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Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases

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Science supporting an endangerment finding for atmospheric greenhouse gases: an update

One-Sentence Summary: We summarize scientific evidence newly available since 2009 and find that this evidence increases confidence that atmospheric greenhouse gases endanger the public health and welfare as defined in the Clean Air Act.

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Abstract

We assess scientific evidence that has emerged since EPA's 2009 Endangerment Finding for six well-mixed greenhouse gases and find that this new evidence lends increased support to the conclusion that these gases pose a danger to the public health and welfare. Newly-available evidence about a wide range of observed and projected impacts (1) strengthens the association between risk of some of these impacts and anthropogenic climate change; (2) indicates that some impacts or combinations of impacts have the potential to be more severe than previously understood; and (3) identifies substantial risk of additional impacts through processes and pathways not considered in the endangerment finding.

Introduction

The Clean Air Act requires the Environmental Protection Agency (EPA) to regulate air pollutants when the EPA Administrator finds that they "cause, or contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare." (*1*). In *Massachusetts v. EPA*, the U.S. Supreme Court held that EPA has the authority to regulate greenhouse gases (GHGs) under the Clean Air Act (CAA), and that EPA may not refuse to regulate these pollutants once it has made a finding of endangerment (*2*).

The courts have long held that the CAA embraces a precautionary approach to findings of endangerment. For example, the federal court of appeals in Washington, D.C. has held that "evidence of potential harm as well as actual harm" meets the endangerment threshold, and that EPA's degree of certitude may even be lower where the hazards are most grave (*3*). Moreover, public health and welfare are broad concepts under the Acts, encompassing not only human morbidity and mortality, but also effects on soils, water, crops, vegetation, animals, wildlife, weather, and climate itself (*4*).

In December 2009, EPA released its "Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act," known informally as the Endangerment Finding (EF). The EF found that six long-lived GHGs, in combination, should be defined as "air pollution" under the CAA, and may reasonably be anticipated to endanger the health and welfare of current and future generations. In addition, EPA went on to consider effects beyond U.S. borders, explaining that "[i]t is fully reasonable and rational to expect that events occurring outside our borders can affect the U.S. population." (*5*).

The EF is an essential element of the legal basis for regulating GHG emissions under the CAA. It provides foundational support for important aspects of US climate policy, including vehicle mileage standards for cars and light trucks, and the emissions standards for fossil fuel-fired electric utility generating units (the "Clean Power Plan").

As the D.C. Circuit held in affirming EPA's 2009 Endangerment Finding, EPA may not decline to find endangerment based on the perceived effectiveness or ineffectiveness of the regulations that may follow in the wake of an endangerment finding (*6*). Nor must EPA find that the air pollutants it regulates are the dominant source of the harms it identifies, as the Act provides that the pollutants being regulated need only "contribute to" (or, under some provisions of the statute, "significantly" contribute to) (*7*) harmful air pollution.

The EF was based on careful evaluation of observed and projected effects of GHGs, with assessments from the US Global Change Research Program (USGCRP), Intergovernmental Panel on Climate Change (IPCC), and US National Research Council (NRC) providing primary scientific evidence. The EF was clear that, while many aspects of climate change were still uncertain, the evidence available in 2009 strongly supported the finding. Since the original EF, scientific information about the causes, historical impacts, and future risks of climate change has increased rapidly. This review assesses that new information in the context of the EF. We find that the case for endangerment, which was overwhelming in 2009, is even stronger now.

The EF was structured around knowledge related to public health and public welfare, with a primary focus on impacts on the United States. The information on public welfare was grouped in sections on (1) air quality, (2) food production and agriculture, (3) forestry, (4) water resources, (5) sea level rise and coastal areas, (6) energy, infrastructure, and settlements, and (7) ecosystems and wildlife. We follow that organization here. Some of the most important advances in understanding the risks of climate change involve sectors or impact types not highlighted in the EF. Here, we summarize the evidence for four of these that are broadly important: ocean acidification, violence and social instability, national security, and economic wellbeing. We characterize changes since the EF in terms of (1) strength of evidence for a link with anthropogenic climate change, (2) potential severity of observed and projected impacts, and (3) risks of additional kinds of impacts, beyond those considered in the EF (Fig. 1).

Public Health

Since the EF, numerous scientific reports, reviews, and assessments have strengthened our understanding of the global health threats posed by climate change (e.g., (*8, 9*)) (Fig. 1, column A). New evidence validates and deepens understanding of threats, including increased exposure to extreme heat, reduced air quality, more frequent and/or intense natural hazards, and increased exposure to infectious diseases and aeroallergens. New evidence also highlights additional health-related threats not discussed in the EF, including reduced nutritional security, impacts on mental health, and increased risk of population displacement and conflict (Fig. 1, column C).

Extreme heat is the most direct health impact (Fig. 2). With future warming, >200 United States cities face increased risk of aggregated premature mortality (*10*). In addition, extreme heat is linked to rising incidence of sleep loss (*11*), kidney stones (*12*) , low birth weights (*13*), violence (*14*), and suicide (*15*) (Fig. 1, column B).

New studies also strengthen evidence for health impacts via increased exposure to ozone and other air pollutants (*16*), including smoke from forest fires (*17*). Likewise, evidence for links among climate change, extreme weather, and climate-related disasters is growing rapidly (*18*). These events often lead to physical trauma, reduced air quality, infectious disease outbreaks, interruption of health service delivery, undernutrition, and both acute and chronic mental health impacts (*19*).

Changes in temperature, precipitation, and soil moisture are also altering habitat, life cycles, and feeding behaviors of vectors for most vector-borne diseases (*20*), with recent research documenting changes in exposure to malaria (*21*), dengue (*22*), West Nile virus (*23*), and Lyme disease (*24*), among others. Recent work also reinforces the evidence that increased outbreaks of water-borne (*25*) and food-borne illness (*26*) are likely to follow increasing temperatures and extreme precipitation. Likewise, recent research reinforces the conclusion that rising temperatures and carbon dioxide (CO_2) levels will increase pollen production and lengthen the pollen season for many allergenic plants (*27, 28*), leading to increased allergic respiratory disease (*29*).

One area of new understanding, not covered in the EF, is threats to global nutrition. Staple crops grown at 550 ppm CO_2 have lower amounts of zinc, iron, and protein than the same cultivars grown at ambient CO_2 (*30*). These nutrient losses could push hundreds of millions of people into deficiencies of zinc (*31*), protein (*32*), and iron (*33*), in addition to exacerbating existing deficiencies in over one billion people. These impacts on nutritional quality exacerbate effects on yield, discussed below. Together, these effects underscore a significant headwind in assuring access to nutritious diets for the global population (*34*).

Another area of new understanding is mental health impacts of climate change (*35*). In particular, increased exposure to climate and weather disasters are associated with post-traumatic stress, anxiety, depression, and suicide (*15, 36*).

Finally, climate change is increasingly understood to function as a threat magnifier, raising the risk of population displacement and armed conflict, also discussed below.

Public Welfare

Air Quality

Evidence for the "climate penalty" on air quality stressed in the EF has strengthened (Fig. 1, column A). Mechanisms include extreme heat enhancing production of surface ozone (*37, 38*), stagnant conditions, and strong temperature inversions increasing concentrations of particulate matter (PM; (*39, 40*). The most persistent and extreme episodes of elevated ozone, PM, and elevated temperatures in the U.S. have a high incidence of co-occurrence (*41*). Further global warming is likely to cause air stagnation events to increase over many mid-latitude regions, including the western U.S. (*42*).

Recent studies confirm the increased risk of higher surface ozone as climate changes (e.g., (*43, 44*)). By the 2050s, the U.S. could experience more ozone episodes (days with 8-hour maximum daily averaged ozone greater than 75 ppb), including 3-9 more episodes per year in the Northeast and California (*45*). By the 2090s, increases could reach 10 episodes per year across the

Northeast (*46*). The U.S. ozone season, typically confined to summer, could lengthen into spring and/or fall as climate warms (*47*) (Fig. 1, column B).

Modeling studies of changes in particulate matter (PM) present a mixed picture, arising from the complex response of PM emissions and chemistry to meteorology (e.g., (*48, 49*)). However, as the measurement record has lengthened, more robust estimates have come from observationally based statistical models. Using this approach and assuming no change in emissions of anthropogenic PM sources, one study projected that annual mean $PM_{2.5}$ could increase 0.4-1.4 μg m^{-3} in the eastern U.S. by the 2050s, with small decreases in the West (*45*). However, summertime mean $PM_{2.5}$ was projected to increase as much as 2-3 μg m^{-3} in the East due to faster oxidation and greater biogenic emissions.

Warmer and drier conditions in the West and Southwest (e.g., (*50*)) will have implications for wildfire smoke and dust storms, as discussed below. By the 2050s, increased wildfire activity could elevate the concentrations of organic particles across the West by 46-70%, depending on the ecoregion (*51*), and the frequency of smoke episodes could double in California (*52*) (Fig. 1, column C). Future projections of the frequency of dust storms are mixed (e.g., (*53*)). However, seasonal means of fine dust particles are projected to increase by 26-46% by the 2050s in the Southwest under a scenario of very high greenhouse gas emissions (*54*).

Food Production and Agriculture

Research since the EF has confirmed the EF's conclusion that "the body of evidence points towards increasing risk of net adverse impacts on U.S. food production and agriculture over time, with the potential for significant disruptions and crop failure in the future." (Fig. 1, column A). There is still an expectation that certain aspects of increasing CO_2 and temperature will be beneficial in the next few decades for some crops and locations within the U.S. but that these positive effects are expected to be outweighed by negative impacts.

There is significant new evidence quantifying and understanding the mechanisms behind crop yield losses that result from short periods of exposure to high growing season temperatures (e.g., greater than 30C or 86F) (*55, 56*) (Fig. 1, column B). Likewise, warmer winter nights will also negatively affect perennial crops such as apples and cherries that require a certain amount of winter chill for high yields (*57*), an impact not included in the 2009 EF.

New understanding of weed and pest responses to climate and CO_2 highlights the risks from these biotic stresses. For example, weeds typically respond more quickly than crops to higher CO_2, which “will contribute to increased risk of crop loss due to weed pressure” (*56*).

Understanding of agricultural vulnerability has also extended beyond the main commodity crops (Fig. 1, column C). For example, national aggregate agricultural total factor productivity (TFP) exhibits strong sensitivity to weather in regions having high value crops, livestock production, or specializing in commodity crops (*58*). Sensitivity was highest in recent time periods, and projected warming could reduce TFP at a faster rate than that of technological improvement.

Measurements since the EF enable more thorough characterization of ongoing impacts and adaptation responses. Climate changes since 1980 have had net negative impacts on yields of maize and wheat in most major producing regions globally, with less significant impacts for rice and soybean (*55*). Warming trends in the U.S. have been more muted than in other regions, resulting in smaller impacts to date. Studies have also assessed the ability of farmers to adapt to ongoing changes, for example by comparing regions with different rates of warming, or by evaluating sensitivity to spatial gradients in temperature at different points in time. These studies generally indicate a limited ability of farmers to simultaneously raise yields and reduce yield sensitivity to warming (*59, 60*), which is consistent with the increased aggregate sensitivity to TFP. Other adaptations such as switching crops or adding irrigation have been less rigorously tested. Overall, the conclusion of the 2014 NCA was that “although agriculture has a long history of successful adaptation to climate variability, the accelerating pace of climate change and the intensity of projected climate change represent new and unprecedented challenges to the sustainability of U.S. agriculture.” (Fig. 1, column B).

Forestry

Evidence available at the time of the EF indicated that anthropogenic climate change would likely bring more harm than benefits for US forests during the 21st century. Research since the EF broadly confirms that forest ecosystems are not in equilibrium with ongoing and projected trends in extreme heat and drought, making large ecological shifts in U.S. forests likely (*61-64*) (Fig. 1, column A).

Anthropogenic warming has reduced snowpack across the majority of the montane western U.S. (*65, 66*) and earth system models project reduced summer soil moisture across most of the U.S. (*50, 67*). Warming also elevates plant respiration rates and atmospheric evaporative demand, aggravating drought stress and risk of tree mortality. Further, projected continued increases in precipitation variability (*68*), promoting increasingly severe droughts even in regions of increased mean precipitation (*69, 70*).

While CO_2 fertilization and warming-induced lengthening of growing season pose potential benefits to trees, models substantially overestimate CO_2-driven increases in global vegetation productivity over recent decades (*71*).

A large body of new evidence points to increasing risks of tree mortality or forest loss in the western U.S. from wildfire and bark-beetle outbreaks (Fig. 1, column B). Although such disturbances occur naturally, increases in disturbance size, frequency, and severity can have long-term impacts on forest ecosystems (*62, 72*). Annual western U.S. forest-fire area increased by approximately 1000% during 1984-2017 (*73, 74*) (Fig. 3). Studies consistently attribute a substantial fraction of this trend to warming-induced fuel drying (*75-77*) and suggest continued increases in western U.S. forest-fire activity (*78, 79*) and resultant tree mortality (*80*) until fuels become limiting (*81*).

Land management has amplified effects of warming on western U.S. forest-fire activity (Fig. 1, column A). A century of fire suppression caused fuels to accumulate, creating fire deficits (*82*). Accumulated fuels and warming combine to aggravate risk of large, high-intensity wildfires (*83-85*). This risk may be further exacerbated where CO_2 fertilization or precipitation trends enhance biomass (*86*), or where humans add to natural ignitions (*87*).

Recent bark-beetle outbreaks in western North America appear more massive than in previous centuries (*88*), with new research since the EF documenting millions of hectares of tree mortality (*89, 90*) (Fig. 1, column B). Warming may intensify bark-beetle outbreaks by decreasing cold-season beetle mortality, accelerating the beetle life cycle, and weakening tree defenses (*91*). However, the full range of effects of climate change on bark-beetle outbreaks remains unconstrained (*92, 93*).

Climate-change impacts on eastern forests have been more ambiguous due to legacy effects of land management, complex competition dynamics, and, in some locations, muted warming and/or increased precipitation. Nonetheless, eastern U.S. forests are vulnerable to extreme heat and drought (*94, 95*). Warming is implicated in northward expansion of eastern forest pests, including the southern pine beetle (*91*) and non-native hemlock woolly adelgid (*96*). Recent drought-driven fires in the southeast may portend warming-exacerbated fire activity in that region (*97*).

The current distributions and assemblages of vegetation species are not in equilibrium with future climate and CO_2 levels. Research over the past decade suggests that the velocity of climate change (Fig. 4) could exceed the rate of migration of some forest species (*98, 99*), enhancing the evidence in the EF that rapid 21st-century climate change will profoundly disrupt U.S. forest ecosystems (*62*).

Water Resources

Climate change impacts on snow hydrology and water scarcity are especially pronounced in the western U.S. Observed trends towards warming-induced reductions in snowpack were first widely reported by Mote et al. (*100*). Likewise, up to 60% of climate-related trends in earlier river flow, warmer winter air temperature, and lower snowpack from 1950 to 1999 are attributed to human activities (*65*).

Since the EF, progress in quantifying trends and causes of changes in snowpack and water availability has been substantial (Fig. 1, column A). Springtime warming over the past half century has resulted in: a higher proportion of precipitation falling as rain vs snow in the western U.S. (*101*); earlier snowmelt onset by 1-2 weeks in the western U.S. (*102*); reductions in stream flow during the driest part of the year in the Pacific Northwest (*103*); a trend towards earlier-in-the-year streamflow in snow-fed rivers in North America (*104*); and reductions in snow cover and snowpack over the Northern Hemisphere (*105*).

Climate models project accelerated changes in snow hydrology, in the western U.S. as well as globally. Projected decreases in mid-latitude snowfall (*106, 107*) result in reduced snow cover and depth (*105, 106*), accelerating hydroclimatic change in snow-dominated regions of the western U.S. (*108*), and losses in annual maximum water stored in snowpack of up to 60% in the next 30 years (*109, 110*). Losses of snow cover and water equivalent depth will fundamentally change the sources and timing of runoff in the mid-latitudes and mountainous regions with snow (*111*), including the western (*112*), midwestern, and northeastern parts of the U.S. (*113*) (Fig. 1, column B).

New research highlights risks from extreme minimum snowpack values (or even no snowpack) — snowpack droughts (*111, 114*). Snowpack droughts negatively affect water supply and other aspects of the Earth system, including rare and endangered species (e.g. salmon, trout, and wolverine; (*115, 116*)) (Fig. 1, column C).

Global urban freshwater availability is threatened by climate forcing and water management practices (*117, 118*), leading to a projected increase in the number of people living under absolute water scarcity (*118, 119*) (Fig. 1, column C). In addition, new evidence suggests that further global warming is likely to erode water quality in the U.S. by increasing nutrient loading and eutrophication, particularly in the midwest and northeast (*120*) (Fig. 1, column C).

Sea Level Rise and Coastal Areas

Understanding of the present rates of global and regional sea level rise (SLR), the role of contributing processes, the range of future rates, and the observed and projected impacts have all improved since the EF (*121*) (Fig. 1, column A). Still, understanding and predicting coastal change in the context of rapid SLR and intensifying extreme events is exceedingly challenging (*122, 123*).

Recent studies project SLR at greater than 7 mm/yr after ~2050 (*124*). This is a global average SLR rate unprecedented in the last 7000 years (*125*). To date, SLR has changed nonlinearly at some locations (*126*). Annual exceedances of flood thresholds are increasing or accelerating at locations along the U.S. coastline (*127*), and cities around the U.S. are projected to experience more than 30 high-tide flooding events per year, well before 2100 (*128*). With these rates of SLR, the stratigraphic record and modern analogs that serve as our traditional sources of insight are lacking, limiting our ability to predict the form, magnitude, and spatial extent of future changes to the coastal landscape (*129, 130*).

Research since the EF increases documentation of the risks of SLR, especially for the higher levels of SLR now understood to be possible by 2100 (*131*) (Fig. 1, column B). SLR has and will increasingly expose coastal populations, economies, and infrastructure to hazards including flooding, erosion, and extreme events. A sea-level rise of 0.5 m by 2100 would result in at least 182 days y^{-1} of tidally-forced flooding across the U.S. and its Pacific Islands, except in the eastern Gulf of Mexico (*132*). When coupled with projected U.S. population growth, a 0.9 m rise in sea-level by 2100 could affect 4.2 million people; a 1.8 m rise could affect 13.1 million people and drive widespread human migration (*133*).

Coastal erosion and flooding risk are already affecting real estate values. For example, in Miami-Dade County, property subject to high tide flooding is appreciating at a lower rate than properties at higher elevations, causing displacement through "climate gentrification" (*134*). Furthermore, as older and less resilient residential structures are damaged or destroyed by coastal storms and chronic shoreline retreat, they are typically replaced by more resilient but also more expensive structures (*134, 135*).

New evidence since the EF highlights interactions between SLR and other sectors (Fig. 1, column B). SLR and extreme events threaten the movement of goods among major port cities (*136*), which can lead to economic disruption (*137*), with cascading impacts far from the coastal zone, as well as opportunity costs associated with ensuring the viability of ports and other coastal infrastructure. Likewise, the domestic and international missions of the U.S. military, including disaster relief and humanitarian assistance, are increasingly impacted by SLR, as discussed below.

Energy, infrastructure, and settlements

The EF found that "the evidence strongly supports the view that climate change presents risks of serious adverse impacts on public welfare from the risk to energy production and distribution as well as risks to infrastructure and settlements." This evidence has become stronger and broader since the EF (Fig. 1, column A).

Melillo et al. (*138*) reported that "changes in water availability, both episodic and long-lasting, will constrain different forms of energy production [including] from fossil fuels (coal, oil, and natural gas), nuclear power, biofuels, hydropower, and some solar power systems…" (*139*). "Reduced availability of water for cooling, hydropower, or absorbing warm water discharges into water bodies without exceeding temperature limits will continue to constrain power production at existing facilities and permitting of new power plants." (*140*). In some parts of the country, electric utilities and energy companies compete with farmers and ranchers, other industries, and municipalities for water rights and availability." (*141*).

Recent work documents an increase in energy demand for cooling buildings, with a shift from predominantly heating to predominantly cooling in some regions, and a greater reliance on electricity relative to other energy sources (*142, 143*).

Given that a significant fraction of America's energy and transportation infrastructure is located in low-lying coastal and riverine areas, much that infrastructure is vulnerable to flooding from extreme weather events (*144*). Likewise, adverse effects on U.S. military infrastructure and surrounding communities have resulted most notably from drought and flooding, as discussed below.

The Third US National Climate Assessment concluded that "In parts of Alaska, Louisiana, the Pacific Islands, and other coastal locations, climate change impacts …are so severe that some communities are already relocating from historical homelands to which their traditions and cultural identities are tied." (*145, 146*). In particular, "physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population, increase the vulnerability of rural communities." (*147*).

The effects of rising temperatures are perhaps most severe in the Arctic, which is warming more than twice as fast as the global average (*148*) (Fig. 1, column A). Communities across the Arctic are experiencing impacts, including from loss of sea ice, SLR, erosion, and permafrost thaw. These changes have been underway for decades, but much of the documentation has occurred since the EF. Arctic warming is endangering human health, destroying public infrastructure, and threatening water resources, cultural resources, and access to subsistence resources and traditional food storage (*149, 150*).

The risk and severity of climate impacts are particularly high for coastal communities in Alaska, where loss of land-fast sea ice is increasing storm impacts, and permafrost thaw is exacerbating coastal erosion rates (*151*) (Fig. 1, column B). Thirty-one Alaskan villages face imminent threats from flooding, erosion and permafrost thaw (*152*). None of these villages has yet relocated, largely because of a lack of a governance framework to facilitate relocation efforts (*153*).

There is a substantial economic cost of permafrost thaw, quantified mainly since the EF. Ground subsidence and collapse, particularly in ice-rich areas, negatively impacts the structural integrity of buildings, roads, and industrial infrastructure, including gas and oil development (*150*). Cumulative projected costs of climate change damages to public infrastructure in the state of Alaska are estimated at $5.5 billion for a high-emissions scenario (RCP8.5) and $4.2 billion for a medium emissions scenario (RCP4.5) for 2015-2099 (*154*). The greatest economic impact is expected to result from road flooding followed by building damage as a result of near-surface permafrost thaw.

Ecosystems and Wildlife

The first global meta-analyses of climate change impacts on wild species, mostly from terrestrial ecosystems, estimated that about half had responded by shifting their ranges poleward and upward (Fig. 4), and about two-thirds had responded by advancing their timing of spring events such as tree budburst and bird nesting (*155*). New studies since 2009 have clarified and extended these findings, and also expanded documentation for marine systems and illuminating responses at all levels of biological organization (*156*) (Fig. 1, column A). This new evidence makes clear that prior global estimates underestimated the impacts of anthropogenic climate change on ecosystems and wildlife.

Research since 2009 illuminates new range boundary dynamics that are more complex than simple northward or poleward shifts (*157*). For example, terrestrial range limits are shifting faster where local warming is stronger (*158*). Likewise, lower elevation limits set by precipitation can expand downwards in response to increased rainfall, despite regional warming (*159*).

In contrast, marine limits are typically set by physiological thermal tolerances and thus respond more strongly and predictably to warming than equivalent terrestrial limits (*160*). The mean rate of movement in marine systems (*161*) reflects the faster poleward movement of isotherms in the oceans compared to land (*162, 163*). The rapid poleward shift of marine taxa includes important disease organisms, such as *Vibrio* bacteria. In both Alaska and the Baltic, *Vibrio* have recently caused unprecedented outbreaks of food poisoning from shellfish and systemic poisoning by infection of wounds (reviewed in (*164*)).

Research since 2009 on timing of spring events illuminates changes that defy simple expectations (Fig. 1, column A). In plants that require chilling ("vernalization") to determine that winter is over, winter warming slows development, while spring warming speeds development. Actual changes in timing reflect the combination of these opposing effects, potentially resulting in development that is accelerated, delayed, or unchanged (*165*).

Prior to the EF, it was predicted that biological responses would lag changes in climate (*166*). Studies since 2009 have documented that this process is already occurring. Across Europe, species are responding more slowly than climate is warming, causing bird and butterfly communities to suffer a "climate debt" (*167*). Likewise, populations of yellow warbler with detectable climatic debts had the lowest population growth rates across the USA (*168*). In contrast, plants that have advanced their timing most strongly have had more positive population growth rates (*169*).

Similarly, at the time of the EF, there was an assumption that a sensitivity to warming would be most important at the limits of species' ranges. However, several newer studies demonstrate that life-history tradeoffs can cause species to be constrained by the limits of their climatic tolerances even in central areas of their ranges (*170, 171*) (Fig. 1, column A).

Biological diversity and the services that ecosystems provide to humans face risks from climate change. The magnitude and timing of these risks is influenced not only by direct effects of climate on organisms but also by compounding effects of other stresses (*172, 173*), especially land use by humans, changes in disturbance regimes, defaunation (*174*), and ocean acidification (see below). Biotic interactions related to pollination, food resources, competition, pests, diseases, and predators can also amplify the risks (*175*). Since the EF, new research has provided additional detail on many of these risks and on the groups of species and ecosystem services that are most vulnerable (*176*) (Fig. 1, Column A).

Extinction risk from climate change is broadly distributed across taxonomic groups, with 21st-century warming threatening about 15% of all species, in a world of continued high emissions (*176*). Risks are especially great for species with small ranges or in habitat types that are spatially limited or rapidly shrinking, including Arctic sea-ice ecosystems (*177*) and mountaintops (*172*). Recent large-scale bleaching in warm-water coral reefs (*178*) and forest mortality events (*179*) provide clear evidence of risk under current conditions. Research since the EF underscores risks of climate change for diverse ecosystem services, ranging from the role of coral reefs in supporting fisheries (*180*) (Fig. 1, Column B) to the contribution of forests and soils in GHG balance (*181*).

Ocean acidification

Removal of anthropogenic CO_2 emissions by air-sea gas exchange and chemical dissolution into the ocean alters the acid-base chemistry of the ocean. Since the EF, there has been improved scientific understanding of this process, and of its possible negative impacts on marine life (Fig. 1, column C).

Excess CO_2 gas in the ocean reacts with water, resulting in a series of chemical changes that include reductions in pH, carbonate ion (CO_3^{2-}) concentrations, and the saturation state for carbonate minerals used by many organisms to construct shells and skeletons (*182*). Such chemical changes are now well documented in the upper ocean. Acidification in coastal waters can be exacerbated by local pollution sources (*183*). Over the next several decades, trends in near-surface acidification are likely to closely track atmospheric CO_2 trends (*184*), with acidification hotspots in coastal upwelling systems, the Arctic, and the Southern Ocean (*185, 186*).

Evidence since the EF reveals a wide-range of biological responses to elevated CO_2 and ocean acidification (Fig. 1, column C). For all marine species, the impact of current and future ocean acidification must be framed in the context of a rapidly changing ocean environment with multiple human-driven stressors, particularly ocean warming (*187*).

Model and data syntheses indicate that acidification may shift reef systems to net dissolution during the 21st century (*188*). Acidification, together with coral bleaching from ocean warming, may have striking negative consequences for biologically-rich coral reef ecosystems that provide food, income, and other valuable ecosystem services to >500 million people around the world (*189*).

Different kinds of organisms vary substantially in their responses to acidification, from generally negative effects for many mollusks and some plankton, to neutral and even positive effects for other species (*190*). Lower seawater carbonate saturation states reduce calcification and may restrict geographic habitat for planktonic pteropods (*191*) that are prey for many fish, marine mammals, and seabirds.

Many shellfish, and perhaps some kinds of crustaceans, are vulnerable to acidification, especially in larval and juvenile stages, with possible repercussions for valuable U.S. and international fisheries (*192, 193*) (Fig. 1, column C). During the mid-2000s, low pH waters associated with coastal upwelling led to reduced larval survival of Pacific oysters in some U.S. Pacific northwest shellfish hatcheries, a problem that has been largely addressable so far through adaptive strategies (*194*). Wild-harvest fisheries may be more at risk, particularly in regions with combined social and ecological vulnerability (*195*). Less is known about acidification responses in fish, with most studies indicating weak or no effects on growth and reproduction, while a number of studies suggest intriguing negative effects on olfaction and behavior (*196*).

Violence and Social Instability

Since the EF, a number of studies have used historical data to explore whether changes in environmental conditions influence the risk of violence or instability (*197*). In general, high temperatures and rainfall extremes amplify underlying risks (*14*) (Fig. 1, column C). These effects are not uniform (*198*). Many factors, including political institutions (*199*), income levels

(*200*), and local economic structures (*201*) play a role in determining the structure of these effects.

A robust and generalizable finding is increased risk of threatening and violent interactions between individuals under hot conditions (Fig. 1, column C). In the U.S., exposure to high temperatures is associated with higher rates of domestic violence (*202*), rape, assault, and murder (*203, 204*), as well as greater use of threatening behaviors such as aggressive language in social media posts (*205*), horn honking in traffic (*206*), and higher rates of violent retaliation in sports (*207*). Emerging evidence also indicates that hot periods elevate the risk that individuals harm themselves, including by suicide (*15, 208*). U.S. data indicate no evidence of adaptation (*15, 204*).

Effects of temperature (+2.4% per σ) and rainfall (0.6% per σ) on interpersonal violence are both highly statistically significant, based on a meta-analysis (*209*). If these responses to historical fluctuations translate to future climate change, warming of 1˚C could lead to an increase of national violent crime (rape, assault, and murder) by 0.88 (±0.04) % (*210*). Under RCP8.5, this trend projects to a warming-caused increase of violent crime by 1.7-5.4% by 2080-2099. Warming is projected to increase the national suicide rate 0.6-2.6% by 2050 (*15*).

Many studies document heightened risk of violence between groups of individuals when temperatures are hot and/or rainfall is extreme (*14*) (Fig. 1, column C). The pattern is similar for organized violence, such as civil conflicts (*200, 211*), and disorganized violence, such as ethnic riots (*212*), with highly statistically significant effects of temperature (+11.3% per σ) and rainfall (3.5% per σ, over two years) (*209*).

Political instability is heightened in hot periods, even in contexts where political institutions are sufficiently robust to avoid outright violence (Fig. 1, column C). The probability of political leadership changes, both through democratic process (*213, 214*) and "irregular" conditions (*215, 216*), rises in warm periods. Coups are more likely in hot years with extreme rainfall in agriculturally dependent countries (*217*).

Through degrading economic conditions, climate events may contribute to out-migrations of populations seeking better opportunities. Drought and soil loss during the Dustbowl induced mass out-migration from the rural Midwest (*218*), and young working-age individuals left the corn-belt during periods of extreme heat in recent decades (*219*). Likewise, periods of high temperatures have been linked to migration from rural regions of Mexico to the U.S. (*219, 220*).

Population movements following extreme heat or dryness have been documented in multiple regions (*221-223*), and high temperatures in agrarian regions elevate international applications for political asylum (*224*).

National Security

Since the EF, the American military and intelligence communities have significantly increased their integration of climate change into national security strategies, policies and plans. These considerations have been reflected in analyses of the national security implications of climate change by the Department of Defense, with almost 50 reports considering climate security impacts published between 2010 and 2018 (*225*) (Fig. 1, column C).

The National Intelligence Council has warned congress about the security risks of climate change every year since 2008, following release of the landmark report by the CNA Military Advisory Board, "National Security and the Threat of Climate Change" (*226*). The NIC's 2018 "Worldwide Threat Assessment," which reflects the intelligence community's consensus on the most significant risks to national security, this year for the first time included a robust section titled "Environment and Climate Change," noting a range of security risks related to environmental concerns (*227*). The 2018 Defense Authorization Act, signed by President Donald J. Trump, stated, "Climate change is a direct threat to the national security of the United States…" (*228*).–During the Trump presidency, 16 military leaders, including Secretary of Defense James Mattis (*229*) have voiced concerns about climate change and its security implications.

New studies strengthen the evidence that climate change causes weather patterns and extreme events that directly harm military installations and readiness through infrastructure damage, loss of utilities, and loss of operational capability (Fig. 1, column C). A sea-level rise of 3.7 feet would threaten 128 military bases (*230*). Thawing permafrost exposes foundations to damage, while loss of Arctic sea-ice causes coastal erosion near critical facilities. Intensifying wildfires threaten facilities, transportation infrastructure, and utility lines. Fire-hazard days and inclement weather suspend outdoor training, while droughts limit the use of live-fire training. Greater storm frequency and strength strains Defense Support to Civilian Authorities requirements at home, as well as assistance to humanitarian efforts and disaster relief around the world (*231*). As of 2018, 50% of military installations both at home and abroad had already reported damage due to climate change (*231*). Droughts or unpredictable rainfall could leave armed forces stationed abroad vulnerable to being disconnected from potable water supplies, a cause for concern given that protecting convoys to transport water and fuel accounted for "one-third of U.S. Army casualties in Afghanistan in 2007," (*232*).

Climate change increasingly disrupts existing international security dynamics in geostrategic environments (Fig. 1, column C). Reduced Arctic sea ice extent will open the way for more trade as well as oil and gas extraction, turning a historically neutral territory into a potential political flashpoint. Moreover, the US military now has to operate in an increasingly open water Arctic region as sea ice retreats. Or, as SECDEF Mattis recently stated, "America has to up its game in the Arctic" (*233*). Both China and Russia have been deepening their Arctic presence through investment and the development of ports. As much as 15 percent of China's trade value could travel through the Arctic by 2030, while between 20 and 30 percent of Russia's oil production will come from deposits in the Arctic shelf by 2050 (*234*). These interests will require further American military and coast guard activity in the region, as well as broader diplomatic and scientific engagement.

Indirectly, climate change has a major impact on national security by acting as a "threat multiplier" or "accelerant of instability" (*235*) (Fig. 1, column C). This means that climate change heightens the risk posed by threats the United States is already facing, and in aggregate fundamentally alters the security landscape (*236*). In both the 2010 and 2014 Quadrennial Defense Review, the DOD emphasized how seriously the military takes this dangerous dynamic, a commitment that receives meaningful redress every year in its annual Strategic Sustainability Performance Plans (*237*).

As discussed in other parts of this review, an expanding body of evidence reinforces how climate change fuels economic and social discontent, and even upheaval. Extreme weather events raise the risk of humanitarian disasters, conflict, water and food shortages, population migration, labor shortfalls, price shocks, and power outages (*227*).

Economic wellbeing

Research on the economic consequences of climate change has advanced substantially since the EF, with important progress on understanding non-agricultural sectors and broad measures of wellbeing (*197, 238*) (Fig. 1, column C). In the U.S., economic impacts of hot temperatures and changing tropical cyclone environments are clearly documented (*210*) and growing evidence indicates long-term adverse effects on the labor force (*239-241*). Other impacts, such as from water availability or wildfire risks, are thought to be important but remain less well understood (*242*).

Since the EF, new "top down" analyses of overall macro-economic performance estimate that warming by an additional 1˚C over 75 years can be expected to permanently reduce U.S. Gross Domestic Product (GDP) ~ 3% through direct thermal effects (*243*), and that U.S. GDP can be expected to be ~4% greater at 1.5˚C than at 2˚C above pre-industrial (*244*) (Fig. 1, column C). The average projected alteration of cyclone activity under "business as usual" may cost the U.S. the equivalent of 29% of one year of current GDP (net present value discounted at 3% annually, (*245*)). In one study, the net cumulative market-based cost of thermal effects in RCP8.5 by 2100 should be valued at $4.7-10.4 trillion (net present value discounted at 3% annually, (*246*)).

"Bottom up" analyses examining impacts on individual sectors or industries have key advantages, including capturing the value of non-market impacts such as loss of human life or biodiversity (*210*). Evidence based on combining sector-specific analyses of impacts such as agricultural output (*247*), quantity of labor supplied by workers (*248*), expenditures on energy (*142, 249*), mortality rates (*249*), crime rates (*204*), sea level rise (*250*) and tropical cyclone changes (*251*) suggests U.S. costs equivalent to 1.2% of GDP for each 1˚C of warming, with poorer counties suffering an economic burden roughly five times larger than wealthier counties (*210*) (Figure 5) ((Fig. 1, column C).

Conclusions

The EPA Administrator found in 2009 that the Endangerment Finding (EF) for six long-lived greenhouse gases was "compellingly" supported by "strong and clear" scientific evidence. Since 2009, the amount, diversity, and sophistication of the evidence has increased dramatically, clearly strengthening the case for endangerment. New evidence about the extent, severity, and interconnectedness of impacts to date and projected for the future reinforces the case that climate change may reasonably be anticipated to endanger the health and welfare of current and future generations. For the sectors analyzed in the 2009 EF, new evidence expands the range of case studies, deepens the understanding of mechanisms, and analyzes the contribution of climate-related extremes. In many cases, new evidence points to the risk of impacts that are more severe or widespread anticipated in 2009. Several categories of climate-change impacts, including effects on ocean acidification, violence, national security, and economic well-being, are now supported by such broad evidence that they warrant inclusion in the framing of endangerment. In sum, the EF, fully justified in 2009, is much more strongly justified in 2018.

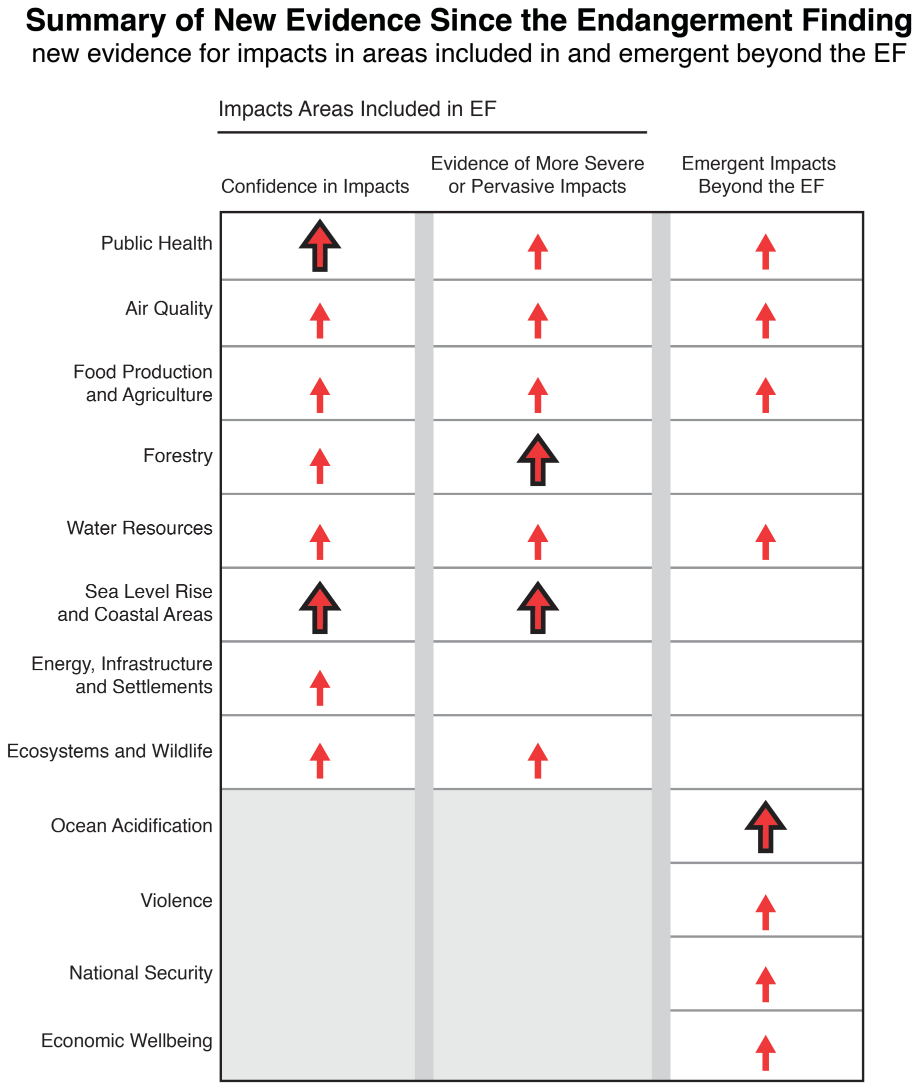

Figure 1: Summary of changes in the amount and implications of new evidence, since the EF, on each of the impact areas discussed in the EF and four additional impact areas, where evidence of climate sensitivity has matured since the EF. An upward pointing arrow indicates increasing evidence of endangerment. A downward pointing arrow indicates decreasing evidence of endangerment. A solid arrow indicates that the new evidence is abundant and robust. An outlined arrow indicates that the new evidence, in addition, comes from multiple approaches, is based on independent lines of information, or builds on a new level of mechanistic understanding. Column A refers to confidence in the impacts discussed in the EF. Column B refers to impact areas that are discussed in the EF but where new evidence points to specific impacts that are fundamentally more severe or pervasive than those discussed in the EF. Column C refers to types of impacts not discussed in the EF.

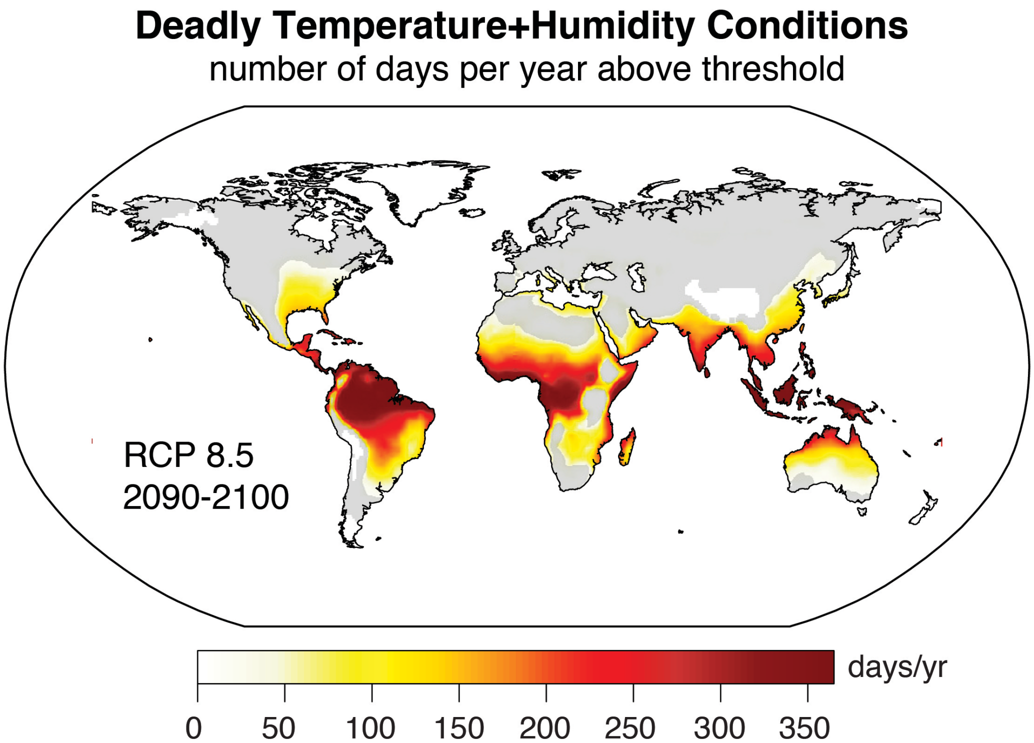

Figure 2: Number of days per year exceeding the threshold of temperature and humidity beyond which climatic conditions become deadly averaged between 2090 and 2100 under a scenario of continued high emissions (RCP8.5). Results are based on multimodel medians. Grey areas indicate locations with high uncertainty (that is, the multimodel standard deviation was larger than the projected mean; coefficient of variance >1). Adapted from (*252*).

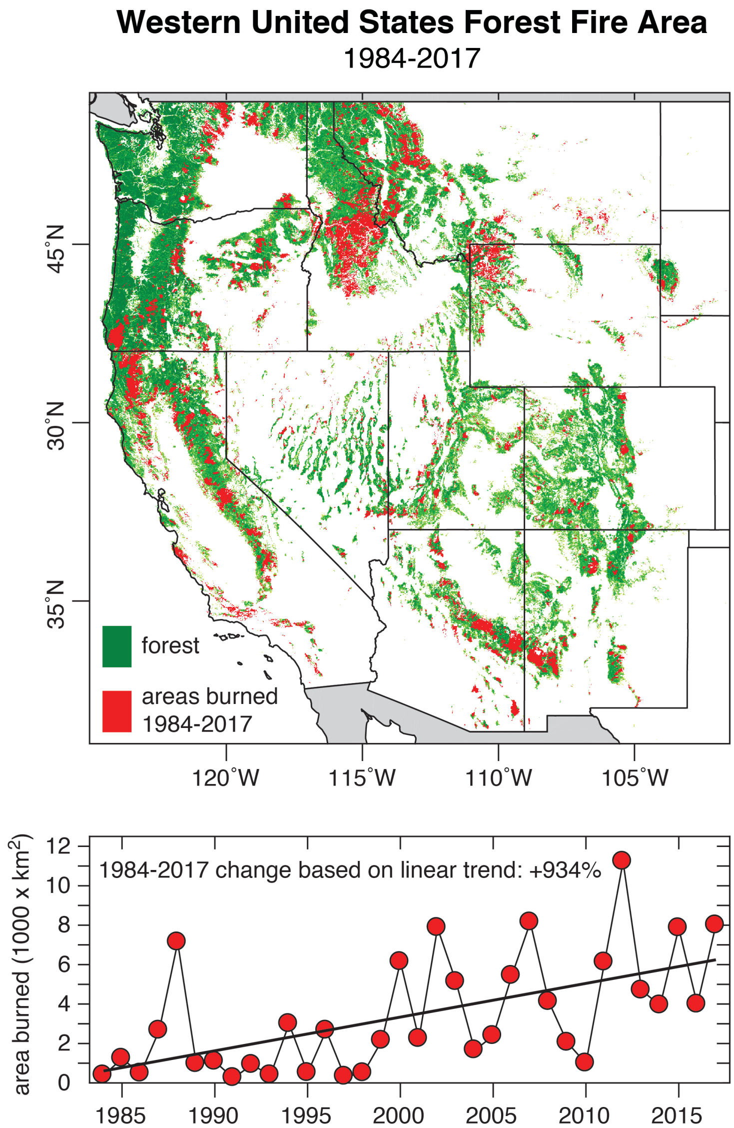

Figure 3: Western U.S. trends for number of large fires per year in each ecoregion. Fires mapped by the Monitoring Trends in Burn Severity project of the U.S. Geological Survey are shown in red. The surrounding bar plots display the number of large fires in each ecoregion over the 1984–2011 study period. The black line on each plot indicates the Theil-Sen estimated slope for each ecoregion. The Wyoming Basin and Colorado Plateau ecoregions had too few large fires for trend analysis at the ecoregion level, and are shown in gray. Adapted from (*253*).

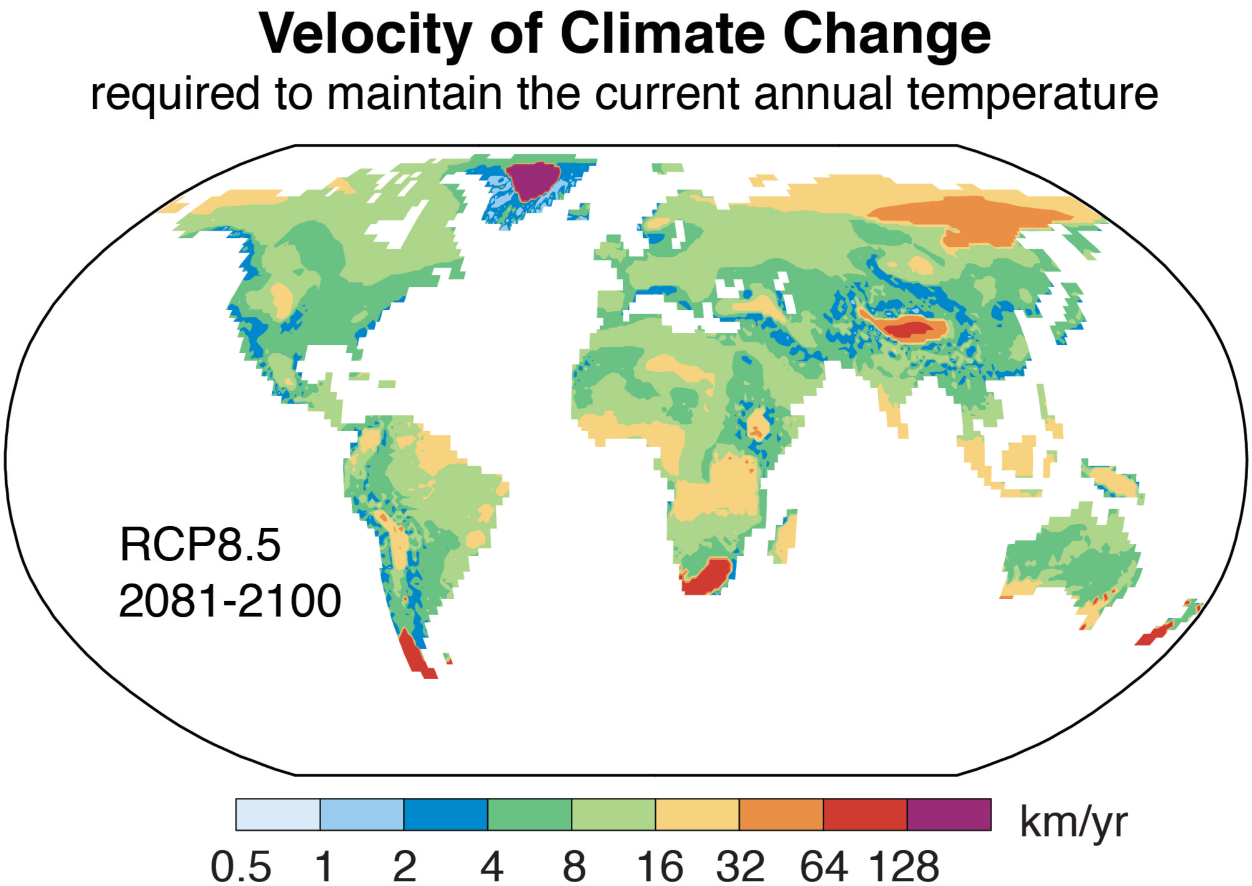

Figure 4: The velocity of climate change under a scenario of continued high emissions (RCP8.5), calculated by identifying the closest location (to each grid point) with a future annual temperature that is similar to the baseline annual temperature. Adapted from (*98*).

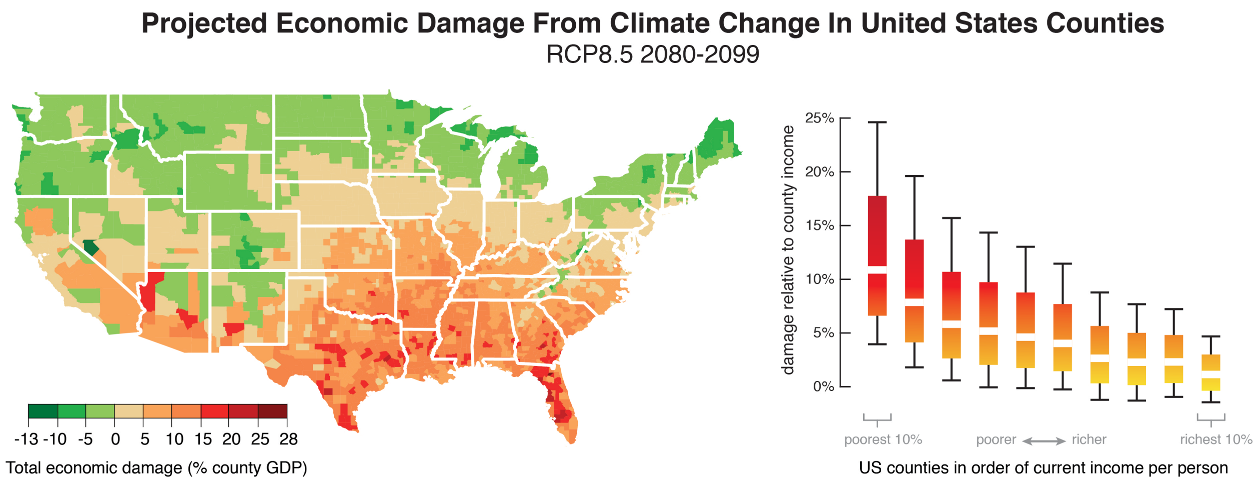

Figure 5: Total direct economic damage integrated over agriculture, crime, coastal storms, energy, human mortality, and labor in 2080-2099 under a scenario of continued high emissions (RCP8.5), adapted from (*210*). Left: damages in the median scenario for each county, negative damages indicate benefits. Right: Range of economic damages per year for groupings of US counties, based on their income (29,000 simulations for each of 3,143 counties) in fraction of county income (white lines=median, boxes=inner 66% of possible outcomes, outer whiskers=inner 90% of possible outcomes).

References

1. *42 U.S.C. § 7521(a)(1)*.
2. United States Supreme Court, *Massachusetts v. EPA, 549 U.S. 497* (2007).
3. United States Supreme Court, *Ethyl Corp. v. EPA, 541 F.2d 1, 17-18*. (1976).
4. *42 U.S.C. § 7602(h)*.
5. *74 Fed. Reg. 66496, 66514*.
6. U.S. Court of Appeals D.C. Circuit, *Coalition for Responsible Regulation v. EPA, 684 F. 3d 102, 117-18* (2012).
7. *42 U.S.C. § 7411(b)(1)(A)*.
8. K. R. Smith *et al.*, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change,* C. B. Field *et al.*, Eds. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014), chap. 11, pp. 709-754.
9. G. Luber *et al.*, in *Climate change impacts in the United States: the third National Climate Assessment,* J. Melillo, T. T. Richmond, G. Yohe, Eds. (US Global Change Research Program, Washington, D.C., 2014), pp. 220-256. doi:210.7930/J7930PN7993H7935.
10. J. D. Schwartz *et al.*, Projections of temperature-attributable premature deaths in 209 US cities using a cluster-based Poisson approach. *Environmental Health* **14**, 85 (2015).
11. N. Obradovich, R. Migliorini, S. C. Mednick, J. H. Fowler, Nighttime temperature and human sleep loss in a changing climate. *Science advances* **3**, e1601555 (2017).
12. G. E. Tasian *et al.*, Daily mean temperature and clinical kidney stone presentation in five US metropolitan areas: a time-series analysis. *Environmental Health Perspectives* **122**, 1081 (2014).
13. O. Deschênes, M. Greenstone, J. Guryan, Climate change and birth weight. *American Economic Review* **99**, 211-217 (2009).
14. S. M. Hsiang, M. Burke, E. Miguel, Quantifying the influence of climate on human conflict. *Science* **341**, 1235367 (2013).
15. M. Burke *et al.*, Warming increases suicide rates in the United States and Mexico. *Nature Climate Change* **in press**, (2018).
16. B. J. Bloomer, J. W. Stehr, C. A. Piety, R. J. Salawitch, R. R. Dickerson, Observed relationships of ozone air pollution with temperature and emissions. *Geophysical Research Letters* **36**, (2009).
17. B. J. Harvey, Human-caused climate change is now a key driver of forest fire activity in the western United States. *Proceedings of the National Academy of Sciences* **113**, 11649-11650 (2016).
18. IPCC, in *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change,* C. B. Field *et al.*, Eds. (Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2012), pp. 592.
19. J. Bell *et al.*, "Ch. 4: Impacts of Extreme Events on Human Health," (US Global Change Research Program, Washington, DC, 2016).
20. S. Altizer, R. S. Ostfeld, P. T. Johnson, S. Kutz, C. D. Harvell, Climate change and infectious diseases: from evidence to a predictive framework. *Science* **341**, 514-519 (2013).
21. V. Ermert, A. H. Fink, A. P. Morse, H. Paeth, The impact of regional climate change on malaria risk due to greenhouse forcing and land-use changes in tropical Africa. *Environmental Health Perspectives* **120**, 77 (2012).

22. C. W. Morin, A. C. Comrie, K. Ernst, Climate and dengue transmission: evidence and implications. *Environmental Health Perspectives* **121**, 1264 (2013).
23. S. Paz, Climate change impacts on West Nile virus transmission in a global context. *Phil. Trans. R. Soc. B* **370**, 20130561 (2015).
24. R. S. Ostfeld, J. L. Brunner, Climate change and Ixodes tick-borne diseases of humans. *Phil. Trans. R. Soc. B* **370**, 20140051 (2015).
25. L. Vezzulli, R. R. Colwell, C. Pruzzo, Ocean warming and spread of pathogenic vibrios in the aquatic environment. *Microbial ecology* **65**, 817-825 (2013).
26. R. S. Hellberg, E. Chu, Effects of climate change on the persistence and dispersal of foodborne bacterial pathogens in the outdoor environment: A review. *Critical Reviews in Microbiology* **42**, 548-572 (2016).
27. Y. Zhang *et al.*, Allergenic pollen season variations in the past two decades under changing climate in the United States. *Global Change Biology* **21**, 1581-1589 (2015).
28. L. Ziska *et al.*, Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *Proceedings of the National Academy of Sciences* **108**, 4248-4251 (2011).
29. N. Fann *et al.*, in *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment,* A. Crimmins *et al.*, Eds. (United States Global Change Research Program, Washington DC, 2016), pp. 69.
30. S. S. Myers *et al.*, Increasing CO 2 threatens human nutrition. *Nature* **510**, 139 (2014).
31. S. S. Myers, K. R. Wessells, I. Kloog, A. Zanobetti, J. Schwartz, Effect of increased concentrations of atmospheric carbon dioxide on the global threat of zinc deficiency: a modelling study. *The Lancet Global Health* **3**, e639-e645 (2015).
32. D. E. Medek, J. Schwartz, S. S. Myers, Estimated Effects of Future Atmospheric [... formula...] Concentrations on Protein Intake and the Risk of Protein Deficiency by Country and Region. *Environmental Health Perspectives* **125**, (2017).
33. M. Smith, C. Golden, S. Myers, Potential rise in iron deficiency due to future anthropogenic carbon dioxide emissions. *GeoHealth* **1**, 248-257 (2017).
34. S. S. Myers, Planetary health: protecting human health on a rapidly changing planet. *The Lancet* **390**, 2860-2868 (2017).
35. S. Clayton, C. Manning, K. Krygsman, M. Speiser, Mental health and our changing climate: impacts, implications, and guidance. *American Psychological Association and ecoAmerica: Washington, DC*, (2017).
36. E. Goldmann, S. Galea, Mental health consequences of disasters. *Annual review of public health* **35**, 169-183 (2014).
37. L. Camalier, W. Cox, P. Dolwick, The effects of meteorology on ozone in urban areas and their use in assessing ozone trends. *Atmospheric Environment* **41**, 7127-7137 (2007).
38. E. M. Oswald, L.-A. Dupigny-Giroux, E. M. Leibensperger, R. Poirot, J. Merrell, Climate controls on air quality in the Northeastern US: An examination of summertime ozone statistics during 1993–2012. *Atmospheric Environment* **112**, 278-288 (2015).
39. A. P. Tai, L. J. Mickley, D. J. Jacob, Correlations between fine particulate matter (PM2. 5) and meteorological variables in the United States: Implications for the sensitivity of PM2. 5 to climate change. *Atmospheric Environment* **44**, 3976-3984 (2010).
40. C. D. Whiteman, S. W. Hoch, J. D. Horel, A. Charland, Relationship between particulate air pollution and meteorological variables in Utah's Salt Lake Valley. *Atmospheric Environment* **94**, 742-753 (2014).
41. J. L. Schnell, M. J. Prather, Co-occurrence of extremes in surface ozone, particulate matter, and temperature over eastern North America. *Proceedings of the National Academy of Sciences* **114**, 2854-2859 (2017).

42. D. E. Horton, C. B. Skinner, D. Singh, N. S. Diffenbaugh, Occurrence and persistence of future atmospheric stagnation events. *Nature climate change* **4**, 698 (2014).
43. M. Lin, L. W. Horowitz, R. Payton, A. M. Fiore, G. Tonnesen, US surface ozone trends and extremes from 1980 to 2014: quantifying the roles of rising Asian emissions, domestic controls, wildfires, and climate. *Atmospheric Chemistry & Physics* **17**, (2017).
44. A. Wilson *et al.*, Climate change impacts on projections of excess mortality at 2030 using spatially varying ozone–temperature risk surfaces. *Journal of Exposure Science and Environmental Epidemiology* **27**, 118 (2017).
45. L. Shen, L. J. Mickley, L. T. Murray, Influence of 2000–2050 climate change on particulate matter in the United States: results from a new statistical model. *Atmospheric Chemistry and Physics* **17**, 4355-4367 (2017).
46. H. E. Rieder, A. M. Fiore, L. W. Horowitz, V. Naik, Projecting policy-relevant metrics for high summertime ozone pollution events over the eastern United States due to climate and emission changes during the 21st century. *Journal of Geophysical Research: Atmospheres* **120**, 784-800 (2015).
47. M. Trail *et al.*, Sensitivity of air quality to potential future climate change and emissions in the United States and major cities. *Atmospheric environment* **94**, 552-563 (2014).
48. H. Pye *et al.*, Effect of changes in climate and emissions on future sulfate-nitrate-ammonium aerosol levels in the United States. *Journal of Geophysical Research: Atmospheres* **114**, (2009).
49. M. C. Day, S. N. Pandis, Effects of a changing climate on summertime fine particulate matter levels in the eastern US. *Journal of Geophysical Research: Atmospheres* **120**, 5706-5720 (2015).
50. B. I. Cook, T. R. Ault, J. E. Smerdon, Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances* **1**, e1400082 (2015).
51. X. Yue, L. J. Mickley, J. A. Logan, J. O. Kaplan, Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21st century. *Atmospheric Environment* **77**, 767-780 (2013).
52. J. C. Liu *et al.*, Particulate air pollution from wildfires in the Western US under climate change. *Climatic change* **138**, 655-666 (2016).
53. B. Pu, P. Ginoux, Projection of American dustiness in the late 21 st century due to climate change. *Scientific Reports* **7**, 5553 (2017).
54. P. Achakulwisut, L. J. Mickley, S. C. Anenberg, Drought-driven increases in fine dust in the U.S. Southwest under future climate change: Implications for public health. *Environmental Research Letters* **13**, 054025 (2018).
55. J. R. Porter *et al.*, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change,* C. B. Field *et al.*, Eds. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014), chap. 7, pp. 485-583.
56. J. Hatfield *et al.*, in *The Third National Climate Assessment,* J. Melillo, T. Richmond, G. Yohe, Eds. (U.S. Global Change Research Program, Washington, D.C., 2014), pp. 150-174. doi:110.7930/J7902Z7913FR.
57. J. A. Santos, R. Costa, H. Fraga, Climate change impacts on thermal growing conditions of main fruit species in Portugal. *Climatic Change* **140**, 273-286 (2017).
58. X.-Z. Liang *et al.*, Determining climate effects on US total agricultural productivity. *Proceedings of the National Academy of Sciences* **114**, E2285-E2292 (2017).
59. D. B. Lobell *et al.*, Greater sensitivity to drought accompanies maize yield increase in the US Midwest. *Science* **344**, 516-519 (2014).
60. M. Burke, K. Emerick, Adaptation to climate change: Evidence from US agriculture. *American Economic Journal: Economic Policy* **8**, 106-140 (2016).

61. A. P. Williams *et al.*, Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change* **3**, 292 (2013).
62. C. I. Millar, N. L. Stephenson, Temperate forest health in an era of emerging megadisturbance. *Science* **349**, 823-826 (2015).
63. J. S. Clark *et al.*, The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Global Change Biology* **22**, 2329-2352 (2016).
64. R. Seidl *et al.*, Forest disturbances under climate change. *Nature Climate Change* **7**, 395 (2017).
65. T. P. Barnett *et al.*, Human-induced changes in the hydrology of the western United States. *Science* **319**, 1080-1083 (2008).
66. P. W. Mote, S. Li, D. P. Lettenmaier, M. Xiao, R. Engel, Dramatic declines in snowpack in the western US. *npj Climate and Atmospheric Science* **1**, doi: 10.1038/s41612-41018-40012-41611 (2018).
67. A. Berg, J. Sheffield, P. C. Milly, Divergent surface and total soil moisture projections under global warming. *Geophysical Research Letters* **44**, 236-244 (2017).
68. A. G. Pendergrass, R. Knutti, F. Lehner, C. Deser, B. M. Sanderson, Precipitation variability increases in a warmer climate. *Scientific reports* **7**, 17966 (2017).
69. O. Mazdiyasni, A. AghaKouchak, Substantial increase in concurrent droughts and heatwaves in the United States. *Proceedings of the National Academy of Sciences* **112**, 11484-11489 (2015).
70. N. S. Diffenbaugh, D. L. Swain, D. Touma, Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences*, 201422385 (2015).
71. W. K. Smith *et al.*, Large divergence of satellite and Earth system model estimates of global terrestrial CO 2 fertilization. *Nature Climate Change* **6**, 306 (2016).
72. J. S. Littell, D. L. Peterson, K. L. Riley, Y. Liu, C. H. Luce, A review of the relationships between drought and forest fire in the United States. *Global Change Biology* **22**, 2353-2369 (2016).
73. J. Eidenshink *et al.*, A project for monitoring trends in burn severity. *Fire ecology* **3**, 3-21 (2007).
74. L. Giglio, W. Schroeder, C. O. Justice, The collection 6 MODIS active fire detection algorithm and fire products. *Remote Sensing of Environment* **178**, 31-41 (2016).
75. J. T. Abatzoglou, A. P. Williams, Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* **113**, 11770-11775 (2016).
76. A. L. Westerling, Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Phil. Trans. R. Soc. B* **371**, 20150178 (2016).
77. M. Wehner, J. Arnold, T. Knutson, K. Kunkel, A. LeGrande, in *Climate Science Special Report: Fourth National Climate Assessment,* D. J. Wuebbles *et al.*, Eds. (U.S. Global Change Research Program, Washington, DC., 2017), pp. 231-256. doi:210.7930/J7930CJ7938BNN.
78. M. A. Moritz *et al.*, Climate change and disruptions to global fire activity. *Ecosphere* **3**, 1-22 (2012).
79. T. Kitzberger, D. A. Falk, A. L. Westerling, T. W. Swetnam, Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. *PloS one* **12**, e0188486 (2017).
80. P. J. van Mantgem *et al.*, Climatic stress increases forest fire severity across the western U nited S tates. *Ecology letters* **16**, 1151-1156 (2013).
81. D. McKenzie, J. S. Littell, Climate change and the eco-hydrology of fire: Will area burned increase in a warming western USA? *Ecological Applications* **27**, 26-36 (2017).

82. J. R. Marlon *et al.*, Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences* **109**, E535-E543 (2012).
83. M. D. Hurteau, J. B. Bradford, P. Z. Fulé, A. H. Taylor, K. L. Martin, Climate change, fire management, and ecological services in the southwestern US. *Forest Ecology and Management* **327**, 280-289 (2014).
84. S. A. Parks *et al.*, Wildland fire deficit and surplus in the western United States, 1984–2012. *Ecosphere* **6**, 1-13 (2015).
85. P. E. Higuera, J. T. Abatzoglou, J. S. Littell, P. Morgan, The changing strength and nature of fire-climate relationships in the northern Rocky Mountains, USA, 1902-2008. *PloS one* **10**, e0127563 (2015).
86. W. Knorr, L. Jiang, A. Arneth, Climate, CO_2, and demographic impacts on global wildfire emissions. *Biogeosciences Discussions* **12**, (2015).
87. J. K. Balch *et al.*, Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences* **114**, 2946-2951 (2017).
88. K. F. Raffa *et al.*, Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *AIBS Bulletin* **58**, 501-517 (2008).
89. W. R. Anderegg *et al.*, Tree mortality from drought, insects, and their interactions in a changing climate. *New Phytologist* **208**, 674-683 (2015).
90. J. A. Hicke, A. J. Meddens, C. A. Kolden, Recent tree mortality in the western United States from bark beetles and forest fires. *Forest Science* **62**, 141-153 (2016).
91. A. S. Weed, M. P. Ayres, B. J. Bentz, in *Bark Beetles*. (Elsevier, 2015), pp. 157-176.
92. B. J. Bentz, C. Boone, K. F. Raffa, Tree response and mountain pine beetle attack preference, reproduction and emergence timing in mixed whitebark and lodgepole pine stands. *Agricultural and forest entomology* **17**, 421-432 (2015).
93. D. L. Six, E. Biber, E. Long, Management for mountain pine beetle outbreak suppression: Does relevant science support current policy? *Forests* **5**, 103-133 (2014).
94. N. Pederson *et al.*, The legacy of episodic climatic events in shaping temperate, broadleaf forests. *Ecological Monographs* **84**, 599-620 (2014).
95. N. D. Charney *et al.*, Observed forest sensitivity to climate implies large changes in 21st century North American forest growth. *Ecology letters* **19**, 1119-1128 (2016).
96. J. Kim *et al.*, Increased water yield due to the hemlock woolly adelgid infestation in New England. *Geophysical Research Letters* **44**, 2327-2335 (2017).
97. A. P. Williams *et al.*, The 2016 southeastern US drought: An extreme departure from centennial wetting and cooling. *Journal of Geophysical Research: Atmospheres* **122**, (2017).
98. N. S. Diffenbaugh, C. B. Field, Changes in ecologically critical terrestrial climate conditions. *Science* **341**, 486-492 (2013).
99. S. R. Loarie *et al.*, The velocity of climate change. *Nature* **462**, 1052 (2009).
100. P. W. Mote, A. F. Hamlet, M. P. Clark, D. P. Lettenmaier, Declining mountain snowpack in western North America. *Bulletin of the American meteorological Society* **86**, 39-50 (2005).
101. J. T. Abatzoglou, Influence of the PNA on declining mountain snowpack in the Western United States. *International Journal of Climatology* **31**, 1135-1142 (2011).
102. S. Kapnick, A. Hall, Causes of recent changes in western North American snowpack. *Climate Dynamics* **38**, 1885-1899 (2012).
103. C. H. Luce, Z. A. Holden, Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. *Geophysical Research Letters* **36**, (2009).
104. H. Fritze, I. T. Stewart, E. Pebesma, Shifts in western North American snowmelt runoff regimes for the recent warm decades. *Journal of Hydrometeorology* **12**, 989-1006 (2011).

105. R. D. Brown, P. W. Mote, The response of Northern Hemisphere snow cover to a changing climate. *Journal of Climate* **22**, 2124-2145 (2009).
106. S. B. Kapnick, T. L. Delworth, Controls of global snow under a changed climate. *Journal of Climate* **26**, 5537-5562 (2013).
107. J. P. Krasting, A. J. Broccoli, K. W. Dixon, J. R. Lanzante, Future changes in Northern Hemisphere snowfall. *Journal of Climate* **26**, 7813-7828 (2013).
108. M. Ashfaq *et al.*, Near-term acceleration of hydroclimatic change in the western US. *Journal of Geophysical Research: Atmospheres* **118**, 10,676-610,693 (2013).
109. J. C. Fyfe *et al.*, Large near-term projected snowpack loss over the western United States. *Nature communications* **8**, 14996 (2017).
110. A. M. Rhoades, P. A. Ullrich, C. M. Zarzycki, Projecting 21st century snowpack trends in western USA mountains using variable-resolution CESM. *Climate Dynamics* **50**, 261-288 (2018).
111. N. S. Diffenbaugh, M. Scherer, M. Ashfaq, Response of snow-dependent hydrologic extremes to continued global warming. *Nature Climate Change* **3**, 379 (2013).
112. D. Li, M. L. Wrzesien, M. Durand, J. Adam, D. P. Lettenmaier, How much runoff originates as snow in the western United States, and how will that change in the future? *Geophysical Research Letters* **44**, 6163-6172 (2017).
113. E. M. Demaria, J. K. Roundy, S. Wi, R. N. Palmer, The effects of climate change on seasonal snowpack and the hydrology of the northeastern and upper Midwest United States. *Journal of Climate* **29**, 6527-6541 (2016).
114. A. Harpold, M. Dettinger, S. Rajagopal, Defining snow drought and why it matters. *EOS-Earth & Space Science News* **98**, (2017).
115. D. Isaak, S. Wollrab, D. Horan, G. Chandler, Climate change effects on stream and river temperatures across the northwest US from 1980–2009 and implications for salmonid fishes. *Climatic Change* **113**, 499-524 (2012).
116. K. S. McKelvey *et al.*, Climate change predicted to shift wolverine distributions, connectivity, and dispersal corridors. *Ecological Applications* **21**, 2882-2897 (2011).
117. R. I. McDonald *et al.*, Urban growth, climate change, and freshwater availability. *Proceedings of the National Academy of Sciences* **108**, 6312-6317 (2011).
118. J. Schewe *et al.*, Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences* **111**, 3245-3250 (2014).
119. J. S. Mankin *et al.*, Influence of internal variability on population exposure to hydroclimatic changes. *Environmental research letters* **12**, 044007 (2017).
120. E. Sinha, A. Michalak, V. Balaji, Eutrophication will increase during the 21st century as a result of precipitation changes. *Science* **357**, 405-408 (2017).
121. S. C. Moser *et al.*, in *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, T. T. C. Richmond, G. W. Yohe, Eds. (U.S. Global Change Research Program, Washington, DC, 2014), pp. 579-618. doi:510.7930/J7930MS7933QNW.
122. A. J. Dougherty, Extracting a record of Holocene storm erosion and deposition preserved in the morphostratigraphy of a prograded coastal barrier. *Continental Shelf Research* **86**, 116-131 (2014).
123. D. M. FitzGerald *et al.*, in *Barrier Dynamics and Response to Changing Climate,* L. J. Moore, A. B. Murray, Eds. (Springer, Cham, 2018), pp. 3-56.
124. W. V. Sweet *et al.*, Global and regional sea level rise scenarios for the United States. (2017).
125. K. Lambeck, H. Rouby, A. Purcell, Y. Sun, M. Sambridge, Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences* **111**, 15296-15303 (2014).

126. J. D. Boon, M. Mitchell, Nonlinear change in sea level observed at North American tide stations. *Journal of Coastal Research* **31**, 1295-1305 (2015).
127. T. Ezer, L. P. Atkinson, Accelerated flooding along the US East Coast: on the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic oscillations. *Earth's Future* **2**, 362-382 (2014).
128. W. V. Sweet, J. Park, From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future* **2**, 579-600 (2014).
129. E. E. Lentz *et al.*, Evaluation of dynamic coastal response to sea-level rise modifies inundation likelihood. *Nature Climate Change* **6**, 696 (2016).
130. A. D. Ashton, J. Lorenzo-Trueba, in *Barrier Dynamics and Response to Changing Climate,* L. J. Moore, A. B. Murray, Eds. (Springer International Publishing, Cham, 2018), pp. 277-304.
131. R. E. Kopp, R. L. Shwom, G. Wagner, J. Yuan, Tipping elements and climate–economic shocks: Pathways toward integrated assessment. *Earth's Future* **4**, 346-372 (2016).
132. W. V. Sweet, G. P. Dusek, J. Obeysekera, J. J. Marra, *Patterns and Projections of High Tide Flooding Along the US Coastline Using a Common Impact Threshold*. (US Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services, 2018), pp. 56.
133. M. E. Hauer, J. M. Evans, D. R. Mishra, Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change* **6**, 691 (2016).
134. J. M. Keenan, T. Hill, A. Gumber, Climate gentrification: from theory to empiricism in Miami-Dade County, Florida. *Environmental Research Letters* **13**, 054001 (2018).
135. K. F. Nordstrom, N. L. Jackson, Constraints on restoring landforms and habitats on storm-damaged shorefront lots in New Jersey, USA. *Ocean & Coastal Management* **155**, 15-23 (2018).
136. S. Hallegatte, C. Green, R. J. Nicholls, J. Corfee-Morlot, Future flood losses in major coastal cities. *Nature Climate Change* **3**, 802 (2013).
137. P. Chhetri, J. Corcoran, V. Gekara, C. Maddox, D. McEvoy, Seaport resilience to climate change: mapping vulnerability to sea-level rise. *Journal of Spatial Science* **60**, 65-78 (2015).
138. J. M. Melillo, T. T. C. Richmond, G. W. Yohe, Eds., *The Third National Climate Assessment. Climate Change Impacts in the United States*, (U.S. Global Change Research Program, Washington, D.C., 2014), pp. 841 doi:810.7930/J7930Z7931WJ7932.
139. J. Dell *et al.*, in *Climate change impacts in the United States: The third national climate assessment,* J. Melillo, T. T. Richmond, G. Yohe, Eds. (US Global Change Research Program, Washington, D.C., 2014), pp. 113-129. doi:110.7930/J7930BG7932KWD.
140. Electric Power Research Institute, "Water Use for Electricity Generation and Other Sectors: Recent Changes (1985-2005) and Future Projections (2005- 2030) Technical Report," (Electric Power Research Institute, Palo Alto, CA, 2011).
141. O.-D. Cardona *et al.*, in *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Determinants of Risk: Exposure and Vulnerability. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change,* C. B. Field *et al.*, Eds. (Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2012), pp. 65-108.
142. M. Auffhammer, P. Baylis, C. H. Hausman, Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. *Proceedings of the National Academy of Sciences*, 201613193 (2017).
143. T. Wilbanks, D. Bilello, D. Schmalzer, M. Scott, "Climate Change and Energy Supply and Use. Technical Report to the U.S. Department of Energy in Support of the National

Climate Assessment," (Oak Ridge National Laboratory, U.S. Department of Energy, Office of Science, Oak Ridge, TN., 2012).
144. T. Wilbanks *et al.*, "Climate Change and Infrastructure, Urban Systems, and Vulnerabilities. Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment," (Oak Ridge National Laboratory. U.S. Department of Energy, Office of Science, Oak Ridge, TN, 2012).
145. T. Bennett *et al.*, in *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. Melillo, T. T. Richmond, G. Yohe, Eds. (US Global Change Research Program, Washington, D.C., 2014), pp. 297-317 doi:210.7930/ J7909G7935JR7931.
146. J. K. Maldonado, C. Shearer, R. Bronen, K. Peterson, H. Lazrus, The impact of climate change on tribal communities in the US: displacement, relocation, and human rights. *Climatic Change* **120**, 601-614, doi:610.1007/s10584-10013-10746-z. (2013).
147. P. Lal, J. R. Alavalapati, E. D. Mercer, Socio-economic impacts of climate change on rural United States. *Mitigation and Adaptation Strategies for Global Change* **16**, 819 (2011).
148. J. Huang *et al.*, Recently amplified arctic warming has contributed to a continual global warming trend. *Nature Climate Change* **7**, 875 (2017).
149. T. J. Brinkman *et al.*, Arctic communities perceive climate impacts on access as a critical challenge to availability of subsistence resources. *Climatic change* **139**, 413-427 (2016).
150. E. Hong, R. Perkins, S. Trainor, Thaw settlement hazard of permafrost related to climate warming in Alaska. *Arctic*, 93-103 (2014).
151. A. E. Gibbs, B. M. Richmond, "National assessment of shoreline change: historical change along the north coast of Alaska, US-Canadian border to Icy Cape," (US Geological Survey, 2015).
152. US Government Accountability Office, "Alaska Native Villages: Limited Progress Has Been Made on Relocating Villages Threatened by Flooding and Erosion," (US Government Accountability Office, Washington, DC, 2009).
153. R. Bronen, F. S. Chapin, Adaptive governance and institutional strategies for climate-induced community relocations in Alaska. *Proceedings of the National Academy of Sciences* **110**, 9320-9325 (2013).
154. A. M. Melvin *et al.*, Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences* **114**, E122-E131 (2017).
155. C. Parmesan, G. Yohe, A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**, 37 (2003).
156. B. R. Scheffers *et al.*, The broad footprint of climate change from genes to biomes to people. *Science* **354**, aaf7671 (2016).
157. J. Lenoir, J. C. Svenning, Climate-related range shifts–a global multidimensional synthesis and new research directions. *Ecography* **38**, 15-28 (2015).
158. I.-C. Chen, J. K. Hill, R. Ohlemüller, D. B. Roy, C. D. Thomas, Rapid range shifts of species associated with high levels of climate warming. *Science* **333**, 1024-1026 (2011).
159. M. W. Tingley, M. S. Koo, C. Moritz, A. C. Rush, S. R. Beissinger, The push and pull of climate change causes heterogeneous shifts in avian elevational ranges. *Global Change Biology* **18**, 3279-3290 (2012).
160. J. M. Sunday, A. E. Bates, N. K. Dulvy, Thermal tolerance and the global redistribution of animals. *Nature Climate Change* **2**, 686 (2012).
161. C. J. Brown *et al.*, Ecological and methodological drivers of species' distribution and phenology responses to climate change. *Global Change Biology* **22**, 1548-1560 (2016).

162. M. T. Burrows *et al.*, The pace of shifting climate in marine and terrestrial ecosystems. *Science* **334**, 652-655 (2011).
163. E. S. Poloczanska *et al.*, Global imprint of climate change on marine life. *Nature Climate Change* **3**, 919 (2013).
164. C. Parmesan, M. J. Attrill, in *Explaining Ocean Warming: Causes, Scale, Effects and Consequences. IUCN Full Report,* D. Laffoley, J. M. Baxter, Eds. (IUCN, Gland, Switzerland, 2016), pp. 439-450.
165. B. I. Cook, E. M. Wolkovich, C. Parmesan, Divergent responses to spring and winter warming drive community level flowering trends. *Proceedings of the National Academy of Sciences* **109**, 9000-9005 (2012).
166. L. F. Pitelka *et al.*, Plant migration and climate-change: A more realistic portrait of plant migration is essential to predicting biological responses to global warming in a world drastically altered by human activity. *American Scientist* **85**, 464-473 (1997).
167. V. Devictor *et al.*, Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Climate Change* **2**, 121 (2012).
168. R. A. Bay *et al.*, Genomic signals of selection predict climate-driven population declines in a migratory bird. *Science* **359**, 83-86 (2018).
169. C. G. Willis *et al.*, Favorable climate change response explains non-native species' success in Thoreau's woods. *PloS one* **5**, e8878 (2010).
170. M. C. Singer, C. Parmesan, Phenological asynchrony between herbivorous insects and their hosts: signal of climate change or pre-existing adaptive strategy? *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **365**, 3161-3176 (2010).
171. M. C. Singer, Shifts in time and space interact as climate warms. *Proceedings of the National Academy of Sciences*, 201718334 (2017).
172. J. Settele *et al.*, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change,* C. B. Field *et al.*, Eds. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014), chap. 4, pp. 271-359.
173. H. O. Pörtner *et al.*, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change,* C. B. Field *et al.*, Eds. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014), chap. 6, pp. 411-484.
174. R. Dirzo *et al.*, Defaunation in the Anthropocene. *science* **345**, 401-406 (2014).
175. J. L. Blois, P. L. Zarnetske, M. C. Fitzpatrick, S. Finnegan, Climate Change and the Past, Present, and Future of Biotic Interactions. *Science* **341**, 499-504 (2013).
176. M. C. Urban, Accelerating extinction risk from climate change. *Science* **348**, 571-573 (2015).
177. J. N. Larsen *et al.*, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change,* V. R. Barros *et al.*, Eds. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014), chap. 28, pp. 1567-1612.
178. T. P. Hughes *et al.*, Global warming transforms coral reef assemblages. *Nature* **556**, 492-496 (2018).
179. C. D. Allen *et al.*, A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* **259**, 660-684 (2010).

180. O. Hoegh-Guldberg, E. S. Poloczanska, W. Skirving, S. Dove, Coral Reef Ecosystems under Climate Change and Ocean Acidification. *Frontiers in Marine Science* **4**, (2017).
181. H. Tian *et al.*, The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. *Nature* **531**, 225 (2016).
182. S. C. Doney, V. J. Fabry, R. A. Feely, J. A. Kleypas, Ocean acidification: the other CO2 problem. (2009).
183. A. L. Strong, K. J. Kroeker, L. T. Teneva, L. A. Mease, R. P. Kelly, Ocean acidification 2.0: Managing our changing coastal ocean chemistry. *BioScience* **64**, 581-592 (2014).
184. L. Bopp *et al.*, Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences* **10**, 6225-6245 (2013).
185. C. Hauri *et al.*, Ocean acidification in the California current system. *Oceanography* **22**, 60-71 (2009).
186. J. T. Mathis, J. N. Cross, W. Evans, S. C. Doney, Ocean acidification in the surface waters of the Pacific-Arctic boundary regions. *Oceanography* **28**, 122-135 (2015).
187. D. L. Breitburg *et al.*, And on top of all that… Coping with ocean acidification in the midst of many stressors. *Oceanography* **28**, 48-61 (2015).
188. B. D. Eyre *et al.*, Coral reefs will transition to net dissolving before end of century. *Science* **359**, 908-911 (2018).
189. O. Hoegh-Guldberg, E. S. Poloczanska, W. Skirving, S. Dove, Coral reef ecosystems under climate change and ocean acidification. *Frontiers in Marine Science* **4**, 158 (2017).
190. K. J. Kroeker *et al.*, Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology* **19**, 1884-1896 (2013).
191. N. Bednaršek *et al.*, Limacina helicina shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. *Proc. R. Soc. B* **281**, 20140123 (2014).
192. D. K. Gledhill *et al.*, Ocean and coastal acidification off New England and Nova Scotia. *Oceanography* **28**, 182-197 (2015).
193. J. A. Hare *et al.*, A vulnerability assessment of fish and invertebrates to climate change on the Northeast US Continental Shelf. *PloS one* **11**, e0146756 (2016).
194. A. Barton *et al.*, Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography* **28**, 146-159 (2015).
195. J. A. Ekstrom *et al.*, Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nature Climate Change* **5**, 207 (2015).
196. C. Cattano, J. Claudet, P. Domenici, M. Milazzo, Living in a high CO2 world: a global meta-analysis shows multiple trait-mediated fish responses to ocean acidification. *Ecological Monographs*, (2018).
197. T. A. Carleton, S. M. Hsiang, Social and economic impacts of climate. *Science* **353**, aad9837 (2016).
198. T. Carleton, S. Hsiang, M. Burke, Conflict in a changing climate. *The European Physical Journal Special Topics* **225**, 489-511 (2016).
199. J. O'Loughlin *et al.*, Climate variability and conflict risk in East Africa, 1990–2009. *Proceedings of the National Academy of Sciences*, 201205130 (2012).
200. S. M. Hsiang, K. C. Meng, M. A. Cane, Civil conflicts are associated with the global climate. *Nature* **476**, 438 (2011).
201. E. McGuirk, M. Burke, "The economic origins of conflict in Africa," (National Bureau of Economic Research, 2017).
202. D. Card, G. B. Dahl, Family violence and football: The effect of unexpected emotional cues on violent behavior. *The Quarterly Journal of Economics* **126**, 103-143 (2011).

203. B. Jacob, L. Lefgren, E. Moretti, The dynamics of criminal behavior evidence from weather shocks. *Journal of Human resources* **42**, 489-527 (2007).
204. M. Ranson, Crime, weather, and climate change. *Journal of environmental economics and management* **67**, 274-302 (2014).
205. P. Baylis, Temperature and temperament: Evidence from a billion tweets. *Energy Institute at HAAS working paper*, (2015).
206. D. T. Kenrick, S. W. MacFarlane, Ambient temperature and horn honking: A field study of the heat/aggression relationship. *Environment and behavior* **18**, 179-191 (1986).
207. R. P. Larrick, T. A. Timmerman, A. M. Carton, J. Abrevaya, Temper, temperature, and temptation: Heat-related retaliation in baseball. *Psychological Science* **22**, 423-428 (2011).
208. T. A. Carleton, Crop-damaging temperatures increase suicide rates in India. *Proceedings of the National Academy of Sciences* **114**, 8746-8751 (2017).
209. M. Burke, S. M. Hsiang, E. Miguel, Climate and Conflict. *Annual Review of Economics* **7**, 577-617 (2015).
210. S. Hsiang *et al.*, Estimating economic damage from climate change in the United States. *Science* **356**, 1362-1369 (2017).
211. M. B. Burke, E. Miguel, S. Satyanath, J. A. Dykema, D. B. Lobell, Climate robustly linked to African civil war. *Proceedings of the National Academy of Sciences* **107**, E185-E185 (2010).
212. A. T. Bohlken, E. J. Sergenti, Economic growth and ethnic violence: An empirical investigation of Hindu—Muslim riots in India. *Journal of Peace research* **47**, 589-600 (2010).
213. P. J. Burke, A. Leigh, Do output contractions trigger democratic change? *American Economic Journal: Macroeconomics* **2**, 124-157 (2010).
214. N. Obradovich, Climate change may speed democratic turnover. *Climatic Change* **140**, 135-147 (2017).
215. M. Dell, B. F. Jones, B. A. Olken, Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics* **4**, 66-95 (2012).
216. P. J. Burke, Economic growth and political survival. *The BE Journal of Macroeconomics* **12**, (2012).
217. N. K. Kim, Revisiting economic shocks and coups. *Journal of Conflict Resolution* **60**, 3-31 (2016).
218. R. Hornbeck, The enduring impact of the American Dust Bowl: Short-and long-run adjustments to environmental catastrophe. *American Economic Review* **102**, 1477-1507 (2012).
219. S. Feng, M. Oppenheimer, Applying statistical models to the climate–migration relationship. *Proceedings of the National Academy of Sciences* **109**, E2915-E2915 (2012).
220. S. Feng, A. B. Krueger, M. Oppenheimer, Linkages among climate change, crop yields and Mexico–US cross-border migration. *Proceedings of the National Academy of Sciences* **107**, 14257-14262 (2010).
221. P. Bohra-Mishra, M. Oppenheimer, S. M. Hsiang, Nonlinear permanent migration response to climatic variations but minimal response to disasters. *Proceedings of the National Academy of Sciences* **111**, 9780-9785 (2014).
222. J. V. Henderson, A. Storeygard, U. Deichmann, Has climate change driven urbanization in Africa? *Journal of Development Economics* **124**, 60-82 (2017).
223. F. D. Hidalgo, S. Naidu, S. Nichter, N. Richardson, Economic determinants of land invasions. *The Review of Economics and Statistics* **92**, 505-523 (2010).

224. A. Missirian, W. Schlenker, Asylum applications respond to temperature fluctuations. *Science* **358**, 1610-1614 (2017).
225. Center for Climate and Security, "Climate and Security Resources: U.S. Government, Defense," (Council on Strategic Risks, https://climateandsecurity.org/resources/u-s-government/defense/, Washington, DC. , 2018).
226. CNA Military Advisory Board, National security and the threat of climate change. *Alexandria: CNA Corporation*, (2007).
227. D. Coates, "Worldwide Threat Assessment of the US Intelligence Community," (National Intelligence Council, 2018).
228. Congress of the United States, *H.R.2810. National Defense Authorization Act*. (2018).
229. F. Femia, C. Werrell, "Chronology of U.S. Military Leadership on Climate Change and Security: 2017-2018," (The Center for Climate and Security, 2018).
230. Union of Concerned Scientists, "The US Military on the Front Lines of Rising Seas," (Union of Concerned Scientists, 2016).
231. DOD, "Climate-Related Risk to DoD Infrastructure Initial Vulnerability Assessment Survey (SLVAS) Report," (Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, U.S. Department of Defense, 2018).
232. G. Feller, Casualty Costs of Fuel and Water Resupply Convoys in Afghanistan and Iraq. *Army Technology*, (25 February 2010).
233. P. Stewart, in *Reuters*. (2018).
234. Strategic Studies Institute Army War College, "Russia in the Arctic," (Strategic Studies Institute Army War College, 2011).
235. DOD, "Quadrennial Defense Review FY2010," (U.S. Department of Defense, 2010).
236. CNA Military Advisory Board, *National security and the accelerating risks of climate change*. (CNA Corporation, 2014).
237. DOD, "Department of Defense Strategic Sustainability Performance Plan FY2015," (U.S. Department of Defense, 2015).
238. M. Burke *et al.*, Opportunities for advances in climate change economics. *Science* **352**, 292-293 (2016).
239. A. Isen, M. Rossin-Slater, R. Walker, Relationship between season of birth, temperature exposure, and later life wellbeing. *Proceedings of the National Academy of Sciences* **114**, 13447-13452 (2017).
240. T. Deryugina, The fiscal cost of hurricanes: disaster aid versus social insurance. *American Economic Journal: Economic Policy* **9**, 168-198 (2017).
241. K. Karbownik, A. Wray, Long-run Consequences of Exposure to Natural Disasters. *Journal of Labor Economics* **in press**, (2019).
242. T. Houser, S. Hsiang, R. Kopp, K. Larsen, *Economic risks of climate change: an American prospectus*. (Columbia University Press, 2015).
243. M. Burke, S. M. Hsiang, E. Miguel, Global non-linear effect of temperature on economic production. *Nature* **527**, 235 (2015).
244. M. Burke, W. M. Davis, N. S. Diffenbaugh, Large potential reduction in economic damages under UN mitigation targets. *Nature* **557**, 549 (2018).
245. S. M. Hsiang, A. S. Jina, "The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6,700 cyclones," (National Bureau of Economic Research, 2014).
246. T. Deryugina, S. Hsiang, "The marginal product of climate," (National Bureau of Economic Research, 2017).
247. W. Schlenker, M. J. Roberts, Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of sciences* **106**, 15594-15598 (2009).

248. J. Graff Zivin, M. Neidell, Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics* **32**, 1-26 (2014).
249. O. Deschênes, M. Greenstone, Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the US. *American Economic Journal: Applied Economics* **3**, 152-185 (2011).
250. R. E. Kopp *et al.*, Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* **2**, 383-406 (2014).
251. K. A. Emanuel, Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proceedings of the National Academy of Sciences* **110**, 12219-12224 (2013).
252. C. Mora *et al.*, Global risk of deadly heat. *Nature Climate Change* **7**, 501 (2017).
253. P. E. Dennison, S. C. Brewer, J. D. Arnold, M. A. Moritz, Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters* **41**, 2928-2933 (2014).