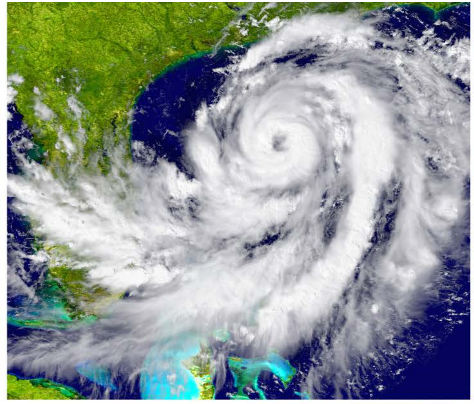
ENVIRONMENTAL LAW INSTITUTE





Climate Science and Law for Judges:

Impacts of Climate Change

January 2023

CLIMATE JUDICIARY PROJECT

ENVIRONMENTAL LAW • INSTITUTE®

Acknowledgements

This module is part of the *Climate Science and Law Curriculum* of the Climate Judiciary Project of the Environmental Law Institute. It was written by Katharine J. Mach. We are grateful to our advisors Jonathan Adler, Ann Carlson, Kristie Ebi, Chris Field, Jeremy Fogel, Inez Fung, Michael Gerrard, Geoffrey Heal, Barry Hill, Michael Oppenheimer, Stephen Pacala, Justice Ronald Robie, Judge Michael Simon, and Judge David Tatel for their contributions to the content of the whole curriculum as well as on this module. We are also grateful for the contributions of the three anonymous reviewers of this module.

This series is edited by Paul A. Hanle and Sandra Nichols Thiam. ELI staff contributing to the curriculum include Staff Attorney Jarryd Page and Senior Manager Sarah Roth, with additional contributions from Jay Austin, Selah Bell, John Doherty, and Rebecca Ramirez.

About the Environmental Law Institute

The Environmental Law Institute makes law work for people, places, and the planet. Since 1969, ELI has played a pivotal role in shaping the fields of environmental law, policy, and management, domestically and abroad. Today, in our sixth decade, we are an internationally recognized, non-partisan publishing, research, and education center working to strengthen environmental protection by improving law and governance worldwide.

Cover design by Evan Odoms and Tori Rickman.

Impacts of Climate Change

by Katharine J. Mach

This module introduces the main consequences of increased heating of the planet and the causal connections between emissions, changes in the climate, and impacts.

Table of Contents

I. Introduction

The warming climate is already affecting people and nature around the globe. As the climate continues to change, the impacts that occur will be determined by how much we reduce emissions of heat-trapping gases and how well communities and societies adapt and prepare.

This module draws from objective, mainstream science to discuss well-understood changes and risks. It relies on major scientific assessments conducted by experienced and accomplished scientists nationally and globally under the auspices of the Intergovernmental Panel on Climate Change (IPCC), the U.S. National Climate Assessment, and the U.S. National Academies of Sciences, Engineering, and Medicine. Before publication, these assessments underwent multiple rounds of comprehensive scientific review, sometimes by thousands of experts, ensuring that they reflect a scientific consensus based on the best available evidence (see module on What Is Causing Climate Change). In addition, each report gained approval through a U.S. interagency process, by the U.S. National Academies, or by a global intergovernmental panel.

The module first introduces the nature of scientific evidence and approaches for the impacts of climate change. It next presents a conceptual framework for climate change impacts, focused on the ways in which climate risks arise from climate hazards and exposure, vulnerability, and responses to them. Major categories of climate impacts and risks, including both impacts that have already occurred and future risks, are then reviewed overall and type by type.

II. Scientific Evidence and Approaches

This module relies on the following recent international and national assessments of the state of science on climate change impacts:

- the IPCC's most recent assessments of the impacts of climate change, all of which are relevant to this module[1]
- the most recent National Climate Assessment (NCA), conducted under the U.S. Global Change Research Program (USGCRP)[2]
- recent reports from the U.S. National Academies relevant to climate change impacts[3]

---

[1] *See* INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC), CLIMATE CHANGE 2014: IMPACTS, ADAPTATION, AND VULNERABILITY. PART A: GLOBAL AND SECTORAL ASPECTS (2014), https://archive.ipcc.ch/report/ar5/wg2/ (part of Fifth Assessment Report) [hereinafter IPCC, CLIMATE CHANGE 2014]; IPCC, GLOBAL WARMING OF 1.5°C (2018), https://www.ipcc.ch/sr15/; IPCC, CLIMATE CHANGE AND LAND (2019), https://www.ipcc.ch/srccl/; IPCC, SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE (2019), https://www.ipcc.ch/srocc/; IPCC, CLIMATE CHANGE 2022: IMPACTS, ADAPTATION AND VULNERABILITY (2022), https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/ (part of Sixth Assessment Report) [hereinafter IPCC, CLIMATE CHANGE 2022].

[2] *See* U.S. GLOBAL CHANGE RESEARCH PROGRAM (USGCRP), CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT VOL. I (2017), https://science2017.globalchange.gov/; USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT VOL. II: IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES (2018), https://nca2018.globalchange.gov/.

[3] *See* NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE (NASEM) & THE ROYAL SOCIETY, CLIMATE CHANGE: EVIDENCE & CAUSES UPDATE 2020 (2020) [hereinafter NASEM, EVIDENCE & CAUSES]; NASEM,

These assessments of climate change impacts rely on diverse types of evidence from different disciplines of scholarship and methods of analysis. These different forms of evidence, which are essential since climate change affects so many sectors of human and natural systems, include empirical observations of the state of and trends in human and natural systems; the results of experiments in laboratories, ecosystems, and social systems; understanding of processes within climatic, ecological, and social systems; statistical analyses; and models that simulate or describe dynamics, occurrences, or trends in coupled human–natural systems.[4]

Often, a given human or natural system is studied through different complementary methods. For example, one form of evidence comes from controlled experiments in laboratories to evaluate the consequences of increases in temperature and carbon dioxide for agricultural crops, coral reef species, and forest tree species. The same agricultural and ecological systems can be studied through outdoor field experiments, in which natural or artificial environmental alterations are used to understand the impacts of increasing temperature, carbon dioxide, and other climate changes. Such experiments might involve coral reef species, for instance, that are exposed to different levels of temperature increase and ocean acidification, with subsequent measurement of consequences for growth or mortality. Or agricultural crops can be exposed to increased temperature and carbon dioxide, with measurements of the plants being made above and below ground to determine the impacts of the experimentally altered climate.

Another approach is to use different models to evaluate impacts that have occurred to date and those that may occur in the future. These types of analyses can involve evaluation of how much human-induced emissions of heat-trapping gases, from fossil fuels, industry, and land use, have contributed to outcomes as diverse as temperature increases, changes in rainfall, rising seas, and impacts for ecosystems, agriculture, societies, and economies. Model-based analyses can assess the relative contribution of emissions of greenhouse gases and other anthropogenic drivers to outcomes that have occurred in the past. They also can determine the impacts expected under different future scenarios of greenhouse gas emissions and other drivers of change.

It is also important to be aware of knowledge gaps relevant to ongoing scientific research. For instance, scientific research and assessment are increasingly identifying the crucial role of compounding and cascading dynamics, such as when wildfire or drought make a region more prone to subsequent flooding because of hardened soils less able to absorb water, even though such interactions have been less well studied to date. As another example, scientific evaluation has often had the highest confidence about central estimates of the impacts that will occur, but increasingly analyses are exploring the distribution of outcomes and the different ways people are impacted.

Scientific and technical evidence on climate change is essential for understanding the impacts of climate change occurring at present and under possible future scenarios. These impacts will depend

---

A DECISION FRAMEWORK FOR INTERVENTIONS TO INCREASE THE PERSISTENCE AND RESILIENCE OF CORAL REEFS (2019); NASEM, UNDERSTANDING THE LONG-TERM EVOLUTION OF THE COUPLED NATURAL-HUMAN COASTAL SYSTEM: THE FUTURE OF THE U.S. GULF COAST (2018) [hereinafter NASEM, NATURAL-HUMAN COASTAL SYSTEM]; NASEM, ATTRIBUTION OF EXTREME WEATHER EVENTS IN THE CONTEXT OF CLIMATE CHANGE (2016); INSTITUTE OF MEDICINE, HEALTHY, RESILIENT, AND SUSTAINABLE COMMUNITIES AFTER DISASTERS: STRATEGIES, OPPORTUNITIES, AND PLANNING FOR RECOVERY (2015); NATIONAL RESEARCH COUNCIL, REDUCING COASTAL RISK ON THE EAST AND GULF COASTS (2014).

[4] IPCC, CLIMATE CHANGE 2014, *supra* note 1.

strongly on the amount of climate change that occurs and on the adaptation policies and measures that are adopted.

III. Conceptual Framework for Climate Risk

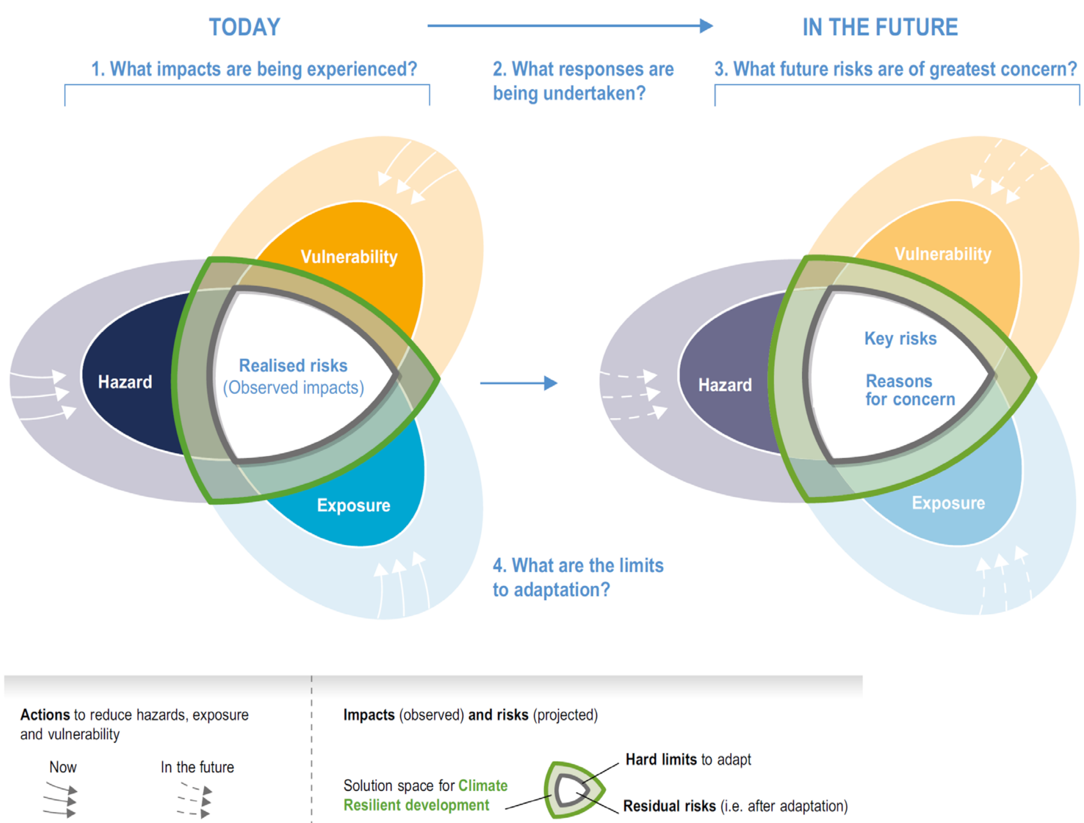


Figure 1. A conceptual framework for climate risk. Climate risk is the potential for climate-related impacts. Climate change has already led to climate risks being realized and observed, and it will continue to increase risks in the future, including risks of great concern, often assessed as key risks and reasons for concern. Climate risk emerges from the interaction of climate-related hazards, vulnerability, and exposure along with actions and responses undertaken. Figure adapted from IPCC (2022).

Climate change impacts are the effects or consequences of climate change for natural and human systems. There are many different types of climate change impacts, including consequences for health and well-being, livelihoods and economies, ecosystems, cultures, and infrastructure.

The impacts of climate change result from complex interactions among the climate, ecosystems, and societies. The likelihoods of diverse impacts are changing as a result of hazardous conditions shifting in their frequency or intensity. For example, more frequent and extreme heat changes the likelihood of health impacts.

Increasingly, a risk framework has been applied in the context of climate change impacts (Figure 1).[5] Risk, in such a framework, is the potential for climate-related impacts. It emerges from the interaction of climate-related hazards, with the vulnerability of exposed human and natural systems, including their susceptibility to harm, their capacities to cope and adapt, and their responses. These determinants of risk are discussed in the subsections below. A focus on risk enables use of tools and methods for assessing the role of risk management, preparedness, and adaptation in determining the scope and severity of potential impacts. Such a focus also can connect climate-related impacts today to those in the future.

A. Hazards

The term "hazards" is used to refer to the potential occurrence of climate-related physical events, trends, or impacts. As the climate warms, many associated changes in the physical climate system pose hazards that place people and ecosystems at risk.[6] The short descriptions of a few major categories of climate-related hazards given below (see *Changing Climate Hazards*) draw closely from the key findings of the *Climate Science Special Report: Fourth National Climate Assessment, Volume I*.

As observed in the module on How Climate Science Works, the current climate is now approximately 1.8°F (1°C) warmer than pre-industrial times, as measured by the global annually averaged air temperature at the surface of the Earth. This warming makes recent times the warmest period experienced by modern civilization. Human activities, especially emissions of heat-trapping greenhouse gases, are the dominant cause of warming that has occurred since the middle of the last century. These emissions of heat-trapping gases are largely from fossil fuels and industry, as well as land use, land use change, and forestry.[7] Other plausible explanations for the observed warming do not exist.

For the United States, annual average temperatures are expected to rise by another 2.5°F in the next few decades (comparing the period 2021–2050 with 1976–2005) across the full range of plausible climate scenarios. In the second half of the century and beyond, the amount of climate change that occurs will depend strongly on levels of greenhouse gas emissions globally, especially of carbon dioxide. With continued high emissions, the global average temperature increase compared with pre-industrial times could be 9°F (5°C) by the end of the century. With ambitious reductions in emissions, global average temperature increase could be limited to 3.6°F (2°C) or less. As discussed below, these different scenarios of potential global warming have profoundly different implications for the scope, severity, and irreversibility of the climate change impacts that will occur.

B. Vulnerability and Exposure

---

[5] IPCC, CLIMATE CHANGE 2022, *supra* note 1.
[6] NASEM, EVIDENCE & CAUSES, *supra* note 3.
[7] IPCC, CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE (2022), https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/.

Climate-related hazards alone do not produce impacts for people, ecosystems, societies, and economies. Instead, impacts result from the interaction of hazards with the exposure and vulnerability of people and nature, including their capacities to cope, adapt, and respond.

Vulnerability refers to the sensitivity of people and ecosystems to be adversely affected—their susceptibility to harm—and the lack of capacity to cope and adapt. Exposure is the presence of people, ecosystems, and assets in places where climate-related hazards could occur. Impacts from climate-related extremes have demonstrated substantial vulnerability and exposure of people and ecosystems from climate changes that have occurred already.

Importantly, people are affected differentially by the impacts of climate change.[8] Vulnerability and exposure to climate change impacts are shaped by inequalities in societies and uneven socioeconomic development. Intersecting social processes, such as the history of redlining and siting of industrial facilities and associated pollutants in communities of color, often result in marginalized individuals and underserved communities being especially vulnerable to climate change and to adverse impacts from climate responses, thus leading to disproportionate risk.

C. Risks

Given these definitions of hazards, vulnerability, and exposure, climate-related risks result from the interaction of hazards with people and ecosystems that are exposed and vulnerable and that respond—which includes most people and ecosystems, albeit in different ways. When a climate-related hazard does occur (e.g., a heat wave, wildfire, flood, or drought), the impacts that result depend on both the vulnerability and the exposure of people, human settlements, economies, agricultural systems, and ecosystems, including their responses and constraints and limits on their abilities to cope and adapt. For example, if individuals live in high-quality housing that is "flood proofed" through elevation of the structures and rigorous building codes, they will be less susceptible to damages from flooding and high winds. Alternatively, if they live in a location with very low probability of flooding, they have much lower flood risks because of reduced exposure to flood hazards. As a contrasting example, people living in poorly constructed housing with inadequate insulation and energy insecurity are more susceptible to heat waves, and across the United States formerly redlined neighborhoods have greater exposure to hazardous heat due to factors exacerbating urban heat, such as lower tree canopy cover and greater presence of impervious surfaces.

A risk framework is useful for understanding the increasingly severe, interconnected, and sometimes irreversible climate-related impacts occurring, the ways in which they differ across communities and sectors of human activities, and the potential for reducing risks at present and into the future through reductions of emissions of heat-trapping gases and through actions to prepare and adapt.[9]

In sum, the impacts of climate change are a function of the ways in which climate change is affecting climate-related hazards. They also depend upon who or what is in the path of harm (i.e., exposure) and the susceptibility of exposed individuals and systems to the hazards (i.e., vulnerability), which includes their capacities to cope, adapt, and respond.

---

[8] IPCC, CLIMATE CHANGE 2022, *supra* note 1.
[9] IPCC, CLIMATE CHANGE 2022, *supra* note 1.

D. Changing Climate Hazards

A large variety of climate-related hazards leading to climate risks have been and will be exacerbated by climate change.[10]

High temperatures. Increases in average temperatures are hazards, as are changes in extreme heat. In the United States and globally, heat waves have become more frequent, and extreme cold temperatures and cold waves are now less frequent.[11] Under additional increases of global average temperatures, heat extremes will also continue to increase, including heat waves, hot days and hot nights, and heat in combination with humidity.

Changing precipitation patterns, including heavy rainfall. A warmer atmosphere can hold more water, and global warming overall is leading to multiple shifts in where, when, and how much precipitation falls. Nationally and globally, heavy rainfall is becoming more intense and frequent. In the United States, the largest changes in heavy rainfall to date have taken place in the Northeast.

Further increases are expected under additional climate change. For example, the frequency and severity of land-falling "atmospheric rivers"—narrow streams of moisture that contribute to snowpack, annual precipitation, and severe flooding events—are projected to increase on the West Coast of the United States.

Drought. With continued emissions of heat-trapping gases (and water resources management similar to the present), the potential for chronic, long-duration hydrological drought will increase within the century. Glaciers have lost mass through melting and snow cover has been reduced due to global warming, which both have consequences for water availability.[12] Additionally, spring melt is occurring earlier, which in combination with reduced snowpack affects water resources in the western United States. These trends are expected to continue.

Wildfire. Wildfire is shaped by many factors, including present-day land use patterns and historical fire suppression. Despite these multiple influences, human-induced climate change is intensifying the occurrence of fires, especially through changes in daily and seasonal temperatures as well as more complex factors involving weather and climate. The occurrence of large forest fires in the American West and Alaska has increased since the early 1980s, and further increases are projected in these regions under additional climate change.

Sea-level rise. A warming climate causes the amount and volume of water in the oceans to increase, resulting in sea-level rise. Changes in sea level have multiple drivers, including the fact that warmer water takes up more volume and that melting of ice now on land leads to increases in the amount of water in the ocean.

Climate change caused by humans has substantially contributed to observed sea-level rise. The global average level of the ocean surface has increased by about 7–8 inches since 1900. Almost one-half of this rise (~3 inches) has taken place since 1993. Sea-level rise over the last century exceeds rates for all centuries over the past 2,800 years at least, which is measured through reconstructions

---

[10] USGCRP, CLIMATE SCIENCE SPECIAL REPORT, *supra* note 2.
[11] NASEM, ATTRIBUTION OF EXTREME WEATHER, *supra* note 3.
[12] IPCC, SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE, *supra* note 1.

of historical sea levels in coastal systems. Based on centuries of tide gauge measurements and also satellite data, sea-level rise has accelerated in recent decades. The occurrence of high-tide flooding, sometimes called sunny day or recurrent flooding, is now increasing in many regions of the United States.

In any given location, the amount of sea-level rise depends on large-scale factors, such as the way that melting ice sheets lead to different amounts of sea-level rise across ocean basins, as well as regional and local factors such as the subsidence or uplift of land or groundwater extraction. As a result of such factors, sea-level rise on the East and Gulf Coasts of the United States is projected to be greater than the global average.

Sea-level rise will continue into the future. As the climate system continues to warm over the next 15 years, several more inches of sea-level rise will occur. By 2100, a total sea-level rise of 1–4 feet is expected. Given substantial uncertainties about potential collapse of ice sheets in Greenland and Antarctica, sea-level rise of as much as 8 feet by 2100 cannot be ruled out.

Ocean acidification. Oceans around the world are absorbing more than one-quarter of the carbon dioxide emitted into the atmosphere from human activities. When carbon dioxide is dissolved into ocean waters, they become more acidic, which can be detrimental to species and ecosystems in the oceans. In addition, oxygen levels in the global ocean have decreased from the surface down to 3,000 feet as a result of multiple interacting factors, such as warmer waters holding less oxygen and global warming leading to changes in ocean circulation.

Extreme weather and storms. Increases in precipitation rates associated with hurricanes are expected into the future, along with a potential for increases in the numbers of very intense tropical cyclones. The combination of increases in tropical cyclone rainfall, extreme waves, and relative sea-level rise have exacerbated extreme sea-level events and coastal hazards. Tornadoes also have become more variable, with more tornadoes now occurring on fewer days.

E. Adaptation and Resilience

The impacts of climate change are modulated by the ways in which people, societies, and ecosystems adjust to and cope with climate—including its variability and extremes and changes over time. Generally, adaptation involves a continuing process of risk management without a defined endpoint.[13] Adaptation plans and implemented measures are often relevant to other development and societal objectives, and their evaluation includes dimensions of equity and justice, cultural heritage, health, and security. In the United States, adaptation planning and implementation are being led by governments, the private sector, and nonprofit organizations. Proactive adaptation can yield benefits in both the near term and the long term.

Adaptation includes consideration of climate change across a range of activities. Entry points to adaptation include resilience, preparedness and safeguarding, and disaster risk reduction. For example, many states and municipalities across the United States are now increasing climate preparedness for both climate shocks and stressors (e.g., the ways in which climate change is intensifying disaster impacts as well as smaller, recurrent episodes such as high-tide flooding). Actions taken include screening infrastructure for climate impacts and adjusting them for greater

[13] *See Chapter 28: Reducing Risks Through Adaptation*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.

resilience, deploying early warning systems attuned to differential needs across affected populations, and developing long-term plans to ensure that ongoing investments can flexibly adapt under intensifying climate change.

In any given state of the climate system, it hardly ever makes sense—or is possible—to invest in adaptation to the point where the probability of climate-related impacts is zero. For example, the costs of eliminating all flooding impacts across the entirety of the United States would be enormous, exceeding the benefits—and these adaptation costs are increasingly a climate impact in and of themselves. The implication is that climate change impacts are a balance of three categories: impacts reduced or avoided through climate change mitigation, impacts reduced or avoided through climate change adaptation, and the impacts that remain (the "residual" after other climate responses have occurred). This residual, which may involve substantial damages and losses, will be determined by how much investment is made in both mitigation and adaptation. And inadequate mitigation increases the likelihood that limits to adaptation are reached, in turn leading to severe, pervasive, and irreversible climate-related impacts.

IV. Dangerous Interference With the Climate System

As explained in the How Climate Science Works and What Is Causing Climate Change modules, emissions of carbon dioxide and other long-lived heat-trapping gases lead to persistent atmospheric warming. The warming from human-induced emissions since pre-industrial times will persist for centuries to millennia. Long-term changes in the climate system—including, importantly, sea-level rise—will continue even after warming of the climate stabilizes because of the inertia of the climate system.

For any given limit on global temperature increase, there is a finite budget for how much long-lived heat-trapping gases can be put into the atmosphere.[14] Therefore, to halt further increases in the warming of the global climate, net global emissions of greenhouse gases must be zero. The maximum temperature that results will be determined by the cumulative emissions of carbon dioxide and other greenhouse gases along with other drivers of warming. In modeled emissions pathways that limit warming to 1.5°C–2°C, global human-induced emissions of greenhouse gases reach net zero between 2050 and 2070 and also involve active removal of carbon dioxide from the atmosphere and substantial "negative" emissions.

Climate change assessment has long focused on identifying potentially severe impacts so that dangerous interference with the climate system from human activities can be avoided or at least limited. Significant risks can result from high climate-related hazards, high vulnerability of societies and systems exposed, or both. At a global scale, five major reasons for concern (Figures 1 and 2) are:

- High risks to unique systems such as Arctic sea ice and coral reef systems
- Intensifying risks from extreme weather events
- Disproportionate risks for disadvantaged people and communities
- Globally aggregated risks for economies and ecosystems
- The increasing potential for abrupt and irreversible changes

[14] *See* IPCC, GLOBAL WARMING OF 1.5°C, *supra* note 1.

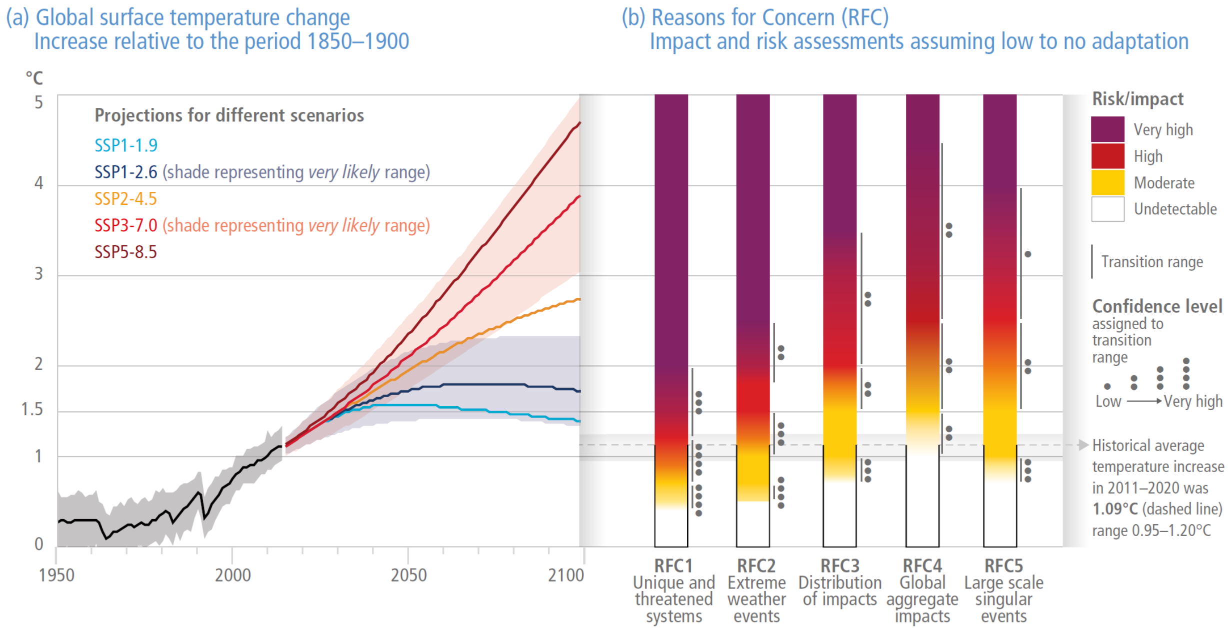


Figure 2. Global risks with increasing levels of warming. Figure from IPCC (2022).

Levels of risks increase with additional warming, and the levels of risks that would occur at 1.5°C, 2°C, and higher temperature increases can be differentiated.[15] When global warming exceeds 1.5°C above pre-industrial levels, risks for unique and threatened systems will start to become very high, risks from extreme weather events will be high, and the distribution of impacts will be widespread. Above 2°C of warming, the risks of global aggregate impacts and large-scale singular events, such as collapse of the West Antarctic Ice Sheet, will also become high. These and other risks have informed global goal-setting for long-term temperature limits, including those in the Paris agreement, which aims to keep warming well below a 2°C global mean temperature increase above pre-industrial levels.

V. Types of Observed Climate Change Impacts and Future Risks

Impacts from climate changes are already widespread and consequential. Under current levels of warming, major impacts from climate change can increasingly be detected and attributed to human-induced emissions of heat-trapping gases.[16] Key risks central to the danger posed by climate change (Figure 1) are risks of food and water insecurity, risks to human health and livelihoods, risks from climate-related extremes (including cascading failures), and risks to ecosystems and biodiversity. These and other potential impacts emphasize the need to combine preparedness for current and ongoing climate change impacts with actions to limit the amount of warming that occurs.

Important types of observed climate change impacts and future risks are discussed in turn below—for ecosystems; human health and well-being; food production and security; water resources and security; infrastructure, economies, and finance; and compounding risks across regions. Each subsection concludes with a description of adaptation options available for increasing the

[15] IPCC, CLIMATE CHANGE 2022, *supra* note 1.
[16] *See* IPCC, GLOBAL WARMING OF 1.5°C, *supra* note 1.

preparedness and resilience of natural and human systems. The most recent global assessment of climate change impacts that are already occurring is summarized in Figure 3. Across types of climate risks, including key risks most deserving of societies attention, risk levels increase multiple fold into the second half of the century in many cases if emissions of heat-trapping gases are not very substantially reduced.[17]

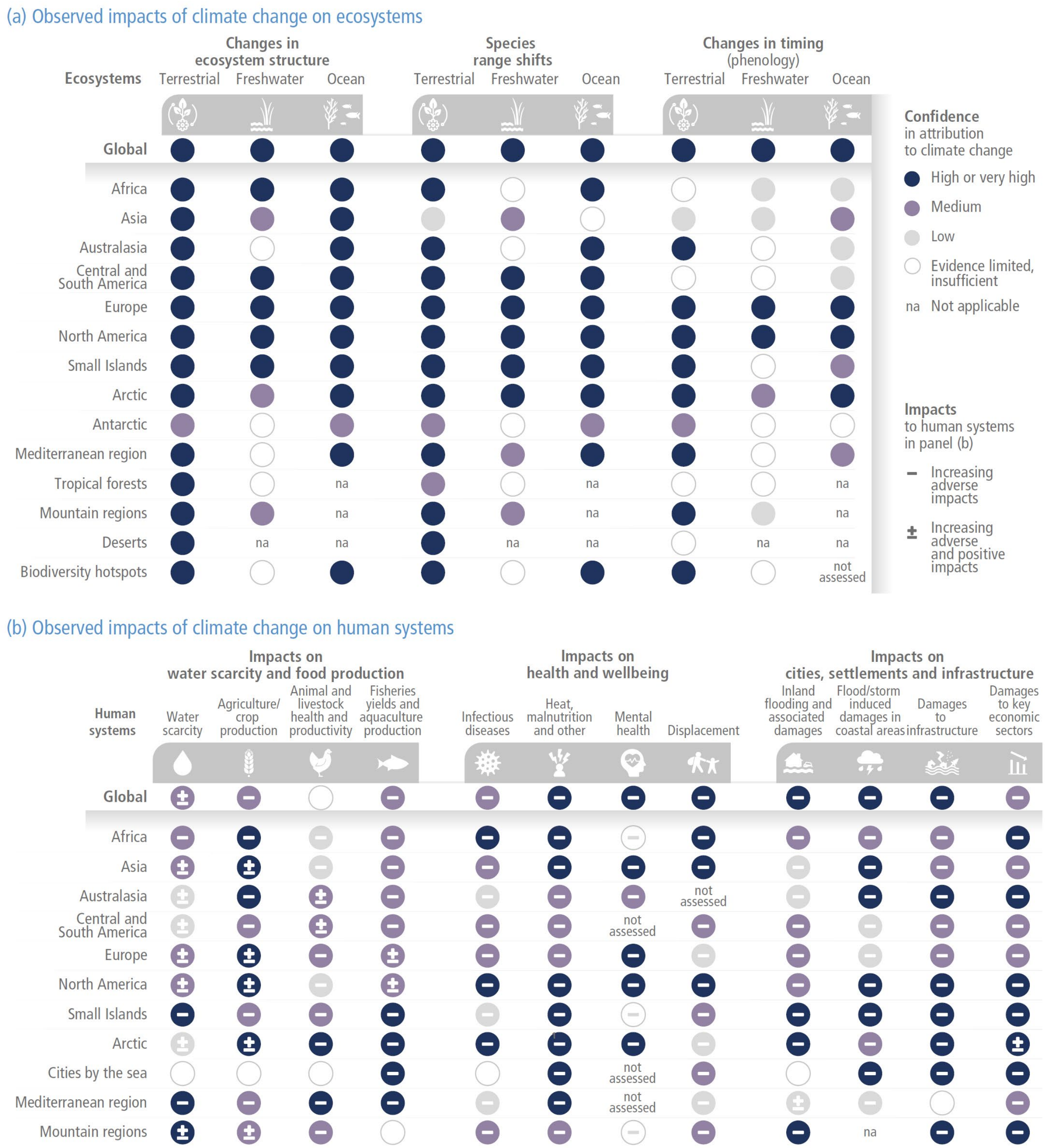


Figure 3. Climate change impacts already occurring. Figure from IPCC (2022).

[17] IPCC, CLIMATE CHANGE 2022, *supra* note 1.

A. Ecosystems

Ecosystems and nature—along with the services and benefits they provide to people—are under substantial threat due to ongoing climate change.[18]
Climate change affects land use, land cover, and ecosystems both directly and indirectly. It changes the suitability of land for specific uses and habitats (e.g., types of crops or ecosystems), alters disturbances that occur (e.g., wildfire, pests, and disease), and shifts distributions of where species live and occur.[19] By altering the productivity of ecosystems, species interactions, and the spread of invasive species, climate change is reconfiguring ecosystems in unprecedented ways.[20] The impacts of climate change on ecosystems, in turn, threaten agricultural and fisheries production, water supply and quality, the buffering of extreme weather and climate events, and resources of cultural value.

Species on land, in rivers and lakes, and in the oceans are changing in their geographic ranges, their seasonal behaviors and migrations, and their interactions within ecosystems.[21] About one-half of all species have shifted polewards or to higher elevations. These shifts are leading to widespread deterioration of ecosystem structure, function, resilience, and adaptive capacity.[22] Local losses of species are occurring, and increasing fractions of species on land and in rivers and lakes face elevated extinction risks under increasing temperatures and other climate changes, in interaction with other stressors to ecosystems (e.g., pollution, habitat fragmentation). For instance, at 1.5°C warming above pre-industrial levels, 3-14% of terrestrial species assessed to date will face very high risk of extinction.[23] Many species will be unable to relocate to suitable climates under even moderate rates of climate change. Adaptation actions, such as assisting species to migrate to more suitable locations, can reduce impacts to ecosystems but not eliminate them.

As a specific example, the structure and function of forests are being and will continue to be affected by climate-related hazards and extremes.[24] The impacts of climate change include severe ecological disturbances, impacts on forest productivity and health, and changing distribution and abundance of species. Warming in high-latitude regions will worsen the effects of wildfire, drought, and pests on high-latitude forests. Under scenarios of continued high emissions, abrupt and irreversible regional-scale changes in ecosystems could occur, such as tree death and forest dieback. In turn, this would release additional carbon and greenhouse gases into the atmosphere, exacerbating warming and affecting water quality, ecosystem services, and economies.

In high-mountain and polar regions, reductions in snow cover, thawing of permafrost, and disappearance of ice cover have already had profound effects on terrestrial and freshwater species and ecosystems. Impacts include shifts in seasonal activities and species abundance, disturbance of ecosystems (e.g., through wildfire or abrupt permafrost thaw), and alteration of ecosystem functioning. Under additional climate change, changes in ice and snow cover will continue to alter

---

[18] *Id.*
[19] *See Chapter 5: Land Cover & Land-Use Change*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[20] *See Chapter 7: Ecosystems, Ecosystem Services, & Biodiversity*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[21] NASEM, NATURAL-HUMAN COASTAL SYSTEM, *supra* note 3.
[22] IPCC, CLIMATE CHANGE 2022, *supra* note 1.
[23] *Id.*
[24] *See Chapter 6: Forests*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.

ecosystem structure and functioning and eventually lead to loss of biodiversity. Further, wildfire is anticipated to increase across the tundra and high-latitude regions in the rest of the 21st century. Beyond impacts on ecosystems themselves, these changes have cultural and economic consequences.

In the oceans, the geographical ranges and seasonal activities of many marine species have shifted in complex ways due to warming of the oceans, changes in sea ice, and oxygen loss in the ocean environment. From the equator to the poles, the species composition and the amount of biological matter produced by marine ecosystems have changed. Warming of the oceans in the 20th and 21st centuries has decreased the amount of fish available for fisheries' catches (called the maximum catch potential), adding to impacts from overfishing of some fish stocks. In the United States, ocean ecosystems have been disrupted by loss of iconic and valued habitats and shifts in species composition and interactions among predators and prey.[25] Ocean acidification, especially with continued high emissions of greenhouse gases, poses risks to coral reefs, as well as to polar ecosystems and other marine habitats.

Decreases in the global biomass of marine ecosystems and in fisheries' catch potential, in addition to regional changes in species composition, are projected under all emissions scenarios for the remainder of the 21st century.[26] The most rapid and largest declines are projected in the tropics, as marine species shift globally in response to warming. These shifts will have differential impacts for fisheries productivity—for example, increasing high-latitude invasions while exacerbating extinction in the tropics and semi-enclosed seas. The effects of warming will be exacerbated in some cases by ocean acidification, loss of oxygen from ocean waters, and reduced sea ice extent, with compounding hazards projected to become more common and severe in the future. Impacts on fish species, in turn, will affect the livelihoods, incomes, and food security of communities dependent upon marine resources. Detecting, forecasting, and mitigating adverse conditions will become increasingly important.

Coastal ecosystems, such as mangroves, coral reefs, and estuaries, also have been impacted by multiple climate change drivers, including the warming of the oceans, increasing marine heat waves, acidification, oxygen loss in coastal waters, intrusion of saline waters inland, and sea-level rise. These and other impacts are affecting biodiversity, the extent of different habitats, and the functioning and services of ecosystems, such as protecting coastlines from storms. Climate change impacts on coastal ecosystems have in turn had cascading consequences for fisheries, tourism, human health, and public safety.[27] Increases in harmful algal blooms have resulted from both climate drivers (e.g., ocean warming, marine heat waves, oxygen loss) and non-climatic drivers (e.g., nutrients runoff), which has negatively impacted food security, human health, tourism, and local economies. Especially for high magnitudes of climate change over the 21st century, risks of severe impacts are projected, including potential losses of species habitat and diversity and degradation of ecosystem functions. Because ecosystems are directly exposed to the changing climate, the prospects for reducing risks through ecological adjustments and adaptation are fundamentally linked to how much climate change occurs and therefore to progress with reductions of greenhouse gas emissions. Species and ecosystems can adapt—for example, through changes in their geographic ranges or the timing of activities such as reproduction—but the degree to which ecosystems can adapt to current and future

[25] *See Chapter 9: Oceans & Marine Resources*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[26] IPCC, SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE, *supra* note 1.
[27] *See Chapter 8: Coastal Effects*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.

climate change is limited, especially given the rate of projected climate change compared with historical shifts. Under scenarios of ambitious emission reductions, the capacity of species to adjust is greater because the rate and amount of climate change are lower, although some ecosystems, such as warm-water corals, will be at very high risk even with global warming limited to 1.5°C increase above pre-industrial levels.

Many human-assisted adaptations can reduce the impacts of climate change on ecosystems. For example, sustainable land and forest management, such as thinning of forests to manage fuels, can prevent and reduce degradation and some adverse climate impacts. Monitoring and early warning systems have helped reduce the impacts of harmful algal blooms. Fisheries, agriculture, and other livelihoods and activities dependent upon ecosystems are shifting in locations and timing. Cost-effective and beneficial measures are available to communities in supporting jobs and livelihoods.

B. Human Health and Well-Being

Climate change is already adversely affecting human health and well-being, including in the United States.[28] Heat-related mortality has increased due to global warming, and cold-related mortality has decreased. Urbanization combined with global warming amplifies heat in cities and their surroundings, and this heat island effect increases night-time as well as daytime temperatures. Higher night-time temperatures can affect vulnerable populations such as the elderly or outdoor workers, as less physiological recovery occurs overnight when night-time temperatures are high. Further, climate change is altering exposures to climate extremes and posing stresses to mental health.[29]

The health impacts of climate change are differentially experienced by people with varying levels of exposure and sensitivity to hazards.[30] Health risks are amplified among the young and the elderly, low-income households, and some communities of color. In addition, the impacts of climate change impacts often result from multiple climate hazards and different forms of exposure and sensitivity to climate-related events and trends.

Under continuing climate change, human health impacts will include increases in morbidity and mortality from heat waves and fires, reduced labor productivity, and increases in food and waterborne diseases as well as vector-borne diseases.[31] Risks from vector-borne diseases such as malaria and dengue fever also result from the ways in which climate change shifts their geographic ranges. Under high magnitudes of climate change, human activities including agriculture and outdoor work will be compromised in some regions for some parts of the year due to temperature and humidity in combination.

Climate change is also exacerbating air pollution through increased wildfire smoke, air-pollution co-emitted with heat-trapping greenhouse gases, and increased formation of ozone.[32] In the United States, over 100 million people already experience air pollution exceeding health-based air quality standards, with impacts on respiratory and cardiovascular health. Wildfire smoke poses health risks, and intensification of wildfires from climate change diminishes air quality, with impacts for

[28] *See Chapter 14: Human Health*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[29] IPCC, CLIMATE CHANGE 2022, *supra* note 1.
[30] *Id.*
[31] *Id.*
[32] *See Chapter 13: Air Quality*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.

respiratory illnesses, visibility, and outdoor activities. Allergic illnesses, including asthma and hay fever, will likely increase due to climate changes increasing plant growth and pollen production, such as earlier onset of spring, warmer temperatures, and higher carbon dioxide levels in the atmosphere. Other environmental consequences of air pollution include reductions in visibility and damages to agricultural crops and forests.

In the Arctic and high mountain regions, the rapid warming of what scientists call the "cryosphere"—snow cover, glaciers and ice, permafrost, and seasonally frozen ground—has negatively impacted multiple aspects of human health and well-being since the middle of the 20th century.[33] Categories of impacts include increased food insecurity and adverse consequences for water resources, infrastructure, tourism, and Indigenous cultures. For example, changes in snow cover, ice, and permafrost in the Arctic have disrupted access of Indigenous communities to areas in which fishing, herding, hunting, and gathering have traditionally occurred, as well as the availability of food in these areas. Under additional climate change in the region, impacts on water resources will affect uses such as hydropower and irrigation of agriculture, as well as livelihoods. Changes in floods, avalanches, and the stability of frozen ground will impact infrastructure, cultures, tourism, and recreation.

For climate change impacts on human health and well-being, effective adaptation options include basic public health measures, essential health care, disaster preparedness and response, infrastructure planning, urban design, livelihood diversification, and poverty reduction.[34] In many communities around the United States, increased preparedness involves consideration of climate in domains already relevant to human health and well-being. For example, physicians are increasingly considering the ways that extreme heat may affect young children, the elderly, or pregnant women, with impacts exacerbated where air conditioning is not available or not affordable for households. Air pollution worsened by wildfire or ozone formation on hot days is particularly impactful for outdoor workers, people with asthma, or individuals facing prolonged exposure

Public health, support of livelihoods, and attention to the most vulnerable communities are all important considerations in adapting and preparing for the impacts of climate change on human health and well-being. Adaptation actions span social scales, from the individual and household level through to national approaches. Adaptation actions also range from activities done in advance of an acute event, such as a heat wave or a wildfire, to warning and emergency management once intense exposures or disasters are underway.

C. Food Production and Security

Climate change has already impacted the production of food and food security as a result of warming, shifts in rainfall patterns, and increases in some types of extreme events.[35] To date, the impacts of climate change on agricultural crop yields have been both positive and negative. While crops such as maize and wheat in lower latitude regions have been negatively impacted by climate changes, some crop yields in higher latitude regions have benefited. On balance, however, climate

[33] IPCC, SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE, *supra* note 1.
[34] IPCC, CLIMATE CHANGE 2022, *supra* note 1.
[35] IPCC, CLIMATE CHANGE AND LAND, *supra* note 1.

change impacts on crop yields have more often been negative than positive, especially for wheat and maize, and food security is being adversely impacted.[36]

In tropical and temperate growing areas, major crops, including wheat, maize, and rice, will be negatively impacted overall under increasing levels of warming, although some locations may benefit. In drylands, climate change combined with desertification will negatively affect both crop and livestock productivity. Climate change has been altering patterns of agricultural pest and disease infestations. Increases in carbon dioxide in the atmosphere also can decrease the nutritional quality of crops.

In some pastoral systems, such as in Africa, animal growth and productivity have been adversely impacted. Increasing temperature extremes negatively affect the health of livestock, with economic implications for producers and also markets and supply chains.

Increasing temperatures pose risks for agricultural workers, including heat exhaustion, heat stroke, and heart attacks. Both heat and air pollution, sometimes in combination, raise issues regarding the time of work, the use of protective equipment, and provision of adequate breaks.

Multiple aspects of food security are affected by climate change, including access to food and the stability of food prices. Projected increases in prices of cereal crops disproportionately increase risks of food insecurity and hunger for low-income, marginalized people. Increases in extreme weather events are also projected to increase food insecurity through disruptions of food chains. Risk to food security increase with continued warming, and food security risks are greater in possible future scenarios with lower income, increases in food demand, more land competition, and limited trade.

In the United States, climate change impacts on agricultural productivity will result from increasing drought and rangeland wildfires, decreases in water supplies for irrigation, and expanding distributions of pests and disease for crops and livestock.[37] Many of these impacts will have long-term consequences. For example, increasing extreme precipitation events degrade soils and water resources through excessive runoff, leaching, and flooding.

Throughout the food system, adaptation options extend from production to consumption, including food loss and waste. They include the use of stress-tolerant crops, heat-tolerant livestock, improved animal housing, and health services in rural areas. Commonly occurring adaptations involve the timing of planting, considerations of water availability and irrigation, and the varieties planted in different locations.

D. Water Resources and Security

Climate change is already negatively impacting water security.[38] Increasing magnitudes of climate change will increase the numbers of people globally who will experience water scarcity. For example, with 2°C global warming above pre-industrial levels, in some snowmelt dependent river basins, water available for irrigation will decline by up to 20%.[39] The impacts of climate change on water

---

[36] IPCC, CLIMATE CHANGE 2022, *supra* note 1.
[37] *See Chapter 10: Agriculture & Rural Communities*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[38] IPCC, CLIMATE CHANGE 2022, *supra* note 1.
[39] IPCC, CLIMATE CHANGE 2022, *supra* note 1.

resources relate to both the quantity and quality of water available for different uses. Current, much less future, impacts require consideration of water infrastructure and management, especially where current systems are already struggling to meet demands for water resources in both rural and urban areas. Integrated water management addresses the interacting risks related to water for both freshwater resources and flooding.

Especially in dry subtropical regions, climate change over the century will decrease the availability of renewable surface waters and groundwater resources. Drought is expected to increase in frequency in already dry regions, whereas water resources will increase at higher latitudes. Risks to water quality result from interactions of increased temperatures, increased sediment and pollution from heavy rainfall, concentration of pollutants during droughts, mobilization of pollutants and sediments by high-intensity rainfall events, and disruption of water treatment during floods.

In the United States, changes in the quantity and quality of water resources are already evident and are expected to worsen.[40] Variability in rainfall and increasing temperatures are intensifying droughts, increasing heavy downpours, and reducing snowpack. Shifts toward rainfall instead of snow are also affecting the timing of water supply.

The deterioration of water infrastructure within the United States compounds climate risks, yet this infrastructure will need to manage increases in extreme precipitation and drought events in the future. Much of current infrastructure was built before there was awareness of climate change risks. Even today, the design and operation of infrastructure does not usually consider the changing climate, the impacts of co-occurring climate-related hazards, or the potential for cascading failures, despite growing evidence and awareness of climate change risks. Given the uncertainties in hydrological changes, adaptation includes scenario planning, strategies grounded in learning, and flexible solutions.

E. Infrastructure, Economies, and Finance

Climate change poses economic and financial risks, which emerge from impacts on infrastructure and the built environment and consequences for markets and other instruments that manage and are affected by such risks. Economic and financial impacts and damages from climate change are already occurring, and the potential costs and losses in the future are substantial, increasing non-linearly with the amount of global warming that occurs.[41]

The impacts of climate change on infrastructure result from weather and climate events and trends that exceed the tolerances to which infrastructure was initially built, and infrastructure that is inadequately maintained and deteriorating is especially at risk. For example, the U.S. energy system, which is essential for most economic sectors in the United States, has already been impacted by extreme weather and climate events. Under increasing climate change, risks include more frequent or longer power outages.[42]

---

[40] *See Chapter 3: Water*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[41] IPCC, CLIMATE CHANGE 2022, *supra* note 1.
[42] *See Chapter 4: Energy Supply, Delivery & Demand*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.

Climate change impacts also pose risks for the reliability of the U.S. transportation system due to such hazards as heavy precipitation, coastal flooding, increasing temperatures, and wildfire.[43] For example, recurrent and disaster floods alike disrupt transportation, and exposure to temperatures outside of design standards threaten the integrity of roadways, bridges, and electricity transmission facilities. Disruption of transportation networks has both economic and social consequences.

The impacts of climate change and climate-related extremes affect trade and the economy—through, for example, internationally interconnected import and export prices or supply chains.[44] Where climate change slows or reverses socioeconomic development globally, the effectiveness of international aid and investments will be decreased, requiring increases in disaster relief and humanitarian assistance.

Coastal economies and properties are at risk.[45] The United States has a trillion-dollar coastal property market. Both properties and public infrastructure will be increasingly impacted by high-tide flooding, storm surge, and heavy rainfall, all of which are exacerbated by sea-level rise. Coastal flooding and erosion are also exacerbating social inequities within coastal communities, raising difficult questions about financing adaptation and hazard mitigation and the potential needs for relocation in some places. Under high magnitudes of climate change, coastal communities will be fundamentally altered by the end of the century. Even with ambitious emissions reductions, financial impacts will increase. Coastal communities will likely be among the first in the United States to test legal frameworks relevant to climate change, because the effects are evident, costly, and directly attributable to human activity.

Adaptation relevant to infrastructure often involves substantial investments with long infrastructural lifetimes. Considering climate change from the start can substantially reduce the costs of adaptive adjustments. Additional considerations are the aging of infrastructure and the complex interconnections across the transportation system and sectors dependent upon it.

Adjustments that increase the climate resilience of infrastructure can have widespread benefits. For example, plans and investments that reduce the frequency, scope, and severity of coastal flooding reduce both the direct impacts of coastal flooding and cascading consequences across economies.

F. Compounding Risks Across Regions

Climate change science to date has necessarily prioritized analysis of climate change impacts within sectors or within regions. However, as climate change increases, it is becoming clear that impacts can cascade and compound both within and across sectors and regions. The sectors and systems exposed to climate change interact with one another and depend upon each other.[46] Increasing climate change increases cascading risks resulting from interactions across categories of risk.[47] Complex dynamics and outcomes can result, and they are generally difficult to fully predict in advance. Examples of interacting risks include increases in dryland water scarcity, erosion of soils,

---

[43] *See Chapter 12: Transportation*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[44] *See Chapter 16: Climate Effects on U.S. International Interests*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[45] *See Chapter 8: Coastal Effects*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[46] *See Chapter 17: Sector Interactions, Multiple Stressors, & Complex Systems*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[47] IPCC, CLIMATE CHANGE AND LAND, *supra* note 1.

wildfire damages, loss of vegetation, thawing of permafrost, degradation of coastal regions, and declines in tropical crop yields.

As a particular example, coastal communities are affected by multiple interacting climate-related hazards, including tropical cyclones, coastal flooding, marine heat waves, loss of sea ice, and thawing of permafrost. Coastal systems and low-lying areas will increasingly be inundated by coastal waters and experience coastal flooding and erosion due to continuing sea-level rise. Low-lying developing countries and small islands already face substantial impacts, and even with ambitious reductions in greenhouse gas emissions, low-lying coastal settlements in atoll islands or Arctic communities face future risks so severe that sufficient adaptation will be extremely difficult. Under continued high emissions, delta regions and high-income coastal cities are expected to face substantial risks after 2050. Without large increases in adaptation and context-specific, integrated responses to reduce risks, infrastructure, homes, communities, financial viability, and livelihoods will all be affected.

Climate change can also exacerbate multiple existing challenges in urban areas, including deteriorating infrastructure, degraded ecosystems, and social inequities. The interdependence of infrastructural, social, and ecological systems in urban areas can transmit and amplify climate change risks—for example when communications or transportation networks fail.

In rural areas, climate change impacts have consequences for water availability, food security, and agricultural livelihoods. Further, the livelihoods, health, and economies of Indigenous peoples are threatened by climate change.[48] Climate change affects agriculture, hunting and gathering, fishing, forestry, energy, recreation, and tourism. Impacts can simultaneously degrade the foundations of economies and practices, locations, and relationships that have cultural importance.

Different groups will be differentially affected by risks. Within populations, some individuals will be more at risk than others, including the poor, the young and the elderly, and women. Over this century, climate change impacts will make poverty reduction more difficult, especially due to multiple compounding climate-related risks.

Finally, with regard to conflict and security, climate change over the 21st century will increase the displacement of people and amplify well-documented drivers of violent conflict. Changes in climate will cause environmentally induced migration internally within countries and also across national borders. In addition, shared resources along borders are impacted by climate change, necessitating transboundary processes for their management. The impacts of climate change already have consequences for U.S. military infrastructure—for example, through damages to roads, runways, and other infrastructure in low-lying coastal areas. Violent conflict also substantially increases vulnerability to the impacts of climate change through its adverse consequences for government institutions, infrastructure, and livelihoods.

Cascading impacts are already putting risk management to the test and revealing limits to capacities to cope and adapt. Jointly managing interacting systems can increase their resilience, although such coordination can be challenged by the many different agencies and levels of government, along with the private sector and communities, that are involved.[49] For example, adaptation responses in almost

---

[48] *See Chapter 15: Tribes & Indigenous Peoples*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.
[49] *See Chapter 17: Sector Interactions, Multiple Stressors, & Complex Systems*, *in* USGCRP, FOURTH NATIONAL CLIMATE ASSESSMENT, *supra* note 2.

any local community in the United States often benefit from coordination of local, state, and federal efforts, and actions at one level of government can enable or constrain actions by other levels of government. In addition, most responses to date have been reactive rather than proactive. For instance, adaptive actions implemented have generally occurred after extreme events and disasters rather than before.

In many cases, adaptation relevant to cascading risks has favored "hard" infrastructure, such as sea walls, levees, and storm barriers. Approaches combining ecosystems and infrastructure, such as the buffering of waves that occurs through wetlands or mangroves combined with "armoring" infrastructure near human settlements, are starting to become more common. In addition, adaptation actions are starting to address future sea-level rise or changes in extremes. There is increasing recognition of the profound importance of combining infrastructural approaches with preparedness measures relevant to the response capacity of government agencies, communities, and the private sector.

VI. Conclusion

Climate change is substantially impacting people and ecosystems globally. Risks will increase into the future, depending on both climate-related hazards and the exposure and vulnerability of societies and ecosystems to these hazards. Ultimately, the level of heat-trapping greenhouse gases in the atmosphere, arising mostly from fossil fuels and industry, will be the most important determinant of climate risks and impacts that occur, especially into the second half of the century and beyond.

Through mitigation and adaptation at different scales, from the local to the national to the global, these risks can be reduced. But current and future generations will nevertheless experience losses and damages, with risks growing enormously if mitigation remains adequate. These negative impacts will disproportionately be borne by marginalized and underserved communities in the United States and other countries, although all regions, societies, and ecosystems will be affected by severe, pervasive, and in some cases irreversible impacts and damages.