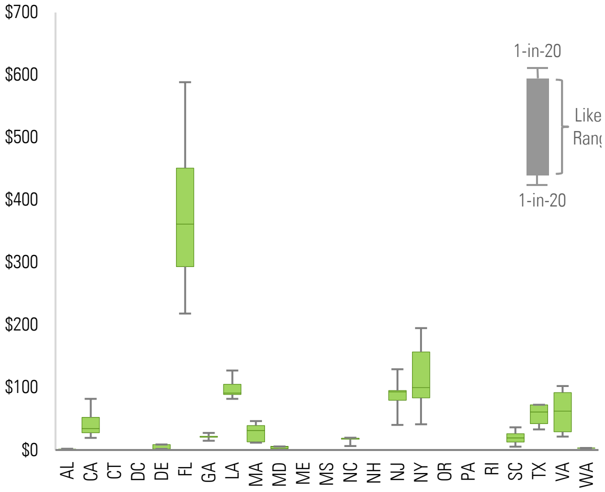


Figure 11.4: Value of additional current property below MHHW due to SLR by 2100

RCP 8.5, billion 2011 USD



more than $681 billion of current Florida property (17%) could be lost by 2100 unless defensive measures are taken. Nationwide, there is a 1-in-20 chance that more than $701 billion worth of current property is below MSL by 2100, and a 1-in-100 chance it will be more than $1.1 trillion (Table 11.2).

While roughly two-thirds of all current property *likely* below MSL by 2050 is in Louisiana and Florida, and three-quarters of all property by the end of the century, Maryland, Texas, Massachusetts, North Carolina, New York, New Jersey, and California also face meaningful inundation risk. In Maryland, for example, between $13 and $23 billion (0.7 and 1%) of current state-wide property will *likely* be below MSL by 2050, with losses concentrated in Queen Anne's and Talbot counties located on the east side of the Chesapeake Bay. In Texas, up to $44 billion of current property is *likely* below MSL by the end of the century, including important industrial and energy infrastructure.

Inundation risk from SLR extends beyond those properties underwater at average tide levels. There is currently $1.6 trillion in coastal property that is above mean sea level, but at or below peak high tide levels, often referred to as Mean Higher High Water levels or MHHW. Most of this property is protected by shoreline defense built up over the course of decades, or even centuries. As mean sea levels rise, the high tide mark

Table 11.1: Additional current property below MSL and MHHW by 2050

Billion 2011 USD, at current property prices

Probability	RCP 8.5		RCP 4.5		RCP 2.6	
	MSL	MHHW	MSL	MHHW	MSL	MHHW
1-in-100 chance above	$156	$523	$143	$472	$129	$456
1-in-20 chance above	$126	$465	$107	$400	$106	$397
Likely range	$66 to $106	$323 to $389	$62 to $85	$294 to $366	$62 to $85	$287 to $360
1-in-20 chance below	$61	$256	$60	$240	$60	$226
1-in-100 chance below	$52	$186	$51	$181	$50	$172

Table 11.2: Additional current property below MSL and MHHW by 2100

Billion 2011 USD, at current property prices

Probability	RCP 8.5		RCP 4.5		RCP 2.6	
	MSL	MHHW	MSL	MHHW	MSL	MHHW
1-in-100 chance above	$1,114	$1,636	$719	$1,433	$613	$1,332
1-in-20 chance above	$701	$1,432	$495	$1,135	$431	$990
Likely range	$238 to $507	$724 to $1,144	$175 to $339	$759 to $926	$150 to $276	$430 to $830
1-in-20 chance below	$166	$509	$134	$400	$116	$362
1-in-100 chance below	$131	$383	$105	$313	$102	$246

will rise as well, putting additional property in the line of fire. Without defensive investments (see Chapter 22 for a discussion), these properties risk significant damage.

Figure 11.3 and Figure 11.4 show the share and value of additional current property below MHHW by 2100 due to mean sea-level rise. The value is two to four times larger than property below MSL, depending on time frame and sea-level rise scenario (Table 11.1 and Table 11.2).

To illustrate the risks presented by local sea-level rise to coastal communities, we map inundation levels in 2100 at mean sea levels in the median, 1-in-100, and 1-in-200 projections for RCP 8.5 for Miami, Norfolk, Houston and Wilmington, NC, in Figure 11.5 through Figure 11.8 below. The inundation threat to Miami is particularly grave at a citywide level, but will also challenge the viability of several neighborhoods in New York City, Wilmington, and elsewhere. In Houston, while the center of the city is reasonably safe, critical energy infrastructure is at risk. In Norfolk, major naval installations are threatened by SLR. This choice of examples is illustrative only. Many other cities in the country face significant SLR risk. These maps also do not show property at or below MHHW but above mean sea levels.

Figure 11.5: Wilmington MSL in 2100 under RCP 8.5

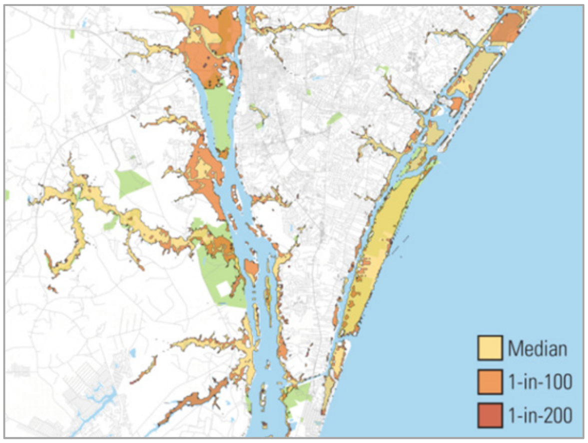


Figure 11.6: Miami MSL projections in 2100 under RCP 8.5

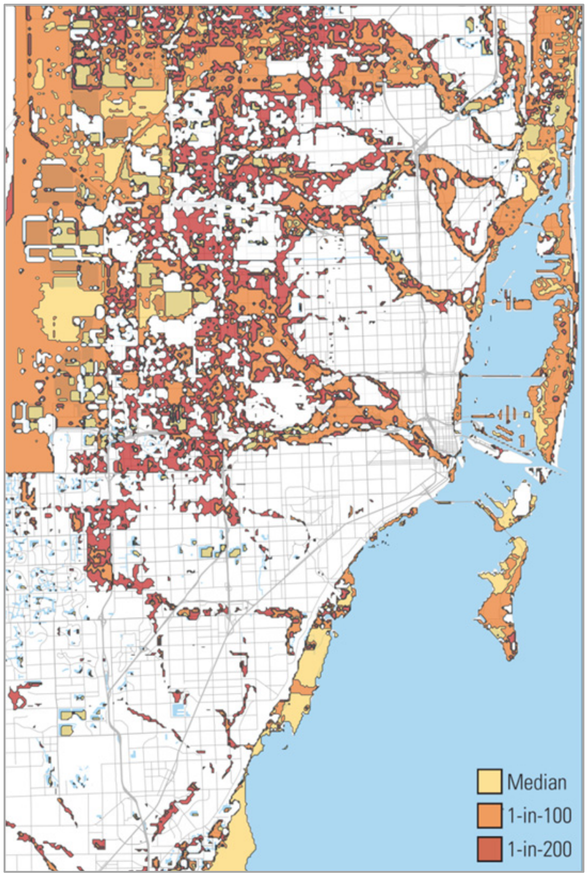


Figure 11.7: Norfolk MSL projections in 2100 under RCP 8.5

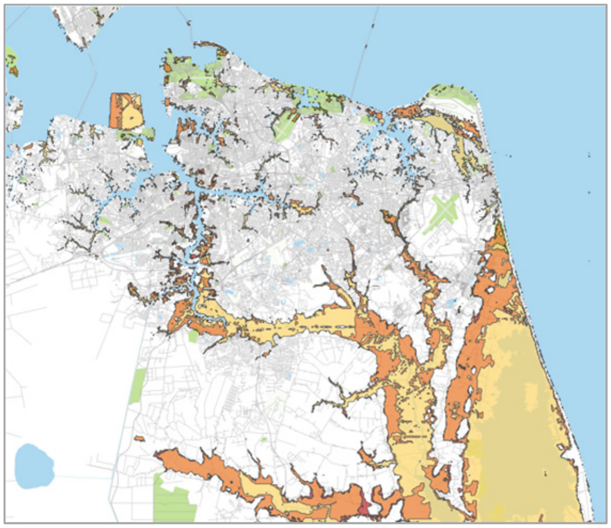
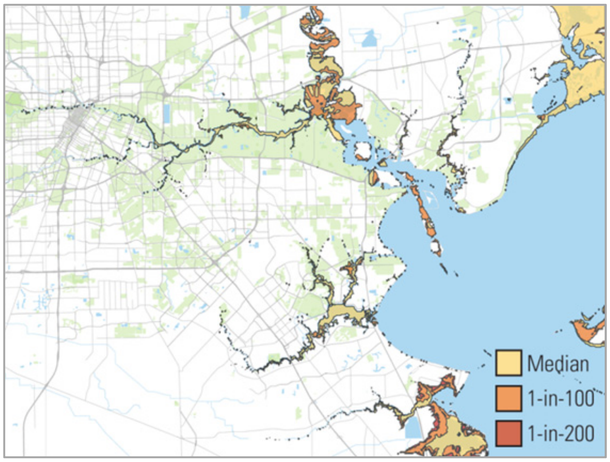


Figure 11.8: Houston MSL projections in 2100 under RCP 8.5



Storm surge

As mentioned above, higher sea levels also mean greater flooding during hurricanes and other coastal storms. These storms currently result in roughly $27 billion in average annual average commercial and residential property damage and business interruption costs along the East Coast and Gulf of Mexico, with roughly half of that occurring in Florida. The impact of climate change on flooding during coastal storms is larger and more immediate than the impact of gradual SLR-driven inundation discussed above. Assuming current hurricane activity continues, SLR under RCP 8.5 will *likely* increase average annual losses by $2 to $3.5 billion per year as early as 2030, a 7 to 13% increase over current levels. This increase in storm damage, like the storms themselves, will not be evenly spread across time. These numbers expect the expected average annual loss of all storms across different scenarios for sea-level rise.

As with inundation from sea-level rise, this climate-driven increase in expected storm damage hits some states harder than others (Figure 11.9 through 11.14). The largest relative *likely* increases occur in Delaware (16 to 39% by 2030), New Jersey (14 to 36%), New York (11 to 27%), and Virginia (13 to 28%). In absolute terms, Florida faces a far greater increase in expected storm damage due to higher sea levels than any other state. By 2030, average annual losses *likely* grow by $738 million to $1.3 billion.

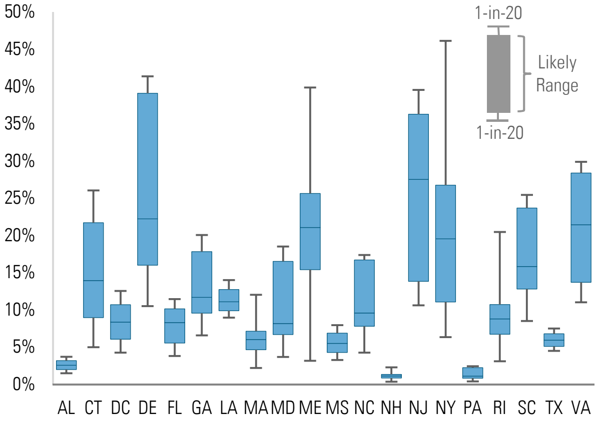


Figure 11.9: Relative increase in average annual coastal storm damage due to higher sea levels in 2030

Percent change from 2010 expected average annual losses

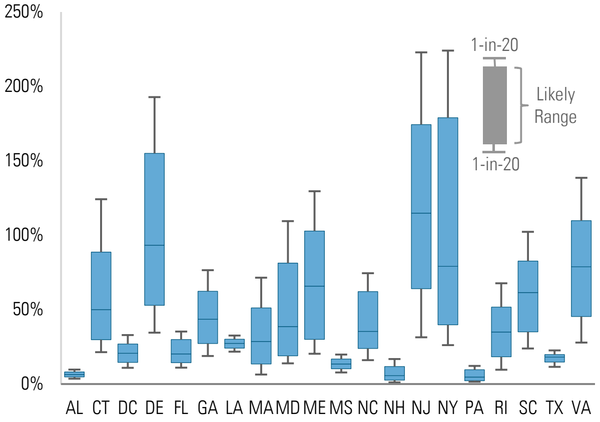


Figure 11.10: Relative increase in average annual coastal storm damage due to higher sea levels in 2050

Percent change from 2010 expected average annual losses

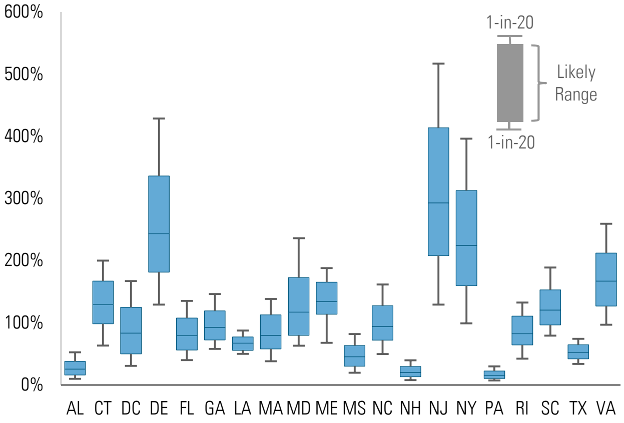


Figure 11.11: Relative increase in average annual coastal storm damage due to higher sea levels in 2100

Percent change from 2010 expected average annual losses

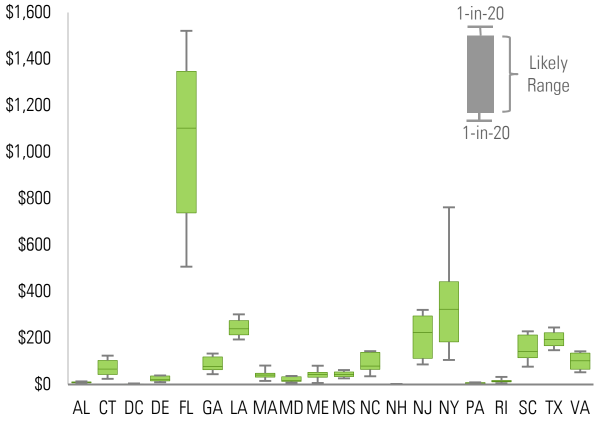


Figure 11.12: Absolute increase in average annual coastal storm damage due to higher sea levels in 2030

Million 2011 USD relative to 2010 expected average annual losses

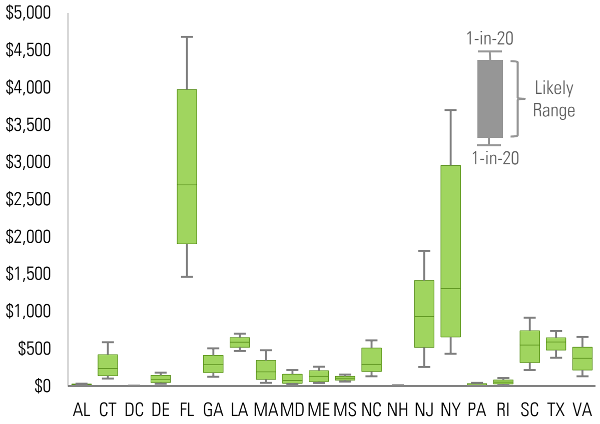


Figure 11.13: Absolute increase in average annual coastal storm damage due to higher sea levels in 2050

Million 2011 USD relative to 2010 expected average annual losses

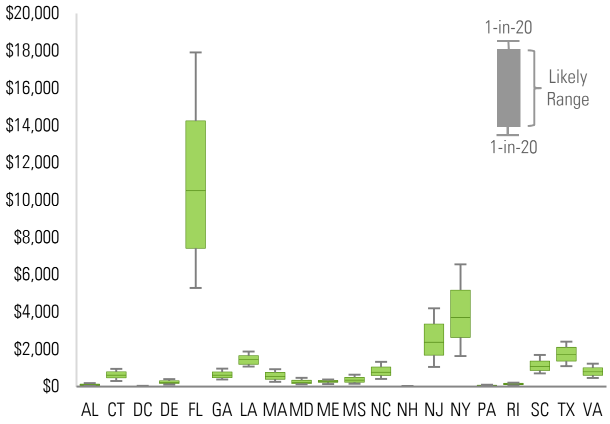
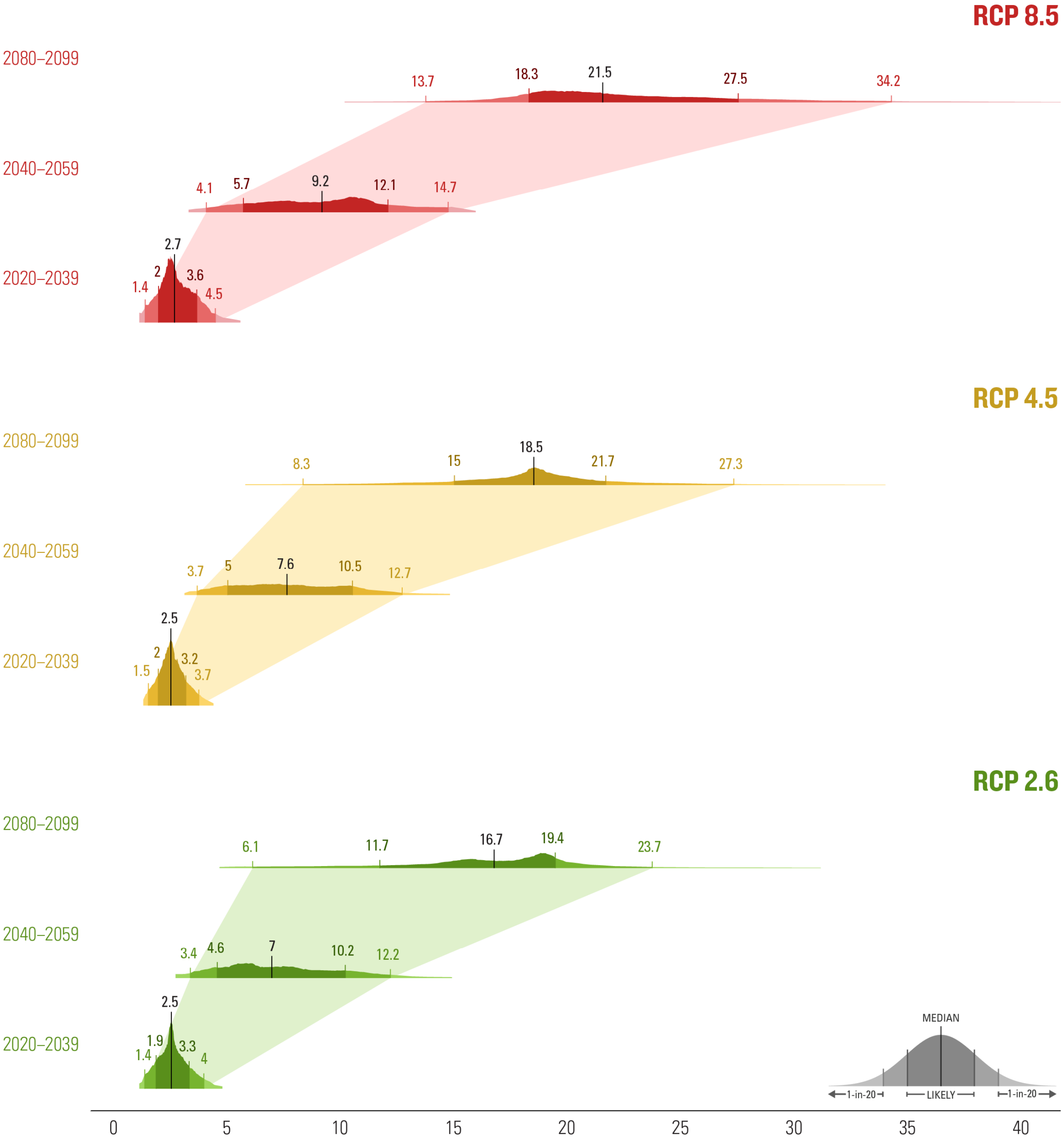


Figure 11.14: Absolute increase in average annual coastal storm damage due to higher sea levels in 2100

Million 2011 USD relative to 2010 expected average annual losses

Figure 11.15: Increase in expected annual property losses as a result of SLR, assuming no change in hurricane activity

Billion 2011 USD



By 2050 average annual losses from hurricane and nor’easters will *likely* grow to $5.8 to $13 billion nationwide under RCP 8.5, a 21 to 48% increase from current levels, due just to mean sea-level rise. Average annual losses in New Jersey will *likely* increase by between 64 and 174%, by 53 to 155% in Delaware, and by 45 to 110% in Virginia. In absolute terms, Florida will *likely* see an additional $1.9 to $4 billion a year in storm damage by 2050 unless protective measures are taken, while New York will *likely* see an additional $658 million to $3 billion in coastal storm-related costs each year.

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By 2100, SLR-driven increases in average annual hurricane and nor'easter damage *likely* grow by $19 to $33 billion under RCP 8.5, a 71 to 122% increase from current levels. There is a 1-in-20 chance that damages could grow by more than $42 billion by 2100, and a 1-in-100 chance they could grow by more than $50 billion. Conversely, there is a 1-in-20 chance that average annual losses will only grow by $15 billion or less, and a 1-in-100 chance of a less than $8.6 billion increase. Florida will *likely* see a $7 to $14 billion, or 60% to 104%, increase above current levels. New York will *likely* see a $2.6 to $5.2 billion increase, or 159% to 313%, and New Jersey *likely* sees a $1.4 to $3.7 billion increase, or 208% to 414%.

Averaged over the two decade intervals used for other impact categories, *likely* SLR-driven increase in average annual coastal storm damage is $2 to $3.6 billion on average by 2020-2039, $5.7 to $12 billion on average by 2040-2059, and $18 to $28 billion on average by 2080-2099 (Figure 11.15).

The relatively small difference in SLR in this century between RCPs translates into a relatively small difference in SLR-driven surge damage between RCPs as well. In RCP 4.5, the *likely* increase in average annual coastal storm damage due to mean SLR by 2040-2059 is $5 and $11 billion, and $15 and $22 billion by 2080-2099. In RCP 2.6, the *likely* range falls to $4.6 to $10 billion on average by 2040-2059 and $12 to $19 billion on average by 2080-2099.

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Figure 11.16: NYC 100 year floodplain under median RCP 8.5 sea-level rise

Assumes historical hurricane activity

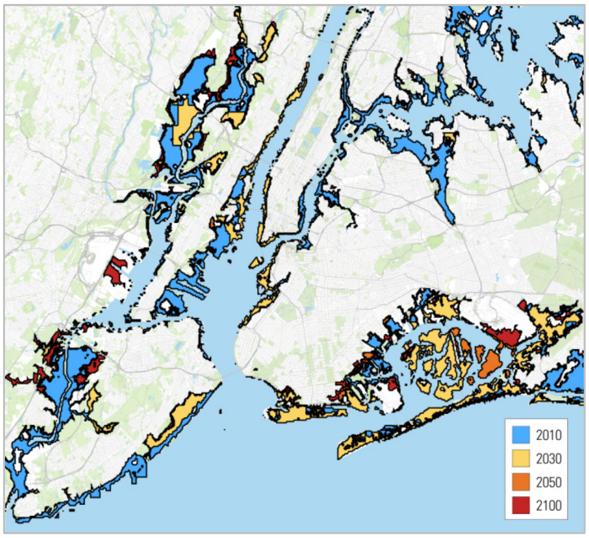
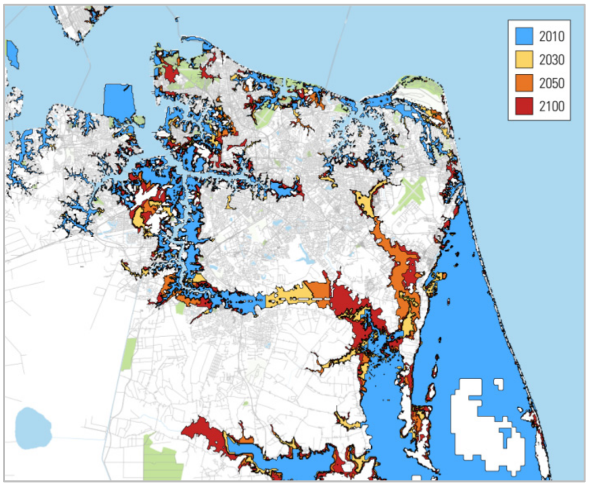


Figure 11.16: Norfolk 100 year floodplain under median RCP 8.5 sea-level rise

Assumes historical hurricane activity



Another way to think about the risk to coastal property of SLR-driven increases in storm surge is to map the change in extent of flooding during a 1-in-100 year flood. Or, put another way, areas with a 1% chance of being flooded any given year. Buildings within the 100-year floodplain are generally required to purchase flood insurance by the federal government. Projected local sea-level rise will materially change the 1-in-100 year flood plain in many communities, and as soon as the next 10 to 20 years. Figure 11.11 and Figure 11.12 show the change in New York City's and Norfolk's 100 year floodplains, respectively, as a result of projected SLR in our median RCP 8.5 scenario.

CHANGES IN HURRICANE FREQUENCY AND INTENSITY

There is considerable uncertainty about how climate change will influence the frequency and intensity of hurricanes going forward, but the impact of potential hurricane activity change is significant. For example, using ensemble projections from Emanuel (2013) for changes in hurricane frequency and intensity under RCP 8.5, average annual damage from East Coast and Gulf of Mexico hurricanes and nor'easters will *likely* grow by $3.0 to $7.3 billion by 2030, an 11 to 22% increase from current levels (Figure 11.17). By 2050, the combined impact of higher sea levels and modeled changes in hurricane activity *likely* raise annual losses by $11 to $23 billion, roughly twice as large of an increase as from changes in local sea levels alone. By the end of the century, the combined *likely* impact of

Figure 11.17: Increase in average annual losses with historical and projected hurricane activity

Billion 2011 USD, RCP 8.5 ensemble tropical cyclone activity projections from Emanuel (2013)

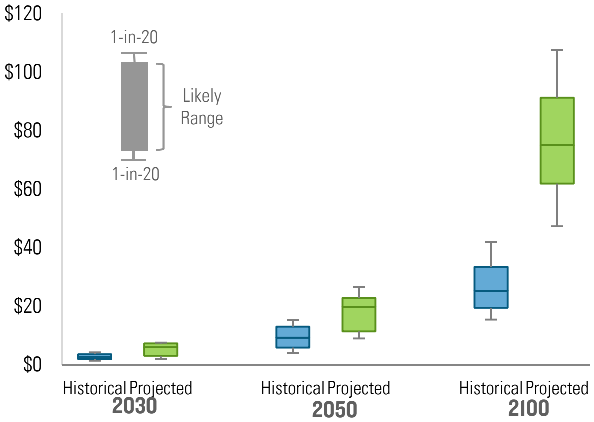
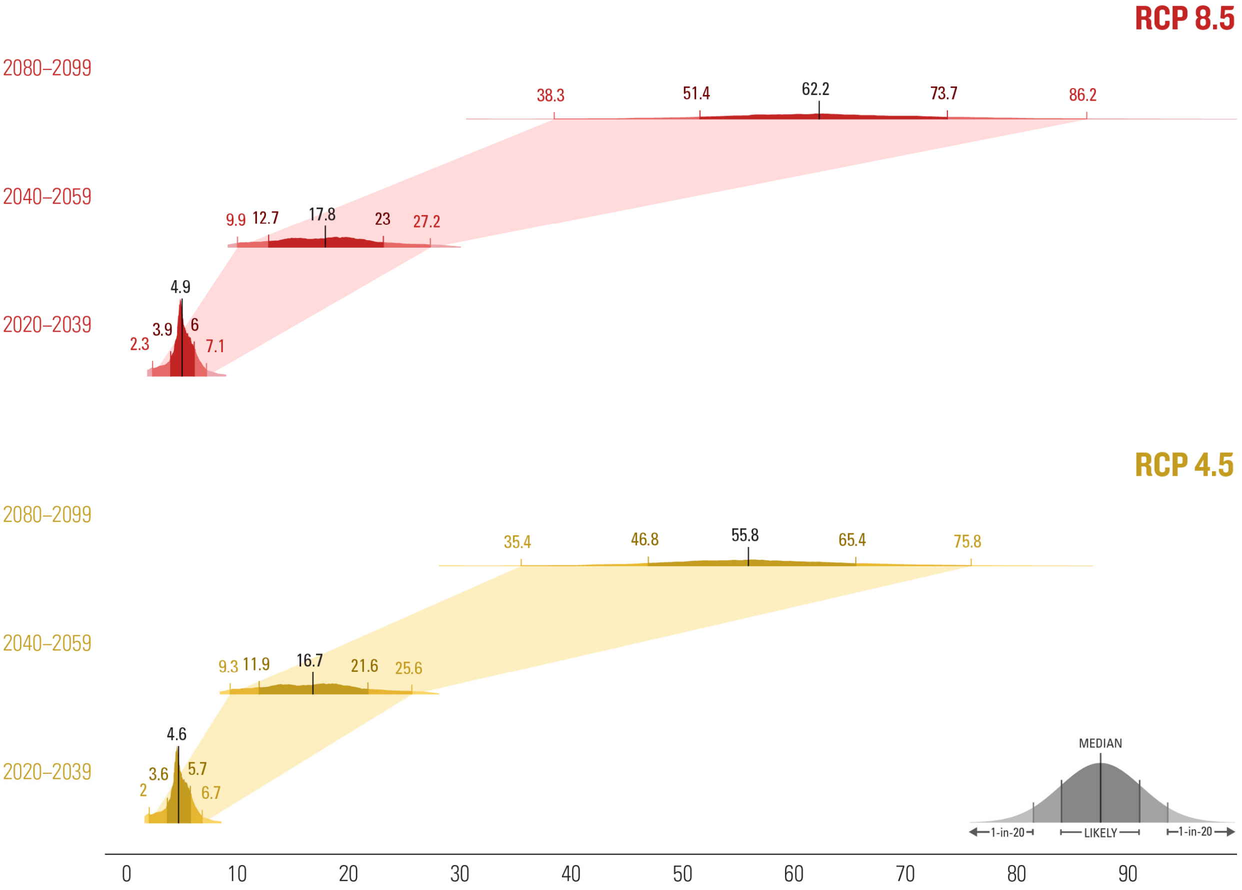


Figure 11.18: Increase in average annual losses with projected hurricane activity

Billion 2011 USD, RCP 8.5 tropical cyclone activity projections from Emanuel (2013) RCP 4.5 projections from Knutson et al. (2013)



sea-level rise and modeled changes in hurricane activity raise average annual losses by $62 to $91 billion, three times as much as higher sea levels alone.

Under RCP 4.5, using changes in hurricane activity projected by Knutson et al. (2013), the increase in average annual commercial and residential property damage as a result of climate change is *likely* $2.7 to $7.0 billion by 2030, $11 to $22 billion by 2050, and $56 to $80 billion by 2100. Averaged over the two decade intervals used for other impact categories, the increases are $3.6 to $5.7 billion by 2020-2039, $11 to $22 billion by mid-century and $47 to $65 billion by late century (Figure 11.14). The increase in damage resulting from either Emanuel or Knutson et al.'s projections for future changes in hurricane activity are due both to greater storm surge (even without climate-driven SLR) and greater wind damage.

While examining different RCPs, both Emanuel and Knutson et al. find significant changes in hurricane activity as a result of warmer sea surface temperatures. Should this finding turn out to be correct, changes in storm activity could be a more important determinant of climate-driven changes in hurricane damage than sea-level rise alone in the years ahead.

KEEPING OUT THE SEA

There are a number of steps individual building owners, community organizations, and policymakers at the local, state and national level can take to guard against some of these coastal impact. These include strengthening buildings, constructing sea walls, and nourishing beaches. We analyze the extent to which these adaptive measures can reduce the risk coastal communities face in Part V of this report.

Part III

Pricing Climate Risk

CHAPTER 12

From Impacts to Economics

What are the economic consequences of the climate impacts described in the preceding chapters? Rising sea levels, increased flooding, and more frequent and intense coastal storms damage capital that must be rebuilt. Changing yields impact the financial health of both agricultural producers and farming communities. Climate-driven changes in mortality rates shape overall labor supply, and temperature influences the productivity of that labor. Higher energy prices reduce real household income and raise business costs. Changes in crime rates impact property values and public expenditures on police and other security services. The costs of climate change will not be evenly spread throughout the country. The nature and magnitude of the economic risks Americans face depends very much on who they are and where they live.

Economists began studying the impact of climate change on modern economies in the early 1990s, starting with the pioneering work of Yale professor William Nordhaus (1991), Peterson Institute for International Economics fellow William Cline (1992), and London School of Economics professor Samuel Fankhauser (1993). Research focused on combining climate and economic models to enable an integrated assessment of the relationship between a) economic activity and GHG emissions, b) GHG emissions and global temperature increases, and c) global temperature increases and economic activity. The first of these "benefit-cost integrated assessment models" (IAMs) were developed by Nordhaus (1994), Cambridge professor Chris Hope (1993), and University of Sussex professor Richard Tol (1995). These three models continue to be among the most often used, although a few others have joined their ranks (Revesz et al. 2014).

IAMs are primarily used to conduct cost-benefit analysis of emission reduction strategies at the global level (Mastrandrea et al. 2010). The cost of climate change is quantified through one or more climate "damage functions," which provide monetary estimates of climate impacts associated with different increases in global average temperatures, often expressed as a percentage loss of GDP. This is mapped against an "abatement cost function" that provides a monetary estimate of the cost of reducing GHG emissions, also generally expressed as a percentage loss of GDP, to estimate the economically optimal level of emissions reduction.

Because their scope of coverage is so broad, IAMs necessarily rely on simplified representations of individual components of both climate and economic systems (Kopp and Mignone 2012). For example, most models explore changes in global mean temperatures and sometimes sea level, but not how these changes shape temperature, precipitation, and sea level at a local scale. Economic costs are generally assessed and presented as global aggregates or aggregates for a small number of multinational regions, with no sub-national geographic detail and often no sectoral detail. Most IAMs assume the economy naturally adapts to climate change to the extent it makes economic sense to do so. Those climate costs that can't be addressed through adaptation are weighed against the cost of reducing emissions based upon a single representative decision-maker's attitude towards risk and level of concern regarding future economic liabilities.

These features make IAMs less useful for the type of risk assessment we seek to provide with this report than the national or global benefit-cost analysis for which they have traditionally been employed. American businesses and households experience climate change in the form of shifts in local daily temperature and precipitation patterns, rather than global annual averages. Global or nationwide economic cost estimates are useful in international or national policy-making, but do little to inform local risk management decisions. Indeed, local decision-makers, whether state infrastructure planners, property developers, agricultural producers, or individual households, need more tailored information in order to make the adaptation investments the IAMs assume will occur. These individuals and institutions differ in both risk tolerance, and in planning and investment time horizons, making economy-wide risk aversion and time preference assumptions irrelevant to their individual decision-making process.

Over the past decade, researchers have begun taking a more granular approach to assessing the economic cost of climate change, including in the United States. For example, in 2004, economist Dale Jorgenson used a computable general equilibrium (CGE) model of the US economy, and the best climate projections and impact estimates available at the time to assess national costs at a sectoral as well as economy-wide level (Jorgenson et al. 2004). In 2009, David Abler, Karen Fisher-Vanden and colleagues conducted a similar assessment for Pennsylvania, providing a greater level of geographic resolution (Abler et al. 2009). A 2010 report by Sandia National Laboratory analyzed potential economic impacts in the US across a wider range of climate scenarios than past assessments (Backus et al. 2010).

A category of IAMs distinct from the benefit-cost IAMs discussed above, known as process-based IAMs, contain detailed representations of the energy and agriculture sectors. These process-based IAMs have traditionally been used for analyses of the cost-effectiveness of climate change mitigation strategies rather than for assessments of the risks of climate change. Recent work, however, has begun to incorporate feedbacks from climate change onto these models' representation of the national and global economy, laying the groundwork for assessments of the economic costs of climate change (Calvin et al. 2012; Reilly et al. 2012).

Building on this work, in this section we quantify the economic consequences of the climate impacts described in Part 2 by sector, state, and region, and across a full range of potential climate futures. We assess the impact on those sectors, states, and regions directly affected (Chapter 13), how those impacts ripple throughout the region and the country, and how climate impacts in a given year affect the rate of economic growth in subsequent years (Chapter 14). Finally, we explore how the differences in time preference, risk appetite, and concern about inequality shape the national significance of these economic impacts (Chapter 15).

CHAPTER 13

Direct Costs and Benefits

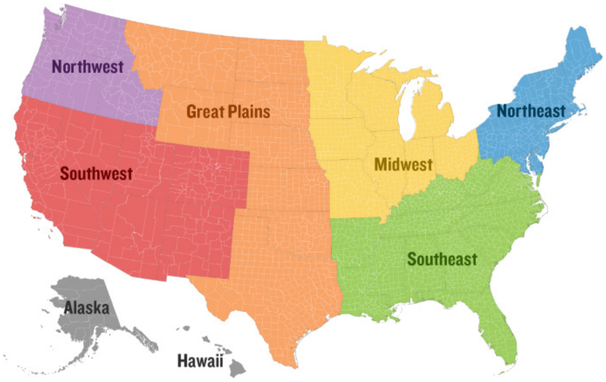
All assessments of the economic consequences of developments that may occur decades in the future must grapple with uncertainty about how the economy will evolve going forward absent those developments. This assessment of the economic risk of climate change is no different. Researchers are left with two choices: *(a)* assess the consequences of future developments relative to current economic structure and population distribution, or *(b)* try to predict how the structure of the economy will change and assess the consequences of future developments relative to a hypothetical economic future. To quantify the direct costs and benefits of the climate-driven changes in agricultural production, labor productivity, mortality, crime, energy demand and coastal storm damage described in previous chapters, we take approach (a). As stated from the outset of this report, our goal is to provide decision-makers with a better understanding of the risks they face, and their views on the likely evolution of particular sectors or the US economy as a whole in the years ahead may well differ from ours—but we can all agree on the structure and size of the current economy.

Of course, some of the following costs may be ameliorated by populations adapting to changes in the climate (an issue we discuss and explore quantitatively in Chapter 22), and one notable form of adaptation will the out-migration of individuals away from increasingly adverse climates, a response that directly contradicts the assumption above of a fixed population distribution. If this out-migration occurs it will slightly dampen the effects of climate change and reduce the magnitude of costs (and benefits) estimated below, but it is unlikely that it will cause our direct estimates to be off by a large amount. The size of the difference between our estimates (when populations are fixed) and actual costs (when some populations migrate) is equal to the product of two relatively small numbers: the fraction of the population that migrates and the fraction of the sector that is lost to climate. Because the product of two small numbers is a very small number, the distortion in our estimates introduced by assuming no migration is small (Hsiang, 2011). For example, if 1% of a population migrates out of a region due to climate change and the mortality rate in that region rose by 9.5 deaths per 100,000 due to climate change (our median estimate for the nation), the mortality that is averted by this migration would be roughly 0.095 deaths per 100,000 in the original population (1% times 9.5 deaths per 100,000). This means our baseline mortality estimate of 9.5 deaths per 100,000 is 0.095 deaths per 100,000 too large and should be corrected to 9.4 deaths per 100,000, a very minor adjustment given the scale of other uncertainties in our analysis.

All results presented in this chapter are for RCP 8.5. We assess the extent to which global emission reductions consistent with an RCP 4.5 or RCP 2.6 scenario, as well as investments in adaptation, reduce these costs (and benefits) in Part 5. Direct costs are reported at the county level (either for illustrative counties or binned by decile) and at the state level[1] on an annual basis, grouped by National Climate Assessment region (Figure 13.1).

Figure 13.1: US regional definitions

Regions as defined for the US National Climate Assessment



AGRICULTURE

We quantify the direct costs and benefits of climate-driven changes in commodity crop yields described in Chapter 6 using the Bureau of Economic Analysis' National Income Product Accounts and more detailed input-output tables from the Minnesota IMPLAN group (see Appendix IV). We assume any future change in commodity crop yields (maize, wheat, soy and cotton) translates into a change in overall agricultural output proportional to maize, wheat, soy and cotton's current share of total agricultural output (using current crop prices) for the county, state, or region in question. We count the change in agricultural output as the direct cost

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[1] We have less confidence in many impact estimates for Hawaii and Alaska than the Lower 48 and exclude them from our analysis in this chapter. That does not, however, mean they do not face economic risks from climate change.

or benefit in that geographic area. At the national level, assuming current farming practices continue, the *likely* change in yields under RCP 8.5 range from an average annual direct cost of -$8.5 billion (i.e., a $8.5 billion benefit) to +$9.2 by 2020-2039, -$8.2 to +$19 billion by 2040-2059, and -$12 to +$53 to billion by 2080-2099.

These are relatively modest impacts in the context of today's $17 trillion US economy against which they are measured – as expected, because these four crops account for less than one-third of US agricultural output by value, and for just 0.2% of total national economic output. As described in Chapter 6, climate change will likely result in an increase in yields in some parts of the country and a decrease in others, the combination of which results in relatively modest net changes at the national level. The local economic significance of this regional heterogeneity in agriculture impacts is exacerbated by the wide variation in agriculture's importance in different state economies (Figure 13.2). The four commodity crops included in our analysis accounted for 2.6%, 2.2%, 2% and 1.2% of total economic output in Nebraska, South Dakota, Iowa and North Dakota respectively in 2011. These states, and key counties within them, face economically significant changes in agricultural output (both positive and negative) over the course of the century.

Figure 13.2: Agricultural production as a share of state output

2011, broken down by crops quantified in this report and those excluded

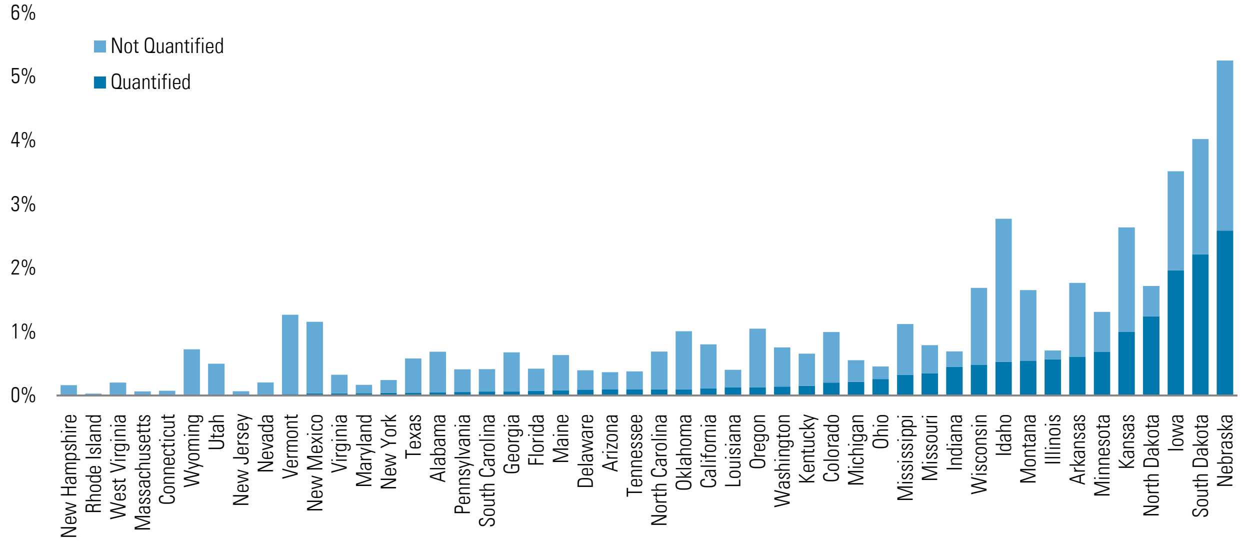


Figure 13.3: County-level per capita direct costs from changes in agricultural yield by decile in RCP 8.5, 2020-2039

2011 USD per capita, assumes current economic structure, crop mix and agricultural prices. Negative values indicate net benefits.

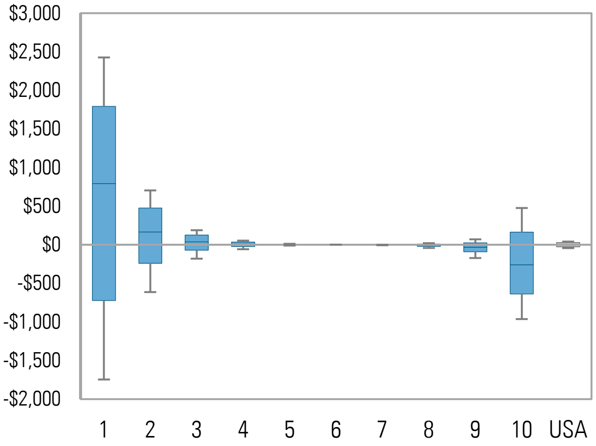


Figure 13.4: County-level per capita direct costs from changes in agriculture yield by decile in RCP 8.5, 2040-59

2011 USD per capita, assumes current economic structure, crop mix and agricultural prices. Negative values indicate net benefits.

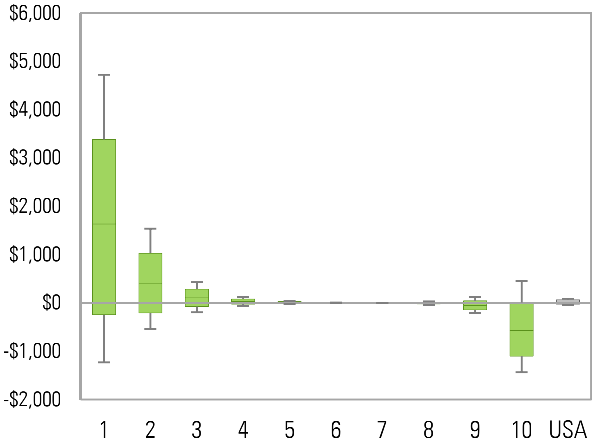
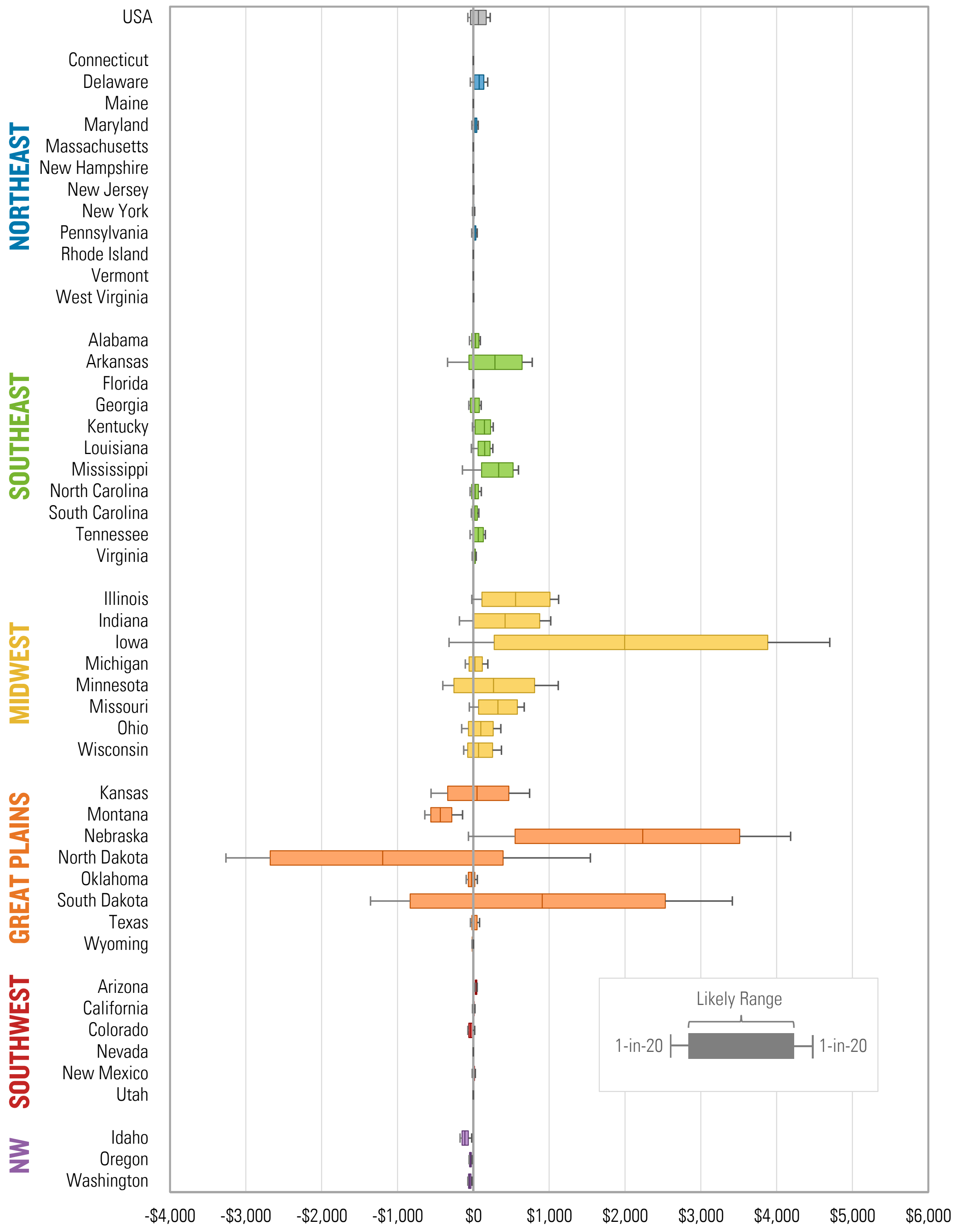


Figure 13.5: State-level per capita direct costs from changes in agricultural yields in RCP 8.5, 2080-2099

2011 USD, assumes current economic structure, crop mix and agricultural prices. Negative values indicate direct benefits



Likely nationwide, agricultural impacts per capita range from a $27 benefit to a $29 cost on average by 2020-2039 and from a $26 benefit to a $61 cost by 2040-2059. Figure 13.3 and 13.4 compare these national estimates to the *likely* range for individual counties, ranked by median projected per capita cost and binned by decile. Within each decile bin, critical values for the probability distribution of impacts (e.g. medians) are averaged across counties. The most vulnerable 10% of counties fare considerably worse than the national average, with *likely per capita* costs of -$722 to +$1,793 (median of +$793) by 2020-2039, and -$244 to +$3,382 (median of +$1632) by 2040-2059. The most positively impacted counties see *likely* per capita costs of -$638 to +$164 (median of -$261) by 2020-2039, and -$1102 to +$8 (median of -$574) by 2040-2059.

By late century, the impacts described in Chapter 6 translate into *likely* per capita costs of -$37 to +$169 (median of +$68) nationwide, with regional disparities getting even larger (Figure 13.5). Iowa and Nebraska see the largest *likely* costs on a per capita basis at +$275 to +3,882 (median of +$1,996) and +$550 to +$3,416, respectively. North Dakota sees the largest *likely* net benefit, per capita, with Montana, Oklahoma and the Pacific Northwest seeing more modest *likely* gains.

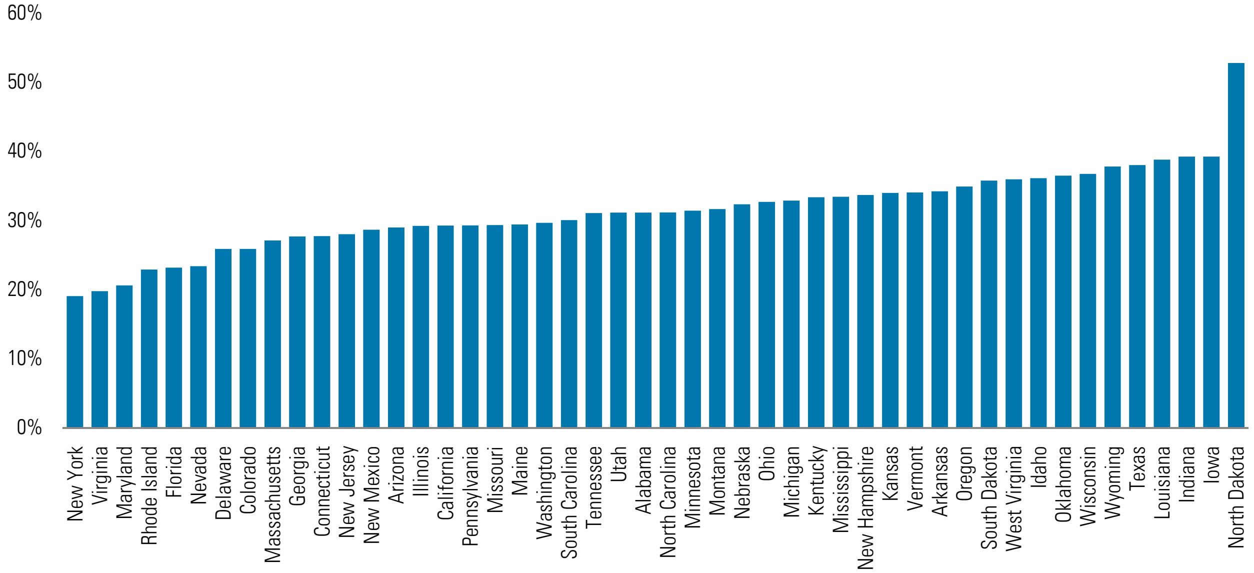
LABOR

We assess the direct costs and benefits of the climate-driven changes in labor productivity described in Chapter 7 by mapping projected percentage changes both in high-risk and low-risk sectors against the value added by those sectors in the 2011 IMPLAN input-output tables by geographic area. We assume that a 1% change in high-risk sector labor productivity results in a 1% change in high-risk sector value-added and calculate the direct cost of that 1% of change in value-added at 2011 prices. At the national level, assuming that the current sectoral mix in the economy remains constant, *likely* average annual direct labor productivity costs (high-risk and low-risk combined) under RCP 8.5 are +$0.1 to +$22 billion by 2020-2039, +$10 to +$52 billion by 2040-2059, and +$42 to +$150 billion by 2080-2099 – considerably larger than the nationwide agricultural impacts.

The regional variation of the impact of changes in temperature on labor productivity in high-risk sectors is not as geographically varied as the impact on agricultural productivity, nor is the economic importance of those high-risk sectors. That said, there is still a meaningful amount of variation in high-risk sectors' share of total state employment, ranging from 53% in North Dakota to 19% in New York in 2011 (Figure 13.6). Combined with modest variation in the climate-driven rate of high-risk labor productivity decline, this variation produces meaningful differences across counties and states. By 2020-2039, climate-driven changes in labor productivity will *likely* cost between +$0.3 and +$69 per capita on average nationwide (Figure 13.7). For the most vulnerable counties, binned by decile, the *likely* range is -$19 to +$270. By 2040-2059, *likely* national average per-capita costs grow to +$36 to +$171, with the most vulnerable 10% of counties *likely* seeing +$94 to +$473 in per capita costs.

Figure 13.6: Share of state employment in high-risk sectors

2011



By late-century, national average per capita costs from climate-driven labor productivity declines grow to +$133 to +$479. The Northeast and the Northwest see smaller *likely* costs than the national average, while most states in the Southeast, Great Plains, Southwest and Midwest see larger *likely* costs. At a state level, the largest direct per capita cost of climate-driven changes in labor productivity are in Texas (+$276 to +$1,040), Louisiana (+$262 to +$962), and North Dakota (+$233 to +$957), and due in large part to the relatively large share of the workforce in the states in high-risk sectors and, in the case of Texas and Louisiana, larger percent reductions in productivity (Figure 13.9).

Figure 13.7: County-level per capita direct costs from changes in labor productivity by decile in RCP 8.5, 2020-2039

2011 USD. Negative values indicate net benefits.

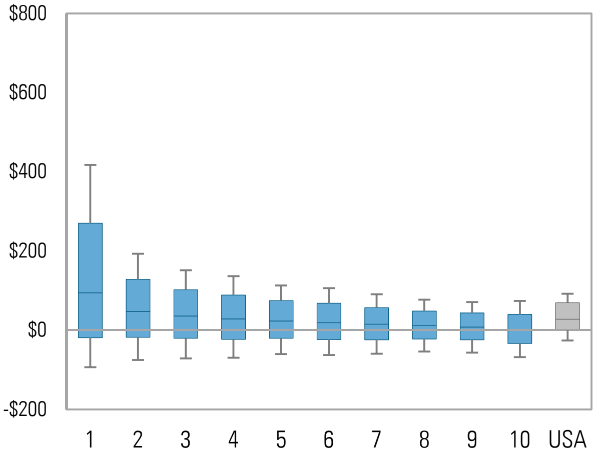
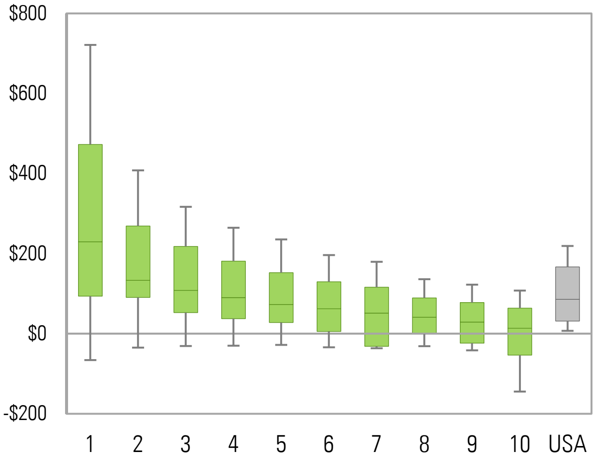


Figure 13.8: County-level per capita direct costs from changes in labor productivity in RCP 8.5, 2040-2059

2011 USD. Negative values indicate net benefits.



HEALTH

The climate-driven changes in temperature-related mortality discussed in Chapter 8 directly impact economic activity by changing available labor supply. We measure these "market" costs and benefits by calculating the change in state-level labor supply resulting from climate-driven changes in temperature-related mortality. We assess mortality by age cohort, as discussed in Chapter 8, using IMPLAN socio-economic data and labor force participation rate estimates by age cohort from the Bureau of Labor Statistics.[2] As with labor productivity, we assume a 1% change in labor supply translates into a 1% change in value-added.

Unlike climate-driven changes in labor productivity, however, the direct cost or benefit of mortality changes compounds over time. Workers who die in one year do not return to the labor force in the next year, during which time additional workers may die from climate-driven temperature increases. This leaves two options for assessing market costs. The first is to assess the lost or gained lifetime labor productivity of a projected climate-driven change in mortality in a given year and discount (using a 3% discount rate) those future losses to the year in which the death occurred. The second is to use a population model to assess changes in the composition of the workforce over time as climate-driven mortality impacts evolve. In this chapter, we employ the former technique (described in the Technical Appendix). We employ the second as part of our exploration of how macroeconomic effects might shape direct climate costs and benefits in the following chapter.

At a national level, the present value of lost lifetime labor supply from *likely* annual climate-driven mortality under RCP 8.5 is +$3.4 billion to +$14 billion on average by 2040-59, but with a net benefit likely in a significant number of states in the Northeast, Upper Midwest, Upper Great Plains and Northwest due to fewer cold-related deaths. By late century, many of these states still see *likely* benefits, but not enough to offset a sharp increase in heat-related mortality across the Southeast and in many Midwest, Great Plains and Southwestern states (Figure 13.10). Nation-wide *likely* mortality costs rise to +$13 to +$41 billion, or +$42 to +$130 per person. Louisiana, Texas, Oklahoma and Florida see the highest *likely* mortality increases, more than twice the national average, while New England, Oregon and Washington see the largest *likely* mortality declines.

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[2] Available online at
http://www.bls.gov/emp/ep_table_303.htm

Figure 13.9: State-level per capita direct costs from changes in labor productivity in RCP 8.5, 2080-2099

2011 USD. Negative values indicate net benefits.

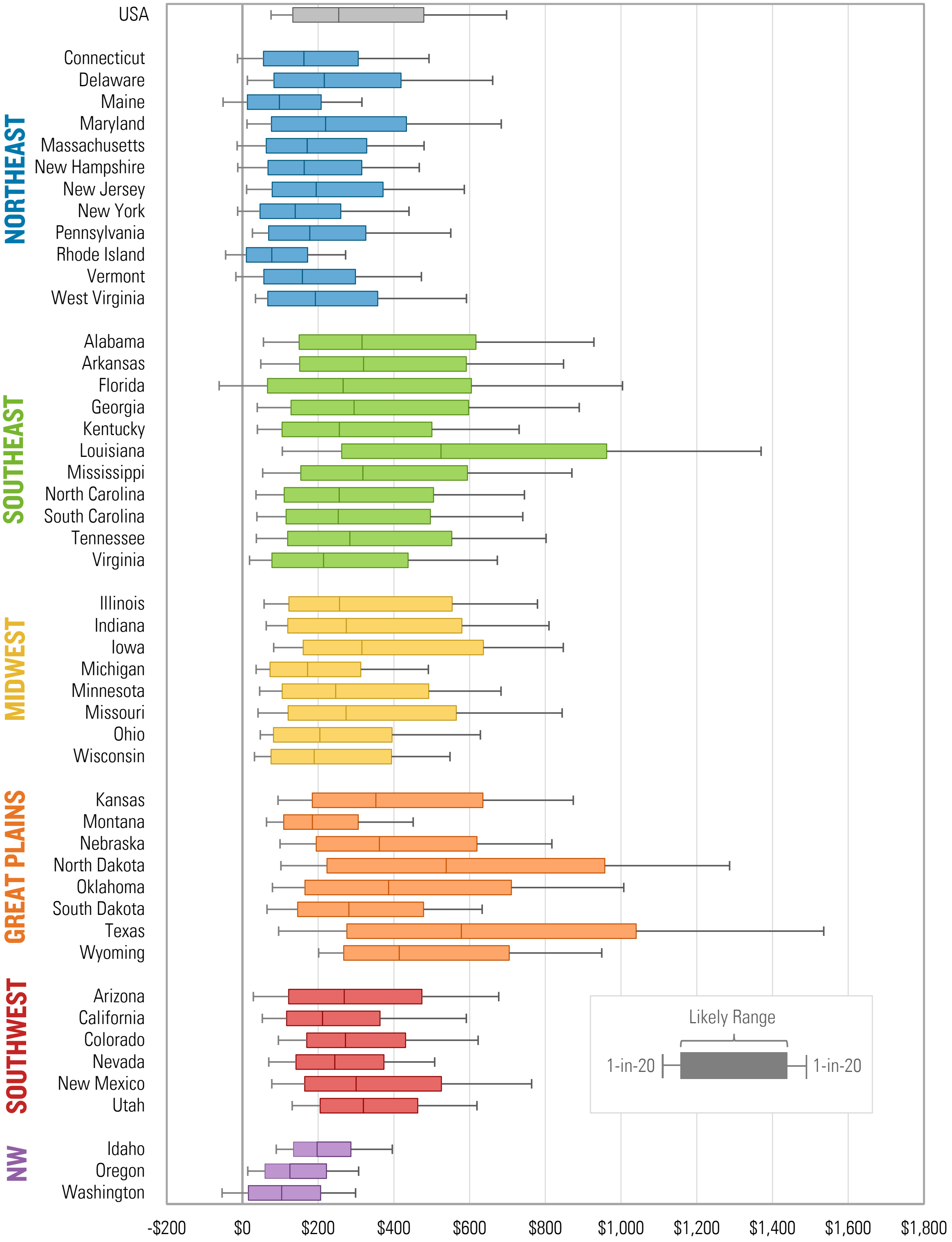


Figure 13.10: State-level per capita direct costs from changes in mortality, based on changes in labor income in RCP 8.5, 2080-99

2011 USD. Negative values indicate direct benefits.

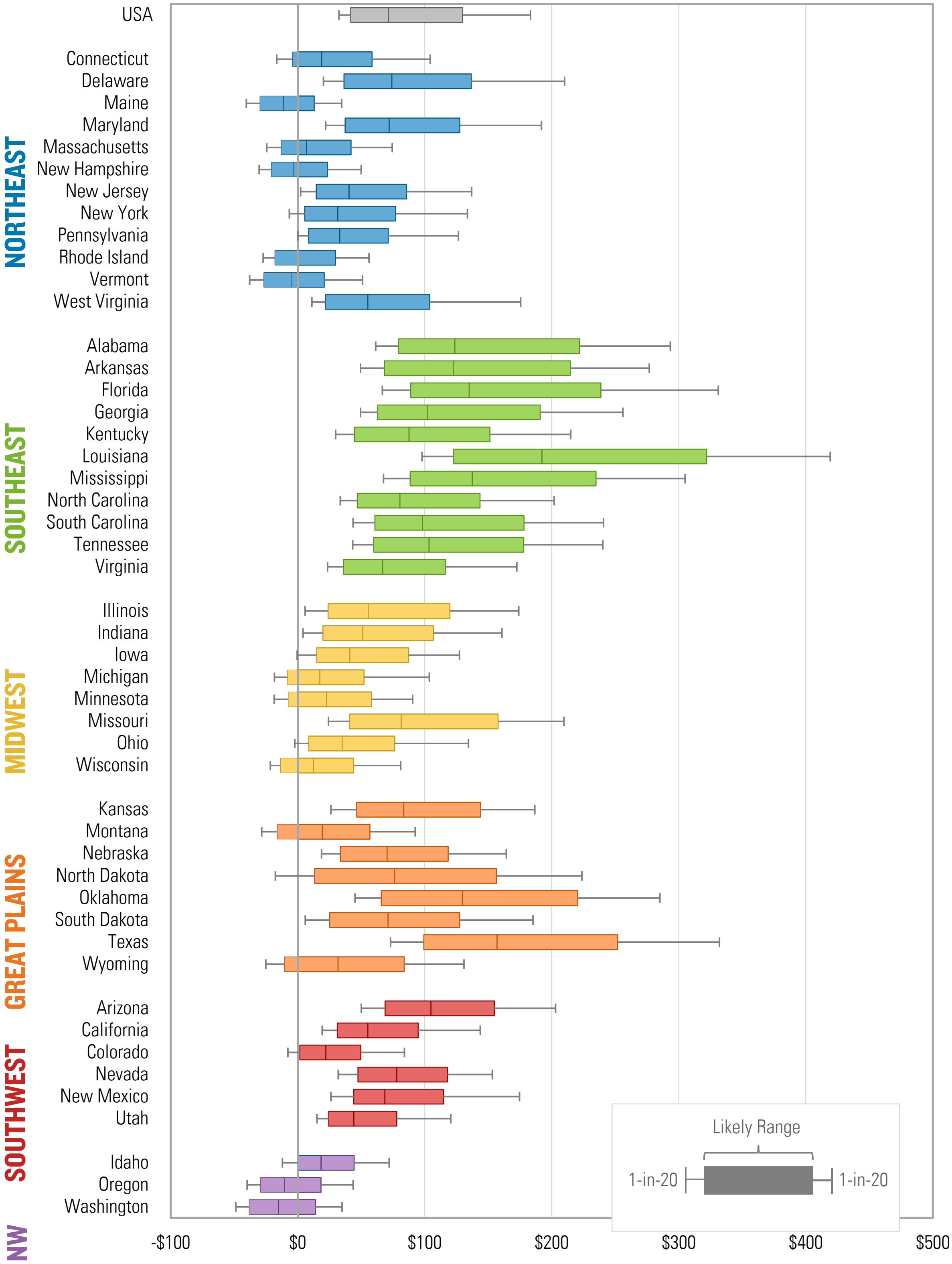
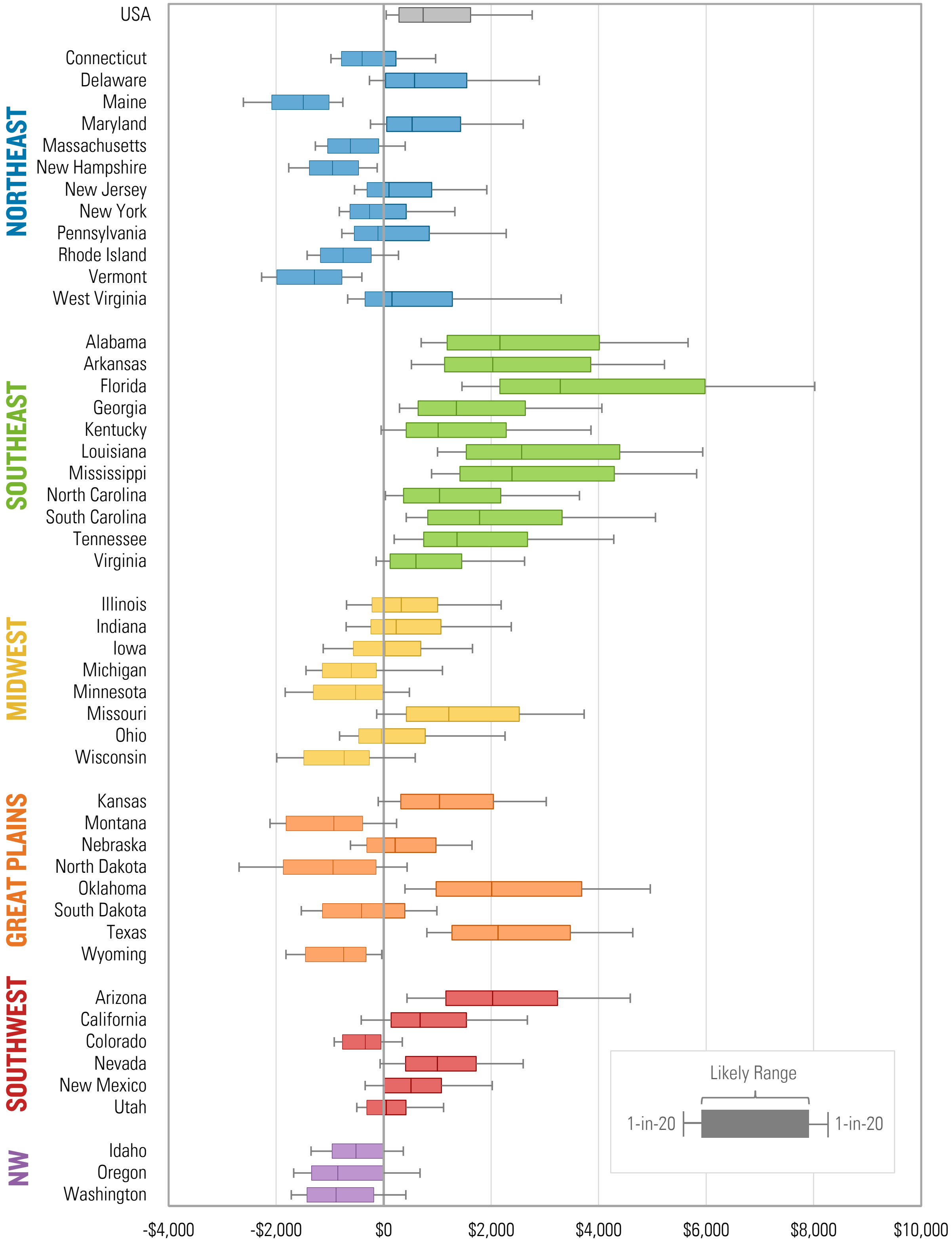


Figure 13.11: State-level per capita direct costs from changes in mortality, using a VSL of $7.9 million in RCP 8.5, 2080-99

2011 USD, Negative values indicate direct benefits.



Changes in lifetime labor income is, of course, a somewhat narrow measure of the value of a human life. In analyzing the benefits and costs of policies with an impact on mortality rates, governments often look to a population's "willingness-to-pay" for small reductions in their risk of dying (Viscusi and Aldy 2003). This is often referred to as the "value of statistical life" (VSL). In the United States, the Environmental Protection Agency (EPA) uses a central estimate of $7.9 million per person (in 2011 dollars) regardless of age, income or other population characteristics (EPA 2010). Aldy and Viscusi (2007) have found important differences in willingness to pay by age cohort, and as temperature-related mortality affects older Americans more than the population on average, the EPA VSL could be an overestimate of the "willingness-to-pay" to avoid these impacts. As it is the standard used by the US Government, we include it here as an upper-bound estimate.

Using the EPA central VSL estimate, we find *likely* average annual nationwide mortality costs under RCP 8.5 of -$12 billion to +$161 billion (median estimate of +$69 billion) by 2040-2059. Late century, this grows to +$90 to +$506 billion, more than twice as high as the market costs of climate-driven mortality. These values translate into +$287 to +$1,617 on a nationwide per capita basis (Figure 13.11). As with the market costs of the mortality impacts described above, there is considerable variation among states. Florida sees the highest *likely* costs, at +$2,163 to +$5,979 per capita, while Maine sees the lowest, at -$2,080 to -$1,015.

CRIME

We assess the direct costs of the climate-driven increase in violent and property crime described in Chapter 9 using average cost estimates for specific types of crimes, such as homicide or larceny (Heaton, 2010). The costs of specific crimes are estimated by combining accounting-based estimates, which attempt to enumerate costs incurred by victims (such as doctor's bills or lost assets), and contingent valuations of specific crimes, which try to elicit individuals' willingness to pay to avoid specific crimes using surveys. We assume that, in the future, the relative frequency of specific violent crimes and specific property crimes remains fixed within each state, but that the overall rate of these two classes of crimes evolves with the climate. At the national level, the *likely* change in direct property and violent annual crime costs under RCP 8.5 is $0 to $2.9 billion on average by 2020-2039, $1.5 to $5.7 billion by 2040-2059, and $5.0 to $12 billion by 2080-2099, making crime the least economically significant impact quantified in this report at a national level.

There is meaningful regional variation in climate-driven crime costs due both to differences in local climate projections and underlying crime rates (Figure 13.12 and Figure 13.13). *Likely* national direct crime costs average $16 to $37 on a per capita basis in 2080-2099. Michigan, New Mexico, Maryland, Louisiana and Illinois see the largest increases, though still relatively modest on a per capita basis. The per capita increases in crime costs are lowest in Utah, New England and the Pacific Northwest.

Figure 13.12: Violent crime rates by state

Crimes per 100,000 people, 2011, FBI Uniform Crime Reporting

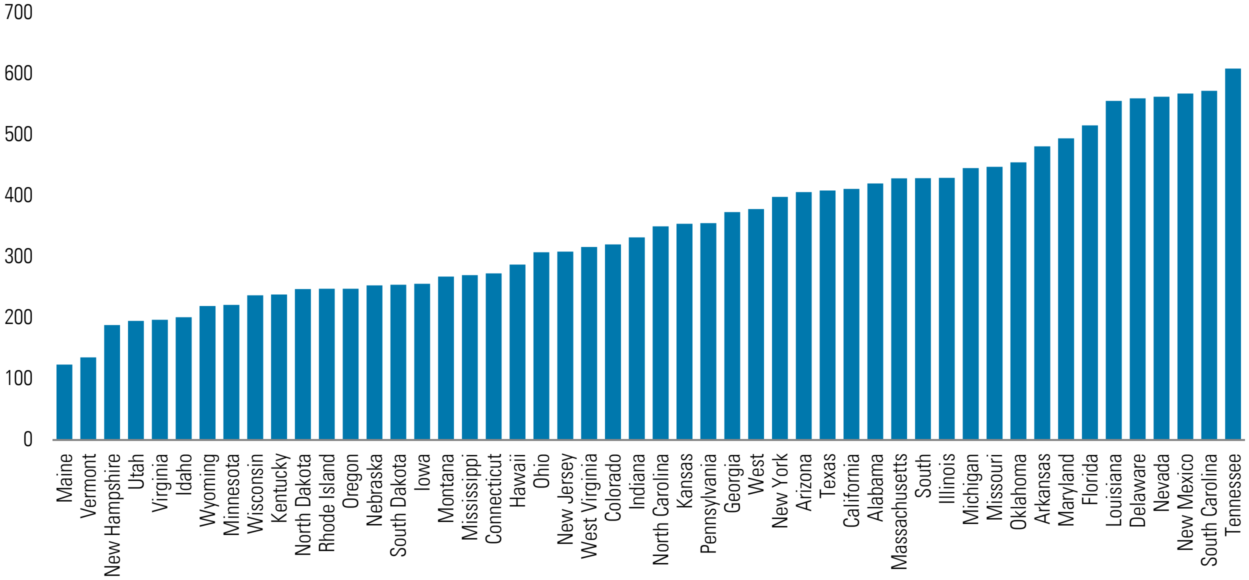


Figure 13.14: State-level per capita direct costs from changes in crime rates in RCP 8.5, 2080-2099

2011 USD

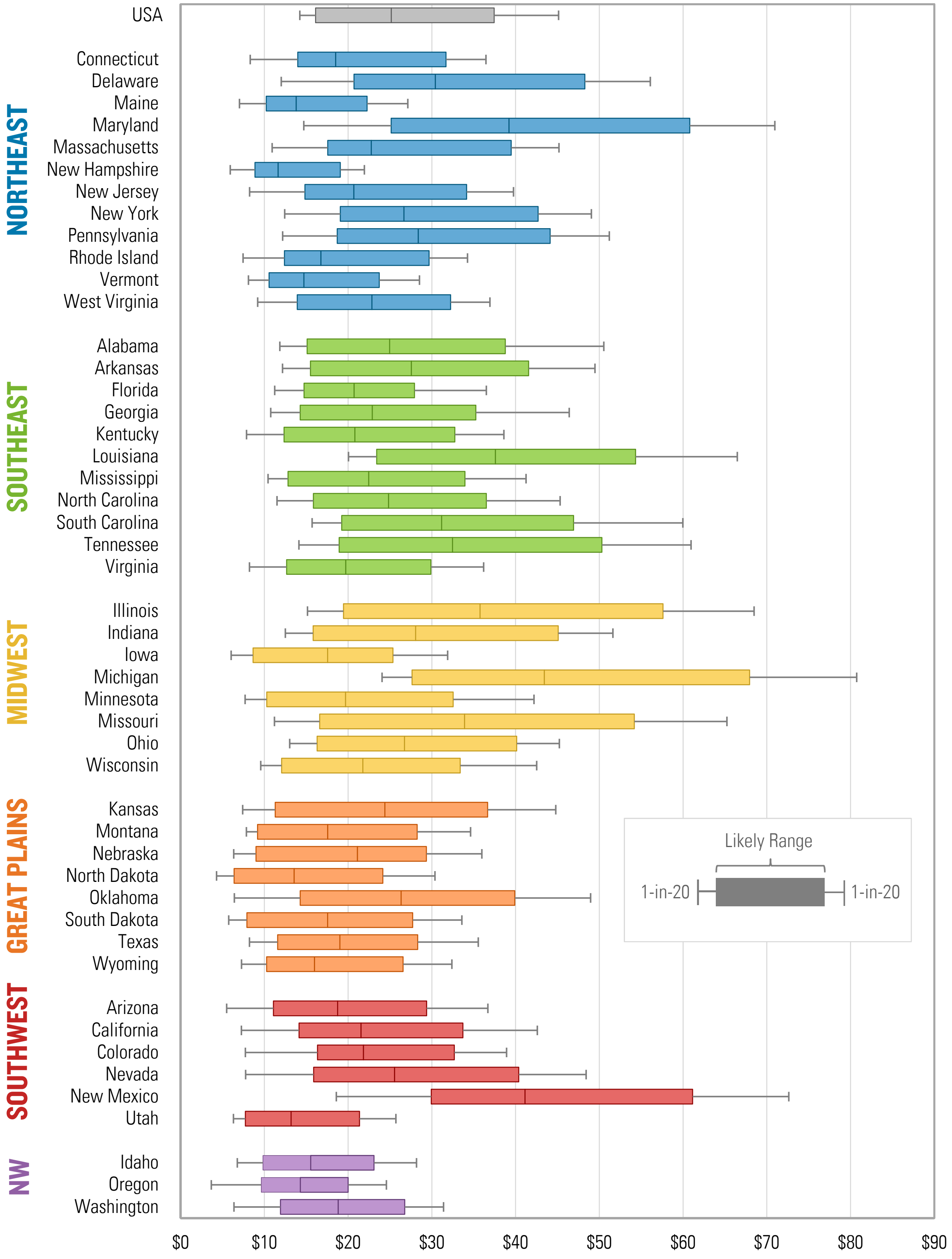
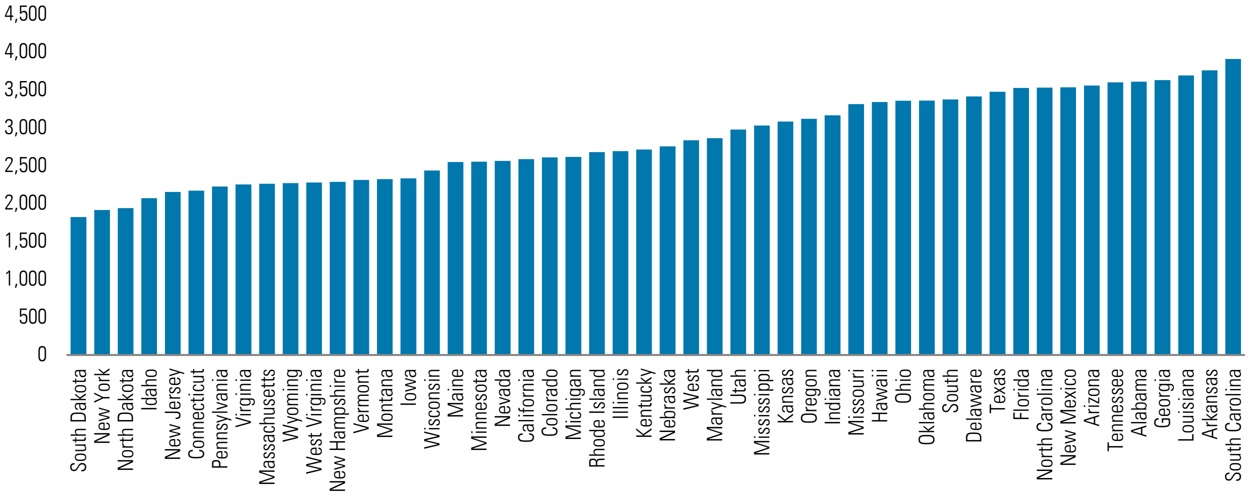


Figure 13.13: Property crime rates by state

Crimes per 100,000 people, 2011, FBI Uniform Crime Reporting



ENERGY

We assess the direct cost and benefits of climate-driven changes in energy demand using the estimates of percentage change in energy expenditures outlined in Chapter 10 relative to current energy expenditure levels. At the national level, future changes in temperature mapped against today's US energy market *likely* increases average annual energy expenditures under RCP 8.5 by $0.5 to $11 billion on average by 2020-2039, $8.3 to $29 billion by 2040-2059, and $32 to $87 billion by 2080-2099. Local changes in energy expenditures vary based both on local climate projections and local energy market conditions. Nationwide *likely* average annual energy expenditure increases by 2020-2039 are $1.5 to $37 on a per capita basis (Figure 13.15), growing to $27 to $94 on average by 2040-2059 (Figure 13.16). For the most vulnerable 10% of counties, however, the *likely* average per capita increase is $4 to $119 in 2020-2039 and $78 and $229 in 2040-2059. At the other end of the spectrum, 10% of counties see a *likely* combined decrease in energy expenditures of $3 to $60 per capita by 2020-2039 and $15 to $78 by 2040-2059. By late-century, annual per capita energy expenditures *likely* increase by $102 to $279 (Figure 13.17). The Northeast and Northwest see a much more modest increase (with some states seeing decreases in the median projection), as declines in heating costs offset much (and some places all) of the increase in cooling costs. Expenditures rise most in the Southeast and more southern states in the Great Plains and Southwest regions, where temperatures reach their highest levels and states currently have little heating demand to lose. In Arizona and Florida, for example, per capita energy expenditures rise by more than twice the national average.

Figure 13.15: County-level per capita direct costs from changes in energy expenditures in RCP 8.5, 2020-2039

2011 USD, negative values indicate net benefits

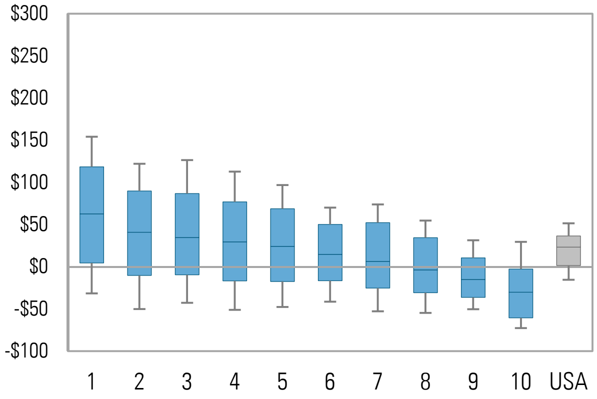


Figure 13.16: County-level per capita direct costs from changes in energy expenditures in RCP 8.5, 2040-2059

2011 USD, negative values indicate net benefits

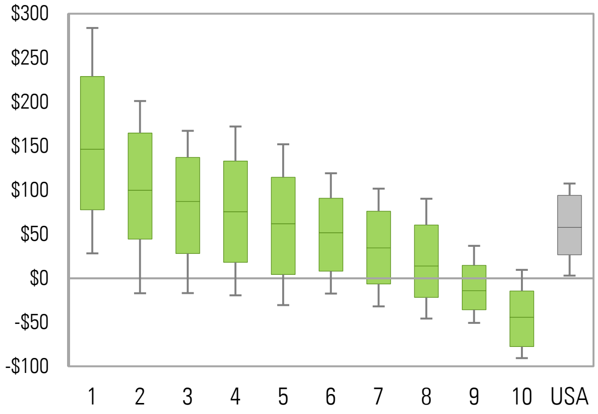
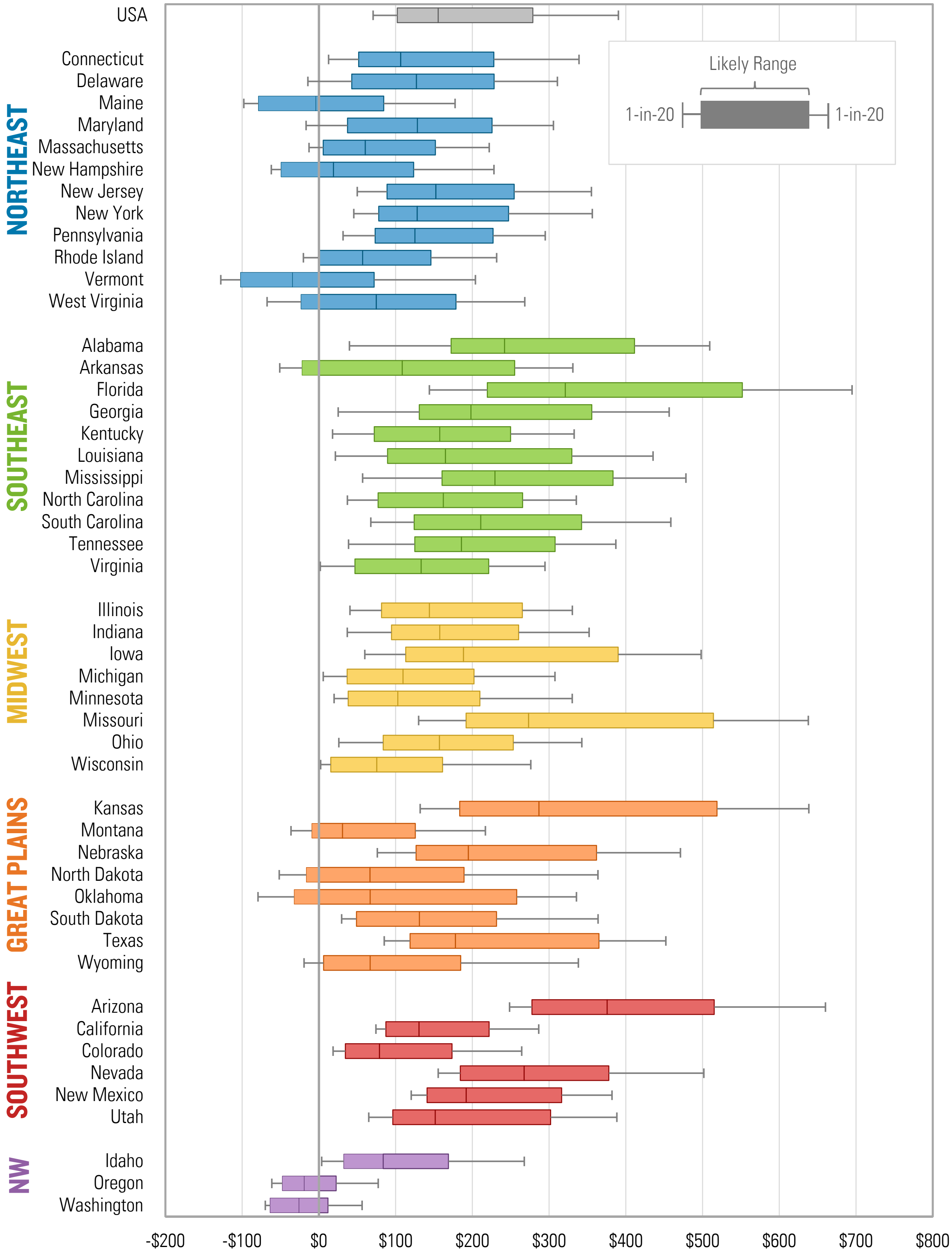


Figure 13.17: State-level per capita direct costs from changes in energy expenditures in RCP 8.5, 2080-99

2011 USD, negative values indicate net benefits



COASTAL COMMUNITIES

We assess the direct cost of climate-driven changes in coastal storms using the average annual loss estimates described in Chapter 11. At the national level, assuming coastal property exposure remains unchanged, projected sea-level rise increases average annual losses from hurricanes and other coastal storms by $2 to $3.7 billion on average by 2020-2039 under RCP 8.5, $6 to $12 billion by 2040-2059, and $18 to $27 billion by 2080-2099.

As discussed in Chapter 11, the impact of these SLR-driven changes in storm damage is not evenly spread. Potential costs vary, not only between coastal and non-coastal states, but also within coastal states. The direct risk of SLR-driven changes in storm damage is concentrated in particularly vulnerable coastal communities over the next few decades, broadening to entire coastal states by mid-century.

Figure 13.18: Per capita increase in average annual coastal storm damages due to SLR, 2030

2011 USD, RCP 8.5

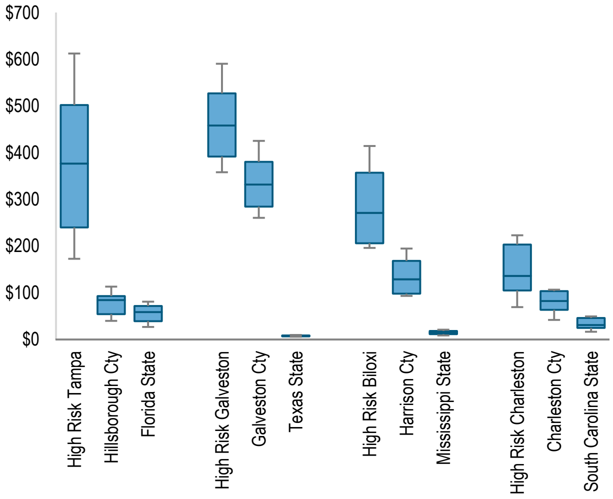
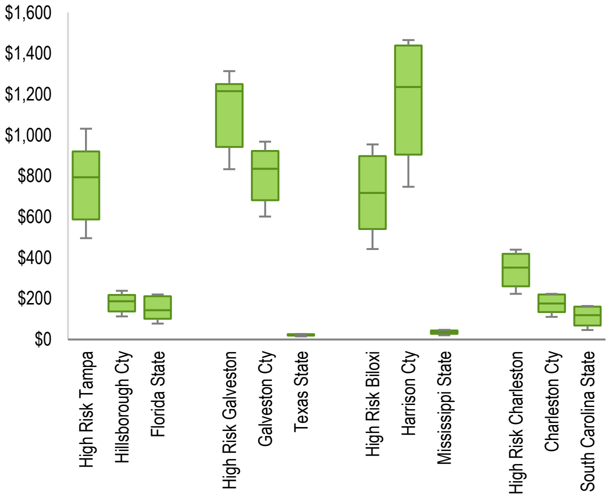


Figure 13.19: Per capita increase in average annual coastal storm damages due to SLR, 2050

2011 USD, RCP 8.5



Take, for example, a single-family wood home on the coast in Tampa, Florida. In the RMS exposure dataset, such a home has an insurable value of $222,000, with an average annual hurricane loss of $5,005. By 2030, higher sea levels in Tampa will *likely* raise this structure's annual average loss by $627 to $1,310, growing to increases of $1,534 to $2,404 by 2050. Based on the average number of people per household in Tampa, that translates into a per-resident *likely* increase in average annual losses of $240 to $502 by 2030 and $588 to $921 by 2050. In Figure 13.18 and Figure 13.19, we compare that to the increase in per capita average annual loss in Hillsborough County (in which Tampa resides) as a whole, and the entire State of Florida. In Hillsborough County and Florida, per capita average annual losses *likely* grow by $54 to $93 and $39 to $72 respectively by 2030 and $137 to $218 and $101 to $211 respectively by 2050.

We provide similar comparisons for Galveston, TX, Biloxi, MS and Charleston, SC. In Galveston, a typical single-family coastal home worth $191,000 faces $4,752 in average annual hurricane losses today that *likely* grow by $1,035 to $1,392 by 2030 and $2,488 to $3,303 by 2050. In Biloxi, a typical single-family coastal home worth $194,000 faces $10,800 in average annual hurricane losses today that *likely* grow by $527 to $915 by 2030 and $1,384 to $2,299 by 2050. In Charleston, a typical single-family coastal home worth $180,221 faces $2,329 in average annual hurricane losses today that *likely* grow by $254 to $492 by 2030 and $629 to $1,016 by 2050. In Figure 13.18 and Figure 13.19 these increases are translated into per capita terms using the average number of people per household in those cities, and compared to the *likely* per capita increase in losses for the counties and states that house those cities as a whole.[3]

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[3] Note that for all these estimates we assume home values remain unchanged. Over time, home values will appreciate, increasing damages in dollar terms. Incomes will also rise, however, so the relative impact of those damages on household budgets will be less than the absolute damages. As with all costs discussed in this chapter, we compare future climate impacts to current incomes, asset prices, and economic output.

Figure 13.20: Per capita inundation damage and increase in average annual coastal storm damages due to SLR alone, 2080-2099

RCP 8.5, 2011 USD

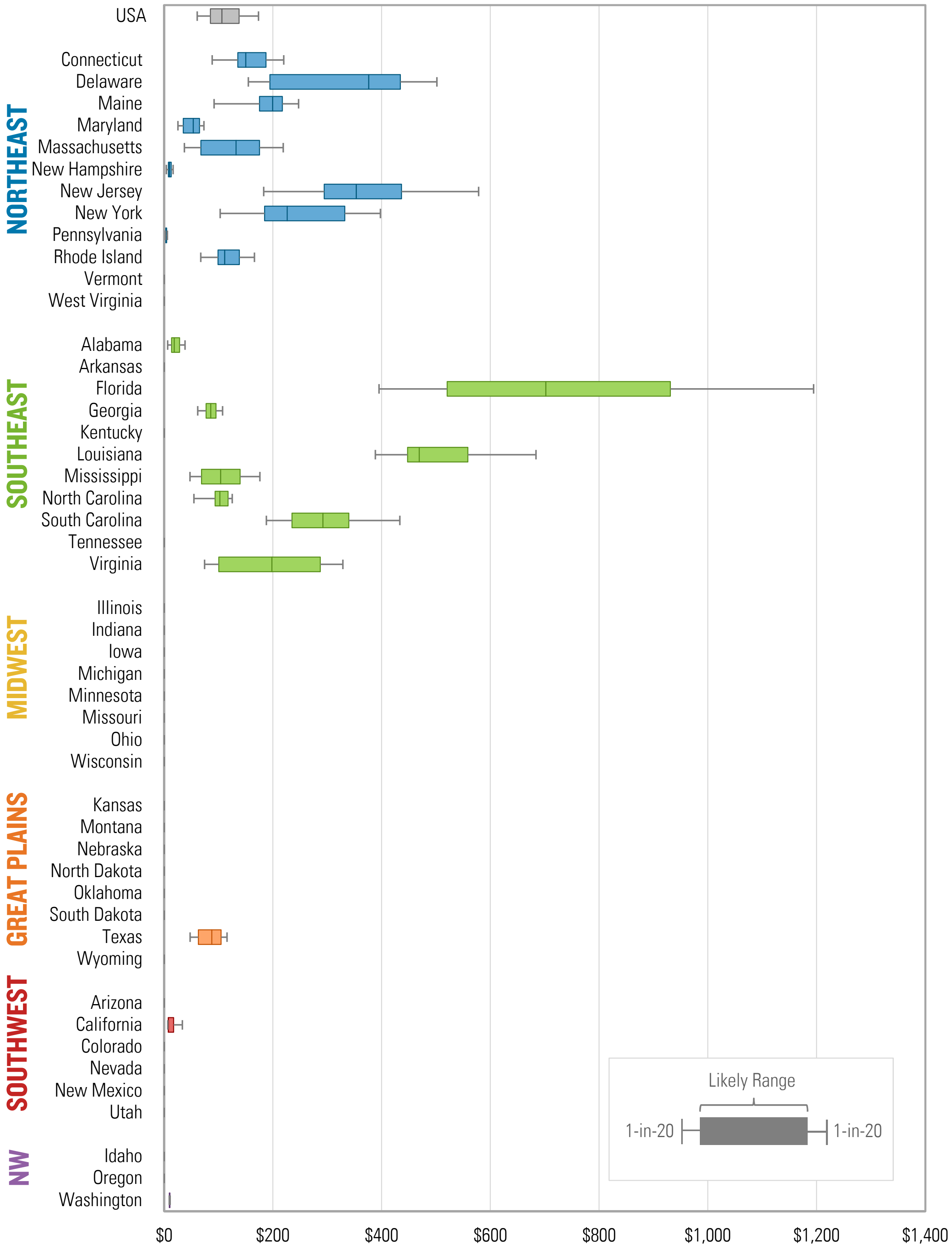
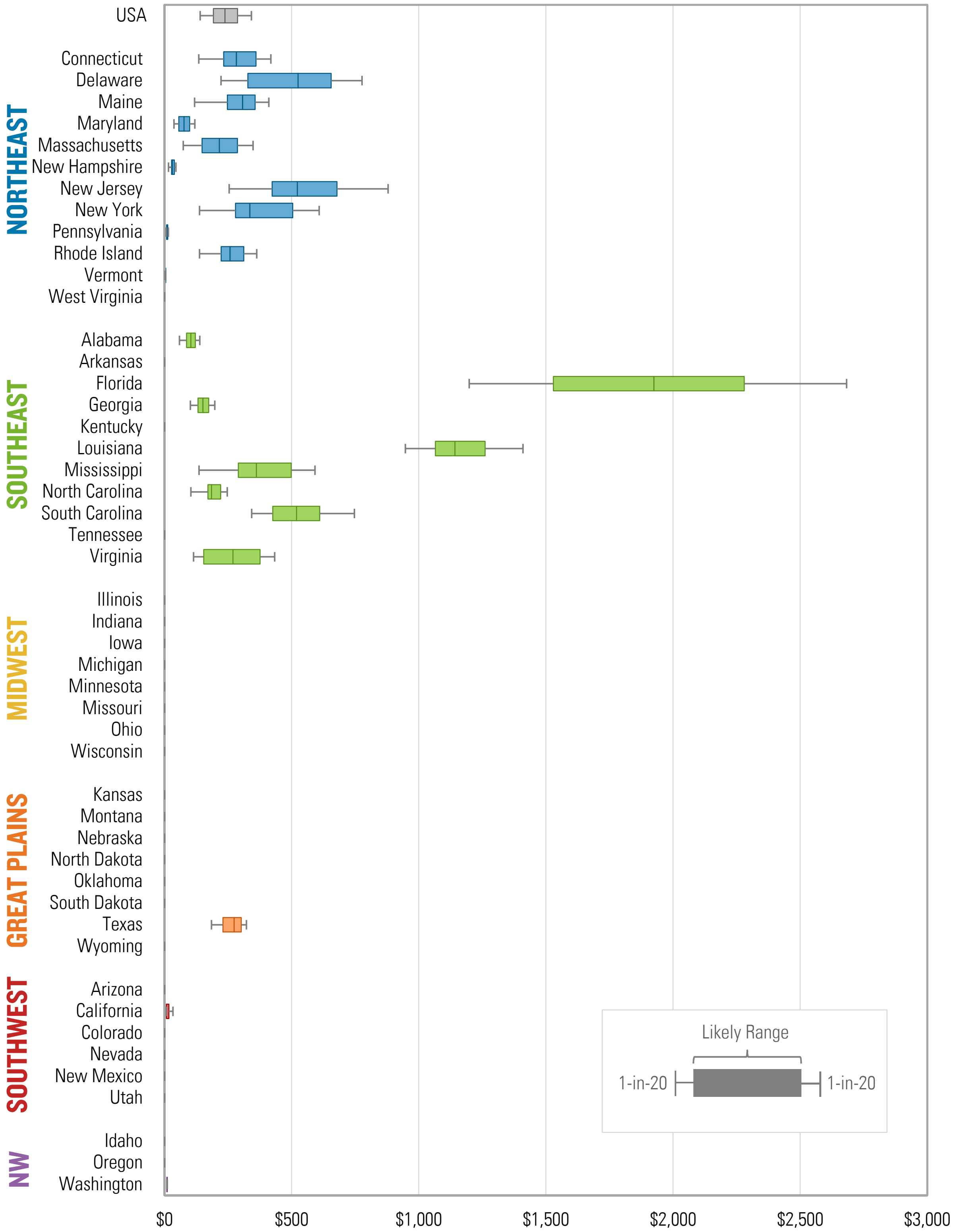


Figure 13.21: Per capita inundation damage and increase in average annual coastal storm damages due to SLR and potential hurricane activity changes, 2080-2099

RCP 8.5, 2011 USD, hurricane activity projections from Emanuel (2013)



Of course, much of the ultimate cost for these concentrated damages will not be borne by the impacted households themselves, but will be spread more broadly through private insurance to other policy-holders and through state and federal government-backed insurance and disaster relief to other taxpayers.

While specific communities within coastal states continue to bear considerably more risk from SLR-driven increases in storm damage than the state as a whole, over time statewide costs in certain parts of the country begin to mount, particularly when combined with *likely* inundation damages from mean sea-level rise (MSL) and rising mean higher high water levels (MHHW) (see Chapter 11). By late in the century (2080-2099 average), the *likely* SLR-driven increase in average annual inundation (at the MHHW level) and storm loss for the country as a whole translates into $85 to $138 per American based on current population and property prices. For Florida, however, the increase is more than five times that amount, at $520 to $931 per person (Figure 13.20). The *likely* per capita increase in damages in New Jersey is roughly three times the national average at $294 to $437 per year. For the average New Yorker, the direct annual costs of a SLR-driven increase in inundation and storm damage late-century is $185 to $332 per capita.

In exploring the potential impact of modeled changes in hurricane activity, we only looked at changes in frequency and intensity of different storms, not changes in the geographic distribution of where hurricanes make landfall. Such changes may well occur but were beyond our ability to analyze for this report. If storm geography remains the same but storm intensity and frequency change as modeled by Emanuel (2013) for RCP 8.5, the *likely* increase in national average annual storm losses grows to $4 to $6 billion on average by 2020-2039, $13 to $23 billion by 2040-2059, and $51 to $74 billion by 2080-2099. Adding average annual inundation from MHHW rise, the *likely* increase in average annual losses by 2080-2099 grows to $59 to $89 billion, or $193 to $287 on a per capita basis nationwide. The *likely* increase in per capita losses in Florida grows to $1,530 to $2,280. In New Jersey and New York, the *likely* per capita increase in losses grows to $423 to $679 and $280 to $504 respectively.

SUMMING UP

This assessment of direct costs and benefits helps illuminate which of the climate impacts quantified in this report matter most from an economic standpoint, and for which parts of the country. At a national level, mortality (using the VSL), labor productivity, coastal damages and energy demand are the most significant, both at mid-century (Figure 13.22) and late century (Figure 13.23). Interestingly, commodity agricultural impacts are relatively small at a national level, though they have received the most research attention in the academic community. Climate-driven changes in labor productivity, which has received comparatively scant research focus, likely poses a much more substantial nationwide economic risk.

Figure 13.22: Direct costs and benefits under RCP 8.5 as a share of GDP, 2040-59

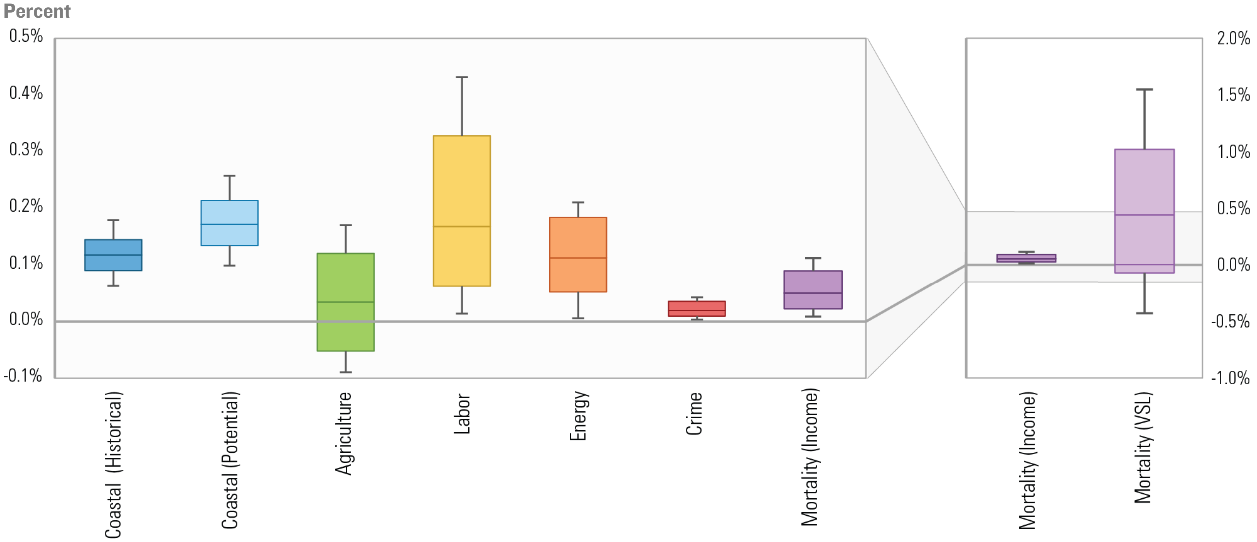
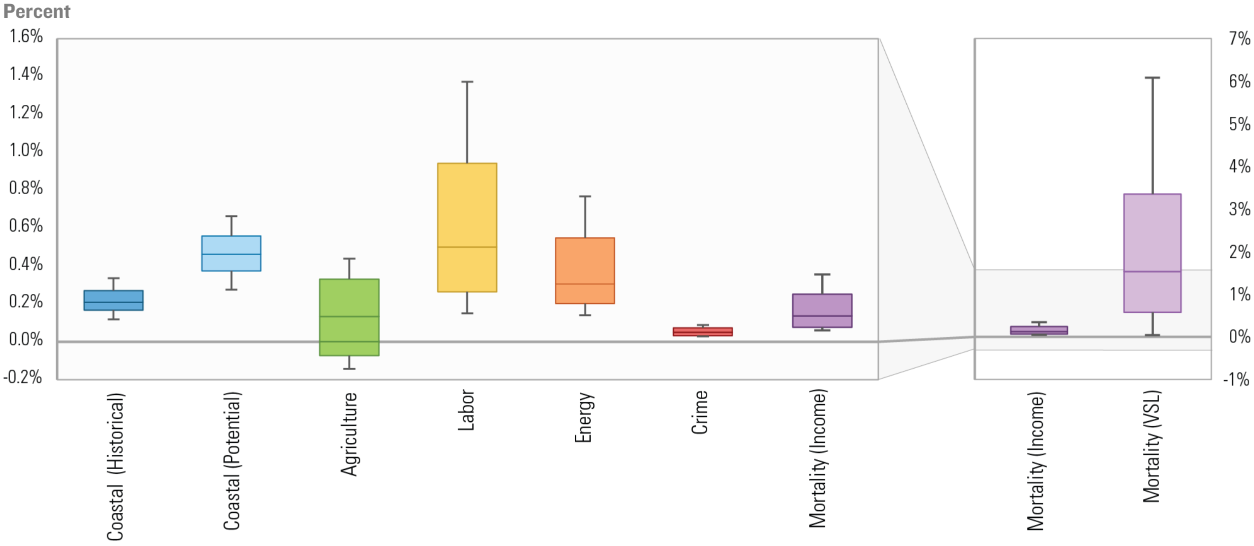


Figure 13.23: Direct costs and benefits under RCP 8.5 as a share of GDP, 2080-2099



At a state level, the relative importance of each impact varies greatly (Figure 13.24). Coastal damages rank relatively high in the Northeast and Southeast, while agricultural impacts play a considerably larger role in the Midwest and Great Plains than for the country as a whole. Labor productivity costs are meaningfully-sized and relatively evenly spread, while mortality costs, which are large, are positive for some states and negative for others.

The combined *likely* direct cost of these six impacts in late century, using changes in labor income estimates for mortality and historical hurricane activity, is 0.7% to 2.4% of GDP, with a 1-in-20 chance of costs less than 0.4% or more than 3.4%. The Southeast sees *likely* combined direct costs considerably higher than the county as a whole. The *likely* range for Florida is 2.3% to 6.0% of economic output, and for Mississippi is 1.8% to 5.7% (Figure 13.25). A number of Midwest and Great Plains states also see *likely* combined impacts considerably higher than the national average, while most Northeast and Northwest states *likely* see relatively little direct costs.

Switching from changes in labor income to the VSL as the measure of mortality costs significantly increases the total. At a national level, the combined *likely* direct cost of our six quantified impacts is 1.2% to 5.4% of economic output late century (Figure 13.26). In Florida and Mississippi *likely* direct costs rise to 7.6% to 20.6% and 5.7% to 17.8%. The difference between impacts in the South and in the Northwest and Northeast grows using this measure, with net benefits in the median projections for eight Northwest and Northeast states.

At the upper bound of our estimates, using projected hurricane activity and the VSL for mortality costs, late century *likely* combined direct costs at a national level are 1.4% to 5.7% of economic output (Figure 13.27). For Florida, the most at-risk state, combined *likely* direct costs rise to 10.1% to 24% of state economic output, while Vermont sees combined *likely* direct benefits of 0.8% to 4.5% of total output.

Finally, note that because we are taking an enumerative approach and many known impacts are not quantified, the numbers presented in this chapter should not be viewed as a comprehensive portrait of all economic costs and benefits (Pindyck, 2013; Stern, 2014). Many of these unquantified impacts are discussed in Part 4 of this report, while some of methods for evaluating the costs of 'deep' structural uncertainties in climate impacts (Weitzman, 2009; Heal and Millner 2013) are discussed in Chapter 15.

Figure 13.24: Direct costs as a share of economic output at the median under RCP 8.5, 2080-99

Percent

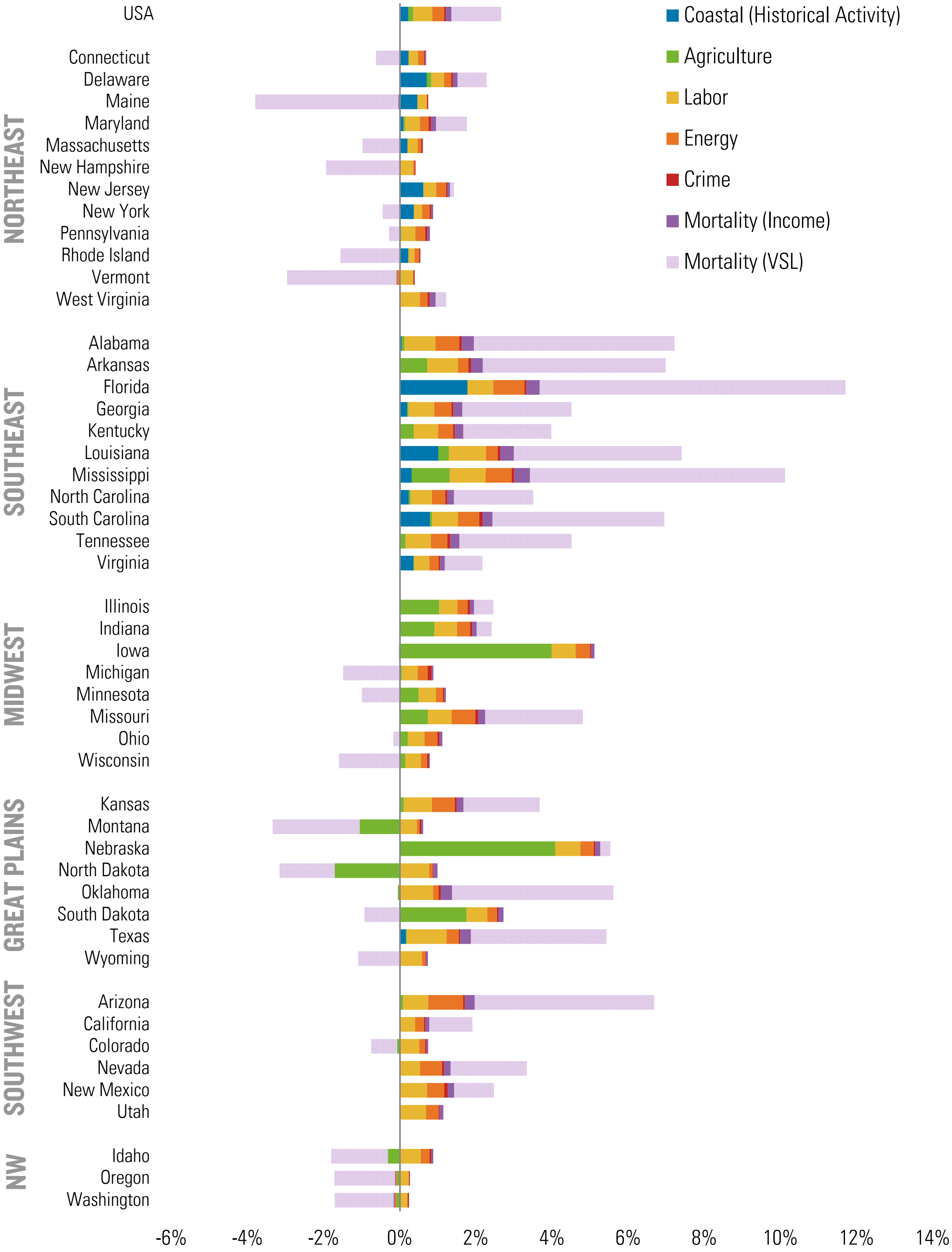


Figure 13.25: Six quantified impacts with historical hurricane activity and changes in labor income mortality cost, 2080-2099

RCP 8.5. Percent of economic output. Negative values indicate net benefits.

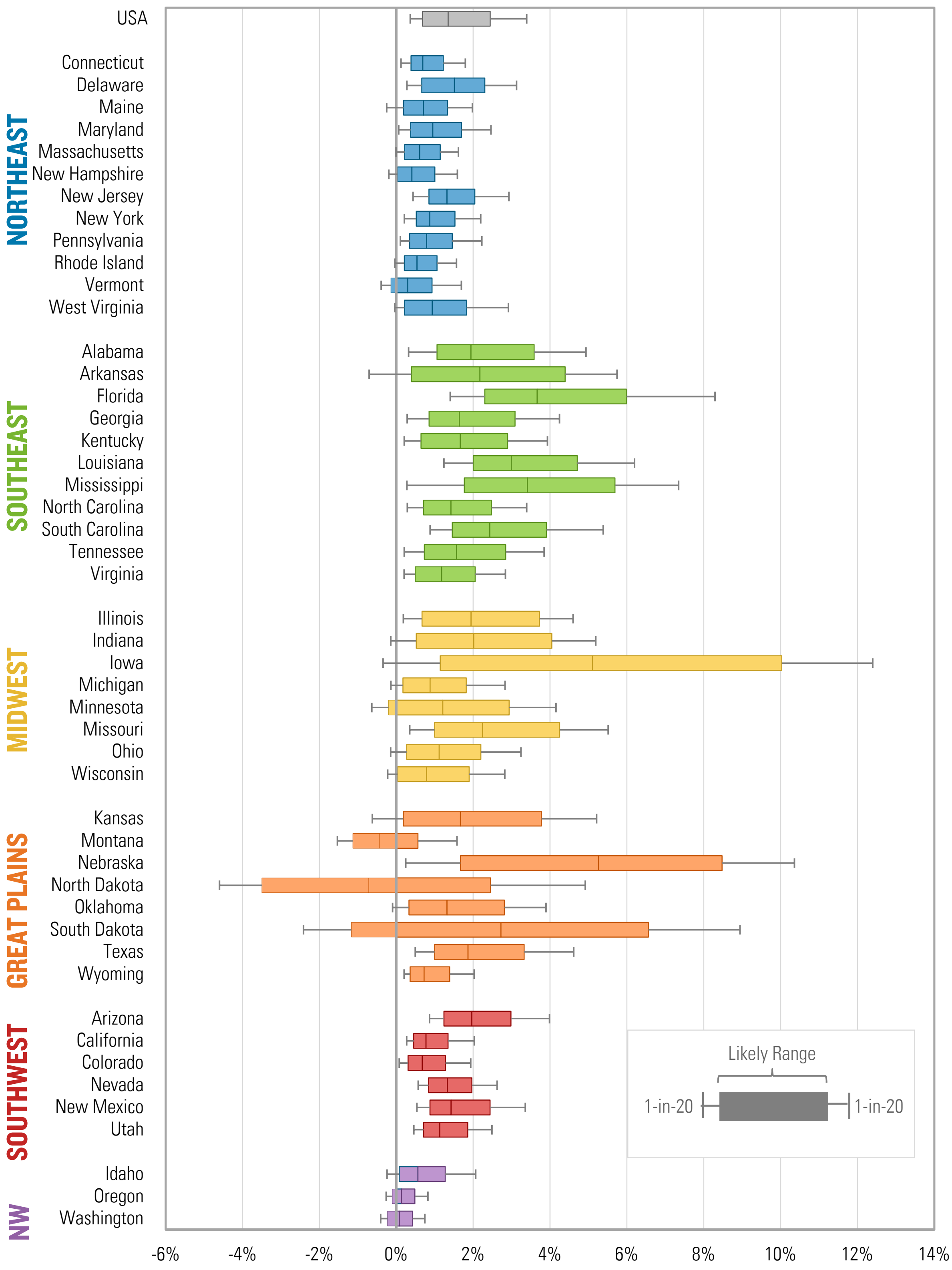


Figure 13.26: Six quantified impacts with historical hurricane activity and using VSL mortality cost, 2080-2099

RCP 8.5. Percent of economic output. Negative values indicate net benefits

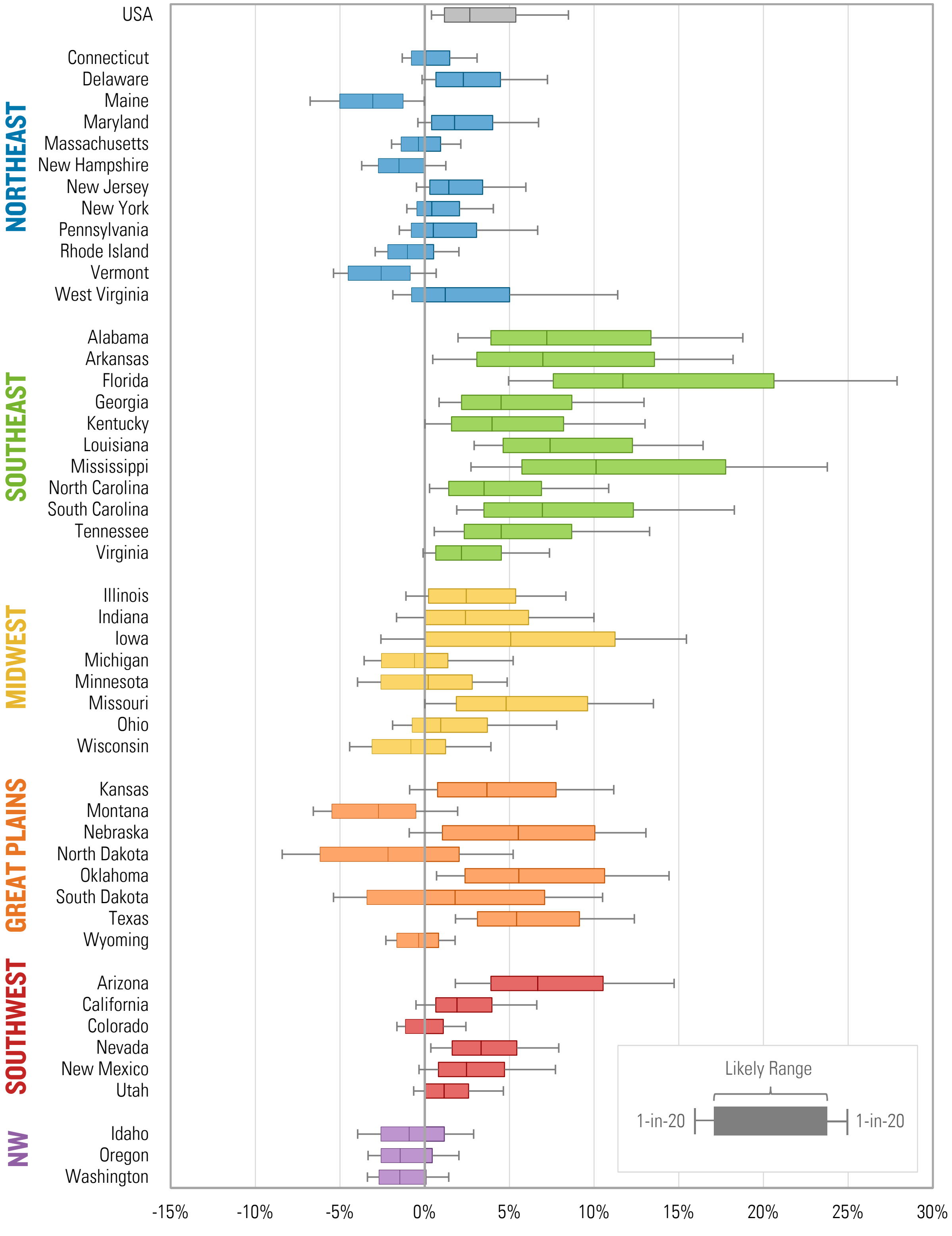
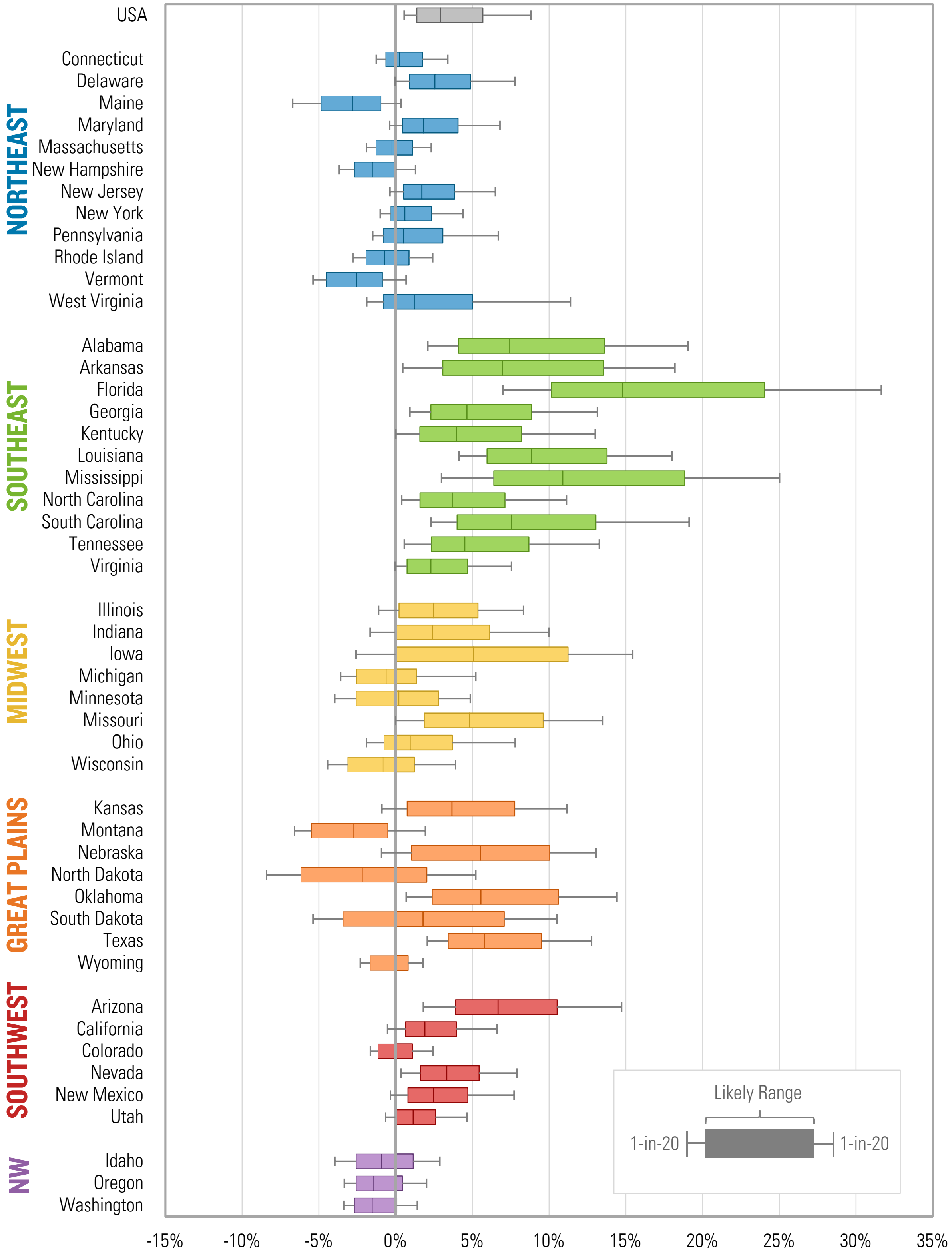


Figure 13.27: Six quantified impacts with projected hurricane activity and using VSL mortality cost, 2080-2099

RCP 8.5. Percent of economic output. Negative values indicate net benefits



CHAPTER 14

Macroeconomic Effects

In the preceding chapter we assessed the direct costs and benefits of the climate impacts covered in this report and found significant variation by state. US states are all part of the same national economy, however, and direct impacts in one sector or region have implications for other sectors and regions as well. For example, a decrease in agricultural output in Iowa impacts food prices nationwide (and globally). Damage to coastal property raises borrowing costs in non-coastal regions due to the national (and global) nature of capital markets. Higher energy costs flow through the economy and can increase the price of a wide range of goods, and changes in labor productivity alter what people do for a living and where they work. This chapter examines the extent to which some of these macroeconomic effects shape the overall magnitude and the regional variation in the direct costs and benefits of the climate impacts quantified in this report.

METHODOLOGY

To illustrate some of these concepts, we employ RHG-MUSE, a dynamic recursive computable general equilibrium (CGE) model of the US economy developed and maintained by the Rhodium Group and integrated into the SEAGLAS platform. RHG-MUSE represents sectoral and regional relationships as they exist in the economy today, based on a framework developed by Rausch and Rutherford (2008) and similar to CGE models used in other climate change assessments, such as Jorgenson et al. (2004) and Abler et al. (2009). RHG-MUSE is solved annually from 2012 to 2100 and simulates the growth of the US economy through changes in labor, capital and productivity. The model is calibrated using state-level social accounting matrices (SAMs) from the Minnesota IMPLAN Group.[4] For computational simplicity, we aggregated the 440 sectors in the IMPLAN SAMs to create nine sectors tailored to the impacts covered in this report. A full description of RHG-MUSE is available in Technical Appendix IV.

Our hesitation in predicting how the US economy will evolve between now and 2100, expressed in the preceding chapter, still holds. Yet as some of the macroeconomic consequences of the direct climate impacts unfold over time, projections are necessary. We calibrate RHG-MUSE to maintain the country's current economic structure and demographic profile in the baseline scenario throughout the modeling timeframe. Both population and economic output grow, but the sectoral and geographic shares of both employment and output remain roughly the same. This allows for a relatively apples-to-apples comparison with the direct economic impacts described in Chapter 13 and maximizes consistency with our empirically-based impact estimates.

We represent the climate impacts covered in this report in RHG-MUSE as follows (with a detailed discussion available in Technical Appendix IV).

Agriculture

We represent climate-driven changes in agricultural productivity impacts as a percent change in total output productivity affecting the baseline productivity in that year. This means that, for a given level of capital, labor, and intermediate goods use, a state's agricultural output will be equal to the baseline output given the same level of inputs multiplied by the productivity change. The model propagates this change across the economy through price and quantity effects.

Labor Productivity

We represent climate-driven changes in labor productivity through the productivity of labor inputs to high-risk and low-risk sectors by state. New production activities are able to respond to this change and substitute labor for capital, or vice-versa, but extant production suffers a proportional reduction in output and a loss of productive capital.

Health

Unlike in the preceding chapter, we represent climate-driven changes in mortality by tracking their impact (by age cohort) on the size and composition of the US population using a population model incorporated into RHG-MUSE and reducing available labor supply accordingly.

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[4] More information on IMPLAN is available at http://www.implan.com/

Crime

We exclude crime from the CGE model because of the mixture of market and non-market factors in our direct economic impact estimates.

Energy

We increase residential and commercial energy costs by state based on the energy expenditure estimates laid out in Chapter 10.

Coastal Communities

We represent climate-driven inundation, flood, and wind damage to coastal property as a direct reduction of capital stock. This is implemented before each run of the model's static core, such that some fraction of the depreciated capital stock will be unavailable for earnings and use in the coming period. Because rates of return must equalize across states and sectors in RHG-MUSE, new capital formed by savings/investment replaces lost capital stock until rates are equal. We also capture business interruption by reducing industrial productivity in impacted states consistent with RMS business-interruption estimates for that particular SLR scenario.

RESULTS

The macroeconomic dynamics in RHG-MUSE alter the direct costs and benefits of the climate-driven changes in agricultural production, labor productivity, mortality, energy costs and coastal property in several ways. The ability of firms to substitute factors of production in response to changes in prices, capital stock or labor supply reduce direct costs. For example, the impact of climate-driven reductions in labor productivity on economic output is decreased over time through increased application of capital. Likewise, SLR-driven damage to coastal capital stock is offset in part through greater application of labor. When changes in prices as a result of climate impacts reduce demand for goods from a sector, labor and capital are freed up for other sectors, offsetting the direct costs.

There are other macroeconomic effects in the model that amplify direct costs. Most important in our analysis is the impact of damaged coastal capital stock in a given year on economic growth in subsequent years. The need to rebuild damaged coastal property redirects investment that would have otherwise occurred elsewhere in the economy, reducing economic output in the process. We find that, over the course of decades, the cumulative impact on growth of single year coastal capital stock damage is several times larger than direct cost to the coastal property receiving the damage.

On net, the economy-wide cost estimates from RHG-MUSE are slightly higher than the direct costs presented in Chapter 13. Under RCP 8.5, the likely late century combined direct cost for climate-driven changes in coastal damages (assuming historical activity rates), labor productivity, energy demand, mortality (using market estimates), and agricultural production are 0.7% to 2.4% of GDP nationwide (Figure 14.1). The *likely* range from RHG-MUSE is 1.0% to 3.0%. We may be underestimating costs in RHG-MUSE due to the different treatment of mortality. In calculating direct climate-driven mortality costs and benefits in a given period, we estimate the net present value (at a 3% discount rate) of lifetime earnings lost by deaths in that period. In RHG-MUSE, the late century mortality costs are the cumulative impact of all climate-driven mortality occurring up until that point. Thus the late century estimates of direct mortality costs include lifetime earnings lost after 2100, while the RHG-MUSE estimates do not. Especially as net national climate-driven mortality increases sharply in the second half of the century, this difference in approach leads to higher mortality-related estimates in the direct cost approach.

For some impacts, the macroeconomic effects captured in RHG-MUSE reduce regional variation in costs, due primarily to free movement of capital and goods across state borders in the model (agriculture is a notable exception, as discussed below). For example, the increase in investment demand in coastal states as a result of SLR-driven damages draws investment away from other states equally. This is likely an optimistic assumption; the price of investment goods like cement and steel will probably rise more in storm-damaged areas than the national average, even if borrowing costs rise equally nationwide.

At the same time, however, we assume that labor is fixed by state, which prevents additional regional smoothing from occurring. As a result, the relative return on labor rises in more heavily impacted states, which could attract labor from other parts of the country. On the other hand, if the climatic changes causing those damages also reduce relative livability, the state-level reduction in labor supply could be even greater than the direct labor productivity and mortality costs suggest.

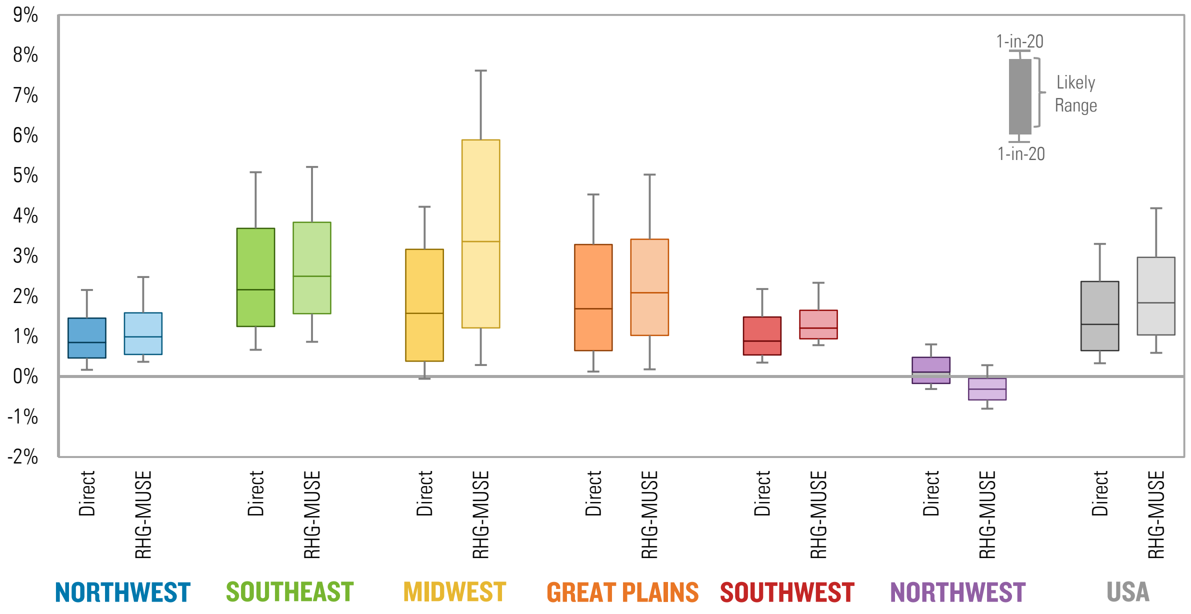
The Southeast and Great Plains fare better once the macroeconomic effects captured in RHG-MUSE are included, while the Midwest does considerably worse. This is due to the indirect economic impacts in the region of a climate-driven decline in commodity agricultural production. Interestingly, the Pacific Northwest sees even greater net benefits in RHG-MUSE, despite being part of the same national economy, due largely to the long-run growth benefits of increased labor supply from a decline in cold-related deaths.

This macroeconomic modeling exercise should serve primarily as a conceptual exercise. Predicting how markets will respond to climate impacts over the course of eight and a half decades is extremely challenging. In addition, national macroeconomic conditions are heavily shaped by events around the world, and other countries will also be impacted by climate change – impacts not assessed in this report. Nonetheless, this illustration shows the macroeconomic dynamics we do capture modestly decrease the combined national cost of the five modeled impacts, and that, while they reduce regional inequality somewhat, significant differences remain.

There are a number of research groups actively working to build more sophisticated economic models that can capture a broader range of national and international dynamics, such as the Project on Integrated Assessment Model Development, Diagnostics and Inter-Model Comparisons (PIAMDDI). In addition to continuing to improve the SEAGLAS platform in the months and years ahead, we have designed the analysis to be modular and open source in the hopes that other researchers can integrate those components they find useful into their own work and build upon the findings of this prospectus.

Figure 14.1: Combined agriculture, labor, mortality (changes in labor income), energy and coastal (historical activity) impacts calculated as direct costs, and modeled using RHG-MUSE, under RCP 8.5 in 2080-2099

Percent of output. Negative values indicate net benefits.



CHAPTER 15

Valuing Risk and Inequality

Two central contributions of this report are to characterize the uncertainty associated with the economic impacts of climate change and to estimate the extent to which these impacts will be borne unequally among Americans. In both cases, we note that average impacts gloss over an important aspect of the story: if the climate changes, there is a sizable chance that different types of impacts will be larger or smaller than the central estimate, and in many cases specific regions of the country experience impacts that differ substantially from the national average. While the primary purpose of this report is to provide empirically-based, spatially-explicit information about the risks businesses, investors and households in different parts of the United States face from climate change, these insights are also important in how we price climate risk at a national level.

Both risk and inequality can increase the perceived costs of climate change above the expected cost of climate change, i.e., the average impact we expect to see across possible futures and across regions of the United States. Uncertain outcomes and unequal impacts increase our perception (or valuation) of these costs because as individuals and as a society, we generally dislike uncertainty in our futures—for example, individuals buy home insurance in part because the risk that a catastrophe could bankrupt a family is worrisome—and we dislike strong social inequalities—for example, individuals donate money to charity in part to alleviate hardships of poorer individuals. *How much* we dislike uncertainty and inequality affects how much these factors should influence our decision-making process, and they inform us of how much we should focus on future uncertainty or inequality in climate change impacts relative to the average impact of climate change. In economics, the extent to which we are concerned about risk and inequality is can be described by two factors:

- *Risk aversion*: How averse are we to the uncertain possibility of bad future outcomes?
- *Inequality aversion:* How much do we dislike having some individuals suffer greater losses than others, especially if proportionally greater losses fall on poorer individuals?

Both of these types of aversion reflect our underlying preferences and can thus be measured empirically, although it is possible that a decision-maker may be more risk averse or inequality averse than one would estimate by observing individuals in a population. This might be true, for example, if increasing inequality has indirect effects on the economy or a population's social well-being that are not understood or internalized by individuals within a population; it might also be true because the preferences of individuals acting collectively through democratic processes may differ from individuals acting individually in a market. It is worth noting that in many assessments of climate change impacts risk aversion and inequality aversion are assumed to be the same, although recent work suggests that the two need not, and very likely should not, be treated that way (Fehr and Schmidt 1999; Engelmann and Strobel 2004; Bellemare, Kröger, and Soest 2008; Crost and Traeger 2014)

Here we use our new results describing the probability distribution of impact across states within the US to illustrate through example how one could adjust their valuation of the damages from climate change to account for aversion to risk and inequality (see Technical Appendix V for mathematical details). In both cases, we summarize the additional costs imposed by risk and inequality as a *premium*, which is the additional cost that we would be willing to bear to avoid the inherent risk and additional inequality imposed by climate change impacts. We assume the well-being of all Americans should be treated equally and consider how the value of mortality (using the VSL) and direct agricultural losses could be adjusted to account for the structure of their risk and their unequal impact, in large part because these two example sectors have nonlinear response functions that generate some of the largest variations in damages.

RISK AVERSION

Accounting for risk aversion stems from the observation that individuals, and society at large, dislike uncertainty in future costs. For example, suppose Anna has a salary of $40,000 this year. Further suppose that Anna knows that, if she stays at her current job, there is a 95% chance that she will get a 10% raise (a gain of $4,000) and a 1% chance that she will be fired (a loss of $40,000). The expected value of staying at her current job is therefore $41,800 (the sum of 95% times $44,000 and 5% times $0). Further suppose she has the opportunity to switch to a new job that also pays $40,000 but guarantees her employment next year (with no raise). If she is risk-neutral, then her current job is worth $1,800 more to her than the alternative; if she is risk-averse, she might nonetheless opt for the more certain alternative because she wished to avoid the possibility of being fired.

Following conventional practice, we measure risk aversion with a coefficient of relative risk aversion (RRA). A RRA of zero reflects risk neutrality; higher values reflect higher levels of risk aversion. Studies of the relative rates of return of safe investments (such as US treasury bonds) and risky investments (such as stocks) suggest that the RRA reflected in US financial investments is between 2.5 and 6, although it could be as low as 1 or as high as 12 (Ding et al. 2012). Another study of investments, aimed at separating risk aversion from preferences between current and future consumption, suggests a RRA of 9.5 (Vissing-Jørgensen and Attanasio 2003). Experimental results from a survey of individuals in the US, the UK, Canada, Australia and Mexico similarly suggest that the central third of individuals surveyed have values between 3 and 5, although one-third have values less than 3 (half of whom are between 1.5 and 2.0) and one-fifth have values greater than 7.5 (Atkinson et al. 2009).

We can use the RRA to turn the projected probability distributions of losses in each state in each period into *certainty-equivalent* losses per capita in that period: in other words, we find the losses that an individual would bear with certainty that have the same welfare impact as the distribution of losses characterized in this report (See Technical Appendix V). The *risk premium* is the difference between the certainty-equivalent loss and the expected actual loss; it is the hypothetical quantity one would be willing to pay just to avoid the uncertainty in climate impacts (Kousky, Kopp and Cooke, 2011).

Because the production of commodity crops (maize, wheat, soy and cotton) represents a small fraction (about 0.8%) of total economic output, it can have only a small effect on total income; the 1-in-20 worst case for RCP 8.5 in 2080-2099 in the hardest hit state, Iowa, agricultural losses constitute a 9% loss of overall output. The risk premium is therefore small relatively, ranging up to 7% of the value of the lost output for a high RRA of 10 (see first row of Table 15.1, where IA = 0). By contrast, because the mortality impacts can be quite large – the 1-in-20 chance loss for RCP 8.5 in 2080-2099 is equivalent to 20% of output in Florida if measured using VSL – the risk premium can be significant. Even in the absence of inequality aversion, strong risk aversion can add as much as 16% to the value of the mortality losses (see first row of Table 15.2, where IA = 0).

INEQUALITY AVERSION

Accounting for inequality aversion is important because most individuals dislike the notion that some individuals bear far more of a group's cost than other members of a group. For example, in team efforts, most individuals usually find themselves unhappy if some members of the team do not "pull their weight," thereby forcing others to do additional work to make up for this shortfall. In a more extreme example, if a foreign country were to invade a single US state, Americans throughout the rest of the country would not simply stand by and let the population of that one state fend for itself; rather the whole country would come the aid of the invaded state. There are many similar cases, such as natural disasters, where the nation spends both effort and money to protect and support small groups of individuals because we do not believe those individuals should be left to suffer tremendous costs alone—instead, the country expends additional resources to share these burdens.

The degree of inequality aversion can be measured with a coefficient of inequality aversion (IA), analogous to the RRA. An IA of 0 reflects inequality neutrality, implying there is no cost to inequality, while higher values reflect increasing levels of inequality aversion. Experimental results suggest that different individuals have a very broad range of IA values, with the central third of individuals having values between 2.0 and 7.5, one quarter having values between 0.5 and 1.5, and nearly a third having values greater than 7.5 (Atkinson et al. 2009b).

In any given period, we can use the IA to turn the projected distribution of losses into an equivalent national, *inequality-neutral* loss (Gollier 2013). The inequality-neutral loss is a hypothetical economic loss that has the same welfare impact as the actual loss, but, as a fraction of income, is shared evenly by all Americans. In other words, we find the level of loss that, if equalized across states, would yield the same welfare as the unequal cross-state distribution of output per capita (see Technical Appendix). The *inequality premium* is the difference between the inequality-neutral loss and the expected actual loss; it is the hypothetical quantity one would be willing to pay just to avoid the additional inequality imposed by climate impacts. Inequality-neutral losses will be larger if individuals who are initially poorer are harmed relatively more by climate change; they may be smaller if individuals who are initially richer are harmed relatively more.

Unlike the risk premium, it is possible for the inequality premium to be negative if climate change reduces initial wealth disparities, which can happen if climate change imposes sufficiently larger damages on wealthy populations than on poorer populations. In this case, the unequal distribution of climate impacts would lower the perceived cost of those impacts relative to their expected value. Thus it is not obvious *ex ante* that accounting for inequality aversion will necessarily increase the perceived cost of climate change.

We note that we do not resolve differences in damage across counties within a state—accounting for such differences would likely increase the inequality premium—although cross-state impacts tend to be more unequal than cross-county impacts within each state. We also do not account the distributional impacts of climate change within a state by income or demographic group, which are likely more important than differences across counties.

For both agriculture and mortality, the inequality premium can be significant. Strong inequality aversion alone can increase the value of agriculture losses by up to 20% (see first column of Table 15.1, where RRA=0), although the macroeconomic effects described in the preceding chapter dampen the inequality of direct agricultural impacts to some extent.

Strong inequality aversion can more than double the value of mortality losses, adding a 190% premium for an IA of 10 (see first column of Table 15.2, where RRA=0). The large magnitude of the inequality premium for mortality arises because the mortality increase is highest in some of the nation's poorest states and least in some of the richest. Among the poorest ten states, the per capita median mortality increase is 28 deaths per 100,000 people under RCP 8.5 in 2080-2099 (with additional deaths among the poorest states exceeding 30 per 100,000 in Florida and Mississippi); among the ten richest states, the average is a decrease in deaths of 3 per 100,000 people (with the reduction in deaths among the richest states exceeding 10 per 100,000 in Alaska, North Dakota, and Washington).

PUTTING IT TOGETHER

Above, we separately analyzed the risk and inequality premiums for two types of impacts. However, we can combine both risk aversion and inequality aversion to compute an *inequality-neutral, certainty equivalent damage* (see Technical Appendix V). This value is the hypothetical cost that, if shared equally among all individuals with certainty, would have the same welfare impact as the actual unequal distribution of state-specific risks. The combined *inequality-risk premium* is the difference between this hypothetical cost and expected damages; it is the cost of having unequal economic risks imposed by climate change. Calculating this premium helps us conceptualize how inequality in expected losses, inequality in the uncertainty of losses, and inequality in baseline income together increase the perceived value of climate change damages.

Table 15.1: Combined inequality-risk premiums for agricultural impacts, 2080-2099

RCP 8.5, Premium as percentage of expected losses for maize, wheat, cotton, and soy output

			RRA					
			← Low risk aversion			High risk aversion →		
			0	2	4	6	8	10
CIA	High inequality tolerance →	0	0%	1%	3%	4%	6%	7%
		2	7%	8%	10%	11%	13%	14%
		4	9%	11%	12%	13%	15%	16%
	← Low inequality tolerance	6	10%	11%	13%	14%	15%	16%
		8	13%	14%	15%	16%	17%	18%
		10	20%	21%	22%	23%	24%	25%

Table 15.2: Combined inequality-risk premiums for mortality impacts, 2080-2099

RCP 8.5, Premium as percentage of expected losses, applying value of a statistical life

			RRA					
			<-- Low risk aversion			High risk aversion -->		
			0	2	4	6	8	10
CIA	High inequality tolerance →	0	0%	3%	6%	9%	13%	16%
		2	33%	37%	41%	46%	51%	56%
		4	72%	78%	84%	90%	97%	104%
	← Low inequality tolerance	6	114%	121%	129%	138%	147%	157%
		8	155%	164%	173%	184%	195%	207%
		10	190%	200%	211%	223%	236%	250%

For both agricultural losses and mortality, combining risk aversion with inequality aversion yields a higher inequality-risk premium. The magnitude of the increment from the combination partially reflects the magnitude of the individual effects. For agriculture, the increased premium from layering risk aversion (which is small in this impact category) on top of inequality aversion is small; for strong risk and inequality aversion, it amounts to a 25% increase in the value of losses, compared to 20% from strong inequality and no risk aversion. For mortality, in contrast, strong risk and inequality aversion combined can add a premium of 250%, compared to 190% for inequality aversion in the absence of risk aversion. If we focus on values most frequently observed in experiments (RRA and IA of roughly 4, Atkinson et al. 2009), which for RRA also coincides with the central Ding et al. (2012) estimate based on comparison of the prices of US stocks and bonds, then the inequality-risk premium on agricultural loss and mortality are 13% and 90% of the expected loss. If instead we use a RRA of 10, close to the Vissing-Jørgensen et al. (2003) estimate of 9.5, the mortality premium rises to 104% of the expected loss.

Overall, for the example impact categories we have assessed here, the inequality premium is substantially larger than the risk premium. While on its face this finding may be surprising – risk aversion is, after all, a key motivator for many policies and measures to manage climate change risk – it is not when considered in the broader context of this analysis.

DECISION-MAKING UNDER UNCERTAINTY

While our estimated probability distributions for the impacts we quantify represent a rigorous effort to assess probabilities in a framework that is both internally consistent and consistent with the best available science, they do not represent the only valid estimates. Among other factors, alternative climate model downscaling techniques, alternative probability weightings of climate models, alternative priors for the impact functions, and alternative assumptions about the changing structure of the economy would all change the estimates. There is no single correct approach.

Under such conditions of 'deep' uncertainty, economists and decision scientists have developed a range of alternatives to the classical von Neumann-Morgenstern expected utility paradigm of estimating a single probability distribution that is interpreted as 'true' and using this distribution to weight possible outcomes (as we do above when we estimate our risk premiums). One finding from this work is that many decision-makers are *ambiguity averse*: they view the non-uniqueness of the probability distribution as imposing a cost premium on top of the risk premium (Heal and Millner 2013). Another finding is that if catastrophic outcomes are possible and decision-makers cannot rule them out, the remaining `fat tail' of the probability distribution of potential losses imposes an exceptionally large risk premium (Weitzman, 2009).

Alternative approaches to the expected utility paradigm include a 'maxmin' approach – choosing a course of action that, among all possible worst-case outcomes is the least bad, an approach closely related to the 'precautionary principle' – and an '▯-maxmin' approach – making a decision based on a weighted mixture of the most likely outcome and the worst possible outcome. One might also choose to minimize regret – to find a strategy that, across all possible futures, minimizes the difference between the realized outcome and the best one could have done in the absence of uncertainty. These three approaches could all be applied using the impacts we estimate in this report to characterize worst possible outcomes and most likely outcomes. There are also additional alternative approaches that address the cost of ambiguity by estimating multiple probability distributions, each of which is assigned a probability of being correct (Heal and Millner 2013; Kunreuther et al. 2012).

Finally, we note that in this report we have quantified only a subset of the potential costs of climate change, many of which cannot yet be rigorously assessed in an economic framework. Without the inclusion of the missing impacts described in the next section, any evaluation of worst possible outcomes would be incomplete. The true worst-case future is characterized not just by lost labor productivity and widespread heat-related deaths, but also by (among other changes) international conflict and ecological collapse (Stern, 2013). The next section surveys the gaps in our coverage.

Part IV

Unquantified Impacts

CHAPTER 16

What We Miss

Our analysis is broad, but it is far from complete. As discussed in Chapter 1, we have only been able to quantify a subset of the economic risks of climate change in the US. Figure 16.1 highlights some of the gaps. These gaps can be subdivided into several categories: incomplete coverage within included market impacts, omitted categories of market impacts, interactions between impacts, omitted non-market impacts, effects on international trade and security, out-of-sample extrapolation, and potential structural changes. Many of these limitations parallel those of benefit-cost "integrated assessment models" that lack the empirical calibration and spatial detail of our analysis; some of the literature discussing the limitations of the damage estimates of these models applies here as well (Yohe and Tirpak 2008; Warren 2011; Howard 2014).

MARKET IMPACTS

Incomplete coverage within included impacts

In the seven impact categories we have examined, we have focused on a subset of effects most amenable to quantitative analysis. These limitations of scope are described in the sectoral chapters; we summarize them here.

In the agricultural sector, we have assessed impacts of temperature and precipitation changes on the largest commodity crops, but not on fruits, vegetables, or nuts. These so-called "specialty crops" dominate the agricultural sectors of some states, such as California. We also do not include the effects on livestock, which, like humans, will suffer from humidity as well as heat. Nor do we include the effects of potentially expanded weed, pest, and disease ranges.

While we consider the effects of temperature on the number of hours worked, we do not assess the effects on the intensity of labor during working hours. Nor do we include the effects on labor productivity of the non-lethal health impacts of climate change, whether mediated by respiratory illness, vector-borne disease, or the consequences of extreme weather events.

For health impacts, we include heat- and cold-related deaths. We do not include the respiratory effects of temperature-aggravated air pollution, the health impacts of disease spread by extreme weather, the effect of temperature or weather disasters on birth weight, or the expansion in the range of vector-borne diseases like Lyme disease. We include humidity-related heat stress only to the extent it is indirectly captured in the empirically-calibrated temperature impacts; the effects of increasingly frequent, extremely dangerous Category III and record-breaking, extraordinarily dangerous Category IV Humid Heat Stress Index days are not included.

In the energy sector, we include changes in energy demand, but not supply-side effects such as reductions in the efficiency of thermoelectric generation or electricity transmission. For coastal impacts, we include damages to capital and the cost of business interruption, but we do not include the network effects caused by damaging critical infrastructure.

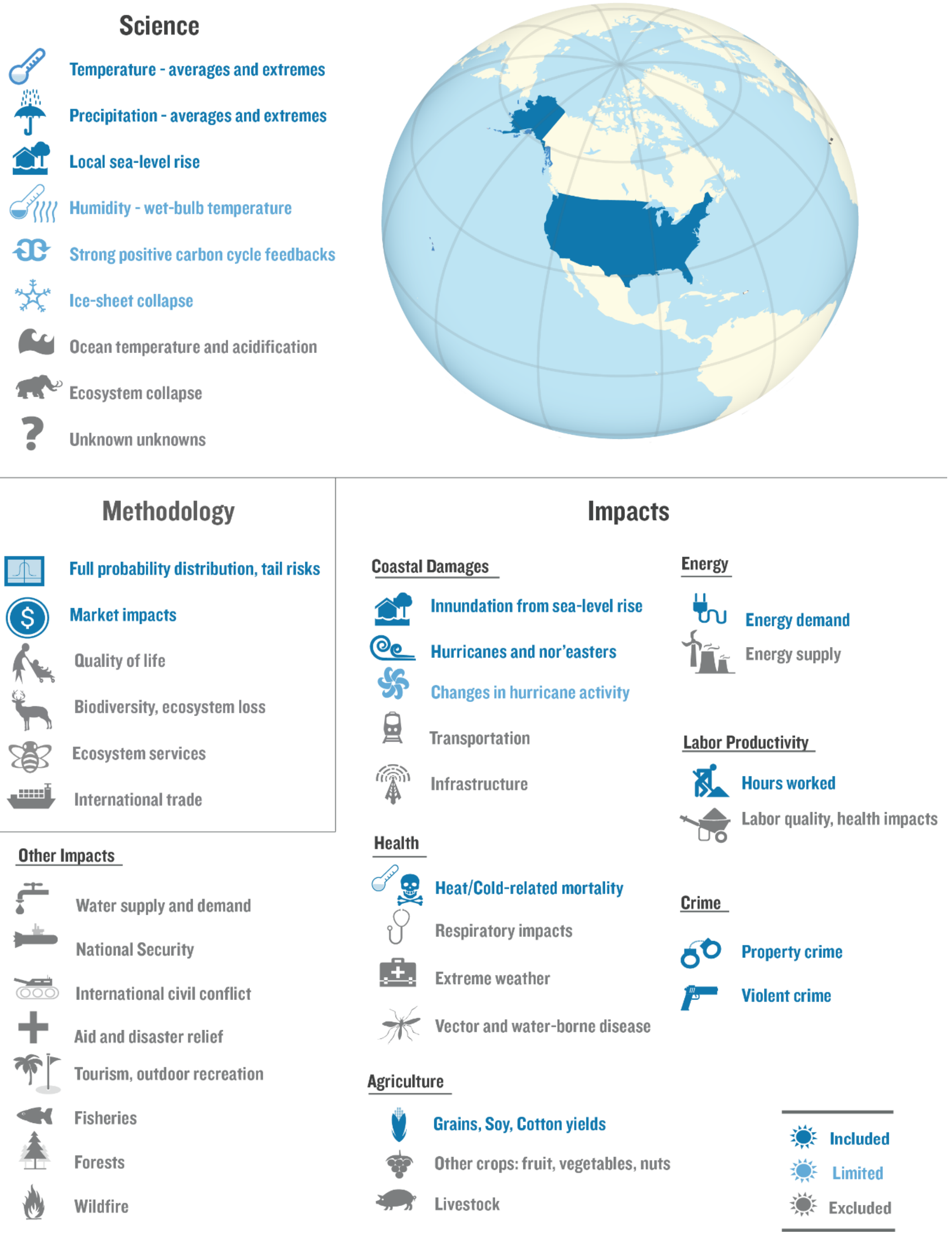
Omitted categories of impacts

Other types of market impacts we miss entirely in our quantitative analysis. Changes in the availability of water will affect the agricultural sector and electricity generation. Like coastal storms, inland flooding driven by intense precipitation events destroys capital and interrupts businesses. Forests, which both serve as an essential resource for the forestry industry and provide less-easily monetized ecosystem services, are threatened by changes in temperature and precipitation, more frequent wildfires, and expansion of pest and disease ranges. As climate changes, the desirability of different areas as tourism destinations will change. We qualitatively address water, forest, and tourism impacts in Chapters 17-20

Interactions between impacts

Although we estimate the direct effects in each impact category independently, there are important linkages between them that extend beyond the market interactions captured by the CGE model. For example, energy supply and agriculture compete for limited water resources. Similarly, estimates of heat-associated mortality and labor productivity reductions include implicit assumptions about the use of air conditioning (and therefore energy) to offset some of the heat and humidity.

Figure 16.1: Scope of this assessment



Science

Temperature - averages and extremes

Precipitation - averages and extremes

Local sea-level rise

Humidity - wet-bulb temperature

Strong positive carbon cycle feedbacks

Ice-sheet collapse

Ocean temperature and acidification

Ecosystem collapse

Unknown unknowns

Methodology

Full probability distribution, tail risks

Market impacts

Quality of life

Biodiversity, ecosystem loss

Ecosystem services

International trade

Other Impacts

Water supply and demand

National Security

International civil conflict

Aid and disaster relief

Tourism, outdoor recreation

Fisheries

Forests

Wildfire

Impacts

Coastal Damages

Innundation from sea-level rise

Hurricanes and nor'easters

Changes in hurricane activity

Transportation

Infrastructure

Health

Heat/Cold-related mortality

Respiratory impacts

Extreme weather

Vector and water-borne disease

Agriculture

Grains, Soy, Cotton yields

Other crops: fruit, vegetables, nuts

Livestock

Energy

Energy demand

Energy supply

Labor Productivity

Hours worked

Labor quality, health impacts

Crime

Property crime

Violent crime

Included

Limited

Excluded

NON-MARKET IMPACTS

Many of the most important risks associated with climate change fall outside the market economy. In this report, we have quantified mortality caused by heat and cold; while mortality affects the labor supply and therefore the market, it also directly affects human well-being. Omitted health impacts, discussed above, do as well.

Humans depend upon the planet's ecosystems in myriad ways, most not valued by the market. To name just a few: ecosystems absorb CO_2 from the atmosphere, recycle nutrients, pollinate plants, serve as storm barriers, and prevent soil erosion (Millennium Ecosystem Assessment 2005). Though placing a dollar value on these services is extremely challenging and highly sensitive to assumptions, the annual value of global ecosystem services has been estimated at twice global GDP (Costanza et al. 2014).

Climate change threatens to disrupt ecosystems both on land and in the ocean, which also face serious threats from land use change, nutrient pollution, and over-exploitation. The oceans also face another CO_2-related threat, that of ocean acidification, which makes it more difficult for calcifying organisms – ranging from corals to shellfish – to produce their skeletons. Climate change related ecosystem disruption has occurred many times in the Earth's past (Barnosky et al. 2012), and may represent one of the most serious climate change risks. Given the complexity of the problem, however, efforts to understand the economic consequences of future ecosystem changes are still at an early stage.

More generally, throughout this analysis, we measure impacts in terms of their effects on GDP. But GDP is a metric of economic output; it is not a measure of human welfare. Agricultural production constitutes only about 6% of world GDP, but the effect on human welfare of an agricultural collapse would be much larger. For many, communities and ecosystems have a value that extends beyond their productive capacity. For a parent, the welfare impact of losing a child to heat-related mortality is much greater than the net present value of that child's expected future earnings. The risks posed by climate change should be viewed in this broader context; in some cases, this may lead to policies or investments that would not be merited based on a monetary benefit-cost analysis alone.

INTERNATIONAL TRADE AND SECURITY

Our analysis focuses on the effects of climate change in the United States, but the US is not a world unto itself. Its fate is bound economically and politically to that of the nearly seven billion people outside its borders. For globally-traded goods, such as crops, trade effects may dominate domestic changes. If the agricultural sectors of other countries are more severely affected than our own, demand for US crops may rise even at elevated prices. Similarly, if the labor productivity impacts in other countries are more severe than in the US, the US may gain a competitive advantage even if the world economy as a whole suffers. Quantifying these linkages would require the extension of our analysis to a full model of the global economy.

Climate change could also prove to be an important factor affecting global security, which is qualitatively discussed in Chapter 20. Extreme weather events and longer-term climate shifts can promote migration both within and between countries. There is significant support in the academic literature for a relationship between climate and civil conflict. The 2014 Quadrennial Defense Review concluded that climate change may increase the "frequency, scale, and complexity" of future missions, while also posing a threat to defense installations.

OUT-OF-SAMPLE EXTRAPOLATION

The impact sectors we consider all are calibrated, either directly (as in the case of the five sectors with empirical models) or indirectly (as in the case of the process-model based analyses) against historical behavior. While history provides us the only data set against which to test and calibrate our projections, climate change will increase the frequency of record-breaking weather that falls outside past experience. Because the structure of empirically-derived dose-responses functions beyond the limits of historical experience is unknowable, there is no fool-proof technique for estimating how impacts will look in these out-of-sample cases. Thus, for simplicity and clarity, throughout this report we have used the conservative assumption that record-breaking temperatures will have impacts similar to the estimated impact of the hottest days on record. We examine the importance of this assumption in a sensitivity test (see Technical Appendix II) in which we instead linearly extrapolate all dose-response functions beyond the hottest conditions observed historically. We find that, in general, this adjustment to our modeling approach has only minor impact, primarily because most days over the next century will be hotter than historical averages, but will not exceed the temperature of historical national maxima and thus are well-described by the in-sample structure of our dose-response functions.

More generally, the likelihood that the climate will produce unexpected surprises will increase as temperatures rise outside the realm of past human experience. The appearance in the eastern half of the countries of summer days so hot and humid that short periods of moderate, shaded outdoor activity can induce heat stroke in healthy individuals is an example of a known phenomenon outside the realm of past experience (see Chapter 3). Some of the tipping points discussed in Chapter 3 represent known unknowns, and in a complex system like the Earth, there almost certainly will be "unknown unknowns" that are entirely beyond our present knowledge.

STRUCTURAL CHANGES

In our analysis, we assume that the structure of the US economy remains as it is today – an assumption almost guaranteed to be wrong. GDP will grow in different regions at different rates, due to a combination of factors ranging from demography, to policy, to climate. By the end of the century, some of the dominant industries may be ones that – like the IT and biotech industries today – were unknown eight decades previously.

As we discuss in Chapter 22, social and technological innovations may reduce some of the damaging effects of climate change. The efficiency of air conditioning may increase significantly faster than demand for cooler air. Genetically engineered crops, different planting schedules, and more efficient irrigation may offset effects on the agricultural sector. Defensive structures, relocation away from threatened coastlines, and structures designed for periodic flooding may all reduce the impacts of coastal storms and sea-level rise. Extreme heat and humidity may not be a problem if the people of 2100 spend their entire lives in climatically-controlled domed cities like those envisioned in the science-fiction novels of the 1950s.

The statistician George Box famously observed that, "all models are wrong, but some are useful." Our analysis provides a projection of what today's economy would look like in the face of 21st century climate change, not a prediction of what the economy of 2100 will look like. The structural changes that can reduce climate risk are more likely if policymakers, business leaders, and citizens are equipped with knowledge about the risks posed by climate change. We have tried to craft our analysis to address this need.

CHAPTER 17

Water

Water is a fundamental resource for our society, our economy, and the health of our communities and ecosystems. It is critical not only for our own consumption but also for food production, electricity generation, and many industrial activities. Although we have dealt with them throughout history, droughts and floods continue to pose significant risks to the US economy, our health, and way of life.

Climate change affects water resources through multiple pathways, changing risks from water scarcity and overabundance, affecting water quality, and shifting patterns of water availability within and among regions and communities. Climate change can affect water supply by altering precipitation, surface runoff, and streamflow patterns, as well as by increasing evaporation from lakes, reservoirs, soils and plants. It can affect water demand directly by increasing irrigation and landscape watering needs and indirectly through increased energy use for air conditioning and thus water use for cooling of thermoelectric power plants. Shifting precipitation patterns and heavier storms can intensify droughts and floods. Rising water temperatures and saltwater infiltration of near-shore groundwater reservoirs can affect water quality.

In concert with demographic, land-use, and other socioeconomic changes, climate change poses novel challenges for water planning and management. Existing water infrastructure and legal frameworks, created assuming an unchanging climate, may not be adequate to address these challenges. Managing water risk in a changing climate requires reevaluating strategies to meet our diverse water needs and protect natural ecosystems, informed by projections of both supply and demand.

WATER DEMAND

Water is a fundamental input to nearly every sector of the US economy, creating competing demands across a wide range of users. Linkages with agriculture and energy production dominate water use in the US. In 2005, freshwater withdrawals from surface and groundwater sources totaled nearly 350 million gallons per day (Kenny et al. 2009). Freshwater withdrawals for thermoelectric power generation (41%) and irrigation (37%) are largest, followed by municipal and residential uses (14%), industry and mining (5.5%), and livestock and aquaculture (3%). Most water for thermoelectric power generation is returned to its original source after use (at a higher temperature), while most water for irrigation is consumed during use. Western States account for most irrigation withdrawals, while eastern States account for most thermoelectric generation withdrawals. Water withdrawal estimates do not include water for in-stream uses such as hydropower production, a significant source of electricity generation in the Northwest, California, New England and Alaska (Energy Information Administration 2013; Georgakakos et al. 2014). Minimum in-stream flow requirements have also been established in many places to protect freshwater ecosystems.

From 1960 to 1980, water withdrawals rose dramatically (Kenny et al. 2009), but they have since been relatively stable due to increases in the efficiency of irrigation and thermoelectric cooling processes and declines in industrial water withdrawals across the US and in irrigated acreage in western States. These have offset increases in municipal and residential use and in livestock and aquaculture (Kenny et al. 2009; Foti, Ramirez, and Brown 2010).

Projections of future water demand are dependent on assumptions about future population growth, socioeconomic development, and technological change, as well as the effects of climate change on water use. One research effort, assuming a continuation of the historical trends described above and the A1B socioeconomic scenario (in which U.S. population growth declines slowly, with total population nearing 500 million by 2100), found that demand for withdrawals in the absence of climate change would increase only 3% from 2005 levels by 2060 and 13% by 2090 (Foti, Ramirez, and Brown 2010; Brown, Foti, and Ramirez 2013). With climate change, however, the same effort projects that demand for withdrawals will increase substantially, mainly due to increased irrigation and landscape watering needs and to a lesser extent to increased water use for electricity production to meet assumed growth in air conditioning (Foti, Ramirez, and Brown 2010; Brown, Foti, and Ramirez 2013). Under the A1B emissions scenario (intermediate between RCP 8.5 and RCP 6.0), demand is projected to increase 12 to 41% by 2060 and 35 to 52% by 2090, depending on the climate model used, with greater increases projected in the West. One uncertainty is the effects on crop water use of climate change-induced changes in growing season and increased CO_2 in the atmosphere, which may compensate to some extent for the effects of higher temperatures reflected in the irrigation demand increases presented here (Wada et al. 2013; Elliott et al. 2013; Prudhomme et al. 2013; Brewer et al. 2014).

WATER SUPPLY AND WATER MANAGEMENT CHALLENGES

Balancing climate-driven changes in supply and demand across water uses poses challenges for water management. Managers are increasingly recognizing the need for adaptive responses. Analyses of potential challenges have been undertaken at the national scale, for specific river basins, for specific municipalities, and for specific water uses. All regions of the US face water management risks, and the Southeast and Southwest including California are seen as most likely to experience water shortages (Georgakakos et al. 2014; Romero-Lankao et al. 2014; Foti, Ramirez, and Brown 2010; Roy et al. 2012; Barnett and Pierce 2009; Rajagopalan et al. 2009).

Changes in precipitation, runoff, and streamflow

The primary source of freshwater is precipitation—falling rain and snow—either through runoff when soils are saturated into rivers, lakes, and other surface water bodies or through recharge of groundwater. Annual average precipitation has increased over the past century in much of the continental US, with notable increases in parts of the Northeast, Midwest, and Great Plains over recent decades (Walsh et al. 2014). Precipitation is very likely to increase in the Northeast and likely to increase in the Midwest, with increases particularly in the winter and spring. Springtime precipitation decreases are likely in the Southwest, and summer precipitation decreases are likely in the Great Plains and Northwest.

Surface runoff has increased in the Northeast and the Mississippi basin and decreased in the Northwest during the past half-century, and a decreasing trend is emerging for the Colorado River basin (Georgakakos et al. 2014; Luce and Holden 2009; McCabe and Wolock 2011; US Department of the Interior Bureau of Reclamation 2012). In the future with continued high emissions of greenhouse gases, surface and groundwater supplies in parts of the Southwest, Southeast, and southern Rockies are expected to be affected by runoff reductions and declines in groundwater recharge, increasing the risk of water shortages (Georgakakos et al. 2014; Seager et al. 2013). Annual runoff is projected to decrease in some river basins in the Southwest, including the Colorado and Rio Grande, with mean and median runoff reductions of ~10% projected for California, Nevada, Texas, and the headwaters of the Colorado river over the next few decades, with greater model agreement for the Colorado headwaters and Texas than for California and Nevada (Georgakakos et al. 2014; Cayan et al. 2010; Seager et al. 2013). Annual runoff is also projected to decrease in the Southeast, driven by temperature-induced reductions in soil moisture (Brewer et al. 2014; Zhang and Georgakakos 2012). Annual runoff is projected to increase in the second half of the century (with little change through the middle of the century) in river basins in the Northwest and north-central US such as the Columbia and Missouri (Georgakakos et al. 2014; Brewer et al. 2014).

The US Bureau of Reclamation has conducted a series of western river-basin-level assessments of climate risk, which provide local illustrations of the broader trends described above. For example, the Colorado River supplies drinking water for almost 40 million people across seven western States, water for irrigation of 5.5 million acres producing 15% of US crops and 13% of US livestock, and water for hydropower facilities totaling 4200 MW of electric generating capacity (US Department of the Interior Bureau of Reclamation 2012). Over the past century there have been multiple years when water use was greater than supply, with resulting shortages in the upper parts of the basin (that rely more on annual stream flow) rather than water storage in the river system. Basin-level projections of water supply and demand by the Bureau of Reclamation indicate that decreasing annual flows and decreased snowpack result in decreased spring/summer runoff in the upper basin. At the same time, demand is projected to increase due to development and climate factors. Comparing median projections of water supply with median projections of water demand yield a 3.2 million acre-foot imbalance in the Colorado River Basin by 2060 (Figure 17.1) (US Department of the Interior Bureau of Reclamation 2012).[1] This imbalance represents about 20% of total average annual Colorado River consumptive use over the past ten years, or roughly equivalent to estimated national water demand for municipal and industrial uses in 2015, which is projected to grow over time.

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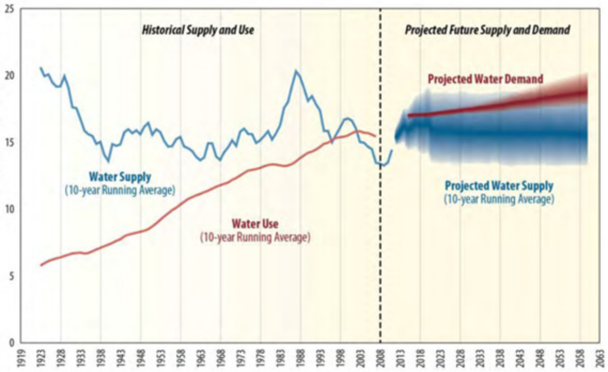
[1] Note that the confidence bands on these estimates are wide and year-to-year demand and supply are variable.

Figure 17.1: Colorado River Basin water supply and demand

Historical supply and use (million acre-feet) (left) and projected future supply and demand (right)



Source: (US Department of the Interior Bureau of Reclamation 2012)

Timing of water availability

Changes in the timing of runoff can also challenge water management efforts. They can increase the need for storage infrastructure and reevaluation of complex allocation and operation frameworks in response to shifts in seasonal streamflow. They can increase the risk of water shortages by creating or widening mismatches between the annual cycles of supply and demand, for example where peak streamflow is shifting earlier in the spring and demand is generally highest later in the summer (Georgakakos et al. 2014). Increases in the amount of precipitation falling as rain rather than snow, decreases in the amount of water stored in spring snowpack, and earlier melting has changed streamflow patterns in many rivers in the Western US (Fritze, Stewart, and Pebesma 2011; Hoerling et al. 2012; Mote 2006; Pierce et al. 2008).

Due in part to continued decreases in spring snowpack and earlier snowmelt (Georgakakos et al. 2014; Diffenbaugh, Scherer, and Ashfaq 2012), increases in winter runoff are projected in north-central US basins, as well as in basins along the West Coast such as the Sacramento and San Joaquin. Decreases in winter runoff are projected in Texas (Seager et al. 2013). Significant decreases in spring runoff are also projected for basins in the Southwest, including in California and southern Rockies (Figure 17.2) (Georgakakos et al. 2014; Brewer et al. 2014; Seager et al. 2013). Declining snowpack can also affect groundwater in many mountainous areas of the US where snowmelt is an important component of recharge (Georgakakos et al. 2014; Earman et al. 2006; Earman and Dettinger 2011).

SECTORAL IMPACTS

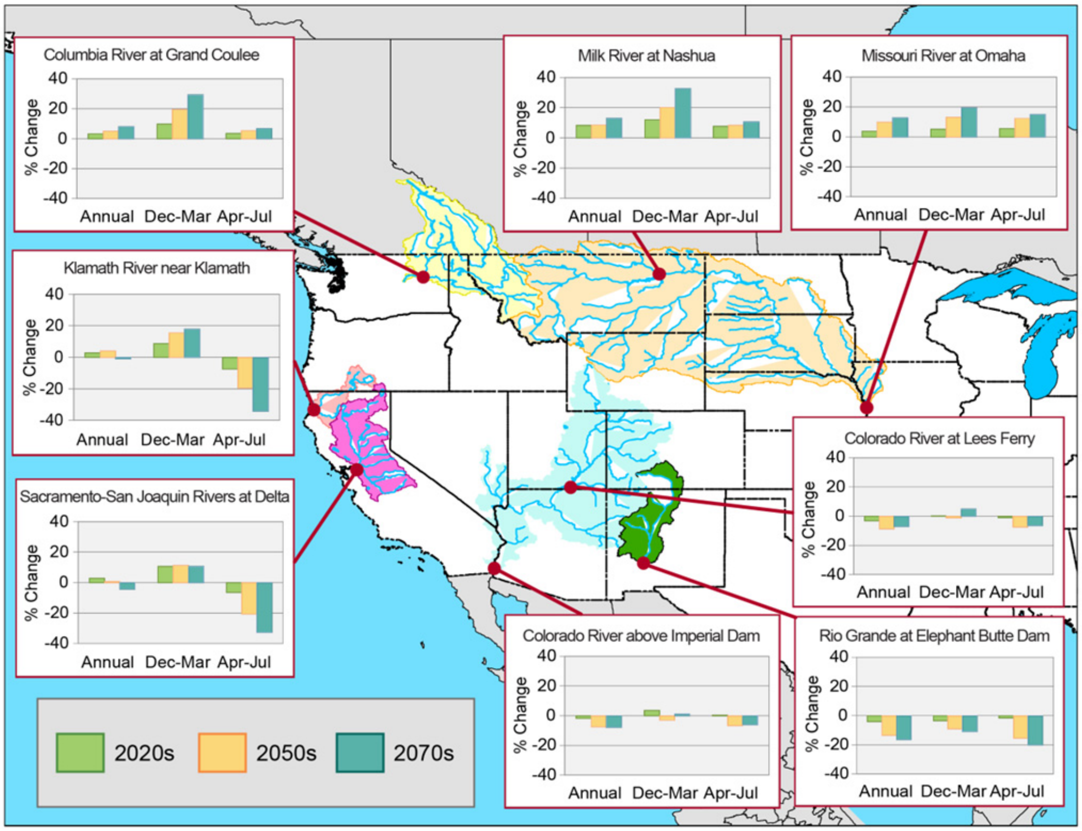
Agriculture

Year-to-year variation in water availability is a key determinant of agricultural production. The changes in precipitation and the amount and timing of water supply described above due to climate change will affect management of water for agriculture and competition with other water uses during times of scarcity. For example, agricultural water use is often curtailed to lessen shortages for municipal/household, commercial, and industrial users, as was the case in Texas in 2012 and 2013, when the Lower Colorado River Authority cut most Coastal Bend rice farmers' water to limit water restrictions in Austin (Phillips, Rodrigue, and Yücel 2013). Reduced water availability for agriculture may also lead to contraction in irrigated acreage in some areas, particularly in the western US (Elliott et al. 2013). As discussed above, warmer temperatures will increase crop water needs and demand for irrigation, although higher atmospheric concentrations of CO_2 can also increase water use efficiency of some crops (Hatfield et al. 2014; Wada et al. 2013; Elliott et al. 2013; Prudhomme et al. 2013; Brewer et al. 2014).

Climate change influences on patterns of climate extremes will also have direct effects on agricultural production. In 2011, flooding of the Mississippi River caused an estimated $1.3 billion in agricultural damage in Arkansas and Mississippi (NOAA 2013). Droughts, often in concert with heat waves, cause significant agricultural damage. In the past three years, drought has had major regional impacts in the US. Drought and heat wave conditions in 2011 in the southern Great Plains and Southwest caused $12 billion in damages across sectors (NOAA 2013a; NOAA 2011). The 2012 drought was the most extensive since the 1930s, with moderate to extreme drought conditions affecting more than half the country from the summer through the end of the year and causing $30 billion in damages across sectors (NOAA 2013a; NOAA 2012). The 2012 drought hit US corn and soybean production particularly hard, with low rainfall and high temperatures during the growing season substantially reducing crop yields (NOAA 2012). Drought conditions receded in many Midwest and Great Plains states in 2013, but remained or expanded in western states (NOAA 2013a). California, for example, experienced the driest calendar year in the 119 years of recorded observations (NOAA 2013b). See Chapter 2 for a discussion of drought projections.

Figure 17.2: Streamflow projections for river basins in the western US

Percent change in average runoff for annual, cool (December-March) and warm (April-July) seasons relative to 1990



Source: (US Department of the Interior Bureau of Reclamation 2011): Reclamation Managing Water in the West. SECURE Water Act Section 9503(c) - Reclamation Climate Change and Water 2011. P. Alexander, L. Brekke, G. Davis, S. Gangopadhyay, K. Grantz, C. Hennig, C. Jerla, D. Llewellyn, P. Miller, T. Pruitt, D. Raff, T. Scott, M. Tansey, and T. Turner, Eds., 226 pp., U.S. Department of the Interior, U.S. Bureau of Reclamation, Denver, CO.

For further discussion of climate-related changes in precipitation and water availability and impacts to agriculture, see Chapter 5.

Impacts on electricity generation

Cooling for thermoelectric power plants is dependent on water availability and water temperature, with power generation particularly at risk during periods of low summer flow and high water temperatures. For example a drought in the southeastern US in 2007 forced nuclear and coal-fired power plants within the Tennessee Valley Authority system to reduce production, pushing up electricity prices (NETL, Kimmell, and Veil 2009).

Water temperature has increased in some US rivers (Kaushal et al. 2010), and temperatures are projected to continue to warm due to climate change (Georgakakos et al. 2014; Cloern et al. 2011; Van Vliet et al. 2011). Higher water temperatures are expected to degrade the efficiency of cooling processes and electric generation and inhibit release of heated water from once-through cooling systems due to regulations protecting ecosystems (Georgakakos et al. 2014; Van Vliet et al. 2012). A recent study projected a decrease in average summer capacity of 12-16% for once-through cooling systems and 4.4-5.9% for recirculation cooling systems by the 2040s, dependent on emissions scenario (Van Vliet et al. 2012).

Hydropower supplies 20% of electricity generation in California, Alaska, and the Northeast, and up to 70% of electricity generation in the Northwest (Georgakakos et al. 2014; Energy Information Administration 2013). Runoff projections suggest hydropower production may decrease in the southern US (particularly the Southwest) and increase in the Northeast and Midwest (Georgakakos et al. 2014). But seasonal changes in the timing and amount of streamflow are also projected to affect the operation of hydroelectric plants, with actual future production dependent on the capacity of facilities, competition with other water uses, and basin-level changes in runoff amount and timing. For example, a study of hydropower production in the Pacific Northwest projected increases in winter of approximately 5%, decreases in summer of 12-15%, and overall annual reductions of 2-3% by the 2040s, with larger decreases in summer production of 17-21% by the 2080s (Hamlet et al. 2010).

These supply-side energy impacts will impose costs on energy consumers above and beyond the climate-driven changes in energy demand discussed in chapter 8.

Water quality

Changes in air and water temperature, precipitation intensity, drought, and streamflow due to climate change directly affect water quality, as do changes in land use and other aspects of use and management of land and water resources. Worsening water quality can affect ecosystems and downstream water users, and several studies project decreasing quality in the future due to the combined effects of climate change and development (Romero-Lankao et al. 2014; Tu 2009; Praskievicz and Chang 2011; Wilson and Weng 2011). Increases in precipitation intensity along with changes in wildfire activity due to climate change can also affect sediment, nutrient, and contaminant loads and water quality, with negative impacts for downstream water use (Georgakakos et al. 2014; Emelko et al. 2010; Osterkamp and Hupp 2010). Increasing air and water temperature is increasing thermal stratification in lakes and reservoirs, which can release nutrients and pollutants from bottom sediments (Romero-Lankao et al. 2014; Georgakakos et al. 2014; Sahoo and Schladow 2008; Sahoo and Schladow 2011; Schneider and Hook 2010).

FLOODING

Flooding causes fatalities and significant damage to property and agriculture, with average annual damages between 1981 and 2010 estimated at $7.8 billion (in 2011 dollars) (NOAA 2013). Floods in 2011, including in the Northeast and along major river basins in Mississippi, Missouri, and Ohio, caused 108 fatalities and $8.4 billion in damages (NOAA 2013). Flash floods, urban flooding, and coastal flooding, are all strongly tied to heavy precipitation events, while river floods are also dependent on basin topography and existing levels of soil moisture. All floods are also affected by human land-use and management decisions.

In most of the US, heavy precipitation events have become more frequent and intense over the past several decades, with the amount of precipitation during such events increasing in all regions of the continental US except the Southwest and Northwest (Walsh et al. 2014). These trends have not yet been linked to changes in flood frequency, but heavy precipitation increases are projected to continue across the US (Walsh et al. 2014; Kunkel et al. 2012; Wehner 2012; Wuebbles et al. 2013).

Flood frequency and severity may increase in the Midwest and Northeast based on climate and hydrologic projections (Georgakakos et al. 2014). Future flood risks across the US are difficult to estimate, given their dependence on land-use trends such as urbanization, but such trends including development in coastal areas and floodplains can exacerbate the impacts of increased flooding (Romero-Lankao et al. 2014; Georgakakos et al. 2014; Doocy et al. 2013; Hejazi and Markus 2009). For example, one study estimated 30 to 40% increases by mid-century in flood discharge associated with a 100-year flood in the West and Northeast, with 50 to 60% increases by the end of the century in areas of the Northeast, in the Pacific Northwest, and in other urbanized areas of the West, due to the combined effects of climate change, population growth, and land-use change (Kollat et al. 2012). Coastal flooding is described in chapter 4.

ECONOMIC DAMAGES AND ADAPTATION COSTS

A small number of studies have estimated water-related economic damages and adaptation costs associated with climate change. A study examining national economic damages from changes in water supply and demand for agricultural, public and domestic, and commercial and industrial use, as well as for hydropower and in-stream flow requirements estimated total damages from climate change by 2100 (in 2007 dollars) of $4.2 billion per year under a business-as-usual scenario that falls between RCP 8.5 and 6.0 and $3.6 billion per year under a policy scenario similar to RCP 4.5 (Henderson et al. 2013). Damage estimates for 2025 in this study are $734 million and $690 million, respectively, and are largest in the West and Southeast. Such cost estimates are highly dependent on assumptions about future runoff and evaporation, the categories of water use included in the analysis, and the handling of reallocation of water among uses (e.g., shifting from agricultural use to other uses during times of scarcity). The cost estimates above, for example, do not include livestock, mining, and cooling for thermoelectric power generation, which may exclude some of the damages from climate change. These estimates also do not include damages due to flooding and changes in water quality, which were large in earlier studies (Henderson et al. 2013; Frederick and Schwarz 1999; B. Hurd et al. 1999). Water transfers may themselves involve substantial transaction costs as well as follow-on social and economic impacts (B. H. Hurd and Coonrod 2012). The analysis also does not include adaptation, which could reduce some damages at an associated cost, nor the potential reductions in agricultural water use associated with carbon fertilization that could reduce agricultural damages.

The estimated investment needs for water infrastructure over the next few decades without considering climate change are quite large. The EPA estimates that US water infrastructure faces 20-year capital investment needs without climate change of $335 billion for drinking water systems and $298 billion for wastewater and stormwater treatment and collection (US EPA 2008; US EPA 2009). But changing infrastructure needs imply additional costs and make it important to consider climate change in such decisions in order to spend money wisely. A preliminary analysis of the costs of adaptation by the National Association of Clean Water Agencies (NACWA) and the Association of Municipal Water Agencies (AMWA) estimated total adaptation costs for infrastructure and operations and maintenance through 2050 of $325 to $692 billion for drinking water systems and $123 to $252 billion for wastewater systems, with the largest costs in the Southwest followed by the Southeast and ranges dependent on assumptions about temperature and runoff changes and stringency of inland and coastal flood protection measures (NACWA and AMWA 2009).

CHAPTER 18

Forestry

From the boreal forests of Alaska, to the California Redwoods, to Northeastern deciduous trees and Southeastern pines, forests span a third of total US land area (about 750 million acres) and provide important natural and economic benefits. In economic terms, they provide valuable commodities like timber and bioenergy, recreational opportunities, and employment for local communities. The US forest products industry produces $200 billion in sales per year and employs about one million workers, generating an additional $54 billion each year in payroll (USDA 2013). Although less easily quantified, forests also provide important ecosystem services including wildlife habitat, clean drinking water, flood control, and carbon storage, as well as other social, cultural and aesthetic benefits (Scholes et al. 2014; Joyce et al. 2013).

US FOREST HEALTH IS HIGHLY CLIMATE-DEPENDENT

The health of US forests and forest-related industries is directly influenced by the climate. Gradual changes in temperature and precipitation patterns, as well as extreme weather events like drought, affect forest growth, species distribution, and overall condition. Climate factors also affect the incidence and extent of damage from forest disturbances like wildfire, pests and disease (Anderegg, Kane, and Anderegg 2013).

A 2012 USDA assessment determined that climate change has already significantly affected the nation's forests through a host of mechanisms (Vose, Peterson, and Patel-Weynand 2012). For example, earlier snowpack melt in spring paired with warmer summer temperatures and extended drought in some regions has led to tree die-off, and more frequent and intense forest fires have caused extensive damage in increasingly dry areas. Milder winter temperatures have contributed to the arrival of bark beetles and other pest outbreaks at higher elevations. Changes in the distribution of tree and plant species, as well as the timing of their natural cycles, have been attributed to rising temperatures, with many plant, insect, and animal species shifting northward over the past century (Joyce et al. 2013). In some areas where tree growth has been limited by cold temperatures and short growing seasons, the warming climate has resulted in acceleration of forest growth (under 1% per decade) (Boisvenue and Running 2006).

Climate is just one among many factors that influence the health of US forests. Some of the most significant changes in US forests over the past few decades are a result of land use changes such as increased urbanization and conversion for agriculture, harvest of forest products and bioenergy development, fire suppression and prevention programs, and air and water contamination. The interaction between changes in these factors and changes in climate make isolation of their individual effects difficult, especially in cases where climate and socioeconomic drivers are related (e.g. as domestic and global demand for forest products, bioenergy and agriculture drive land use change and climate change simultaneously).

CLIMATE-DRIVEN DISTURBANCE PUTS US FORESTS AT RISK

The US National Climate Assessment, based on observed changes over the past 30 years, found with high confidence that future climate change will further shift forest disturbance patterns (Joyce et al. 2013). The type and magnitude of such disturbances will differ regionally, and will likely be more variable going forward, posing significant challenges for state and local resource managers. By the end of the century, nearly half of the western US landscape will experience climate profiles never before seen by forest species currently inhabiting that region, making it difficult to predict how ecosystems will respond (Rehfeldt et al. 2006). Changes in temperature and precipitation patterns are expected to trigger dangerous disturbances, potentially doubling the area burned by mid-century and increasing by an even greater amount the proportion of western forests affected by insect infestations (Vose, Peterson, and Patel-Weynand 2012). Increased drought and warmer temperatures are expected to exacerbate these stresses, leading to higher tree mortality, slow regeneration in some species, and altered species composition.

Climate change is expected to impact US forest health in other ways, including shifting habitat and species composition, changing invasive plant species distribution and success rates, and altering the hydrological cycles that affect local and regional water quality. These impacts, while important to overall forest health and potentially significant when taken as a whole, are complex and subsequently quite difficult to characterize across American forests.

In the following sections, we go into more depth on the likely influence of a changing climate on the frequency and intensity of forest disturbances from wildfires, drought and pest and pathogen infestation.

WILDFIRE

Impacts to US from wildfire are large and growing

In 2013, over 47,500 wildfires burned more than 4.3 million acres, with the highest incidence in California, Nevada, New Mexico, Oregon, Idaho, Colorado and Arkansas according to the National Interagency Fire Center. On June 30, nineteen firefighters were killed while working to contain the Yarnell Hill Fire in Arizona, the third highest firefighter death toll attributed to wildfires in US history. On August 17, 2013, the third largest fire in California's history was sparked, eventually burning over 250,000 acres near Yosemite Park (CAL FIRE 2013).

Fire is a leading source of forest disturbances in the United States (M D Flannigan, Stocks, and Wotton 2000). Since the mid-1980s, large wildfire activity in North America has been marked by increased frequency and duration, and longer wildfire seasons. The annual area burned by large forest wildfires (greater than 400 hectares) between 1987 and 2003 was more than six times as large as the area burned between 1970 and 1986 (Westerling et al. 2006).

Fire plays an important role in ensuring forest equilibrium, but wildfires can also have significant economic, social and environmental costs. The US Forest Service and Department of the Interior spend an average of $3.5 billion a year to fight fires, three times what they spent annually in the 1990s. State governments spend another $2 billion annually on wildfire protection (Congressional Research Service 2013). Lloyds of London estimates direct losses from catastrophic wildfires in the US totaled $28.5 billion between 1980 and 2011 (Lloyds 2013). Nearly half of that cost came in just the past decade. An average of 47% of average losses over the past three decades were insured. In 2012, catastrophic fires caused $595 million of insured losses across the US.

A full accounting of the immediate and long-term costs of wildfire should also take into account a range of impacts to ecosystems, infrastructure, businesses and individuals that are not easily quantified. These include impacts to human safety and health, loss of human life, impacts to regional economies from the loss of livelihood and property and the expense of settlement evacuations.

Fire activity in the US strongly influenced by climatic factors

Fires require biomass to burn, dry, hot, and/or windy atmospheric conditions conducive to combustion, and ignitions. Climate can affect all three of these factors in complex ways and over multiple timescales (Moritz et al. 2012). Climate – including temperature, precipitation, wind, and atmospheric moisture – is a critical determinant of fire activity. Climate controls the frequency of weather conditions that promote fire, whereas the amount and arrangement of fuels influences fire intensity and spread. Climate influences fuels on longer time scales by shaping species composition and productivity (Marlon et al. 2008, Power et al. 2008), and large-scale climatic patterns are important drivers of forest productivity and susceptibility to disturbance (Vose, Peterson, and Patel-Weynand 2012)

Despite marked impacts by human activities, climate conditions were the primary factor in twentieth century wildfire activity in the American West. Between 1977 and 2003, temperature and precipitation provided the dominant controls on wildfire (Littell et al. 2009). Historical fire records going back as far as 500 CE show that biomass burning in the Western US generally increased when temperatures and drought area increased, and decreased when temperatures and drought declined (Marlon et al. 2012). The greatest increases in fire activity have occurred in mid-elevation, Northern Rockies forests, where land-use histories have relatively little effect on fire risks and are strongly associated with increased spring and summer temperatures and an earlier spring snowmelt (Westerling et al., 2006).

Wildfire impacts expected to increase

Future trends of fire severity and intensity are difficult to determine due to the complex and non-linear interactions between weather, vegetation and people (Flannigan et al. 2009). Uncertainty in the link between climate and forest fire increases as climate conditions move outside historical ranges. Without historical analogs, and considering the highly nonlinear climate–fire relationship, it is difficult to predict how potential climate futures —and the forest fuel conditions governed by these climate drivers — will affect fire intensity and activity (Westerling et al. 2011).

Despite these limitations, the US National Climate Assessment determined that there is very high confidence that under projected climate changes there is "high risk that western forests in the United States will be impacted increasingly by large and intense fires that occur more frequently" (Joyce et al. 2013). Several studies have found that fire activity will increase substantially with warming temperatures, in combination with an increase in the frequency and severity of drought, pests and pathogens across much of the western US (Keane et al. 2008; Littell et al. 2009; A. Westerling and Swetnam 2003; Williams et al. 2010). Eastern forests are less likely to experience near-term increases in wildfire as warmer temperatures are less likely to coincide with seasonal dry periods or more protracted drought.

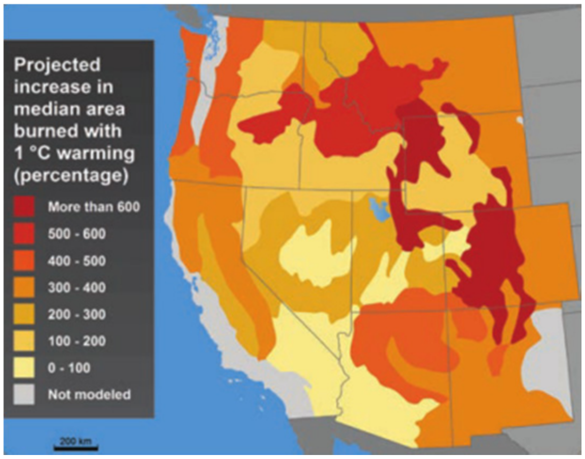
Climate variables – primarily temperature and precipitation – can affect fire impacts through changes to fire area, fire severity, and length of fire seasons. Fire seasons are lengthening for temperate and boreal regions, and this trend is expected to continue in a warmer world (Flannigan et al. 2009). National Park Service data indicate that fire ignitions are now occurring both earlier and later in the season, and the average duration of wildfires has increased from less than 10 days to more than a month (Frost 2009).

Impacts on fire activity are different for each region, due in large part to regional variations in hydrology. Conditions are expected to become more humid and rainy in the East and drier in the West, resulting in fire activity declining in the eastern US, while rising considerably in the West (Pechony and Shindell 2010). Western US forests are particularly vulnerable and will be increasingly affected by large and intense fires that occur more frequently (Joyce et al. 2013). Climate change is expected to increase wildfire risk during the summer and fall on the southeast Pacific coast, Northern Plains and the Rocky Mountains (Liu, Stanturf, and Goodrick 2010). Fire area in the West is projected to increase significantly in most ecological zones, with estimated future increases in annual area burned range from less than 100 percent to greater than 600 percent, depending on the region, timeframe, methods, and future emissions and climatic scenario (Figure 18.1) (Littell et al. 2009).

One study found that a temperature rise of 3.2°F by mid-century would produce a 54% increase in annual area burned in the western United States relative to the present day (Spracklen et al. 2009). As burn area is ecosystem dependent, the study found that forests of the Pacific Northwest and Rocky Mountains will likely experience the greatest increases (78 and 175%, respectively). A study looking at fire risk in California and Nevada predicts a 10–35% increase by mid-century, depending on the greenhouse gas emissions scenario and GCM used (Westerling & Bryant, 2007a). More dramatic increases in temperature (such as those expected under RCP 8.5) when accompanied by drought are likely to produce a response in fire regimes that are beyond those observed during the past 3,000 years. (Marlon et al. 2012).

Figure 18.1: Western wildfires expected to grow as temperatures rise

Percentage increase in median area burned (relative to 1950-2003) for a 1.8°F (1°C) temperature increase



Source: Peterson and Littell 2012, from Vose, JM, Peterson DL, and T Patel-Weynand "Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S," (2012).

DECLINING FOREST HEALTH AND TREE DIE-OFF

In recent decades, warming temperatures, intense droughts, and insect outbreaks have contributed to decreasing tree growth and increasing mortality in many forest types throughout the US, affecting 20 million ha and many tree species since 1997 from Alaska to the Mexico border (Bentz et al. 2010). Average annual mortality rates have increased by a factor of 2 to 3, from less than 0.5% of trees per year in the 1960s to 1.0 to 1.5% today (van Mantgem et al. 2009).

It is difficult to isolate individual causes of tree death, as factors such as drought, higher temperatures, and pests and pathogens are often interrelated (Joyce et al. 2013; Allen et al. 2010). However, according to the 2014 National Climate Assessment, rates of tree mortality have increased with higher temperatures in the Western US (Joyce et al. 2013; van Mantgem et al. 2009; Williams et al. 2010). This effect is less direct in eastern forests, where forest composition and structure appear to drive impacts in recent decades. As the NCA notes, although the extent to which recent forest disturbances can be directly attributed to climate change is uncertain, recent research provides clear indication that climatic variables will impact ecosystems and alter the risks US forests face today.

Tree mortality and forest die-off triggered by dry and hot conditions have been documented in most bioregions of the US over the past two decades, with increases in wildfires and bark-beetle outbreaks in in the 2000s likely related to extreme drought and high temperatures in many western regions (Williams et al. 2010). Coniferous tree species have seen widespread and historically unprecedented die-off in recent years, mainly as a result of drought and pests such as bark beetles (Adams et al. 2009). Forests within the southwestern United States have been particularly sensitive to drought and warmth; from 1984 to 2008 as much as 18% of southwestern forest area experienced mortality due to bark beetles or drought (Joyce et al. 2013). In Alaska, over 1 million hectares of several spruce species experienced die-off. Such die-off events can create significant additional risk to surrounding forests and local communities, as tree death and the accompanying increase of dead wood will influence fire risk of forests (Anderegg, Kane, and Anderegg 2013).

YELLOWSTONE

Large fires have increased in the northern Rockies in recent decades in association with warmer temperatures, earlier snowmelt, and a longer fire season (A. Westerling et al. 2011). Although human activity – through fire suppression, forest thinning, and fuel treatment – plays a role, climatic variables were found to be of primary importance in most forests, especially at higher elevations where human activity is less prevalent. Recent studies indicate that the greater Yellowstone ecosystem, a large conifer forest ecosystem characterized by infrequent, high-severity fire, is approaching a temperature and moisture-level tipping point that could be exceeded by mid-21st century. Westerling et al estimates that climate-related increases in fire occurrence, area burned, and reduced fire rotation (down to 30 years from the historical 100–300 years), there is a real likelihood of Yellowstone's forests being converted to non-forest vegetation during the mid-21st century (A. Westerling et al. 2011).

CALIFORNIA

Wildfire in California comes at a very high price. Seven of the ten costliest U.S. wildfires in history before 2011 occurred in California. Wildfire risks and their associated costs pose significant challenges to state and local governments, with state fire suppression costs of over $1 billion each year. The risk to private property has also increased over recent years as development along the wildland-urban interface has increased, with now more than 5 million homes in over 1,200 communities at risk. The largest changes in property damages occurred in areas close to major metropolitan areas in coastal southern California, the Bay Area, and in the Sierra foothills northeast of Sacramento. In 2003, over 4200 homes were destroyed by wildland fires in southern California, resulting in more than two billion U.S. dollars in damages (RADELOFF et al. 2005).

Changes in temperature, precipitation, pest and pathogen dynamics and more extreme climate events such as drought are expected to lead to increased instances of widespread forest die-off in the future (Anderegg, Kane, and Anderegg 2013). Western forests have experienced the greatest impacts, even more severe than recent estimates, and with projected increases in temperature and aridity out to 2100, substantial reduction in tree growth and increased mortality is expected, in particular in the Southwest (Scholes et al. 2014; Allen et al. 2010; Dale et al. 2001). As temperatures increase to levels projected for mid-century and beyond, eastern forests may be at risk of die-off or decline similar to recent die-offs experienced in the Western US.

Climate influences the survival and spread of insects and pathogens directly, as well as the vulnerability of forest ecosystems infestation. Epidemics by forest insects and pathogens affect more area and result in greater economic costs than other forest disturbances in the United States (Dale et al. 2001). Native and nonnative insect pest species and pathogens can greatly alter forest habitat and modify ecological processes, often leading to extensive ecological and economic damage (Dukes et al. 2009). In the United States, insects and pathogenic disturbances have affect over 20 million hectares on average each year, with an annual cost of $2.0 billion (Dale et al. 2001). Shifts in climate are expected to lead to changes in forest infestation, including shifts of insect and pathogen distributions into higher latitudes and elevations and increased rates of development and number of generations per year (Bentz et al. 2010; Waring et al. 2009). The National Insect and Disease Risk Map (NIDRM), prepared by the US Forest Service to provide a nationwide strategic appraisal and spatial mapping of the risk of tree mortality due to insects and diseases from both endemic and non-endemic forest pests, estimates that by 2027, 81 million acres (over 10% of total US forest land) will be in a hazardous condition for insects and diseases. This assessment does not take into account the potential impacts from climate change, but concludes that climate change will significantly increase the number of acres at risk, including elevated risk from already highly destructive pests (Krist et al. 2014).

CHAPTER 19

Tourism

For many travel destinations across the US, climate is the main attraction. Drawn to the nation's coasts by sun, sand and sea and to mountain ranges by snow and lush forests, tourists, it seems, are the quintessential fair-weather friends. The modern tourism industry in the US has been built to satisfy the highly climate-sensitive desires of the millions of American and foreign visitors. The climate itself, and the amenities it provides – snow in the mountains, abundant water and fish stocks in rivers and lakes, and healthy coral and marine ecosystems – is a natural resource upon which the tourism industry depends. Mountain resorts in the Rockies, for example, depend on regular and abundant snow to support more than 20 million visitors each winter. In Hawaii, hotels, restaurants, and tour operators rely on the state's year-round sun and sandy beaches to draw tourists from all over the world, accounting for a full fifth of the state's economic output.

Climate change will likely significantly reshape the tourism industry nation-wide. Tourist "demand" will be influenced over time as tourists take into account changing conditions when weighing destination options. Climate change will also affect tourism "supply" as some destinations experience loss of or greater instability in the climate resources on which they depend. For example, sea-level rise and increased storm surge may damage beach resorts, low-elevation mountain resorts may have trouble maintaining adequate snow, and water scarcity may limit the season for whitewater rafting in areas facing drought. The risk of these potential impacts creates significant implications for local businesses and communities that depend on tourism and the climate-sensitive resources that attract visitors. Some regions will also gain, as climate change makes certain parts of the country more attractive tourist destinations.

CLIMATE IS ALREADY A MAJOR FACTOR INFLUENCING US TOURISM SUPPLY AND DEMAND

Climate conditions affect the supply of tourism opportunities in several ways. First, climate determines the length and quality of the tourist season. In many areas of the US, warming temperatures have shifted the onset of spring and summer conditions to earlier in the year. Tourist activity has been shifted as well, with peak park attendance in areas of increased average temperatures coming 4 days earlier in the year, on average (Buckley and Foushee 2012). Historical examples of year-to-year variability have shown that warmer, longer summers can provide a significant boost to tourist activity in national parks in northern latitudes. Warmer average temperatures can also mean abbreviated winter seasons, reducing opportunities for winter sports activities. High altitude locations (including the Colorado Rockies), often thought to be more protected from these effects, have experienced substantial shifts in the timing of snowmelt and snowmelt runoff (Clow 2010). Winter tourism has experienced noticeable changes in snow season length and quality, as the Western US and parts of the northern Great Plains, Midwest and Northeast see earlier spring melting (Fritze, Stewart, and Pebesma 2011; Hoerling et al. 2012; Mote 2006; Pierce et al. 2008).

Tourist destinations can also experience direct impacts from climate-related events that affect their ability to attract visitors. Extreme wet or dry years, for example, can make specific destinations unsuitable for the outdoor activities upon which they depend. Wildfires can block access to outdoor recreation areas, and coastal storms and flooding can drive away beach-goers. In the spring and summer of 2002, for example, severe drought in Colorado created dangerous wildfire conditions that kept summer visitors at bay, with a 30% reduction in reservations at state park campgrounds (Butler, 2002). On more rare occasions, storms and other extreme events can wipe out an entire tourist season or even multiple seasons, depriving communities of tourist-related income on top of direct weather-related damages. Louisiana experienced a 24% drop in visitor spending from 2004 to 2006 after Hurricane Katrina, and the number of visitors to New Orleans did not return to pre-Katrina levels until 2013 (University of New Orleans and LSU 2009).

Finally, climate is a significant factor in determining the operating expenses of many tourist destinations, including heating and cooling, snow-making, irrigation and water supply, and insurance costs. The tourist industry has long been exposed to seasonal and inter-annual climate variability, and to date has developed tools to help manage the challenges such uncertainty creates for business planning and operation.

Climate also plays a role in tourism demand across the US. Unlike tourism supply, which is somewhat fixed as destinations are unable to pick up and move to more suitable climes in times of climate variability or extreme events, tourists are by nature fair-weather and flexible in their choice of destination. Studies have shown that economic development is the principal determinant of the *level* of tourist demand: more disposable income means greater travel (Bigano, Hamilton, and Tol 2005). However, once people decide to travel, climate is a significant influence on *where* tourists choose to spend their vacations (UNEP, WMO, and WTO 2008). Studies of tourist destination preferences have identified a universal preference for moderate temperatures (with an optimal temperature of about 70°F), and have found that American tourists in particular display a strong preference for specific precipitation levels (Lise and Tol 2002). As a result, seasonal travel patterns shift toward warmer temperatures and sunny skies in temperate regions of the US. Perceptions of environmental quality – sufficient stream flow and fish stocks, for example, or thriving coral and beach ecosystems – are also important determinants of tourist demand.

CLIMATE CHANGE IMPACTS ON US TOURISM

The sensitivity of US tourist demand to climate and the natural resources it affects means that climate change will expose the industry to a wide range of potential risks. Businesses that have been built to take advantage of local climates will need to adapt to these changes over time. Such changes include rising sea levels and increased storm surge from hurricanes and other coastal storms that may damage tourist infrastructure, disrupt travel in coastal communities, and put beaches and other environmental attractions at risk. Changing hydrological patterns will impact river flows and lake levels that draw tourists for water-sport activities and affect water availability and competition among water users. Activities that require large volumes of water to sustain, such as golf (a single golf course requires the same amount of water as a city of 12,000 people), waterparks and pools, will be most affected by changes in availability and price (UNEP, WMO, and WTO 2008).

Future changes in temperature will have a wide array of impacts. Warmer average temperatures nation-wide mean that "ideal" tourist temperatures will shift northward and to higher elevations, with potential impacts on tourist destination preference. Along with warmer temperatures comes growth in insect populations and the associated vector-borne diseases they carry, which may also affect the quality of tourist activity in some areas. More severe droughts and wildfires may limit or curtail tourist activities in affected areas. Changes in the migration patterns of fish and animals will affect fishing and hunting, and warmer ocean temperatures and ocean acidification will affect coral reefs in popular diving destinations.

The dynamic nature of tourism demand and the wide-array of tourist destination types and locations across the US make it difficult to predict how the sector as a whole will be impacted by a changing climate. The very strong substitution effect on tourist demand makes it is difficult to assess the impact of climate change on overall tourism levels in the US (Lise and Tol 2002).

Several studies that consider the isolated impact of temperature rise on tourism found that the US tourism industry as a whole may actually benefit as Northern temperate regions become more attractive destinations for travelers globally (Deutsche Bank 2008; Scott et al. 2006; Bigano et al. 2006). Tourists, finding traditional Southern destinations increasingly hot, are expected to go north following more ideal recreational temperatures. One study determined that with an increase of 1.8°F of global mean temperatures by mid-century, the US will see a modest decline in foreign travelers (as they stay home or select other destinations), but more Americans (by a factor of three) are expected to choose to stay in the US as a result of milder weather (Berrittella et al. 2006). With domestic tourism making up the vast majority of tourist activity in the US, contributing nearly 90% of total travel and tourism sales in 2012, the net economic impact of warmer temperatures was found to be positive. In general, global tourism demand models find that countries with larger shares of domestic tourism are less affected by climate change, a finding that holds for climates that are currently cool but which may warm over time, like the Northern latitudes of the US (Berrittella et al. 2006). It is important to note that existing studies of global tourism impacts have only explored changes in temperature, omitting potential sea level rise, changing precipitation patterns, or ecosystem impacts.

Nation-wide assessments also obscure important consequences for specific communities. Climate change impacts will be experienced differently from region to region, and may even vary among communities within the same state, depending not only on local climate but also shifting tourism industry dynamics. An analysis of the attractiveness of 143 North American cities, based on seven climate variables associated with tourist demand, found that by the late 21st century, the number of US cities with 'excellent' or 'ideal' climate ratings in the winter months is likely to increase (Scott, Mcboyle, and Schwartzentruber 2004). In contrast, Mexico's ratings decline as temperature rise even further, suggesting that more winter sun-seekers will opt instead to go north, bringing additional revenue to US states. However, as temperatures rise, Southern US states may also see losses of these sunbird tourists to northern states, altering the competitive dynamics within the US market.

Although tourists are flexible enough to respond climate change, the same cannot be said of local providers of tourist services and local economies dependent on tourism revenues. Areas where tourism constitutes the major livelihood of local communities and where such tourism is strongly climate-dependent will be the most affected. Changes in the length and quality of the tourism season will also have considerable implications for the long-term profitability and competitive relationships between destinations. In general, greater variability in climate creates uncertainty for how tourism demand will respond, making it more difficult for the tourism industry to plan and maintain business from year-to-year.

TOURISM FACTS

In 2012, tourist-related output generated $1.46 trillion dollars (3% of US GDP) and 8 million jobs (U.S. Bureau of Economic Statistics 2013). The Outdoor Industry Association estimates recreational activities including hiking, camping, and fishing contribute nearly $650 billion in spending and $80 billion in tax revenue to federal, state and local governments, and support more than 6 million jobs. National Parks see more than 280 million visitors, generating $12 billion in visitor spending and supporting nearly 250,000 jobs (Outdoor Industry

Winter Sports

Climate has long ruled the fortunes of winter destinations dependent on snow for skiing and other winter sports. Across the US, winter temperatures have warmed 0.16°F per decade on average since 1895, and more than tripled to 0.55°F per decade since 1970 (Burakowski and Magnusson 2012). The unpredictability of winter seasons, as warmer temperatures bring increased variability in snow quantity, quality, and season length, has made it increasingly difficult for winter destinations dependent on steady revenue from snow-seeking tourists. The unique vulnerability of the winter tourism industry to climate makes it an important area for studying the near- and long-term impacts of a changing climate on winter tourism in the US.

The businesses and communities that depend on winter sports as a significant source of annual revenues (over $53 billion in annual spending on gear and trip-related sales) are paying close attention to current and future climate trends (Outdoor Industry Foundation 2012). The expectation that climate change will bring even warmer winters, increased rainfall and reduced snowfall, and shorter snow seasons has raised concern that the U.S. winter sports industry could face significant losses. The picture is more complicated, however, as experience to date shows that winter tourists and ski operators have proved able to adapt, to some extent, to these changing conditions, making up for lost snow through artificial production. Tourists have adjusted as well, varying the timing and frequency of winter travel. The key question over time will be whether and how tourists and the winter sport industry react to future climate changes and at what cost.

Looking back at past impacts associated with warmer temperatures can provide some insight into how this single variable may impact future winter sports seasons. The U.S. 2011-2012 winter season was the fourth warmest winter on record since 1896, with the third smallest winter snow cover footprint in the 46-year satellite record. An assessment by the National Ski Areas Association (NSAA) found that winter sport visits were down nearly 16%, despite significant efforts by ski resorts to supplement the lack of snow with snowmaking (National Ski Areas Associations 2013). Snowpack was particularly limited across areas in the West, where parts of California, Nevada, and Arizona had snowpack less than half of average, translating into a 25% drop in visitors. This can have real implications for states that rely on winter tourism and for local resorts and communities that experience declining revenues. One study analyzing the winter snowfall data across the US from 1999-2010 found that lower-snowfall winters were associated with fewer skier visits in nearly all states, with a total revenue difference in low-snow years of over $1 billion (Burakowski and Magnusson 2012).

The ski industry has come to rely heavily on snowmaking in order to reduce vulnerability to variability in snow levels and season length and maintain business from year-to-year. Ski areas have invested millions of dollars in snow-making capabilities and by 2001 all ski areas in the Northeast, Southeast and

Midwest had snowmaking systems covering 62 to 98% of skiable terrain (Scott et al. 2006). Across the rest of the US, by 2012 nearly 90% of ski resorts report snowmaking was used to supplement natural snow cover. The ability to adapt to variability in snowfall is limited, however, as it requires energy to run equipment, significant volumes of water, and below-freezing temperatures. Adaptation in the form of snowmaking, therefore, comes at a high cost, often the biggest expense for ski resorts and at times as much as half of total expenses (Burakowski and Magnusson 2012). In drought-stressed regions, water scarcity may be a limiting factor. Making an acre-foot of snow requires over 160,000 gallons of water; a typical ski run (200 feet wide by 1,500 feet long) would take nearly 7 acre feet of water (or approximately one million gallons) to make one foot of snow (Ratnik Industries 2010).

RECREATIONAL FISHING

A recent study by Lane et al. (2014) assessed the potential climate change impacts to recreational freshwater fishing across the coterminous US. They found that higher air temperatures, and to a lesser extent changes in streamflow, will alter fish habitat, resulting in a decline in more desirable recreational fish species (i.e. cold-water species like trout) and a shift toward less desirable warm-water fisheries. Under their "business as usual" scenario (coinciding with a radiative forcing of 10 W/m2 by 2100), warmer temperatures are expected to result in more than a 60% loss in current cold-water fishery habitat, which will virtually disappear in Appalachia, while habitat in substantial portions of Texas, Oklahoma, Kansas, Arizona and Florida will shift from warm-water fisheries to species of even lower recreational priority. The analysis suggests that such shifts could result in national-scale economic losses associated with the decreased value of recreational

Impacts on coastal tourism

Coastal areas, and the tourist destinations they support, are some of the most vulnerable to climate change. Many of the beaches, wetlands, estuaries, coral reefs and kelp forests that attract visitors from across the US and internationally are managed by the US National Park Service, with more than 5,100 miles of coast and three million acres of coastal lands under their management. These parks attract more than 75 million visitors every year, and generate over $2.5 billion in economic benefits to local communities. Rising sea levels are expected to change shorelines and park boundaries, resulting in a net loss where parks cannot migrate inland. Everglades National Park, which brings in over one million visitors each year, is uniquely vulnerable as even slight increases in sea level are expected to lead to disproportionate increases in inundation periods for broad areas in the park, and have already influenced both surface and subsurface saltwater intrusion (Stabenau et al. 2011). Due to a lack of suitable habitat, species are prevented from migrating upland, resulting in significant changes to the composition of wetland and other forest communities and the species they support.

The potential impacts of climate change on coastal tourism activity across the US will be highly location specific, but localized studies provide examples of the type of impacts communities may face. Sea level rise alone will likely change the coastal tourist dynamic as beach destinations become altered. One result of sea-level rise is coastal erosion, which decreases beach width over time without intervention, and in some instances eventually eliminates a beach altogether. One study estimates the impacts of sea-level rise induced reductions in beach width on beach recreation demand in several southern beach communities in North Carolina (Street et al. 2007). Using estimates of likely sea-level rise in 2030 and 2080 based on local conditions at beach sites in Southern North Carolina, the study found that the lost recreational value to beach goers is $93 million in 2030 and $223 million in 2080, a reduction of 16% and 34% of recreational value, respectively. Although some of the affected beach-goers, finding their preferred beaches diminished or gone entirely, will simply choose beach sites further afield (which are also likely to be impacted), tourist-dependent businesses in the area will be affected.

Climate change will also accelerate coral bleaching and disease caused by increased sea surface temperatures in the Caribbean, which has already led to the loss of more than 50% of reef-building corals in the Virgin Islands park units since 2005 (Buddemeier, Kleypas, and Aronson 2004; Hoegh-Guldberg 1999). A recent study by Lane et al. (2014) found that even under low-emission scenarios, it is likely unavoidable that South Florida and Puerto Rico will experience multiple bleaching and mortality events by 2020. The same study found, however, that low-emission scenarios (associated with a radiative forcing of 3.7 W/m^2 by 2100) may reduce the potential mid-century impact on Hawaii's coral reefs, where sea surface temperatures are cooler and coral cover is greater and more robust. Low-emissions scenarios only delay the extensive bleaching of Hawaii's corals, however, which is expected to still see substantial reductions in coral cover by late century. The discounted loss of recreational benefits of a "business-as-usual" climate scenario (associated with radiative forcing of 10 W/m^2 by 2100) when compared to the low-emissions scenario are estimated at $17.4 billion dollars (with a confidence interval of approximately $9 to 26 billion) (Lane et al. 2014).

CHAPTER 20

National Security

"People are saying they want to be perfectly convinced about climate science projections... But speaking as a soldier, we never have 100 percent certainty. If you wait until you have 100 percent certainty, something bad is going to happen on the battlefield." - General Gordon R. Sullivan (CNA 2007)

The US national security establishment is accustomed to making decisions in the face of uncertainty. In an unpredictable world, assessing potential global risks is essential to making our homeland more secure. Climate change is such a risk. The global conditions associated with climate change, including potential changes in tropical cyclone activity, additional drought and flooding, and rising sea levels, present serious risk factors that could trigger mass migration, elevate border tensions, increase demands for rescue and evacuation efforts, and heighten conflicts over essential resources, including food and water (CNA 2007). In recent years, the US military has come to recognize climate change as a direct threat to national security and has developed a risk-based approach to prepare for and manage the potential impacts both at home and abroad.

In 2006, a panel of eleven retired three-star and four-star admirals and generals formed a Military Advisory Board to assess the impact of global climate change on US national security. They concluded that "climate change can act as a threat multiplier for instability in some of the most volatile regions of the world, and it presents significant national security challenges for the United States" (CNA 2007). The following year, in response to calls from Congress and shifting national strategic priorities, the US intelligence community produced the *National Intelligence Assessment on the National Security Implications of Global Climate Change to 2030* which highlighted "wide-ranging implications for US national security interests" (Fingar 2008).

In recent years, the US military and security establishment has moved beyond exploration and begun integrating climate change risk assessment and management into normal national security planning. In its 2010 Defense Quadrennial Review, the US Department of Defense (DOD) called for a strategic approach to climate to manage the effects on its operating environment, missions and facilities and regularly evaluate risks as new science becomes available (US Department of Defense 2010). This was the first time the Pentagon addressed climate in a comprehensive planning document. Not long after, individual branches of the military began to develop their own assessments of likely impacts and plans for dealing with near- and long-term threats from climate change (US National Research Council Committee on National Security Implications of Climate Change for Naval Forces 2011; U.S. Navy 2010). The most recent Quadrennial Review reinforced the need to incorporate climate risks into planning, stating that "the impacts of climate change may increase the frequency, scale, and complexity of future missions, including defense support to civil authorities, while at the same time undermining the capacity of our domestic installations to support training activities" (US Department of Defense 2014).

These assessments group climate-related risks to US national security into two categories. The first covers direct, physical impacts to the homeland, including threats to US military installations from flooding and storms, threats to nuclear power plants or oil refineries, and the risk that critical US defense forces may be diverted from core national security objectives to aid in the management of domestic extreme weather events, such as Hurricane Katrina. The second, and much larger, category covers the indirect risk that climate change will exacerbate existing conflicts abroad and heighten humanitarian and political crises in vulnerable states and populations (US Department of Defense Science Board 2011). Below we provide a general overview of these indirect international impacts, followed by a more in-depth discussion of the direct impacts within the US.

INDIRECT INTERNATIONAL

Assessments by the Pentagon and national intelligence community have concluded that climate change could have significant geopolitical impacts around the world, contributing to environmental degradation and food and water scarcity, exacerbating poverty, increasing the spread of disease, and spurring or exacerbating mass migration. This is likely to lead to increased demand for defense support to civil authorities for humanitarian assistance or disaster response.

The US military often has a unique ability to respond to large-scale extreme weather or natural disasters. In the wake of Typhoon Haiyan, which struck the Philippines on November 8, 2013, the US not only provided $37 million in humanitarian aid, but also deployed over 14,000 US military personnel to help stabilize the area and provide relief. The US military gets a request for humanitarian assistance and disaster response about once every two weeks (Former Captain Jon Gensler (US Army) 2014). As climate change heightens and exacerbates humanitarian emergencies, the demand for US assistance will further strain US military capacity, limiting readiness for homeland defense or combat operations that may arise (Fingar 2008).

While resource scarcity and natural disasters associated with climate change are significant threats in and of themselves, an associated risk is their potential to weaken already fragile governments, providing opportunity for increased instability and conflict, creating an additional burden on the US military to respond to prevent further destabilization. The National Intelligence Assessment for 2030 concluded that climate change alone is unlikely to trigger state failure in that timeframe, but the exacerbation of existing problems could be enough to endanger domestic stability in some states, giving rise to threats of regional conflict or creating openings for criminal activity or terrorism (US Department of Defense Science Board 2011). For example, a dysfunctional government response to water stress -- of a sort expected to become more common under climate change -- is generally agreed to be one of the contributing factors to the current humanitarian disaster in Syria (de Châtel 2014).

Recent work has applied the same econometric techniques used elsewhere in this report to quantitatively measure the dose-response function linking climatic events to various forms of modern intra-state social conflict, ranging from ethnic riots(Bohlken and Sergenti 2010), land invasions (Hidalgo et al. 2010), local political violence (O'Loughlin et al. 2012), leadership changes (P. J. Burke 2012), and coups (Kim 2014) to full scale civil conflict (Hsiang, Meng, and Cane 2011) and civil war (M. B. Burke et al. 2009). Overall, the body of econometric analysis provides consistent and strong evidence that elevated temperatures tend to increase the risk of intergroup conflict in a location by roughly 13% for each standard deviation of warming, with somewhat weaker evidence that rainfall extremes affect conflict in a quantitatively similar way (Hsiang, Burke, and Miguel 2013b). For perspective on the size of these effects, historically observed oscillations in the global climate have been implicated in contributing to 21% of civil conflicts since 1950 (Hsiang, Meng, and Cane 2011). In contrast to earlier theories that populations fought over increasingly scarce resources (i.e. "water wars"), this new body of evidence suggests that more complex dynamics are responsible for these social conflicts—the leading theory argues that climatic changes cause economic conditions and local labor markets to deteriorate, reducing the opportunity cost of engaging in violence and extractive activities (Miguel, Satyanath, and Sergenti 2004; Chassang 2009; Hidalgo et al. 2010; Dal Bo and Dal Bo 2011).

In contrast to this recent progress on intra-state social conflict, there is no general empirical evidence as to whether or not modern inter-state conflict may be affected by climate, but this may be due to an absence of studies on this topic (Hsiang and Burke 2013).

Climate will also have an impact on strategic resources, including fuels, minerals and food supplies, as well as the security of international transport routes essential to ensuring open access. One important example is the rapid evolution of the Arctic as accelerating sea ice melt opens the region to changing transport routes, competing territorial and resource claims, and potential conflicts. As one of five nations bordering the Arctic (with over 1,000 miles of Arctic coastline) and with a seat on the Arctic Council, this example is of particular importance to the US. With no overarching political or legal structures to oversee the orderly development of the region or mediate political disagreements over Arctic resources or sea-lanes, the potential risk of conflict in the region is meaningful.

By the end of the summer of 2012, the area covered by sea ice shrunk to about 400 thousand square miles smaller than it was the previous summer, leaving the Arctic icecap to less than half the size it had been 30 summers previously (NSIDC 2014). Warming temperatures have resulted in a rapidly evolving Arctic landscape, exposing sea routes that did not previously exist, opening access to transport and resource extraction. Further expected warming could open up shipping shortcuts on the Northern Sea Route (over Eurasia) and the Northwest Passage (over North America), cutting existing oceanic transit times by days. Both American and other vessels (including other navies or smugglers) would have greater access, making the overall impacts to national security hard to predict. It is likely that these Arctic routes would also allow commercial and military vessels to avoid sailing through politically unstable Middle Eastern waters and other pirate-infested waters, thus mitigating other threats (Borgerson 2008).

The US military has long had a presence in the Arctic, but the greater access afforded by melting sea ice will require a shift in the nature of its role and the resources required to sustain it, such as increased capacity for search-and-rescue and border patrolling, alterations of naval vessels, and increased monitoring. Responding to these challenges may require investments in ice-capable technologies and military training; greater resources for management of maritime traffic, search-and-rescue and accident clean-up capacities; and building an ice-capable commercial, scientific and naval fleet, an investment some have suggested is on the order of $11 billion for icebreakers alone (Ebinger and Zambetakis 2009).

DIRECT IMPACTS TO THE US HOMELAND

Military Installations

The most direct national security threat is the potential impact of extreme weather and sea level rise on domestic military installations and the physical infrastructure that supplies them, as well as on our international installations of strategic importance.

The US military manages property in all 50 states, seven US territories and 40 foreign countries, comprising almost 300,000 individual buildings around the globe worth roughly $590 billion (US Department of Defense 2012). About 10% of DOD coastal installations and facilities are located at or near sea level and are vulnerable to flooding and inundation (SERDP 2013). The National Intelligence Council estimated that 30 US military installations were already facing elevated risk from rising sea levels in 2008, jeopardizing military readiness which hinges on continued access to land air and sea for training and transport (National Intelligence Council, 2008). Due to a combination of natural and human-caused factors, Norfolk, Virginia, home to the world's largest naval station, has experienced one of the fastest rates of sea-level rise in the United States.

Several recent disasters have highlighted the vulnerability of military installations to hurricane-related flooding and wind damage, as well as increase in sea level averages. In 1992, Hurricane Andrew damaged Homestead Air Force Base in Florida to the point that it never reopened, while Hurricane Ivan knocked out Naval Air Station Pensacola for a year in 2004, and Hurricane Katrina destroyed 95% of Keesler Air Force Base in Mississippi (Foley and Holland 2012). As demonstrated in all three cases, military bases in the US are important drivers of local and regional economies, and when they are destroyed by natural disasters there is considerable collateral economic damage. As discussed in chapter 2, scientists have a high degree of confidence that global sea levels will continue to rise as a result of current GHG emissions trends, and that higher sea levels alone increase damage from hurricanes and other coastal storms. If climate change increases the frequency and severity of the most intense Atlantic basin hurricanes, as many cyclogenesis models predict, the risks are even higher.

The Pacific Coast is not invulnerable: an uncharacteristic tropical storm ripped through Fort Irwin, California, in 2013 bringing monsoon rains, wind and hail, and leaving homes and facilities flooded. Wildfire also poses a risk in the Western US. In 2013, a 2,500-acre wildfire forced evacuations at Marine Corps Base Camp Pendleton in San Diego County.

In recognition of the growing risk posed by these and other climate-related disruptions linked to climate change, the 2010 Quadrennial Defense Review called for a climate impact assessment at all DOD's permanent installations (US Department of Defense 2010). Several studies have been completed or are currently underway by the individual military service branches, and DOD's Strategic Environmental Research and Development Program (SERDP) launched a comprehensive research project to examine climate change impacts on coastal installations (SERDP 2013). SERDP is using case studies, such as the Norfolk Naval Station, to quantify the potential impacts of near-term sea level rise and storm activity on coastal infrastructure and Pacific islands and atoll systems that are home to critical US military installations.

Critical infrastructure

National security extends beyond protecting the homeland from outside threats. The US Department of Homeland Security has affirmed that protecting and ensuring the resilience of critical domestic infrastructure is essential to the nation's security, and that natural hazards can disrupt the functioning of government and business and result in human casualties, property destruction, and broader economic effects (US Department of Homeland Security 2009).

The daily functioning of most critical infrastructure systems is sensitive to changes in precipitation, temperature, wind, and, for coastal cities, rising sea levels (Love, Soares, and Püempel 2010). Extreme weather events can destroy or temporarily debilitate critical physical infrastructure upon which the country depends, making us less secure as a nation. Electricity transmission and distribution systems face elevated risks of physical damage from storms and wildfires, and fuel transport by rail and barge is susceptible to increased interruption and delay, disrupting US economic activity and impacting millions of Americans who depend upon electricity and fuels to power and heat their homes (US Department of Energy 2013). Roads, airports and bridges are at risk from coastal storms and flooding, potentially incapacitating entire regions. Damage to coastal homes could leave thousands homeless or without access to basic amenities, threatening public health and safety. Impairment of critical infrastructure also hampers disaster response efforts where communications and transportation systems are needed for preparedness, evacuation or provision of food, or to provide water and other emergency services to affected populations.

A significant portion of US transportation infrastructure is in poor shape or deteriorating. The Department of Transportation estimates that approximately 11% of all US bridges are structurally deficient, 20% of airport runways are in fair or poor condition, and more than half of all locks are more than 50 years old (US Department of Energy 2013). More than $3.6 trillion is needed to bring infrastructure in the US up to “good condition” (American Society of Civil Engineers 2013). Absent additional investment in climate resilience, the changes in temperature, precipitation, sea levels and storm patterns described in Chapter 2 will exacerbate these infrastructure vulnerabilities. Climate-related infrastructure risks are concentrated in large cities and low-lying coastal areas. The Gulf Coast, home to critical energy and transport infrastructure, is particularly vulnerable, with 27% of major roads, 9% of rail lines, and 72% of ports at or below 4 feet in elevation (see Chapter 4).

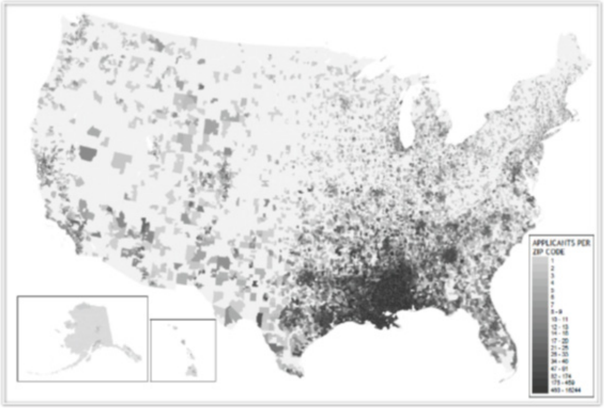
Climate-driven changes in extreme events can also compromise US military capacity by diverting resources from core national security objectives. The military mounted a massive response to Hurricane Katrina, for example, with over 70,000 military personnel involved at the peak (U.S. GAO 2006).

Migration

As Hurricane Katrina demonstrated, extreme weather events can trigger large, unplanned population movements. Although displacement is often only temporary and may not result in long-term migration, even short-term movements can exacerbate a range of problems, including increased stress on resources and ecosystems, and strain on governance and security systems (McLeman and Hunter 2010). In the long-term, regions across the US may be destabilized by rising sea levels, increased storm surge, rising temperatures, among other impacts, increasing migration flows from affected areas (Fingar 2008; Feng, Krueger, and Oppenheimer 2010). Rising sea levels and extreme weather events in coastal zones could contribute to humanitarian disasters and potential refugee flows (Youngblut 2009).

Figure 20.1: Katrina Refugee Diaspora

Location (by zip code) of 800,000 displaced Louisiana residents



Source: (Louisiana Geographic Information Center 2005)

In the long-term, even gradual changes in climate may induce migration from the most affected areas. Evidence has shown that weather extremes (i.e. extreme temperatures, extreme precipitation, and storm frequencies) have a negative influence on where Americans choose to live, and climate-driven changes may influence regional migration within the US (Fan, Klaiber, and Fisher-vanden 2012). In coastal areas, sea-level rise and coastal inundation will lead to gradual land loss, and episodic flooding and permafrost melt will contribute to increasingly marginalized land, all of which may contribute to migration and/or require resettlement (Adger et al. 2014). Some migration flows are sensitive to changes in resource availability. For example, rising temperatures and changing precipitation patterns will lead to relative changes in agricultural production, possibly spurring rural to urban migration, or migration across borders to seek more favorable conditions (Feng, Oppenheimer, and Schlenker 2012). Climate change is projected to increase the rate of immigration to the US from Mexico, as the country’s already marginal water situation deteriorates, and as a result of climate-driven changes in agricultural yields (CNA 2007; Feng, Krueger, and Oppenheimer 2010).

Part V

Insights for Climate Risk Management

CHAPTER 21

Mitigation

Risk is the probability of an event occurring multiplied by the impact of that event should it occur. Climate risk can be managed by reducing the probability of costly climate futures by lowering global greenhouse gas (GHG) emissions, and by minimizing the impact of those futures through defensive investments and behavioral adaptation. Like the climate risk itself, the right combination of these two will depend on who you are, where you live, and the time period of concern. It will also depend on the relative cost of each option, costs which we do not quantify in this report. The fact that our assessment covers a range of global emissions pathways, however, allows us to assess in this chapter the extent to which global efforts to reduce GHG emissions (referred to as "mitigation") can reduce the risks described in this report. In the next chapter we discuss some of the available strategies for adapting to those changes in the climate not avoided through mitigation.

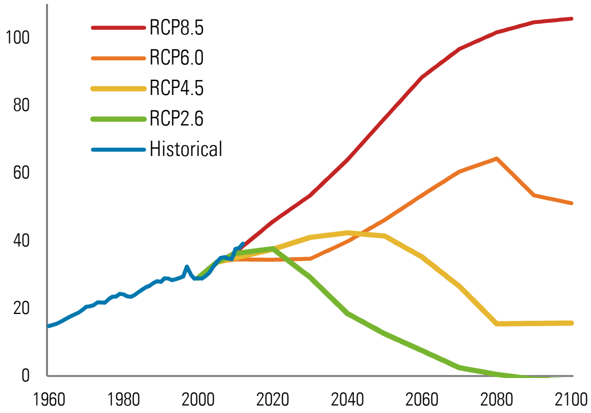
BACKGROUND

As discussed in Chapter 3, the scientific community has developed a set of four harmonized "Representative Concentration Pathways" (RCPs) spanning the plausible range of future atmospheric GHG concentrations (Figures 3.1 and 21.1). RCP 8.5 represents a continuation of recent global emissions growth rates, with atmospheric concentrations of CO_2 reaching 940 ppm by 2100. RCP 2.6 reflects a future only achievable by aggressively reducing global emissions (even achieving net negative emissions by this century's end) through a rapid transition to low-carbon energy sources. Two intermediate pathways (RCP 6.0 and RCP 4.5) are consistent with a slowdown in global economic growth and/or a shift away from fossil fuels and other sources of GHG emissions more gradual than in RCP 2.6 (Riahi 2013).

Under RCP 2.6, global GHG emissions peak around 2020, while under RCP 4.5 and RCP 6.0, they peak around 2040 and 2080, respectively. Under all pathways except RCP 8.5, projected emissions for 2020 are below those that actually occurred in 2012 (Le Quéré et al. 2014). This overshoot implies that future emissions reductions need to be faster than those projected in RCPs 2.6, 4.5, and 6.0 to achieve comparable levels of cumulative emissions and therefore comparable climate outcomes.

Figure 21.1: Global net human-caused CO_2 emissions in the Representative Concentration Pathways

Billion metric tons of CO_2 per year



Source: Historical: LeQuere et al., 2014; RCPs: Malte Meinshausen et al. 2011a

Moving from RCP 8.5 to RCP 2.6 (as well as RCP 4.5 and RCP 6.0) will come at a cost. We did not quantify these costs in this assessment. There is extensive literature on this topic (Weyant and Kriegler 2014), including a recent summary from Working Group III of the IPCC (Clarke et al. 2014). Moving from RCP 8.5 to RCP 2.6 will also require coordinated global action, and we do not evaluate the prospects of such coordinated action occurring. What our analysis provides, however, is a better understanding of the potential for such action to mitigate the risks to the US of continuing on the current global emissions pathway, by region of the country and sector of the economy, as well as its limitations.

STEERING THE SHIP

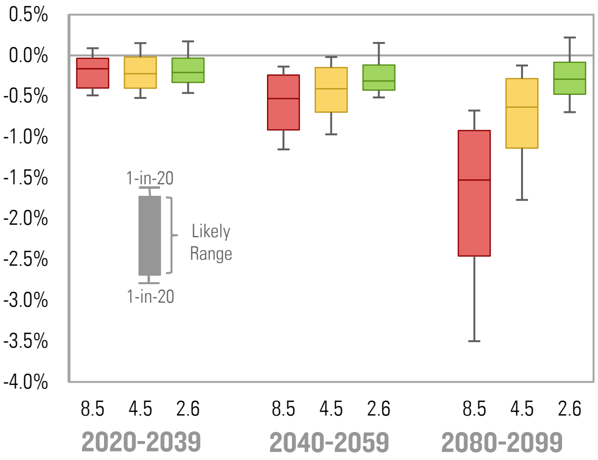
The differences in GHG emissions between RCPs emerge almost immediately. By 2030, global CO_2 emissions are 25% below actual 2012 emissions in RCP 2.6, 5% higher than 2012 emissions in RCP 4.5, and 37% higher than 2012 emissions in RCP 8.5. Because of quirks in the way the RCPs are calculated, emissions in RCP 6.0 are below those in RCP 4.5 until the 2040s.

Inertia in the climate system, however, means that this broad range in emissions does not translate immediately into significant differences in temperature. The global mean temperature increase between 2020-2039 and 1981-2010 is *likely* 0.9–1.6°F in RCP 2.6, 1.0–1.6°F in RCP 4.5, and 1.1–1.8°F in RCP 8.5. Due to natural variability and the greater uncertainty in how global changes translate into regional changes, the *likely* temperature projections for the contiguous US overlap to an even greater extent: 1.2–2.8°F in RCP 2.6 and 1.5–3.2°F in RCP 8.5. The 1-in-20 chance projection for the three RCPs is identical: 3.6°F.

By mid-century, the *likely* global mean temperature changes for RCP 2.6 and 8.5 (1.1–2.2°F in RCP 2.6 and 2.2–3.7°F in RCP 8.5) no longer significantly overlap, although the changes in contiguous US temperature (1.9–3.5°F and 2.6–5.8°F) continue to do so. Only in the second half of the century do temperature differences between the RCPs fully emerge (with a *likely* contiguous US temperature increase of 1.0–2.6°F in RCP 2.6 and 4.7–8.8°F in RCP 8.5 by late century).

Figure 21.2: Change in high-risk labor productivity

Percent



When the effects of climate inertia, physical projection uncertainty, and natural variability are combined with the statistical uncertainty in impact projections, the economic benefits of mitigation do not start to be felt until mid-century and are most obvious in the second half of the century. Figure 21.2 illustrates the time evolution of one impact, change in high-risk labor productivity, over the course of the century under RCPs 2.6, 4.5, and 8.5. Over the next couple decades, the projected labor productivity decline is essentially independent of RCP. By mid-century, the median projection for RCP 2.6 still lies within the *likely* range for RCP 8.5, but differences between RCPs start to be clear in the tails: the 1-in-20 worst case projection for RCP 2.6 is comparable to the median projection for RCP 8.5. By late century, the differences are large: the 1-in-20 worst case projection for RCP 2.6 is only slightly below the median projection for RCP 4.5, and the 1-in-20 worst case projection for RCP 4.5 is only slightly below the median projection for RCP 8.5.

As we highlight in the remainder of this chapter, mitigation today is a crucial tool for managing some types of climate risk in the second half of this century. For the next three decades, however, the climate outcomes are largely already baked into the system. Accordingly, adaptation, as described in the next chapter, is critical for managing climate risk in the near term.

AGRICULTURE

For most of the country, agriculture benefits from mitigation on average, despite the positive benefits of CO_2 fertilization. In addition to shifting the average, a major benefit of mitigation for agriculture is to truncate the large tail risk of extremely bad outcomes in major agricultural regions under RCP 8.5. By end of century at the national level, extreme events in annual yield losses that were historically 1-in-20 year events become 1-in-2 year events under RCP 8.5, but they are restricted to be only 1-in-5 year events under RCP 2.6. Taking the Midwest, the agricultural heartland of the country, as an example, the *likely* range of losses in RCP 8.5 extends from -8.6% (a small gain) down to 61%, whereas losses under RCP 2.6 can be constrained, spanning the much narrower *likely* range of -4.0% to 14%. Similar benefits of mitigation accrue for the Northeast, Southeast, and to a lesser extent the Great Plains. However, mitigation reduces potential agricultural benefits for the Southwest from losses of 5.3% to gains of 17% in RCP 8.5, to losses 4.3% to gains of 3.9% in RCP 2.6; a more exaggerated effect is clear for the Northwest, although there is very limited production in that region.

LABOR

The impact of climate change on labor productivity is more evenly spread geographically than agriculture, as are ubiquitous benefits of mitigation. Mid-century *likely* declines in high-risk labor productivity nationwide are 0.22% to 0.89% in RCP 8.5, 0.09% to 0.67% in RCP 4.5 and 0.14% to 0.4% in RCP 2.6. Late-century, *likely* declines fall from 0.83% to 2.38% in RCP 8.5, to 0.2% to 1.1% in RCP 4.5 and 0.07% to 0.4% in RCP 2.6 (Figure 21.4). Projected labor productivity declines in late century exhibit a long tail, especially in RCP 8.5, with a

Figure 21.3: Change in maize, soy, wheat and cotton yields, 2080-2099

By NCA region and RCP

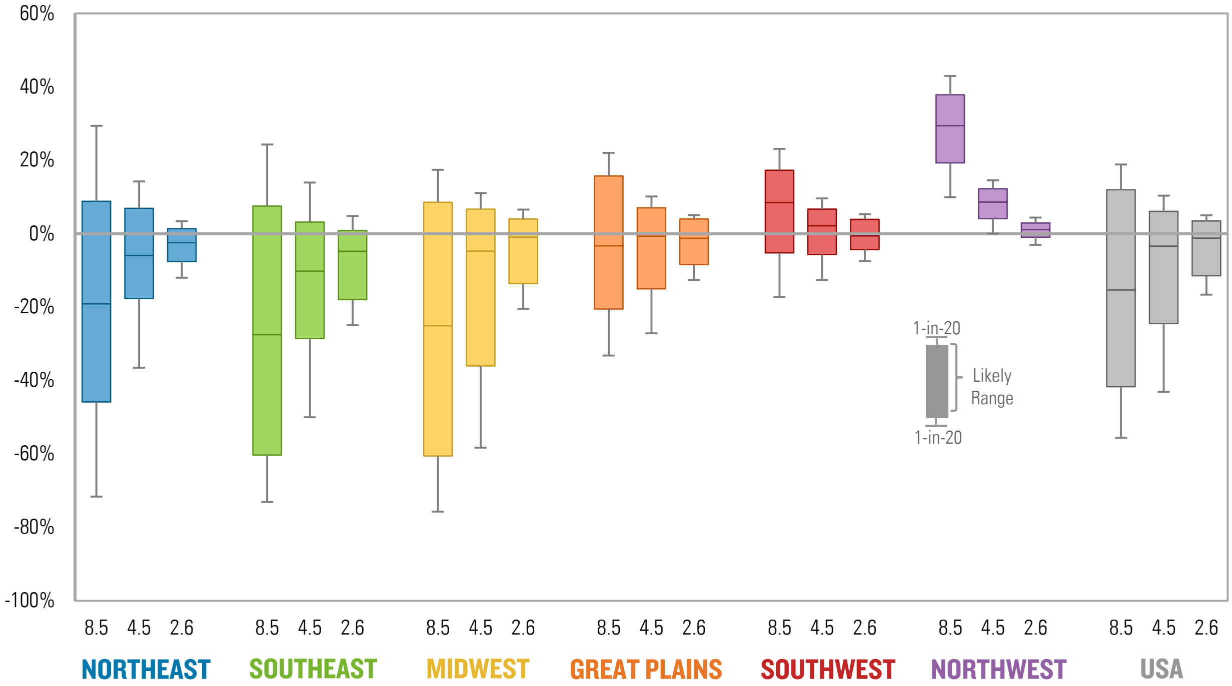
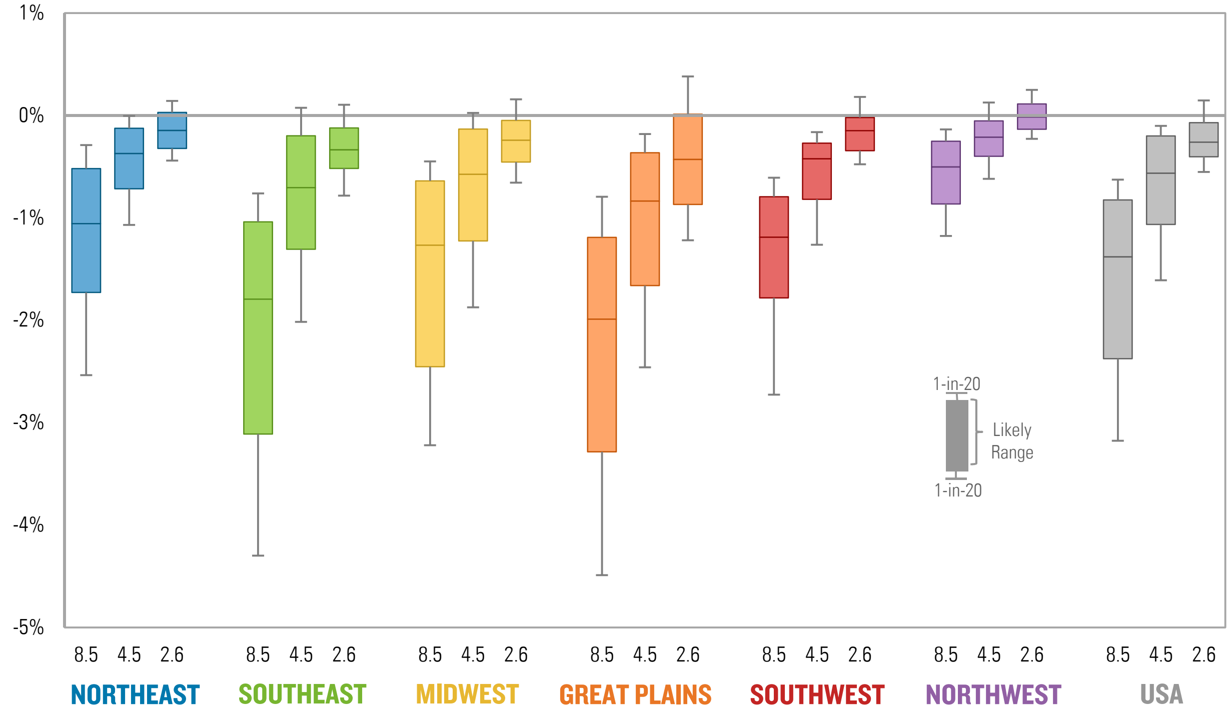


Figure 21.4: Change in labor productivity, 2080-2099

By NCA region and RCP



1-in-20 chance of declines below 3.2% in RCP 8.5 and 1.6% in RCP 4.5. All regions see less labor productivity decline in RCP 4.5 and RCP 2.6, though these changes are more economically important for states like Texas, North Dakota and Louisiana, where high-risk sectors account for a greater share of state employment.

HEALTH

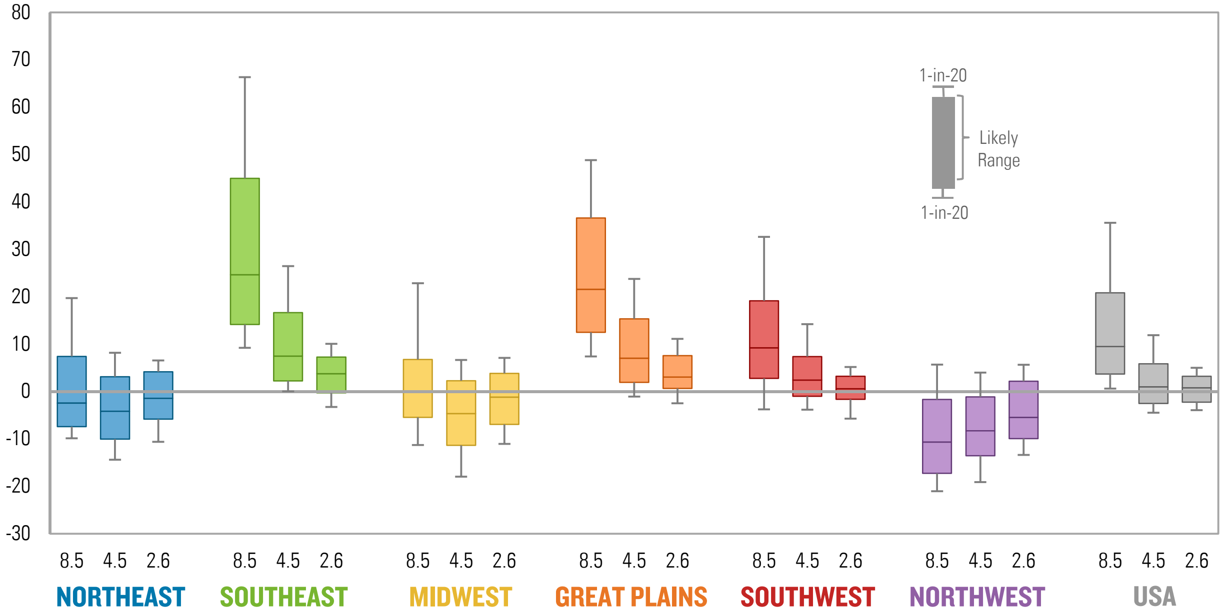
As discussed in Chapter 13, the effect of climate change on temperature-related mortality is one of the most economically significant impacts we quantify, as well as one of the most geographically varied. The nonlinear relationship between temperature and mortality has a strong influence over mortality's response to mitigation. Because the heat-related deaths associated with small amounts of warming roughly offset the same number of cold-related deaths, mid-century and late-century outcomes tend to look very similar in RCP 4.5 and RCP 2.6. However, late-century mortality rises rapidly in RCP 8.5 as average temperatures rise and the higher frequency of extremely hot days causes many more heat-related deaths than the number of cold-related deaths that are avoided. This pattern in mortality creates a strong incentive to avoid RCP 8.5 through mitigation, but it suggests little gain in aiming for RCP 2.6 relative to RCP 4.5.

In RCP 8.5, the *likely* increase in temperature-related mortality is 3.7 to 20.8 deaths per 100,000 people on average between 2080 and 2099. In RCP 4.5 the *likely* range falls to -2.5 to +5.9, and in RCP 2.6 it falls to -2.3 to 3.2 (Figure 21.5). Projected mortality increases in late century exhibit a long tail, especially in RCP 8.5, with a 1-in-20 chance of increases greater than 36 under RCP 8.5, 12 under RCP 4.5, and 5 under RCP 2.6.

The differences between RCPs is even more significant for certain regions than for the country as a whole. The Southeast, southern Great Plains states and parts of the Southwest will *likely* see steep declines in temperature-related mortality in RCP 4.5 or RCP 2.6 compared to RCP 8.5, while the Northwest will *likely* see an increase. The mortality benefits of mitigation in the Northeast and Midwest are more mixed.

Figure 21.5 Change in mortality rates 2080-2099

Deaths per 100,000, by NCA region and RCP

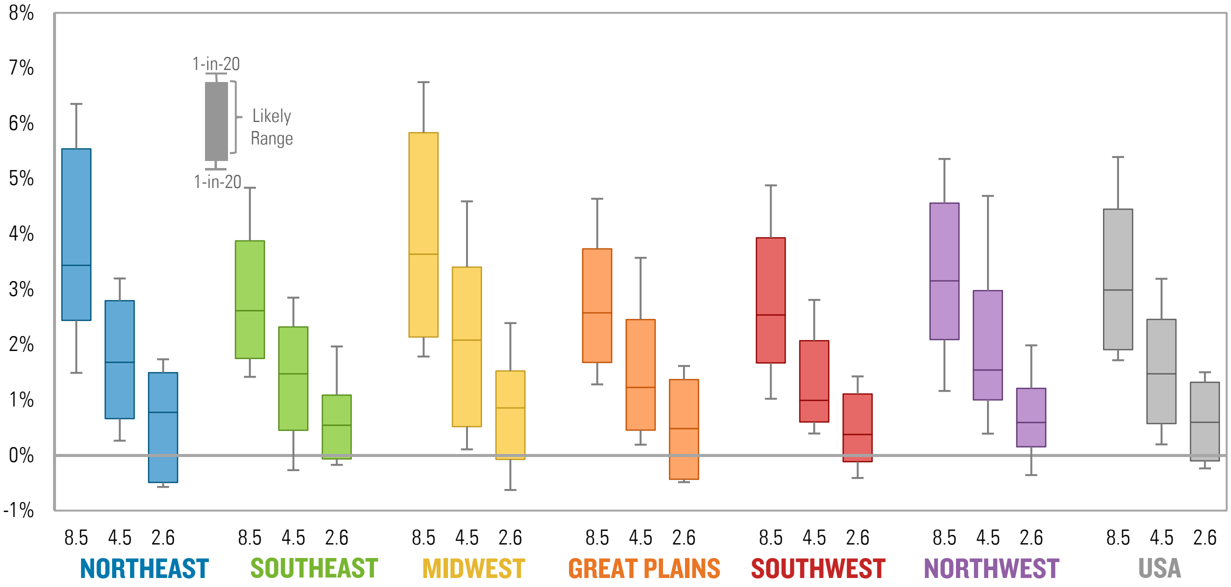


CRIME

The overall impact of climate change on crime rates is unambiguous but modest, particularly when compared to other factors. Climate-driven increases in crime rates are lower under RCP 4.5 and RCP 2.6 than RCP 8.5, but not significantly so until late century. Between 2080 and 2099, the *likely* violent crime rate is 1.9% to 4.5% under RCP 8.5, 0.6% to 2.5% under RCP 4.5, and -0.1% to 1.3% under RCP 2.6 (Figure 21.6). As with labor productivity, the reduction in climate-driven crime rate increase is comparable across regions, though the economic benefit is concentrated in states with higher baseline crime rates.

Figure 21.6: Change in violent crime rates, 2080-2099

By NCA region and RCP

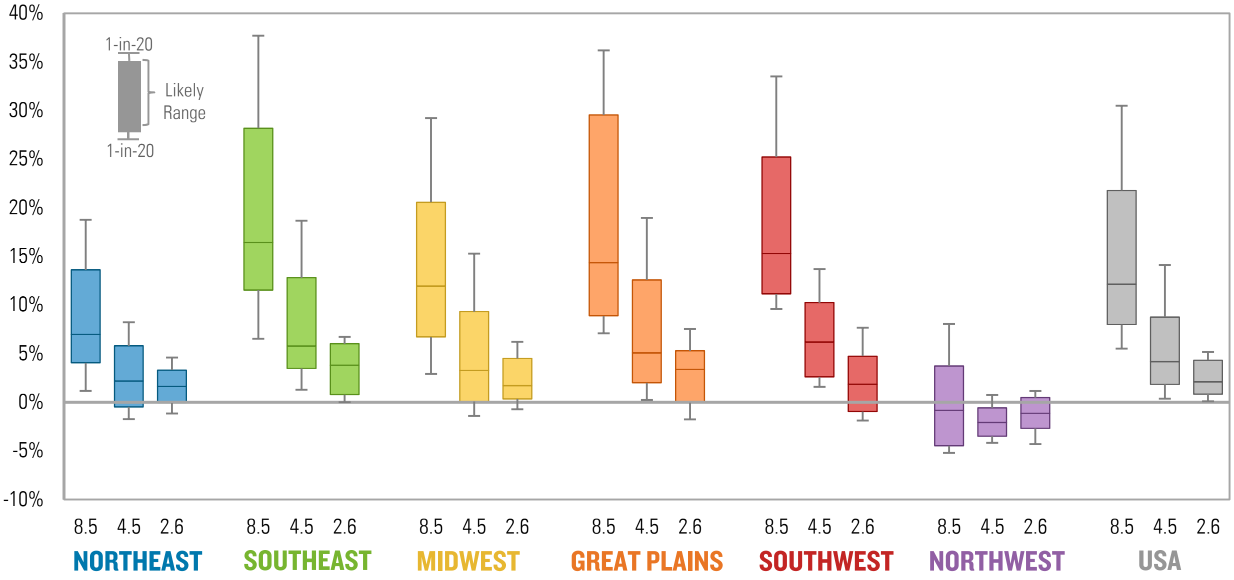


ENERGY

The impact of mitigation on climate-driven increases in nationwide energy expenditures is ambiguous until mid-century, at which point projected increases are roughly half as high under RCP 2.6 as RCP 8.5, with little difference between RCP 2.6 and RCP 4.5. By the end of the century, nationwide cost increases are considerably lower in RCP 2.6 than RCP 4.5, with *likely* ranges of 0.8% to 4.3% and 1.8% to 8.8%, respectively, which in turn are considerably lower than RCP 8.5, with a *likely* range of 8.0% to 22% (Figure 21.7). The largest declines in energy expenditures between RCP 8.5, RCP 4.5 and RCP 2.6 are in the Southeast, Great Plains and Southwest – the regions that see the largest increases under RCP 8.5. Energy expenditures decline much more modestly in the Northeast and remain relatively unchanged in the Northwest.

Figure 21.7: Change in energy expenditures, 2080-2099

Percent



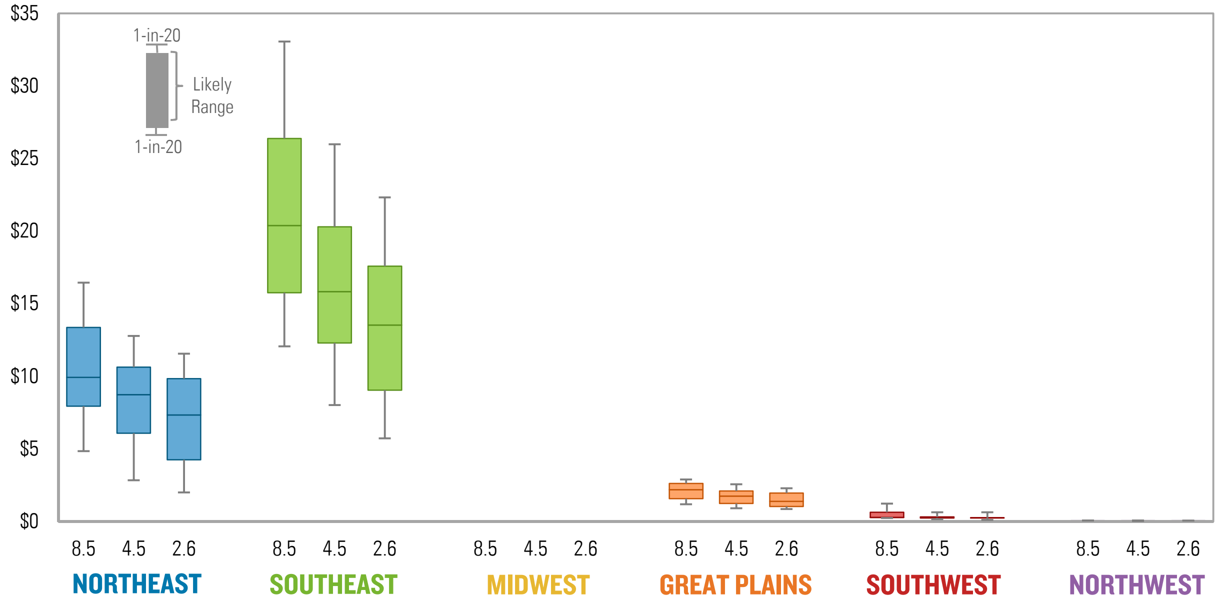
COASTAL

Because sea-level rise responds more slowly to changes in emissions than temperature, the impact of climate change on coastal communities is, in this century, the least responsive to changes in global emissions of the impacts we assessed. In 2050, additional current coastal property value *likely* below Mean Higher High Water levels (MHHW) due to sea level rise (SLR) is $323 to $389 billion. In RCP 2.6 this only falls to $287 to $360. The *likely* SLR-driven increase in average annual hurricane damage in 2050 is $5.8 to $13 billion in RCP 8.5, $5 and $11 billion in RCP 4.5 and $4.6 to $10 billion in RCP 2.6.

By the end of the century, at which point the median projected increase in global sea level differs between RCP 2.6 and RCP 8.5 by about 1 foot (from a total of about 2.6 feet in RCP 8.5), there is a slightly greater difference between RCPs. *Likely* average annual inundation from SLR and SLR-driven increases in average annual hurricane damage combined are $26 to $43 billion between 2080 and 2099 in RCP 8.5. In RCP 4.5, the damages are reduced to $20 to $33 billion, and to $15 to $29 billion in RCP 2.6. This benefit is concentrated in the Northeast and Southeast, where most of the coastal inundation and hurricane risk exists (Figure 21.8).

Figure 21.8: Change in average annual hurricane and inundation damage, 2080-2099

Billion 2011 USD



OTHER RISKS

Not all the risks that mitigation can help manage or avoid are quantified in our economic analysis. As climate conditions pass further outside the realm the planet has experienced for the last several million years, the odds of passing tipping points like those discussed in Chapter 3 or of triggering unexpected planetary behaviors increases. Under RCP 8.5, the magnitude of the *likely* global warming by the first half of the next century (about 9-18°F since pre-Industrial items by around 2150) will be unprecedented in the last 56 million years (see discussion of the Paleocene-Eocene Thermal Maximum in Chapter 5). Under RCP 4.5, the *likely* global temperatures at the end of the century (about 2.2-5.5°F higher than 1981-2010) will be comparable to those the planet last experienced about three million years ago (Hill et al. 2014). Under RCP 2.6, the *likely* increase in global mean temperature is limited to about 0.9-2.6°F, maintaining temperatures close to a range last experienced about 125 thousand years ago (Turney and Jones 2010).

As described in Chapter 4, by late century under RCP 8.5, about a third of the American population (assuming the geographic distribution of population remains unchanged) is expected to experience days so hot and humid that less than an hour of moderate, shaded activity outside can trigger heat stroke (Category IV on the ACP Humid Heat Stroke Index) at least once a year on average. Under RCP 4.5, only one-eighth of the population is expected to experience such a day at least once a decade on average; under RCP 2.6, the risk of such conditions is negligible for almost all Americans.

Given these and other risks not included in our economic analysis, as discussed in Part 4, the results in this chapter should be viewed as highlighting the capacity of mitigation to reduce the specific set of climate risks that we have evaluated – and thus a near-certain underestimate of the overall benefit of mitigation for managing climate risk, especially in the second half of the century and beyond.

CHAPTER 22

Adaptation

While global emission reductions can mitigate much of the climate risk Americans face, as shown in the preceding chapter, there are some climatic changes that are already "baked in" as a result of past greenhouse gas emissions and will occur regardless of how emission levels change. In addition, many decision-makers, from individual businesses and homeowners to local governments, have limited ability to affect global emissions directly, and need to prepare for a range of plausible climate futures. Armed with the kind of forward-looking information provided in this report, decision-makers can, however, reduce their risk exposure through adaptation.

This report provides new information on the relative economic impact of climate change to different sectors, allowing decision-makers to consider where they might focus adaptation efforts. In this chapter, we consider how future populations might adapt, we demonstrate how the modeling approaches used in this report could be used to better understand the potential gains from adaptation, and we highlight weaknesses in our current understanding of the costs and benefits of adaptation.

BACKGROUND

When the climate changes and imposes economic costs on populations, these populations will respond to these changes in an effort to cope. Americans will adapt to climate change, changing how they live and how they do business in ways that are better suited for their altered environment. In general, populations adapt to climatic changes in two different ways: they change their behavior, or they make "defensive investments" in new capital that mitigates the effect of climate. Behavioral changes may involve small or large changes in the actions people undertake, whether they change the time of day that they exercise, plant crops earlier in the season, or move to a different city. Defensive investments are capital investments that individuals or firms make to minimize the effects of climate that they would not have undertaken in a less adverse climate, such as the purchase of air conditioners, the building of sea walls, or the installation of irrigation infrastructure. Both behavioral adaptations and defensive investments are visible in the modern economy. For example, residential air conditioning penetration is virtually 100% in the South, where summers are already uncomfortably warm and humid, and irrigation is extensive in the West, where climates are already arid. Our ability to observe these adaptations demonstrates both their technical and economic feasibility, a notion that encourages us to believe that these adaptations will play an important role in the future of the American economy.

Importantly, however, all of these adaptations have some economic costs and may not be suitable for all future contexts. At present, we do not have a strong understanding of the costs involved with the numerous potential adaptive behaviors and investments that are currently available—although we do know that costs are involved, since if these behaviors and investments were costless, we would expect them to be much more broadly employed at present (Hsiang & Narita, 2012). For example, the fact that some households currently have air conditioners and some do not tells us that some families find this investment worth the cost it imposes and some do not, perhaps because the latter households do not experience extreme heat as often or because purchasing an air conditioner would require that the household forego other expenses that are more essential to their well-being, such as food or education.

Developing a full understanding of the economics of adaptation is an important question closely related to the analysis presented throughout this report. In future analyses, we hope that researchers will provide the details needed to carefully evaluate both the costs and benefits of various adaptive actions and investments, which will enable the design of policies that optimally facilitate adaptation. We note, however, that the quantity of information required to undertake such an exercise is even greater than what we use here: in addition to knowing (1) how the climate affects people, we must also know (2) how adaptation mediates this effect in quantitative terms, i.e. the *benefits* of adaptation, as well as (3) what populations sacrifice in order to undertake these adaptations, i.e. the *costs* of adaption. Material in this report has relied heavily on (1), insights that are just now becoming available due to scientific advances, whereas both (2) and (3) require additional research innovations that build on what has already been achieved. In order to understand how adaptation mitigates the impact of climate on a certain dimension of the economy, we must first develop techniques to measure the effect of climate in the absence of additional adaptation, the focus of this report and the research underlying it, and then we must develop techniques to measure how new behavioral changes or defensive investments alter the quantitative structure of this linkage and the cost of these actions. Since the latter remains a generally unanswered question, our assessment is that the potential gains from adaptation remain unknown, but they may be understood in the near future as research advances.

Since the current body of research is insufficient to project expected patterns of adaptation and their costs and benefits, this report has been exclusively focused on the direct effects of climate change—assuming populations respond to climate similarly as they have in the recent past—and their general equilibrium effects. Nonetheless, because we are certain populations will adapt even in the absence of government actions, it is worth considering what some example adjustments might look like for illustrative purposes, even if we cannot fully quantify their impact and cannot yet evaluate their full economic costs or benefits.

AGRICULTURE

Agriculture is a sector where producers have been adapting to their climate for millennia. We expect that as the climate changes in the future, farmers will make numerous adjustments in an effort to cope with these changes. As explained above, it remains difficult to fully evaluate the cost, benefits, and effectiveness of each one of these adjustments individually, although we do have some sense of what various adjustments might look like based on historically observed adaptations.

For example, we expect that farmers will adjust which crops they plant, shifting towards varieties or products that are more conducive to their new local conditions, probably because they are more tolerant of extreme heat (Mendelsohn, Nordhaus, Shaw, 1994). Current research is insufficient to evaluate the costs of this transition, so it is difficult to know how many farmers will make which crop transitions at which points in time and what their net benefits will be. It is also likely that some producers will change croplands to rangeland, that farmers will expand their use of irrigation to help mitigate the effects of rainfall loss and extreme heat, and that farmers will change their planting dates to earlier in the season so that crops will be exposed to less adverse planting conditions. It is also possible that patterns of agricultural production migrate northward, so that land in the North and West that was not previously used for agriculture but has rising productivity due to warming is brought into production. Longer growing seasons in other parts of the country may enable double or triple-cropping, even if individual crop yields decline. Individuals from farming communities may also simply migrate out of those communities as economic production declines, as was observed in the Dustbowl (Hornbeck, 2012) as well as more recent years (Feng, Oppenheimer, Schlenker, 2012). Finally, genetic technologies and advances in breeding may produce more heat tolerant and drought tolerant varieties of crops in the future. In the past, such efforts have had mixed success, with some advances revolutionizing production in local areas, such as the development of varieties that enabled widespread cultivation in the American West (Olmstead & Rhode, 2011), while in other cases breeding advances brought little to no benefits for decades, such as the persistent heat sensitivity of maize in the Eastern United States (Schlenker & Roberts, 2011; Burke & Emerick, 2012). Because genetic innovations are of a “hit or miss” nature they are more speculative and more difficult to depend on in comparison to other adaptive measures, such as irrigation, where technologies already exist.

Given the state of research, we lack the necessary information to quantify the potential economic benefits and costs associated with these various forms of adaptation. However, we can use existing data to get a quantitative sense for the collective benefits for a subset of these adjustments. Populations have adapted to their local climates in the past, and that provides us with some information about how effectively they utilize technologies that are already within reach. For example, irrigation is used extensively in the West but less so in the East, a fact that makes maize production in the West less sensitive to extreme heat (Schlenker & Roberts, 2009).

To address this question, we can do a thought experiment in which we ask what maize yields would look like if farmers in the East started adopting the farming practices of farmers in the West. This exercise is useful for helping us think about the potential heat-resistance of this particular sector, but it is only half of the story because dramatically expanding irrigation and changing varieties will have costs that we are not measuring (Schlenker, Roberts, Lobell, 2013). A benefit of this approach is that it allows us to model future adaptations using simple assumptions that are calibrated to the actual, real-world behavior of adapting individuals, while a weakness of this approach is that it does not allow us to separately identify the effects of specific adaptive actions. For example, we cannot attribute separate gains to irrigation as opposed to changes in the varieties that farmers plant.

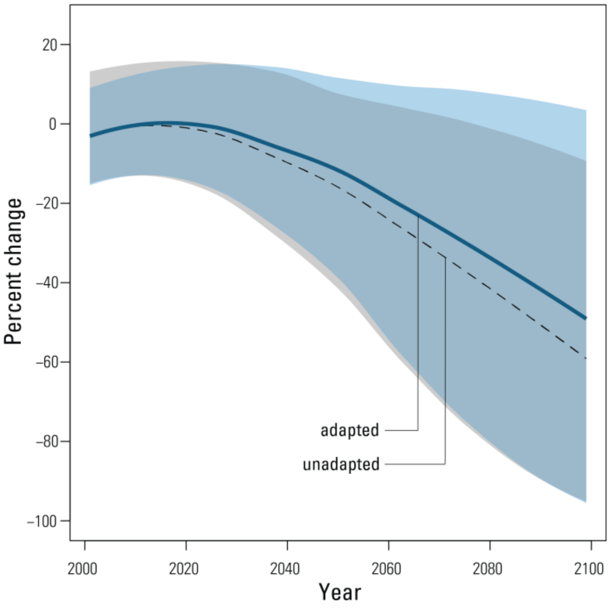
To conduct this thought experiment, we also need to have some sense for how quickly populations in the East can adopt the practices of the West. It is possible that in the future this transition could occur quickly, if policy promotes this behavior. But without knowing whether such policies will occur, a reasonable starting place is to observe how quickly adaptations of this form have occurred in the past. In the case of maize, recent research has estimated the speed with which the relationship between temperature and yields in the East has evolved to look like the relationship in the West (Burke & Emerick, 2013). The measured rate of convergence is 0.28% per year, a very modest value that stands in contrast to some historical experiences in which new technologies were deployed more rapidly (Olmstead & Rhode, 2011).

When we calibrate our model to allow for this thought experiment in adaptation, where farmers who experience hotter weather adopt techniques that weaken their dependence on temperature at historically observed rates (see Technical Appendix for details), we see a modest reduction in projected losses in maize production shown in Figure 22.1. In the median case, national production is estimated to fall only 49% by the end of the century if farmers undertake additional adaptations, rather than the estimated 60% that would occur if we assume maize producers do not adapt beyond their current levels.

The "residual damages" that remain in this particular adaptation scenario are not dramatically smaller than the damages estimated in the benchmark scenario, primarily because observed historical adaptations have been relatively slow. Importantly, however, we stress that *(i)* future technological change and adoption may proceed at a faster (or slower) pace relative to recent history, and *(ii)* this is just one type of possible adaptation. Other adaptations, such as the northward movement of maize production, change in varietals, double and triple cropping and genetic innovation, which are not captured in this simple exercise, may have greater (or smaller) effects. Furthermore, we do not know the costs associated with these changes (e.g., overhauling irrigation systems is expensive), so we cannot be sure whether it will make economic sense to follow this trajectory.

Figure 22.1: National maize production loss in RCP 8.5 without adaptation and a scenario with adaptation calibrated to historical patterns (e.g., expanded irrigation)

Median and 90% range



LABOR

Behavioral change and defensive investments may also help reduce some, but not all, of the impacts on labor productivity associated with rising temperatures across the US. The extent to which adaptation can mitigate these risks will vary by industry, in particular between high- and low-risk sectors, but also among sub-sectors within these categories.

For high-risk sectors, laborers exposed to heat may shift working hours to cooler times of the day or reschedule activities for a cooler day. It is unclear how much such temporal substitutions can minimize the impact of extreme temperatures, though one study by Graff Zivin and Neidell (2013) found very limited intertemporal substitution (shifting activity across days) of high-risk labor. Intratemporal substitution (shifting labor to different times of the day) has not significantly altered the observed influence of warm days on labor supply, perhaps because in many cases workers have little discretion about their activities during core business hours. Other behavioral adaptive strategies focus on improved work practices, such as periodic rest, hydration, and training to facilitate acclimatization over time, which have long been part of the Occupational Safety and Health Administration's (OSHA) guidelines for worker safety. Finally, behavioral adaptation may also take the form of labor migration from the warmer areas of the South to the North, where conditions may be more bearable.

Adaptation investments can also help to reduce heat exposure and the risk of heat-related impacts to labor productivity, including engineering controls, such as air conditioning and ventilation, which are feasible when production occurs indoors. It is likely that, over the course of the next century, new technologies will be developed to further mitigate climate's impact on labor productivity. While it is impossible to predict what these technologies may make possible, this assessment provides insight into the potential value of such innovations to help businesses and American workers cope with future climate change.

HEALTH

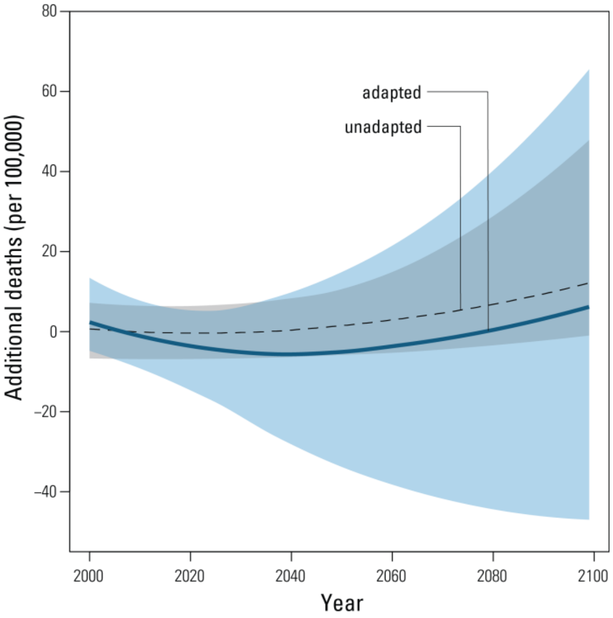
As the climate changes, Americans will likely change their behaviors and make defensive investments to protect their health. Historically, public health programs and education campaigns have been effective in encouraging individuals to adopt behaviors that are both privately beneficial and improve community-level health outcomes. Privately motivated investments, particularly investments in air conditioning, are likely to have been important in reducing mortality due to extreme heat (Barrecca et al., 2013). Since 1950, heat-related mortality has declined in association with the rapid rise in residential air conditioning usage, with penetration rates climbing roughly 1.5% per year from 0% in 1950 to 80% in 2004. The downward historical trend in heat-related mortality, if extrapolated into the future, might suggest that we can continue to make strong gains in cutting future temperature-related mortality. However, caution is warranted, since growth in residential air conditioning penetration has slowed substantially in the last decade, with overall penetration growth rates slowing to around 0.4% per year. (If this current rate is simply extrapolated into the future, air conditioning penetration would be expected to hit 100% around 2055).

In this context, it is difficult to know for sure how future temperature-related mortality will evolve. While continued air conditioning uptake will accrue some benefits, it is unclear how much further continued air conditioning adoption can depress heat-related mortality. Much heat-related mortality occurs outside of homes (Barrecca et al., 2013), and the heat-mortality response in heavily air-conditioned populations—such as in the South, where penetration is close to complete—remains similar in magnitude to the estimates presented in this report. Thus, it seems unlikely that autonomous expansion of air conditioning usage alone will mitigate all heat-related mortality in the future and it is likely that adaptation on other margins will be necessary.

Nonetheless, we may implement a thought experiment, similar to the one above for maize, where we use regional patterns of heat-related mortality to consider potential gains from currently available technologies and practices. In this case, we assume the South represents highly adapted counties and imagine that other locations begin to behave as the South does. We then use trends in sensitivity over time to calibrate the rate at which cooler populations start to behave as the South does. Results from this calibrated thought experiment are shown in Figure 22.2, where we see substantial reductions in temperature related mortality in the RCP 8.5 scenario. In the median case for this thought experiment, additional mortality is estimated to rise by only 7 deaths per 100,000 by end of century, compared to 13 deaths per 100,000 in our baseline projections. As mentioned above, it is unclear whether this relatively rapid and effective adaptation is feasible, since our estimate relies on extrapolating the downward trend in heat-related mortality that was likely driven by rapid adoption of air conditioning, and future adoption of air conditioning may have limited impact since penetration rates cannot exceed 100%.

Figure 22.2: National temperature-related mortality rate changes in RCP 8.5 without adaptation and a scenario with adaptation calibrated to historical patterns (e.g. continued air conditioning adoption)

Median and 90% range (deaths per 100,000)



An additional feature of these results worth noting is the substantial broadening of the 90% confidence interval in Figure 22.2 when adaption is modeled explicitly (light blue shading). Uncertainty increases when we account for adaptation using empirical results because the parameters governing adaptation responses are estimated using real world data and thus exhibit statistical uncertainty (see Technical Appendix for details). Given the current state of research, these uncertainties are large, causing projections to be more uncertain. We hope future research on adaptation may effectively reduce these uncertainties.

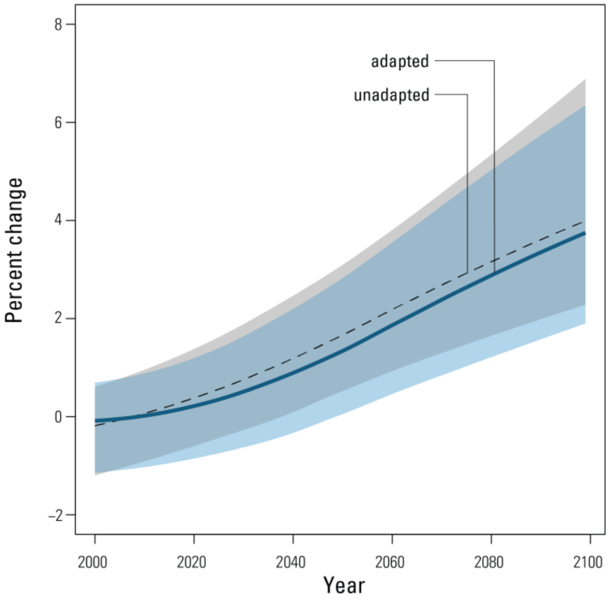
CRIME

Temperature-related effects on violent crime rates is yet another case where behavior changes or defensive investments may potentially offset the future impacts of climate. In general, it is thought that violent crime increases in the heat because of physiological and psychological responses (Hsiang, Burke & Miguel, 2013), and it is unclear how these responses can be mitigated directly. However, it is possible that using adaptive law enforcement practices, such as deploying more police officers on abnormally hot days, potential criminals can be deterred enough to offset the effects of elevated temperature. The continued adoption of air conditioning may also help, as may other small adjustments that reduce the exposure of individuals to higher temperatures. Still, existing evidence suggests that this type of adaptation is challenging: unlike with mortality and maize yields, we do not see strong evidence that warmer populations exhibit very different violent crime responses to temperature than do colder populations (Ranson, 2013), suggesting that there are not currently technologies or practices in use that substantially mitigates this impact.

Nonetheless, historically, the linkage between temperature and violent crime has weakened very slowly (Ranson, 2013), and we can use this trend in a similar fashion to the examples above, where we model populations as adapting by allowing their behavior to converge to the empirically observed response of modern warm counties. We display results from this thought exercise in Figure 22.3, where we see that accounting for historically observed patterns of adaptation mitigates a small portion of the climate-related change in crime rates in RCP 8.5. In the median case, additional violent crime is estimated to rise 3.5% by the end of the century if populations undertake additional adaptations, rather than the estimated 3.7% rise that we project if we assume populations do not adapt beyond their current levels.

Figure 22.3: National climate-related violent crime changes in RCP 8.5 without adaptation and a scenario with adaptation calibrated to historical patterns (e.g., weather-dependent deployment of police enforcement)

Median and 90% range



ENERGY

Several defensive investments and behavioral changes can reduce the impact of the projected changes in temperature discussed in Chapter 4. Improvements in the efficiency of air conditioners and building shells can reduce the amount of electricity required to maintain comfortable indoor temperatures on increasingly hot days, as can changes in how building systems are operated. More expensive electricity could lead to improvements in the efficiency of electricity-consuming devices and behavioral shifts that impact electricity demand. Breakthroughs in electricity storage technology and demand response programs could enable wholesale power market operators and utilities to meet climate-driven increases in daily peak demand without necessitating the construction of as much new generation capacity.

All of these effects are captured to some extent in RHG-NEMS, the energy sector model used in quantifying the impact of projected changes in temperature on electricity demand, total energy demand and energy costs described in Chapter 10. The rate of technological learning in air conditioning is impacted by changes in electricity prices, which occur in our modeling. The same is true to for consumer demand for cooling services and efficiency of end-use appliances and devices. RHG-NEMS estimates match historically-observed responses as found in the econometric literature, but could be too conservative about future efficiency advances.

The area where adaptive advances are likely to have the greatest mitigating effect on climate-driven energy cost increases is on the supply-side. The development and deployment of grid storage technology would significantly reduce the need for the additional generation capacity described in Chapter 10. The cost of such technology, however, remains prohibitively high for widespread commercialization, which is why little of it occurs in RHG-NEMS.

COASTAL COMMUNITIES

As shown in the previous chapter, the risks of climate change to coastal communities are some of the least sensitive to changes in global emissions, at least in this century. Fortunately, households, businesses, community organizations and local governments along the coast have considerable adaptive capacity. To explore the extent to which the construction of coastal defenses, such as sea walls, building modifications and beach nourishment, can reduce the economic cost of inundation from mean sea-level rise (SLR) and SLR-driven increases in storm surge described in Chapter 11, we partnered with Industrial Economics, Incorporated (IEc), the developers of the National Coastal Property Model (NCPM).

NCPM comprehensively examines the contiguous US coast at a detailed 150 x 150 m (about 500 x 500 ft) grid level; incorporates site-specific elevation, storm surge, and property value data; estimates cost-effective responses to the threats of inundation and flooding; and provides economic impact results for four categories of response: shoreline armoring, beach nourishment, structural elevation, and property abandonment (Neumann et al. 2014). The model was originally developed to address the threat of SLR and was modified to incorporate the effect of storm surge on estimates of vulnerability, impact, adaptation response, and economic damages (see Technical Appendix III).

IEc assessed the cost of inundation and greater storm surge from mean SLR, using the same local SLR projections used in the RMS North Atlantic Hurricane Model. In one scenario, they assumed no defensive investments are made (consistent with our baseline analysis described in Chapter 11) and found costs between now and 2100 similar to those from RMS. In a second scenario, IEc assessed the extent to which defensive investments that can be made by individual property owners (i.e. structural elevation) can reduce these costs. In a third scenario, IEc adds beach nourishment to the adaptation options basket, a defensive investment that generally requires collective community action. In a fourth scenario, shoreline arming is added, the option that likely requires the greatest degree of collective/public action.

IEc finds that more than two-thirds of projected inundation damages from *likely* SLR in each decade of the century can be avoided through proactive investments in shoreline arming and beach nourishment, though both will require substantial public coordination. Adaptation is less effective in coping with lower probability, higher SLR projections, but can still cut projected costs by more than half. IEc finds adaptation similarly effective in reducing SLR increases in costal storm flooding, with structural elevation added to shoreline arming and beach nourishment.

A range of barriers can prevent adaptation from occurring in an economically optimal fashion, including government-backed flood insurance that shields coastal homeowners from the cost of hurricane-related flooding and local opposition to shoreline arming and or structural elevation. Indeed, these factors exacerbate coastal property risks today. IEc finds that 86% of expected hurricane flood damage at current sea levels could be avoided through economically efficient adaptive investments that are not occurring.

INFORMING ADAPTATION

While Americans will likely reduce at least some of the impacts of climate change on coastal property, energy systems, crime rates, public health, labor productivity and agricultural production through behavioral change and defensive investments, such adaptive measures are unlikely to occur (at least in a relatively efficient manner) without adequate information regarding the economic risks these investments and behavioral changes are intended to address. Climate change is not, and will not, manifest through consistent year-to-year increases in temperature or changes in precipitation. Storm damage does not occur evenly every year, and neither will a climate-driven changes in storm flooding. The weather will continue to be variable. If adaptive decisions are made based either on that year's weather or past experience, businesses, households and policymakers will always be behind the curve. The goal of this assessment is to provide the best available information on what is coming down the road, so that these individuals may make well-informed decisions.

A better understanding of the costs, benefits and limitations of adaptation is also critical in informing household, business and policy decisions. In our view, empirical work on the benefits of adaptation is currently highly limited and uncertain, while empirical research on the cost of these adaptations is almost nonexistent. Determining the economic valuations of specific adaptive investments and actions is a critical area of research, because there are many unanswered questions. Reliable quantitative estimates will be key in determining the best private sector and policy responses to climate change.

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PART I: PHYSICAL CLIMATE PROJECTIONS

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PART V: INSIGHTS FOR CLIMATE RISK MANAGEMENT

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Corrigenda

Since the June 24, 2014 release of Version 1.0 of this report, the following changes have been made:

Corrections were made to various spelling and typographical errors, and some figures were replaced by higher resolution images.

Figures 4.3 and 4.5 - The summer and winter average temperature maps of version 1.0 reflected an early version of the analysis and did not correspond exactly to the results in the text or the data tables. The discrepancies were most significant in the 95th percentile of late-century average temperatures, where county-level results differed from those displayed by less than +/- 1.5°F in the most extreme case. The mean discrepancy between the county-level final values and those displayed was -0.3°F.

Figure 4.6 – In Version 1.0, the title of Figure 4.6 mistakenly stated: “Number of days with *maximum* temperatures below 32°F, RCP 8.5.” This was corrected to read: “Number of days with *minimum* temperatures below 32°F, RCP 8.5.”

Values in Tables 6.1, 6.2 and 8.1 and Figures 6.3, 6.6, 7.3, 7.4, 8.2, 8.3, 9.3 and 9.4 have changed slightly due to improvements in the application of the climate model model-weighting procedure (as discussed in Technical Appendix I) to the calculation of impacts. Additionally, estimates are based on an increased number of draws from the statistical distribution of impact functions. Results from some runs with positive outliers were dropped, due to unrealistically high mortality impacts.

Figure 8.3 was modified to show changes in mortality rates (deaths per 100,000), replacing the original which showed percentage change in mortality rates.

Figures 6.5, 7.6, 8.4, 9.7, 9.8 - In Version 1.0, the captions read “Average frequencies.” This has been corrected to read “Expected frequencies.”

Page 64 – The mid-century likely range for all-age mortality under RCP 8.5 was changed from -0.5 to +6.7 to -0.5 to +6.6.

Page 65 – The 90% end-of-century confidence interval for all-age mortality under RCP 8.5 was changed from 233 to 232.

Figures 9.5 and 9.6 – The scale right column indicating “Number of crimes each year” has been revised to indicate annual totals. In Version 1.0, the maps showed the number of crimes in an average month.

Table 11.2 – The value at the low end of the likely range for MHHW under RCP4.5 has been corrected to read $546. In version 1.0, this value was incorrectly reported as $759, which is the median value.

Chapter 13 – Improvements in model-weighting procedures slightly altered estimates of the direct costs and benefits of climate-driven changes in labor productivity, crime, and mortality listed in Chapter 13. For Version 1.0, we used 2012 economic data and population for all impacts except coastal, which also resulted in a small change in the direct cost and benefits values reported in Chapter 13. The combined magnitude of these changes is less than 5% in all cases and less than 1% in most. More substantial changes were made to agriculture valuation. In Version 1.0, state-level changes in maize, cotton, wheat and soy production were aggregated by weight and then assigned a value based on the weighted-average output value of those crops in a given state in 2011. For this version of the report, each crop is valued individually at the state level and then combined.

Chapter 13 - The methodology for computing the impact of climate-related mortality changes on income was updated to more accurately weight the mortality effect by age cohort. This resulted in a substantial decrease in the cost of climate-related mortality across all scenarios when using this valuation technique. The term "changes in labor income" was substituted for "present value of changes in labor supply" in the current version to more accurately reflect the data it describes and to highlight the differences between this measure and the value of a statistical life.

Chapter 14 – There was an error in how mortality and agriculture impacts were incorporated in RHG-MUSE in Version 1.0 of this report, which has been corrected in the current version. This impacts all figures and results in Chapter 14. For greater model tractability, we have aggregated RHG-MUSE to assess macroeconomic effects at the NCA region level rather than state level.

Page 157 – *Likely* change in maize, wheat, rice and soy yields on this page were reported in correctly in Version 1.0 and have been corrected in this version.