warming world

impacts by degree

Based on the National Research Council report,
Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia (2011)

❶ Emissions of carbon dioxide from the burning of fossil fuels have ushered in a new epoch during which human activities will largely determine the evolution of the Earth's climate. ❷ Because carbon dioxide is long-lived in the atmosphere, increases in this key gas can effectively lock the Earth and many future generations into a range of impacts, some of which could be severe. ❸ Therefore, emission reduction choices made today matter in determining impacts that will be experienced not just over the next few decades, but also into the coming centuries and millennia. ❹ Policy choices can be informed by recent advances in climate science that show the relationships among increasing carbon dioxide, global warming, related physical changes, and resulting impacts. These impacts include changes in streamflow, wildfires, crop productivity, extreme hot summers, and sea-level rise, along with associated risks and vulnerabilities.

summary

Society faces important choices in this century regarding emissions of heat-trapping (greenhouse) gases and the resulting effects on the Earth's climate, ecosystems, and people. Human activities are responsible for the observed increases in atmospheric concentrations of several important greenhouse gases. These added gases—carbon dioxide in particular—very likely account for most of the globally averaged warming since 1950. There is now more carbon dioxide in the air than at any time in at least 800,000 years. This amount could double or nearly triple by 2100, greatly amplifying the human impact on climate.

There is widespread interest in reducing emissions of carbon dioxide and other greenhouse gases to stabilize atmospheric concentrations. One way to gauge the implications of any such approach is to identify particular concentrations—or stabilization targets—and assess the emissions reductions necessary to achieve them, as well as the climate impacts that would result.

This booklet summarizes the findings of a report from the National Research Council, *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia* (2011). The report evaluates the implications of different stabilization targets, with particular emphasis on avoiding serious or irreversible impacts on the Earth's climate. Each stabilization target results in a different future climate, with changes that may be difficult or impossible to reverse for millennia, such as melting of the Greenland Ice Sheet. Some impacts will take hundreds or even thousands of years to emerge because of inherent lags in the climate system and because of the long atmospheric lifetime of carbon dioxide. This report also evaluates impacts expected to occur in the next few decades to centuries.

The impacts of human activities—particularly emissions of carbon dioxide, but also including other greenhouse gas emissions, land use, and population growth—are so vast that they will largely control the future of the Earth's climate system. This future could bring a relatively mild change in climate, or it could deliver an extreme change from today's climate to entirely different climate conditions that will last many thousands of years. The eventual course of the climate system over millennia will be determined largely by the actions taken this century by governments, businesses, and individuals around the world.

main findings

The human contribution to global warming is due to increases in the concentration of greenhouse gases and aerosol particles, which alter the Earth's energy budget. In the special case of the greenhouse gas carbon dioxide, cumulative emissions are also an important metric or measure of the effect of humans on the climate system. The best estimate is that 1,000 gigatonnes of human-emitted carbon emissions leads to about 1.75°C (3.15°F) increase in global average temperature. Cumulative carbon emissions to date (2010) are about 500 gigatonnes, and the rate of global emissions is increasing. Based on current understanding, this warming is expected to be nearly irreversible for more than 1,000 years.[1]

The higher the total or cumulative carbon dioxide emitted and the higher the resulting atmospheric concentration, the higher the warming will be for the next thousand years. Higher emissions would lead to more warming over many thousands of years, allowing more time for key but slow components of the Earth system to act as amplifiers of climate change. For example, warming of the deep ocean over many centuries will release additional carbon stored in deep-sea sediments, and the Greenland ice sheet could shrink or even disappear if global warming remained in the range of 3.5°-5.0°C (6.3°-9.0°F) for several thousand years, raising global sea level by about 4-7.5 meters (13-24 feet).

Many aspects of climate are expected to change in a linear fashion as temperatures rise. A growing body of research suggests that many important physical changes and impacts in the climate system during the next few decades to centuries will be proportional to global temperature increase. It is now possible to utilize increments of change in globally averaged temperature—increases of 1°C, 2°C, 3°C, and so forth—as a tool for examining a wide range of climate impacts. In turn, each increase in temperature also can be linked to a carbon dioxide emissions stabilization target around which emission policies could be structured. This framework helps decision makers weigh the potential risks of climate change; however, the costs of achieving particular emission reductions are not addressed.

[1] Approaches to 'geoengineer' future climate, e.g., to actively remove carbon from the atmosphere or reflect sunlight to space using particulate matter or mirrors are topics of active research. If effective, these may be able to reduce or reverse global warming that would otherwise be effectively irreversible. This study does not evaluate geoengineering options, and statements throughout this report regarding the commitment to climate change over centuries and millennia from near term emissions should be read as assuming no geoengineering. Reforestation or other methods of sequestration of carbon are also not considered.

In general, each degree C of global temperature increase can be expected to produce:

- 5-10% changes in precipitation across many regions
- 3-10% increases in the amount of rain falling during the heaviest precipitation events
- 5-10% changes in streamflow across many river basins
- 15% decreases in the annually averaged extent of sea ice across the Arctic Ocean, with 25% decreases in the yearly minimum extent in September
- 5-15% reductions in the yields of crops as currently grown
- 200-400% increases in the area burned by wildfire in parts of the western United States

However, many other impacts remain difficult to quantify, in part because they depend on additional factors besides climate change. For example, changes in the risk of flood damage depend not only on precipitation but also on urbanization and other changes in land cover. In addition, some phenomena beyond the next few centuries—such as the potential large-scale release of methane from deep-sea sediments—could act as amplifiers that would greatly increase the size and duration of human impact on climate.

Much recent attention has focused on thresholds or tipping points that might trigger widespread change. However, while thresholds could be important for some phenomena, many potentially serious changes in physical climate and related impacts increase gradually, in line with the per-degree (linear) estimates outlined above. While this study did not find evidence for tipping points that could be related explicitly to particular stabilization targets, the possibility of "surprises" increases the larger the warming becomes.

The impacts of human activities–particularly emissions of carbon dioxide–are so vast that they will largely control the future of Earth's climate system.

Some uncertainty remains in the relationships among the total amount of carbon dioxide emitted over time, the portion that accumulates in the atmosphere, and the resulting climate changes and their impacts. One uncertainty is that, as temperatures warm, the ability of seawater to absorb carbon dioxide is expected to decrease, and the percentage absorbed by land-based ecosystems may also decline. However, these processes will be driven by a number of interacting variables that are not yet well-quantified. Further, the amount of global temperature increase likely to result from a given increase in carbon dioxide ranges from about 30% below the best estimate to 40% above it. Thus, each stabilization target encompasses a range of potential temperature change and associated risks that must be taken into account in evaluating stabilization targets.

What Impacts Can Be Expected?

FOR 1–4°C WARMING

RAIN
- 5–10% less rainfall **per degree** in Mediterranean, SW North America, southern Africa dry seasons
- 5–10% more rainfall **per degree** in Alaska and other high latitude NH areas
- 3–10% more heavy rain **per degree** in most land areas

RIVERS
- 5–10% less streamflow **per degree** in some river basins, including the Arkansas and Rio Grande

FOOD
- 5–15% reduced yield of US corn, African corn, and Indian wheat **per degree**

SEA ICE
- 15% and 25% reductions in Arctic sea ice area **per degree**, in the annual average and September (respectively)

FOR 1–2°C WARMING

FIRE
- 200–400% increase in area burned **per degree** in parts of western US

FOR 3°C

COASTS
- Loss of about 250,000 square km of wetlands and drylands
- Many millions more people at risk of coastal flooding

EXTREMES
- About 9 out of 10 summer seasons expected to be warmer than all but 1 summer out of 20 in the last decades of the 20th century over nearly all land areas

FOR 4°C

EXTREMES
- About 9 out of10 summers warmer than the warmest ever experienced during the last decades of the 20th century over nearly all land areas

FOR 5°C

FOOD
- Yield losses in most regions and potential doubling of global grain prices

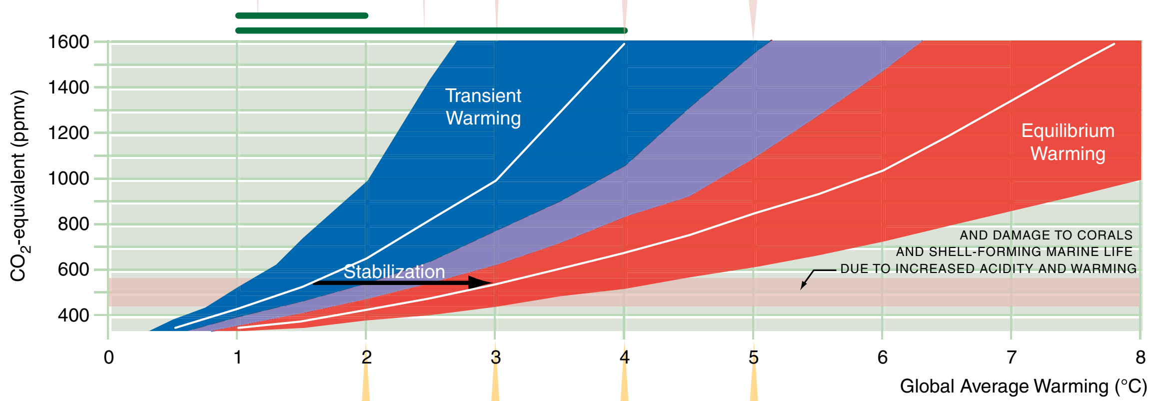


FIGURE 1. As atmospheric concentrations of greenhouse gases rise, global average temperatures also rise. The graph shows that as atmospheric carbon dioxide concentrations increase, there will be near-term or "transient" warming (range of projected temperatures in blue) which is only about half as large as the total or "equilibrium" warming (range of projected temperatures in red) that will eventually occur if concentrations are stabilized at those values. The black "stabilization" arrow shows the difference in transient and equilibrium temperatures if the atmospheric concentration of carbon dioxide were stabilized at about 580 ppm. The top portion of the figure lists key impacts for given temperature increases. The impacts listed for 1-4°C warming and for 1-2°C warming are given per degree of warming. For example, streamflow is projected to be reduced by 5-10% per 1°C warming, by 2-20% at 2°C, by 15-30% at 3°C, and 20-40% at 4°C. Because equilibrium warming is about twice as large as transient warming, the impacts experienced as temperatures rise are expected to double for stabilization.

Large reductions in carbon dioxide emissions would be needed in order to stabilize carbon dioxide concentrations at any chosen target level. Carbon dioxide is the dominant greenhouse gas driving the observed changes in the Earth's climate today and is expected to become even more dominant in the future. The challenge of stabilizing carbon dioxide concentrations is a daunting one. Global emission rates of carbon dioxide have increased in every decade of the industrial era. About 55% of the carbon dioxide emitted by human activities each year is absorbed by oceans, plants, and soil. However, today's emissions are much greater than natural removals. Even if society managed to hold emission rates steady, carbon dioxide would continue to accumulate in the atmosphere, and warming would continue to increase.

To keep atmospheric concentrations of carbon dioxide roughly steady for a few decades and avoid increasing impacts, global emissions would have to be reduced by at least 80% (see Figure 2). Even greater emission reductions would be required to maintain stability in the longer term, as the Earth system continues to respond to emissions already added.

Illustrative Example of the Relationship of Emissions to Carbon Dioxide Concentrations

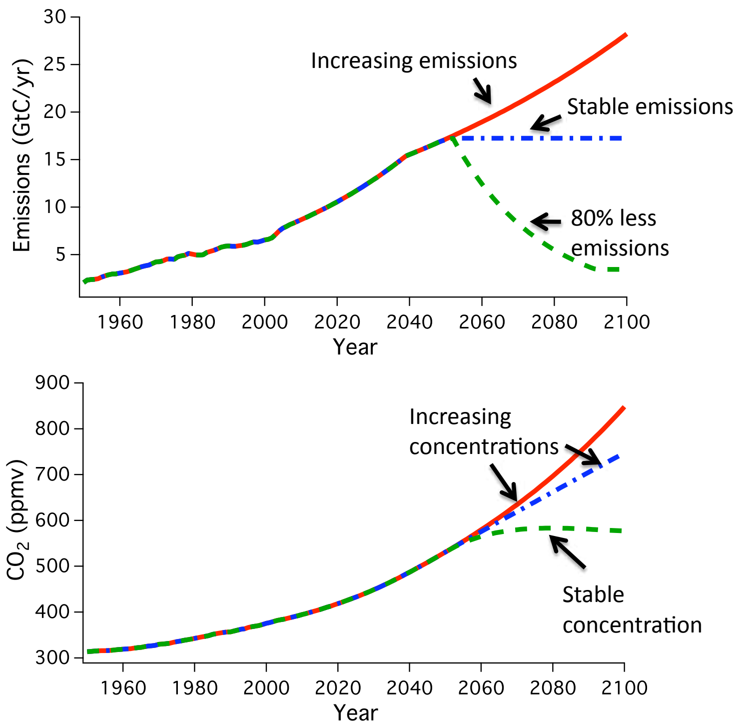


FIGURE 2. Large reductions in greenhouse gas emissions are needed to stop the rise in atmospheric concentrations of carbon dioxide and meet any chosen stabilization target. The graphs show how changes in greenhouse gas emissions (top panel) are related to changes in atmospheric concentrations (bottom panel). It would take an 80% reduction in greenhouse gas emissions (green line in top panel) to stabilize atmospheric concentrations (green line, bottom panel); this is due to the carbon cycle and does not depend on the value of the chosen stabilization target. Stabilizing emissions (blue line, top panel) would result in a continued rise in atmospheric concentrations (blue line, bottom panel), but not as steep a rise as if emissions continue to increase (red lines).

Uncertainties about human behavior affect our ability to project future climate. These uncertainties become more and more important over time.

Nations, organizations, and individuals could take a multitude of actions—whether intentional, inadvertent, or both—that influence emissions in the coming years. We do not yet know how these actions will combine to shape global emissions. Several possible pathways, or potential rates of emission change over time, have been developed by researchers, but we do not yet know which pathway will prove most accurate. This uncertainty increases in importance over time.

The higher the total or cumulative carbon dioxide emitted and the higher the resulting atmospheric concentration, the higher the warming will be for the next thousand years.

Earth and its residents are entering a new geological epoch—one now beginning to be called the Anthropocene—in which human activities are a primary force affecting climate. Our actions this century to reduce or increase greenhouse gas emissions will determine whether the Anthropocene is a relatively mild event or a severe transition extending over many thousands of years.

the human impact on climate

A variety of human-produced substances affect the Earth's energy budget and thus its climate. These include greenhouse gases, whose molecular structure allows them to capture radiation that would otherwise escape from the Earth to space, and aerosols (airborne particles), which can either reflect or absorb incoming radiation from the Sun. A critical task in assessing future climate is to diagnose how atmospheric concentrations of these substances and their effects are likely to change during the coming decades and centuries.

Humans generate greenhouse gases by burning fossil fuels, clearing tropical forests, and other activities. The impact of each type of greenhouse gas on climate depends on the number of molecules emitted, the strength of each molecule in trapping radiation, and the lifetime of each molecule in the atmosphere. Greenhouse gas emissions from human activities are now outstripping the earth's natural ability to remove them, increasing atmospheric concentrations.

Examining how global climate may evolve over thousands of years requires analyzing a number of very slow processes triggered by long-lasting increases in CO_2 concentrations and global temperature. One example of such a process over coming millennia is the growing potential for large-scale release of carbon—perhaps from methane compounds stored in deep-sea sediments or permafrost. Although recent methane releases at specific points may appear dramatic, and a major release could have a substantial effect on climate, it is not yet possible to quantify the long-term risk of a major release.

Ice sheets are another increasing concern over the very long term. Models indicate that Greenland's ice sheet could shrink or even disappear if global warming remained in the range of 3.5°-5.0°C (6.3°-9.0°F) for several thousand years. All else being equal, this would raise global sea level by about 4-7.5 meters (13-24 feet). There is evidence that as little as 5°C (9.0°F) of local oceanic warming over a few thousand years could destabilize and deglaciate the West Antarctic ice sheet, which would raise sea level by about 5 more meters (17 feet). Whether the ice sheets could destabilize more rapidly is a topic of active research.

Geological history confirms the long-term risks posed by enhanced concentrations of greenhouse gas. During the Pliocene period (from about 5.3 to 2.6 million years ago), carbon dioxide concentrations were similar to those today; the difference is that the Northern Hemisphere was free of large ice sheets at that time, and global temperatures were about 3°C (5.4°F) above today's levels. Further in the past, the Paleocene-Eocene Thermal Maximum (roughly 56 million years ago) provides an even more dramatic example. Atmospheric carbon dioxide was far higher than today, and the planet was warm enough to be free of ice.

Ultimately, there are no historical analogues for the mix of temperatures, ice sheets, and CO_2 concentrations already present and projected for the Anthropocene. It is an open question whether the Earth's climate will stabilize after several

three small atoms, lots of warming power

The human-produced greenhouse gas of most concern is carbon dioxide. It is emitted in vast amounts.

10 billion metric tons of carbon in 2008 alone

Higher emissions cause more warming, and more warming causes greater impacts.

thousand years, or whether impacts such as sea-level rise will continue or accelerate.

Greenhouse gases and the carbon cycle

The most important human-produced greenhouse gas is carbon dioxide. It is emitted in vast amounts: 10 billion metric tons of carbon (equivalent to 36 billion metric tons of CO_2) in 2008 alone. Though the emission rates sometimes temporarily decrease from one year to the next (due to economic downturns, for instance), huge amounts of carbon dioxide continue to be added to the atmosphere every year. About 55% of this total is absorbed relatively quickly by plants, soil, and the ocean. The rest stays in the atmosphere for much longer, decreasing only gradually. More than half of the remainder will be in the air a century later. Some of it will persist for more than a thousand years. (See Figure 3.)

Although some other greenhouse gases produced by human activity are stronger absorbers of radiation then carbon dioxide, they are emitted in much smaller amounts, and thus they have less of an impact on climate (see Figure 4). However, as a group, they are still important. In order to simplify the task of climate analysis, these gases are often characterized by the climate effect they would have if they were in the form of carbon dioxide--their carbon dioxide equivalent concentration.

Carbon dioxide is by far the biggest contributor to current global warming. While each molecule of methane has about 25 times the impact of carbon dioxide over a century's time, this is counterbalanced by methane's relative scarcity—it is currently less than 1% as prevalent as carbon dioxide. Overall, this means that the CO_2-equivalent concentration of human-produced methane is about 25 parts per million, compared to 100 parts per million for human-produced carbon dioxide.

The impact of aerosols is more complex than that of greenhouse gases, because they can both warm and cool the Earth's climate. Black carbon (soot)

Why is Carbon Dioxide so Long-Lived in the Atmosphere?

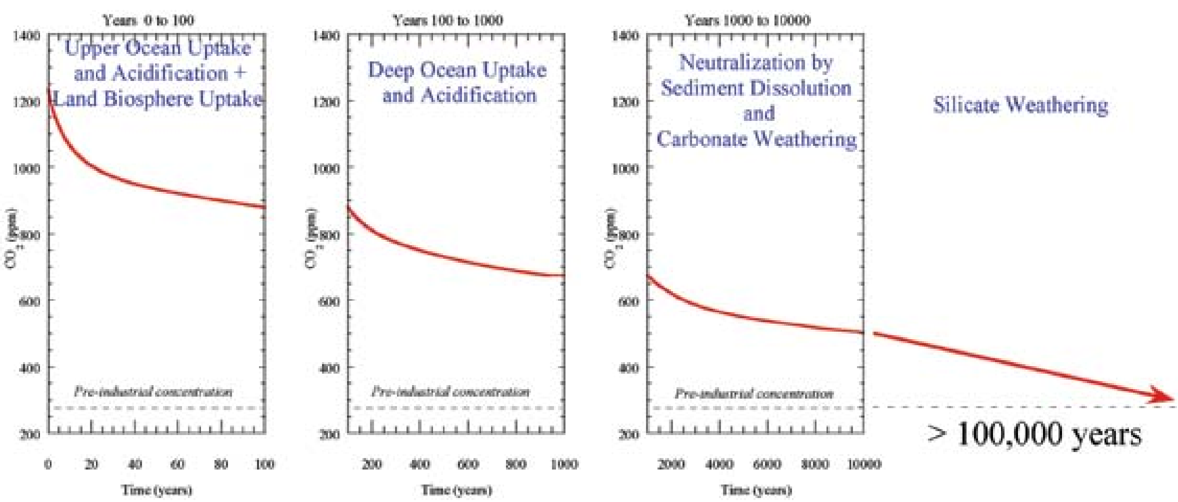


FIGURE 3. This figure shows what happens to anthropogenic carbon dioxide emitted into the atmosphere. During the first 100 years, some CO_2 is absorbed into the upper ocean and on land. The ocean water becomes more acidic, limiting further uptake of CO_2. During the next 900 years, the saturated upper-ocean waters mix with the deep ocean, allowing further uptake of CO_2. Eventually, the deep ocean acidifies as well, limiting further uptake. During the next 10,000 years, carbonate sediments dissolve and wash in from land, reducing ocean acidity, and allowing the ocean to take up additional carbon. During time scales spanning more than 100,000 years, most of the remaining CO_2 is removed by reacting with silicate minerals to form carbonates (e.g. limestone).

Contributions of Human-Produced Greenhouse Gases and Aerosols to Global Warming

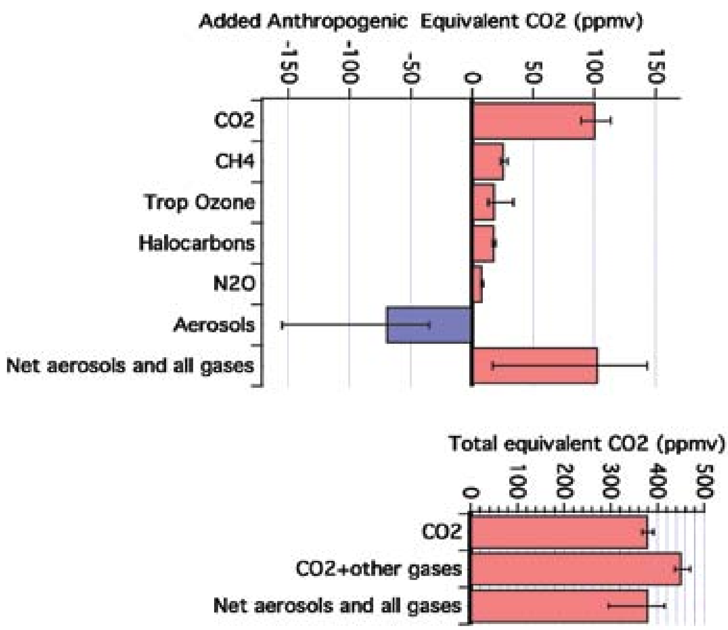


FIGURE 4. **This figure shows the relative contributions of different greenhouse gases (red) and aerosols (blue) to the warming or cooling of the Earth due to human activities in units of equivalent concentration of carbon dioxide. The aerosols bar includes direct effects on climate (those produced as aerosols absorb or reflect radiation) as well as indirect effects (those produced by the influence of aerosols on cloud formation).**

absorbs heat, while some other aerosols reflect energy to space. As a group, aerosols are now believed to be producing a net cooling effect that offsets about half of the total warming from greenhouse gases (see Figure 4).

Because aerosols remain in the air for only a few days on average, their concentrations are focused near the regions where they are emitted, such as the industrialized continents of the Northern Hemisphere. In contrast, the effects of carbon dioxide extend across the world, because CO_2 is mixed throughout the global atmosphere during its long lifetime. Because aerosols do not precisely compensate for greenhouse gases in their regional effects, and because they have a number of negative effects on human health and agriculture—for example, particulates increase the risk of asthma and other respiratory illnesses—it is inaccurate to consider them as offsetting global warming.

Because heat-trapping constituents such as methane and black carbon (soot) exert their warming effects over a shorter period than carbon dioxide, it has been suggested that society can “buy time” by reducing these shorter-lived components quickly and then focusing on the more challenging task of reducing carbon dioxide emissions over the longer term. There could be side benefits to this approach: for example, reducing black carbon also reduces air pollution, and trapping methane emissions may yield natural gas that can be burned for energy. The “buying time” approach would indeed reduce the temperature peak associated with a given stabilization target. However, it would have little impact on the temperatures that would prevail for hundreds of years after stabilization, when the effects of carbon dioxide strongly dominate the future climate change.

The life cycle of carbon

Substantial amounts of carbon dioxide are exchanged routinely between the atmosphere and the rest of the Earth system (soil, plants, and ocean). However, the net imbalance of the natural system is relatively small compared to the amount of carbon dioxide being added to the atmosphere by human activities. Natural processes can take up some, but not all, of the emitted carbon dioxide. Just as a sink with a drain will fill up if water enters it too quickly, human production of carbon dioxide is outstripping the Earth’s natural ability to remove carbon from the air (see Figure 5).

The amount of carbon entering the ocean has increased relatively steadily since 1960, while the amount absorbed by the biosphere varies substantially. For instance, a major El Niño can produce widespread drought and cause a temporary but substantial reduction in the global uptake of carbon dioxide by plants.

The effectiveness of the ocean to remove human-produced carbon dioxide from the atmosphere is expected to decrease slowly over time for several reasons:

• The capacity for seawater to take up additional carbon dioxide decreases as carbon dioxide concentrations rise.

• Carbon dioxide is less soluble in warmer water.

• Climate change will inhibit the vertical circulation of seawater, thus reducing the formation of deep water and the amount of CO_2-absorbing water exposed to the atmosphere.

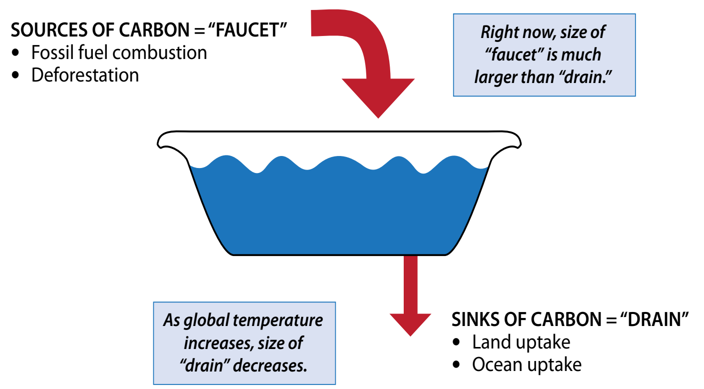
A number of interlocking factors, both natural and human-caused, make it challenging to assess how much carbon dioxide will be absorbed on land. These challenges include the following:

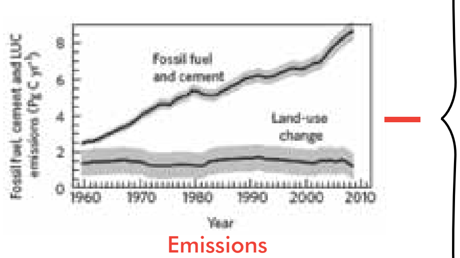
• Deforestation adds carbon to the atmosphere by replacing high-carbon forests with relatively low-carbon pastures and croplands. This process, mainly occurring in the tropics, is being partially offset by forest regrowth in some midlatitude areas, including the United States. The total impact of land-use changes on airborne carbon can take decades to play out, which makes it difficult to separate the impacts of current and past events.

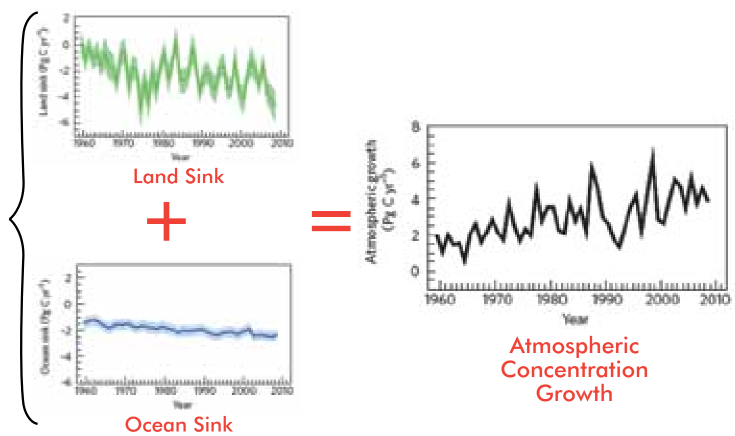
• Laboratory and field studies show that—all else being equal—increasing the amount of carbon dioxide in the atmosphere stimulates photosynthesis and causes plants to absorb greater amounts

The Carbon 'Bathtub' and its Components

FIGURE 5. (right) If the amount of water flowing into a bathtub is greater then the amount of water leaving through the drain, the water level will rise. (below) Emissions of carbon dioxide due to fossil fuel burning, cement manufacture, and land use are like the flow of water into the world's carbon bathtub. "Sinks" in the ocean and on land (such as plants) that take up carbon dioxide are like the drain. There are variations from year to year, especially in the land sink, which can vary greatly due to El Niño and other phenomena that affect plant growth, wildfire, and soil decomposition on a large scale. Today, human activities have turned up the flow from the carbon dioxide "faucet," which is much larger than the "drain" can cope with, and the level of carbon dioxide in the atmosphere (like the level of water in a bathtub) is rising.







of carbon dioxide. While this could help partially offset human-generated emissions, it may not occur if plant growth is limited in other ways, for example, by a deficiency in nitrogen.

• Warmer temperatures may have the net effect of transferring carbon from land-based ecosystems to the atmosphere, because warming often tends to increase soil respiration more than it increases photosynthesis. However, there is a wide range of estimates on the sensitivity of land ecosystems to increases in temperature, with many variables playing a role. Increased drought, for example, could offset the carbon absorption that would otherwise result from longer growing seasons in colder climates.

Just as a sink with a drain will fill up if water enters it too quickly, human production of carbon dioxide is outstripping the Earth's natural ability to remove carbon from the air.

Effects on global temperature

Although the atmospheric greenhouse effect has been understood for more than a century, it remains difficult to know precisely how much the Earth will warm if a given amount of greenhouse gas is added to the air. However, recent research has refined the understanding of uncertainties in estimated ranges of future warming, and new approaches to the problem—such as focusing on the total amount of carbon dioxide emitted over a long period, rather than the rate at which it is added—are yielding new insights.

When large amounts of greenhouse gases are added to the Earth's atmosphere, as is happening now, the planet's energy budget is thrown substantially out of balance. Until that balance is regained, the Earth receives more radiation from the Sun in short-wave (visible) form than it sends back to space through long-wave (invisible) radiation.

If all human-produced warming agents (including all gases and aerosols) were to be kept constant, the Earth would gradually reach a new equilibrium temperature, as a number of processes correct the radiative imbalance and adjust to the elevated levels of greenhouse gas and aerosols over a period of centuries. The difference between the new and old equilibrium temperatures—in other words, the global warming produced by adding a certain amount of global warming

agent—is referred to as climate sensitivity (see Table 1).

The most common way to examine climate sensitivity is to study the impact of doubling the preindustrial concentration of carbon dioxide. Global CO_2 concentrations are now about 35% above preindustrial levels. If present rates of emission growth continue, doubling is likely to occur around the middle part of the 21st century.

Earth's climate sensitivity is not yet known with precision. Many processes interact to shape climate, and not all of them are equally well understood. However, several major components that would produce warming in a doubled-CO_2 environment—such as changes in how the Earth radiates heat to space, and increases in water vapor—are well characterized. Together, these would produce about 1.8°C (3.2°F) of warming, assuming that current global amounts and patterns of cloudiness did not change.

There is much more uncertainty in the amount of warming that could occur in addition to the 1.8°C value. Additional warming depends on the strength of such amplifying feedbacks as the melting of polar snow and ice (see Figure 6), as well as possible changes in aerosols and clouds. Some types of clouds have a net cooling effect, while others—primarily thin, high clouds—have a net warming effect. Most studies point to an increase in warming clouds, but the result varies greatly among different models. The total climate sensitivity from doubled CO_2, including all factors, is likely to lie between 2.1°C to

Carbon Dioxide Concentrations and Increases in Global Mean Temperature

Stabilization CO_2-equivalent concentration (ppmv): range and best estimate			Equilibrium global average warming (°C)
320 ←	**340**	→ 380	1
370 ←	**430**	→ 540	2
440 ←	**540**	→ 760	3
530 ←	**670**	→ 1060	4
620 ←	**840**	→ 1490	5

Note: Green and red numbers represent low and high ends of ranges, respectively; black bolded numbers represent best estimates.

TABLE 1. The table shows the global warming levels that are likely (66% chance) to be associated with rising atmospheric concentrations of carbon dioxide. This information is derived from model results,[1] and is roughly consistent with paleoclimate evidence of changes in temperature and levels of atmospheric carbon dioxide. Similarly, there is a likely uncertainty range in the atmospheric concentrations that are likely to be associated with any particular warming level (1°C, 2°C, 3°C, etc) of about plus or minus 33%, reflecting the fact that Earth's "climate sensitivity"—the amount the world is expected to warm by adding a global warming agent—is not yet known with precision.

[1]The estimated "likely" range corresponds to the range of model results in the Climate Modeling Intercomparison Project (CMIP3) global climate model archive.

Melting Arctic Sea Ice: An Amplifying Feedback Loop

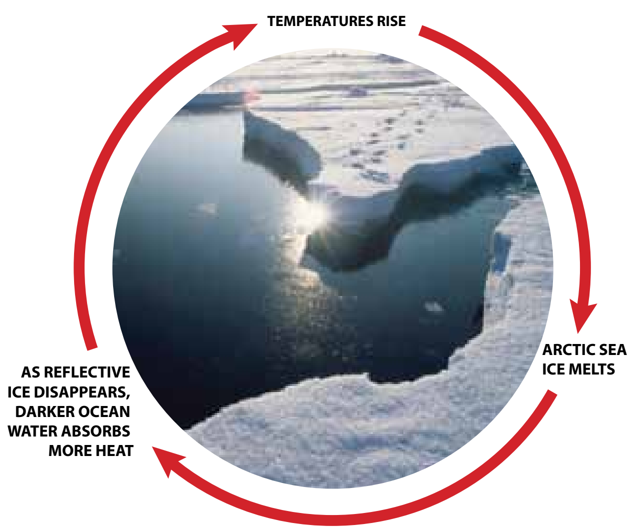


FIGURE 6. The full amount of warming that occurs because of increased greenhouse gas emissions depends in part on feedback loops. Amplifying feedback loops can increase warming, while negative feedbacks can reduce warming. The melting of Arctic sea ice is an example of an amplifying feedback loop. As the ice melts, more sunlight is absorbed into the dark ocean versus being reflected back in to space by ice, causing further warming and further melting of ice.

4.4°C (3.8°F to 7.9°F), with a best estimate of 3.2°C (5.8°F).

If CO_2 emissions stopped at the doubling point, the climate would continue to warm for several more centuries until it reached its new equilibrium temperature (the equilibrium climate sensitivity). Following CO_2 stabilization, it would take many thousands of years for the temperature to slowly decline after emissions stopped, as the Earth gradually reabsorbs the added carbon dioxide.

Another important parameter related to the climate response to greenhouse gas increases is the transient climate response—the amount of warming achieved at the time a given addition of greenhouse gas has occurred, but before a longer-term equilibrium is reached.

By examining temperature and emission patterns for various periods—such as the interval since the late 1970s, during which global temperatures have risen by about 0.5°C (0.9°F)—researchers have obtained a variety of estimates of transient climate response for doubled CO_2. In evaluating the results, this study finds a best estimate of about 1.6°C (2.9°F), with a likely range of 1.3-2.2°C (2.3-4.0°F). If concentrations were to be stabilized, eventually the warming would roughly double.

Another way to look at sensitivity is the carbon climate response—the temperature ultimately reached due to the addition of a given amount of added CO_2. The carbon climate response is linked not only to the warming, but also to the response of the carbon cycle including the strength of carbon sinks. Recent work indicates that the carbon climate response is notably consistent between different models for a given amount of accumulated emissions, regardless of how quickly or slowly the carbon is added (see Figure 7).

This new understanding opens the door to a cumulative carbon framework that would allow policymakers to focus on the total amount of emissions accumulated over the long term, with less emphasis on the concentrations at any point in time. For example, if just over a trillion metric tons of carbon were added to the air, the best estimate of the long-term warming would be close to 2.0°C (3.6°F). Adding the CO_2 more quickly would bring temperatures to that value more quickly, but the value itself would change very little. Thus, emission policies oriented toward the very long term might be able to focus less on when reductions take place and more on how much total CO_2 is emitted over a long period—in effect, a carbon budget. The possibility of greater warming for a given cumulative carbon emission, implying additional risk, cannot be ruled out, and smaller amounts of warming are also possible.

On longer time scales, it is possible that slowly unfolding feedbacks, such as the partial or total loss of polar ice sheets, could continue to transform the Earth's climate for thousands of years after an initial equilibrium is reached. Earth system sensitivity—our planet's vulnerability to these delayed effects—is difficult to quantify, but critical to our long-term future.

Cumulative Emissions and Increases in Global Mean Temperature

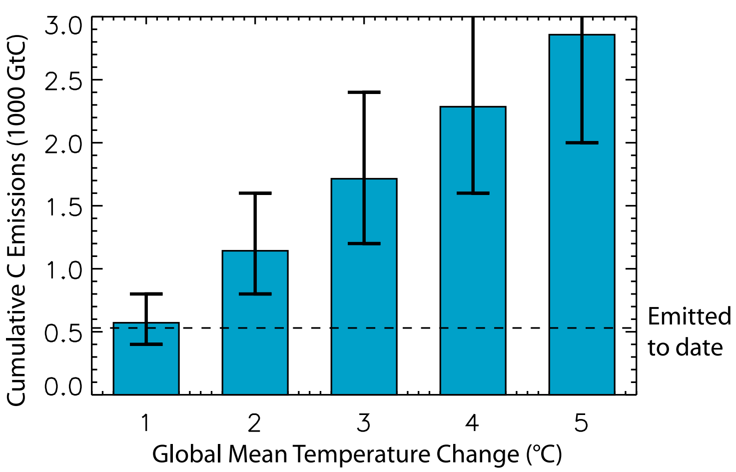


FIGURE 7. Recent studies show that for a particular choice of climate stabilization temperature, there is only a certain range of allowable cumulative carbon emissions. Humans have emitted a total of about 500 gigatonnes of carbon to date. The error bars account for estimated uncertainties in both the carbon cycle and in the climate responses to carbon dioxide emissions. Cumulative emissions shown are in teratonnes of carbon (trillion metric tonnes or 1000 gigatonnes).

Scientific progress has increased confidence in the understanding of how global warming levels of 1º, 2º, 3º, 4º, 5ºC, and so on, affects many aspects of the physical climate system, including regional and seasonal changes in temperature and precipitation, as well as effects on hurricanes, sea ice, snow, permafrost, sea-level, and ocean acidification. *Climate Stabilization Targets* attempts to quantify the outcomes of different stabilization targets on the climate system, as much as is possible based on currently available scientific evidence and information.

physical climate changes in the 21st century

Temperatures by region and season

- **Regional temperatures rise in proportion to the average warming over the entire globe.**

Local temperatures vary widely from day to day, week to week, and season to season. Longer-term changes due to increased greenhouse gases, on the other hand, are more gradual. Many studies suggest that the spatial pattern of these gradual changes remains the same, even for different increases in global average temperature. This allows us to employ a linear approach in projecting future climate changes, introduced on page 15, in which these patterns of warming can be scaled upward or downward based on each °C of average warming over the entire globe.

Climate Stabilization Targets draws on simulations produced for a project that was part of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report[1]. The various models in the project carried out a common set of experiments. Each model generated maps of regional warming for a variety of scenarios, each of which portrays a different plausible future, or "storyline," of global economic development.

After averaging the normalized maps from all models and scenarios, we can assess how much of a rise in average temperature might be expected in different regions for every 1°C of global warming. As shown in Figure 8 (bottom left) for the period December through February, polar regions are expected to warm four or more times more quickly than the planet as a whole by the 2080s and 2090s. During the period June through August, (Figure 8, bottom right) the warming is strongest across northern midlatitudes, including the United States, southern Europe, and central Asia.

Many of these patterns are already evident in observations from the past century (Figure 8, top panels). The second half of the 20th century saw intense winter warming across parts of Canada, Alaska, and northern Europe and Asia (top left) and summer warming across the Mediterranean and Middle East (top right). One of the largest differences between 20th-century data and 21st-century projections is across the central United States during the summer. From 1955 to 2005, this region, on average during June, July and August, warmed at less than half the average global pace, but models project that increased dryness in this area would cause it to warm more rapidly than the planet as a whole over this century.

[1] the third Climate Model Intercomparison Project (CMIP3, conducted in 2005-2006)

one degree: not so small

Physical climate changes that can be identified or quantified per degree of warming include:

- **Precipitation increases or decreases by 5-10% per degree of warming across many regions**
- **Average September extent of Arctic sea ice is reduced by about 25% per degree of warming**
- **Oceans continue to become more acidic (average pH value of seawater continues to decrease)**
- **Risk of very hot summers increases (“very hot” is defined as the hottest 5% of summers)**
- **Amount of rain falling during the heaviest precipitation events increases by 3-10% per degree**

Changes in Regional Warming per Degree Global Warming

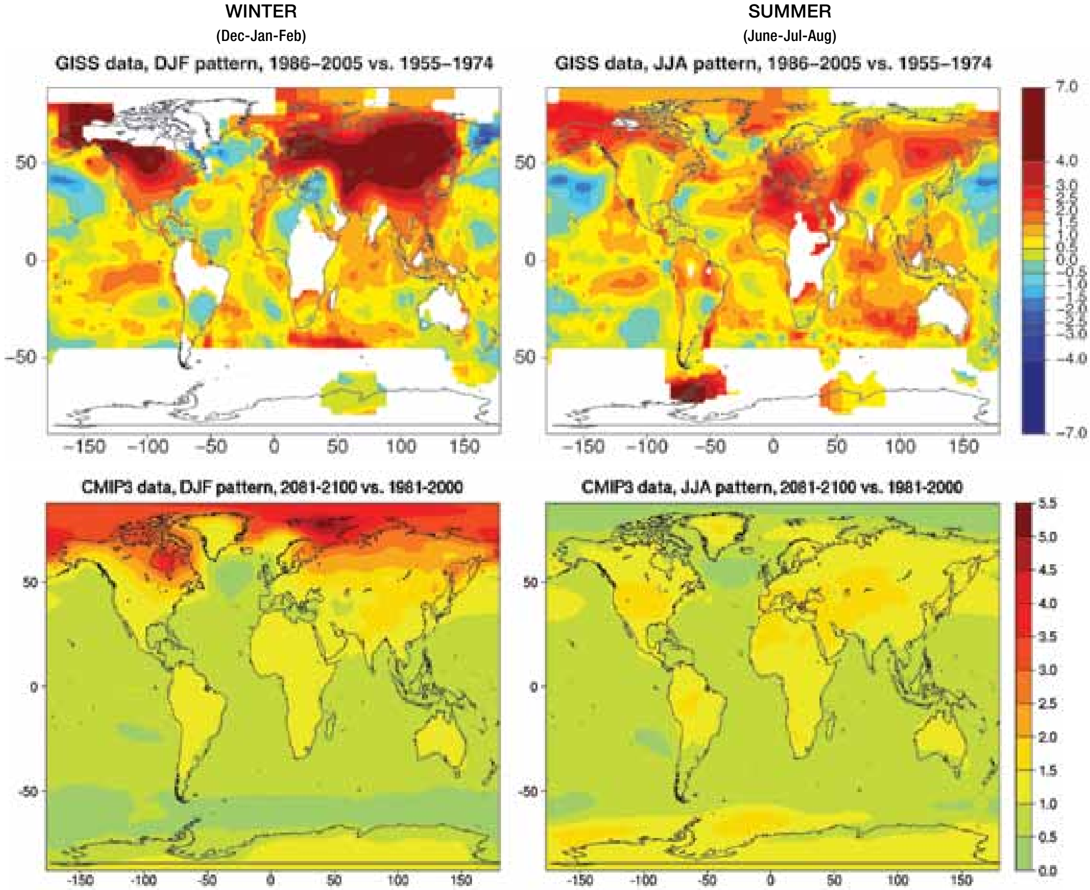


FIGURE 8. Scientists generate maps of the projected regional warming by using climate models to simulate the outcomes of a variety of plausible future storylines about global economic development. The local warmings at each point in the maps are first divided by the corresponding amount of global average warming, and then scaled to show what pattern of warming would be expected in a given region for every 1°C of global warming. The figure compares warming during the past 50 years for winter (December-February, top left) and summer (June-August, top right) to projected warming for the late 21st century (bottom) for the same time periods. Warming is greatest in the high latitudes of the Northern Hemisphere, and warming is generally larger over continents than over the ocean.

Precipitation by region and season

- **Precipitation increases or decreases by 5-10% per degree of warming across many regions**
- **At middle and low latitudes (closer to the equator), wet areas get wetter; dry areas get drier. All high-latitude regions get wetter, even the desert of Antarctica.**

In many ways, global warming is expected to intensify regional contrasts in precipitation that already exist. Warmer temperatures tend to increase evaporation from oceans, lakes, plants, and soil. Theory and observations agree that this should boost the total amount of water vapor in the atmosphere by about 7% per 1°C of warming. Although the enhanced evaporation provides more atmospheric moisture for rain and snow, it also dries out the land surface, which exacerbates the impact of drought in some regions. As a general rule, dry areas are expected to get drier, and wet areas even wetter.

Using the same general approach as for temperatures, regional and seasonal maps have been produced that depict the percentage change in precipitation expected for every 1°C of global warming. The results show that many subtropical areas around 30°N and 30°S, where most of the world's deserts are concentrated, are likely to see reductions of 5-10% in precipitation for every degree of warming across the planet as a whole. In contrast, subpolar and polar regions are expected to see increased precipitation, especially during winter.

The overall pattern of change in the continental United States is somewhat complicated, as the 48 states lie between the drying subtropics of Mexico and the Caribbean and the moistening subpolar regions of Canada. Most models suggest drying in the southwestern United States.

Different complexities arise in the tropics. For example, although many regions near the equator should moisten, the exact locations will be determined by changing interactions between winds and rainfall (including the El Niño/Southern Oscillation) that are difficult for present climate models to capture. Two areas of particular concern are the Amazon, home to the world's largest rainforest, and sub-Saharan Africa, where millions of people are vulnerable to rainfall-induced disruptions in food supply. In both of these areas, some, but not all, models show the potential for dramatic drying.

Temperature and precipitation extremes

- **Risk of very hot summers increases, where "very hot" is defined as the hottest 5% of summers during the 1971-2000 average**
- **Amount of rain falling during the heaviest precipitation events increases by 3-10% per degree of warming**

Extreme periods of heat and cold can kill thousands of people in a single region. Likewise, a few days of unusually heavy rain can have major local and regional impacts. Projecting how extreme events like these will change with global warming is a different and more difficult task than project-

Changes in Precipitation Patterns per Degree Warming

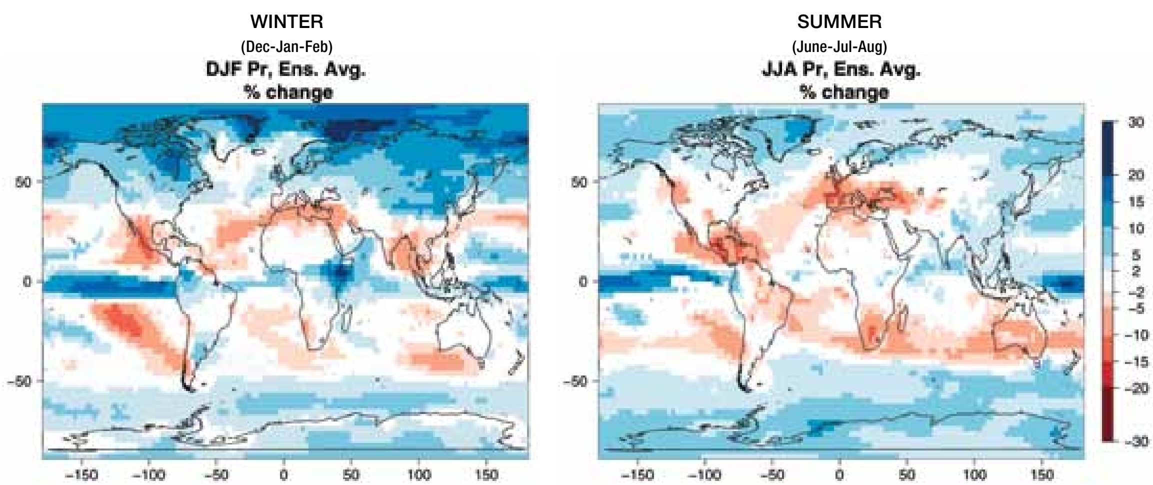


FIGURE 9. Higher temperatures increase evaporation from oceans, lakes, plants, and soil, putting more water vapor in the atmosphere, and in turn producing rain and snow in some areas. However, increased evaporation also dries out the land surface, which reduces precipitation in some regions. This figure shows the projected percentage change per 1°C of global warming for winter (December–February, left) and summer (June–August, right). Blue areas show where more precipitation is predicted and red areas show where less precipitation is predicted. White areas show regions where changes are extremely uncertain at present, because fewer than 12 of the 18 CMIP3 models agree on whether there will be more or less precipitation in those regions.

Projections of Hotter Summers

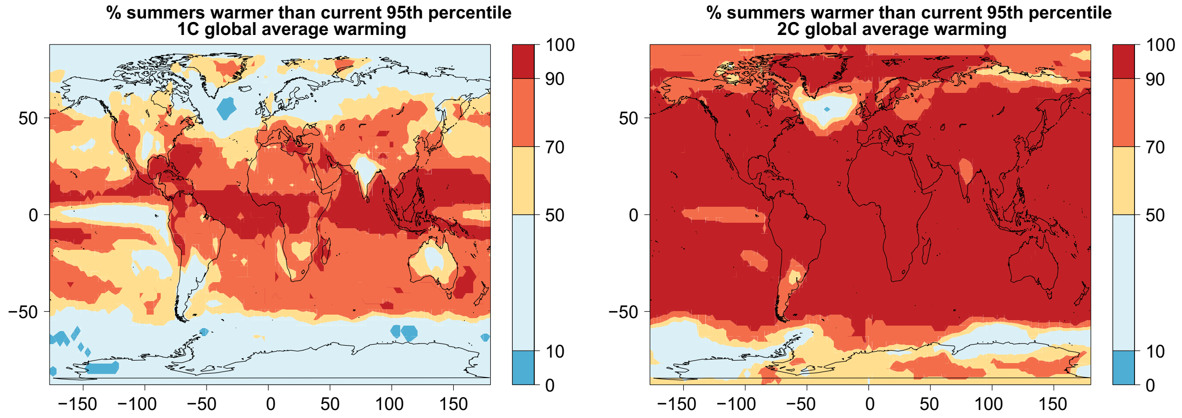


FIGURE 10. Global warming increases the chances that any given summer will be as warm as the warmest 5% of summers between 1971 and 2000. The chances of that happening are high in some places after 1°C warming (shown on the left map). At 2°C warming, nearly every summer over much of the globe will be as warm as the warmest 5% of recent summers.

ing the averaged regional and seasonal patterns of changes in average temperature and precipitation.

If temperatures rise by 1°C, one might expect that extreme daily highs and lows would also tend to rise by 1°C. This would intensify warm extremes and modulate cold ones. It is possible that extremes could change in a less straightforward fashion: for example, temperature variability might increase or decrease over time, or the high end of the range could rise more or less quickly than the low end. However, the studies conducted to date do not yet provide robust projections of how variability will change as a function of global temperature, or, in turn, for how daily temperature extremes might change.

Modeling results do allow us to robustly characterize potential changes in seasonal temperatures. Accordingly, we use average seasonal temperatures as a way to gauge how some local extremes might vary with global warming. Across northern midlatitudes, the kind of extremely warm summer that one might experience only once every 20 years (95th percentile) would be expected every 2 to 10 years should global warming reach about 2°C relative to pre-industrial conditions. If global temperature rises to about 3°C, then the majority of summers across the world's populated areas would be as warm as those experienced only about once every 20 years during the past few decades.

Observations in many parts of the world show that, in many cases, intense bouts of rain are already becoming even more intense.

Observations in many parts of the world show that in many cases, intense bouts of rain are already becoming even more intense. Computer models indicate that this trend will continue as the Earth warms, even in subtropical regions where the overall precipitation goes down. In general, extreme rain events are likely to intensify by 5-10% for every 1°C of global warming. Theory suggests that the greatest intensification should occur in the tropics, where rain is already the heaviest.

Although there is high confidence that extreme rainfall will become heavier, local impacts may not necessarily grow in a corresponding fashion. For example, flood risk depends on land use and many other local and regional variables besides precipitation.

Hurricanes and regional atmospheric circulation

- **Hurricane intensity increases by 1-4% per 1°C of warming**
- **Hurricane destructive power (cube of the wind speed) increases by 3-12% per 1°C of warming**
- **Hurricane frequency decreases by 0-10% per 1°C of warming**
- **Jet streams and storm tracks generally move toward the poles**

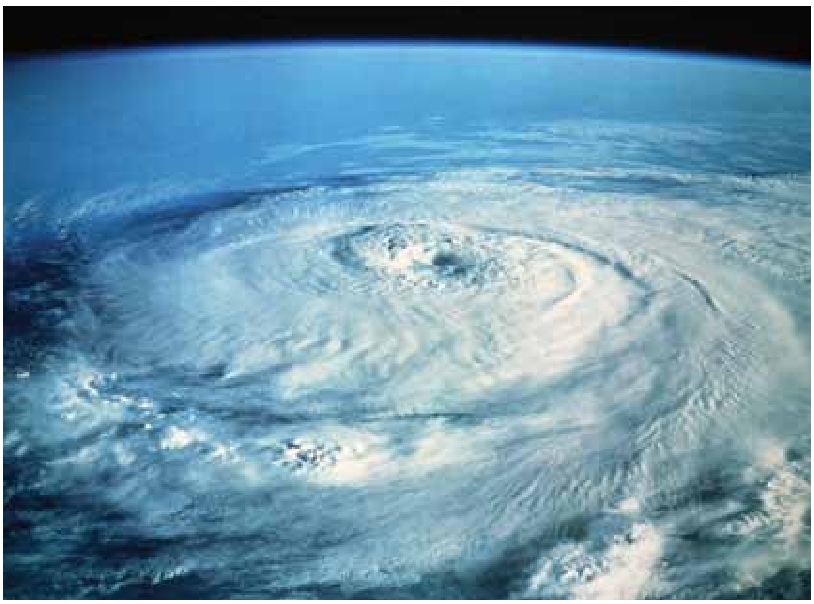
Much research has been carried out over the last few years on how hurricane frequency and intensity might change in a warming climate. Initial studies noted that the number and strength of tropical cyclones observed in the Atlantic Ocean has risen dramatically during the past several decades, largely in sync with sea-surface temperatures over the tropical North Atlantic. Because hurricanes draw energy from warm oceans, the projected rise in sea-surface temperatures across much of the tropics would provide additional energy for any cyclones that form.

Recent observational and modeling studies provide an updated picture of how global warming could affect cyclones. These studies suggest that some of the previously identified increase in Atlantic hurricane numbers can be attributed to a natural cycle causing ocean temperatures in the tropical Atlantic to rise and fall over periods of several decades. Trends during a full century or longer would average across these natural internal cycles. However, claims of significant upward trends over these longer time scales have been questioned as improved observations have revealed that a number of storms went unnoticed in the pre-satellite era.

In general, models of 21st-century climate tend to reduce the number of tropical cyclones observed by 0-10% for every °C of global warming. The average intensity is projected to increase by 1-4% per 1°C, with destructive power (the cube of the wind speed) growing by 3-12% per 1°C. Calculations based on the expected global increase in water vapor show a potential 7% rise per 1°C in the amount of rain falling within 100 kilometers (60 miles) of a tropical cyclone's center.

Although most tropical oceans are expected to warm, a strong case has been made that it is the *relative* amount of warming among oceans that affects where hurricanes increase or decrease in number. Because of the circulation pattern of rising and sinking air driven by relatively warm and cool tropical waters, respectively, regions with warmer sea surface temperatures will tend to generate more cyclones at the expense of regions where less warming occurs. While the tropical Atlantic has warmed more rapidly than the other tropical oceans over the past few decades, models provide no consensus that this will continue into the future.

Regional aspects of global circulation outside of the tropics will also change as the Earth warms. Polar jet streams and associated storm tracks are expected to contract toward the poles. While this has already occurred to a significant



degree in the Southern Hemisphere during recent decades, models suggest that much of that change has been driven by the depletion of stratospheric ozone above Antarctica. By the mid-21st century, this ozone depletion is expected to diminish; from that point onward, greenhouse-driven changes in the southern polar jet stream and associated storm track should become evident. The observational record for contraction of the jet streams and storm tracks in the Northern Hemisphere is less clear, but models also predict a gradual poleward contraction as the century progresses.

Sea ice, snow, and permafrost

- **Annual average extent of Arctic sea ice is reduced by about 15% per degree of warming**
- **Average September extent of Arctic sea ice is reduced by about 25% per degree of warming, with ice-free conditions in September eventually possible**
- **Snow cover is generally reduced; permafrost thaws**

As global warming continues, many forms of ice across the planet are decreasing in extent, depth, and duration. This trend is generally expected to continue, although there are some important exceptions.

The average annual extent of sea ice across the Arctic Ocean has dropped by roughly 3% per decade since satellite monitoring began in 1978. This erosion has been especially strong in late summer, leaving large parts of the ocean ice-free for weeks and raising questions about effects on ecology and commercial shipping routes. Models agree that seasonally ice-free conditions in the Arctic Ocean are likely before the end of this century. Scaling of model projections suggests about a 25% loss in September sea ice extent for every 1°C in global warming, with some models showing abrupt drops lasting one or more years.

Substantial reductions in sea-ice extent have occurred around the West Antarctic Peninsula, while increases have occurred in other parts of Antarctica. In contrast to the Arctic, sea ice surrounding Antarctica has expanded, averaged around the continent, by a slight but significant amount over the past several decades. This increase may be linked to stratospheric ozone depletion, and the effect is expected to wane as ozone returns to normal levels by later this century. Still, Antarctic sea ice may continue to decrease less rapidly than Arctic ice, in part because the Southern Ocean stores heat at greater depths than the Arctic Ocean.

In many areas of the globe, snow cover is expected to diminish, with snowpack building later in the cold season and melting earlier in the spring. According to one sensitivity analysis, every 1°C of local warming may lead to an average 20% reduction in local snowpack. However, in places such as Siberia, parts of Greenland, and Antarctica where temperatures are cold enough to support snow over long periods, the amount of snowfall may increase even as the season shortens, because the increased amount of water vapor associated with warmer temperatures may enhance snowfall. Conversely, the largest reductions in snow cover should occur in moist, low-elevation climates such as that of the Pacific Northwest, where temperatures are already marginal for snow.

Data from Canada, Alaska, Siberia, and Scandinavia show that permafrost (soil that remains frozen for at least 2 consecutive years) has gradually warmed and shrunk during the past century, with its global extent decreasing by about 7%. Models suggest that a further decrease of about 30% to more than 50% is possible by mid-century, depending on the model and the warming scenario. Should rapid loss of sea ice occur in the Arctic, additional heat flowing from the Arctic to areas of permafrost could hasten its decline.

Sea-level rise and ocean acidification

- **By 2100, global mean sea level rises by 0.5-1.0 meters (20-39 inches)**
- **Oceans continue to become more acidic (average pH value of seawater continues to decrease)**

Sea level is of profound interest to millions of people living in some of the most densely settled areas on Earth. The height of the sea at any coastal location

Contributors to Sea-Level Rise

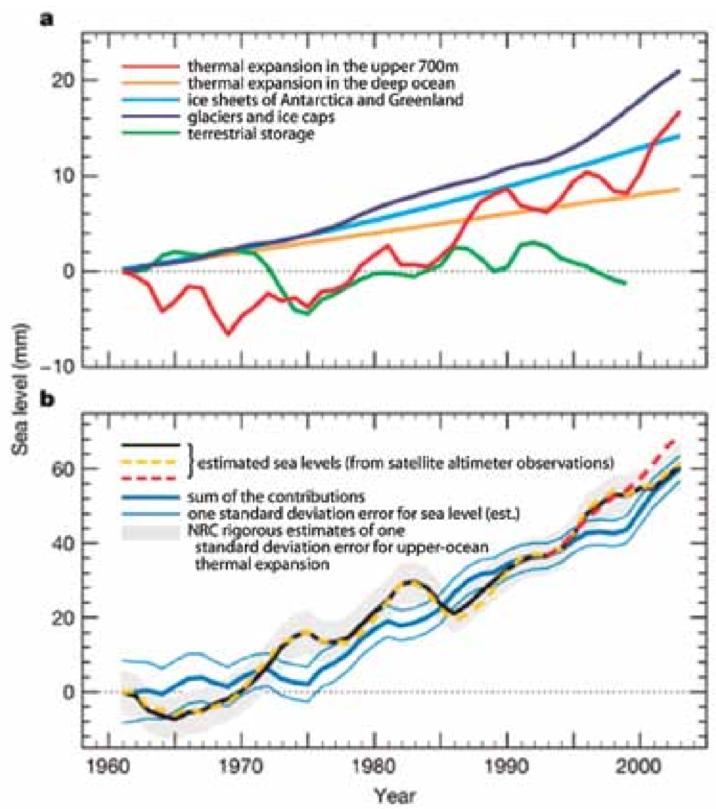


FIGURE 11. Sea level has risen steadily over the past few decades. The bottom panel shows the total observed sea-level rise (blue) with the error range of total sea level (one standard deviation; gray band). The top panel shows the various components that contribute to sea-level rise: thermal expansion in the upper 700 meters of ocean (red) and deeper ocean layers (orange), meltwater from Antarctic and Greenland ice sheets (cyan), meltwater from glaciers and ice caps (purple), and storage on land (green).

continually varies, both over the short term because of tidal cycles and storms, and over the long term because of geological factors and climate change.

On average, however, global mean sea level has risen by about 0.2 meters (8 inches) since 1870. A large fraction of the sea-level rise—roughly half of the total from 1993 to 2003—has occurred because of oceans expanding as they warmed. The rest is mainly due to water entering the sea from melting glaciers, ice caps, and ice sheets.

Globally averaged mean sea level will rise over the next century from further ocean thermal expansion (estimated to contribute 0.14-0.32 meters, or 5-12 inches, by 2100) and from additional meltwater and increased iceberg calving, which will probably grow over time in its importance to total sea level relative to thermal expansion. These factors could lead to an estimated 0.5-1.0 meter (20-39 inches) of mean sea-level rise by 2100, depending on the model and scenario. Because recent studies have shown increased melting from glaciers and ice sheets, these estimates are somewhat higher than those in the 2007 IPCC assessment.

Even larger increases in mean sea level—more than 1.0 meter (39 inches) by 2100—could occur as a result of the dynamic behavior (meaning a mechanical collapse rather than gradual melting) of Greenland and Antarctic ice sheets, which is poorly represented in current climate models. The geological record of past climates can neither confirm nor rule out the possibility of such rapid rises in sea level. Although they are conceivable, it is not yet possible to quantify this risk. Some correlation studies predict sea-level rise up to 1.6 meters (63 inches) by 2100 for a warming scenario of 3.1°C (5.6°F).

As they rise, the world's seas are also gradually acidifying. This is because of the increasing amount of CO_2 absorbed by oceans, which has equaled about a quarter of human-produced CO_2 emissions in recent years. Consequently, the average pH value of seawater in the surface ocean has dropped by about 0.1 pH units since pre-industrial times (from about 8.2 to about 8.1), corresponding to a 26% increase in hydrogenions. In turn, these changes influence aspects of ocean chemistry on which many creatures rely—especially plants and animals that build shells and skeletons from calcium carbonate, because the concentration of carbonate decreases as the pH of seawater drops.

If CO_2 concentrations rise to 550 ppm, pH would drop by an additional 0.15 units, which could begin to jeopardize shell-building marine life in some areas. Increases in CO_2 are projected to harm coral reefs, which also face other stresses due to warming.

Comparison of Projected and Observed Sea-Level Rise

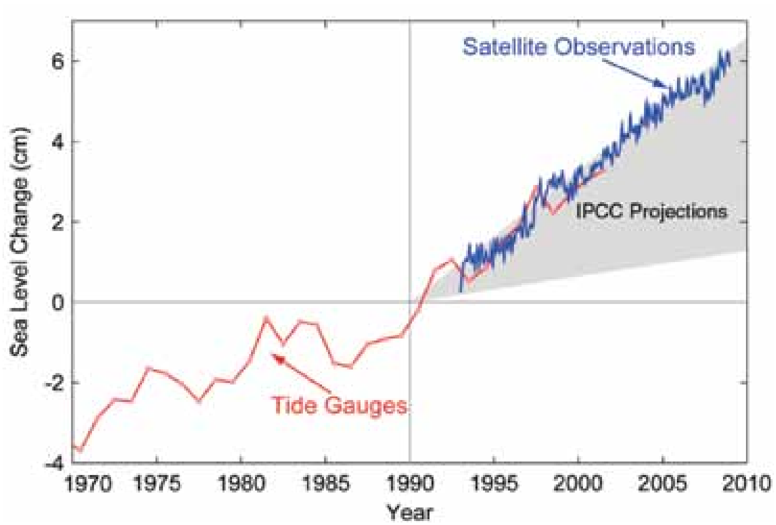


FIGURE 12. Comparison of predicted sea-level change to observed sea-level change shows that observed sea-level rise since 1990 has been near the top of the projected range. The red line shows data derived from tide gauges from 1970 to 2003. The gray band shows the range of model-based projections from the IPCC Third Assessment Report, published in 1990. Blue line shows satellite observations of sea-level change during recent years.

Complexities and surprises in a warming world

As climate change unfolds, there are likely to be surprises, including outcomes that are difficult or impossible for any model to quantify. National security is one area where a warming Earth and its effects on human societies could have substantial implications. Some of the world's most intractable conflicts are in regions of food and water scarcity, which are closely tied to variability in temperature and precipitation. One study has found correlations between global temperature shifts since 1400 and the frequency of wars and related death rates. In Africa, another study suggests that civil wars since 1980 have been roughly 50% more likely in years 1°C warmer than average.

As the time frame of climate change extends to 2100 and beyond, the range of possible outcomes widens further. Ecosystem shifts that are projected to unfold over the next century, such as the expansion of Arctic shrublands and the potential decline of some parts of the Amazonian rainforest due to drought, could grow in breadth and intensity.

Much concern has been expressed about the future of an Atlantic Ocean current pattern known as the "meridional overturning circulation," which keeps parts of Europe milder than they would otherwise be. About half of the climate models used in the Fourth Assessment Report (AR4) from the IPCC extended simulations through the 22nd century, with greenhouse gases held constant during the period from 2100 to 2200. One study found that the meridional overturning circulation, which is projected to decline by as much as 50% by 2100, did not decline further after that. In some models, the circulation strengthened somewhat over the course of the 22nd century. Although this suggests that a complete shutdown of this circulation, and the major cooling across Western Europe that it would bring, may be unlikely, more long-term modeling must be done to assess whether meridional overturning circulation changes might become permanent beyond 2100.

One of the most dramatic changes at Earth's surface linked to global warming is the ongoing loss of sea ice across the Arctic Ocean. Although the predicted year varies, by the end of the 21st century most models predict an essentially ice-free Arctic in late summer. The two models with the most sophisticated treatment of sea ice predict that the Arctic will lose its winter ice as well, should CO_2 quadruple from preindustrial values and remain at that level for several centuries. While an ice-free Arctic could present new economic opportunities, it will also likely have profound impacts on both local and global climate and ecological systems. Among these is the potential to enhance the rate of surface melt of Greenland's glaciers, which would further accelerate sea-level rise.

As climate change unfolds, there are likely to be surprises, including outcomes that are difficult or impossible for any model to quantify.

Just as many effects on the physical climate system can now be identified and quantified for various degrees of global warming, so too can several of the impacts expected during the next few decades and centuries. *Climate Stabilization Targets* identifies and quantifies impacts on food security, coastlines and infrastructure, streamflow, and wildfire. Effects on human health and land and ocean ecosystems are also identified but cannot yet be quantified.

impacts in the next few decades and coming centuries

Food and human health

- **Yields of corn in the United States and Africa, and wheat in India, drop by 5-15% per degree of warming**
- **If 5°C (9°F) of global warming were to be reached, most regions of the world experience yield losses, and global grain prices potentially double**
- **Crop pests, weeds, and disease shift in geographic range and frequency**
- **Risk of heat-related illness and death increases**
- **The timing and geographic range of allergens and vector-borne diseases shifts**

Societal well-being in the United States and elsewhere is expected to be affected by a changing climate both directly—as pathogens and other threats evolve—and indirectly, as changes in climate influence food production.

All else aside, increasing the amount of CO_2 in the atmosphere favors the growth of many plants. Leaf pores, or stomata, shrink in response to the added CO_2, which helps plants to conserve water. The enhanced CO_2 also stimulates photosynthesis in plants with a C3 photosynthetic pathway, such as rice and wheat, although not in plants with a C4 pathway, such as maize (i.e., corn). C3 yields could increase by an average of more than 10% if CO_2 were doubled over preindustrial values, all else being equal.

Enhanced plant growth from elevated CO_2 does not necessarily translate into more food, however, because climate changes caused by CO_2 can reduce yields in many regions. Crops tend to grow more quickly in warmer temperatures, leaving less time to produce grains. In addition, a changing climate will bring other hazards, including greater water stress and the risk of higher temperature peaks that can quickly damage crops.

Modeling indicates that the CO_2-related benefits for some crops will largely be outweighed by negative factors if global temperature rises more than 1.0°C from late 20th-century values. The true risks may be even greater, as some potentially negative changes—including the likelihood of longer, more widespread drought and the potential for weeds, insects, and crop pathogens to spread—are not yet incorporated in most crop models.

Growers in prosperous areas may be able to partially or completely adapt to these threats, for example, by varying the crops they grow and the times at which they are grown. Adaptation may be less effective where local warming exceeds 2°C, however. Its use will also be limited in the tropics, where the growing season is restricted by moisture rather than temperature.

impacts are coming

Some impacts that can be quantified per degree of warming include:

- **5-15% reductions in the yields of crops as currently grown**
- **3-10% increases in the amount of rain falling during the heaviest precipitation events**
- **5-10% decreases in streamflow in some river basins, including the Arkansas and the Rio Grande**
- **200-400% increases in the area burned by wildfire in parts of the western United States**

Loss of Crop Yields per Degree Warming

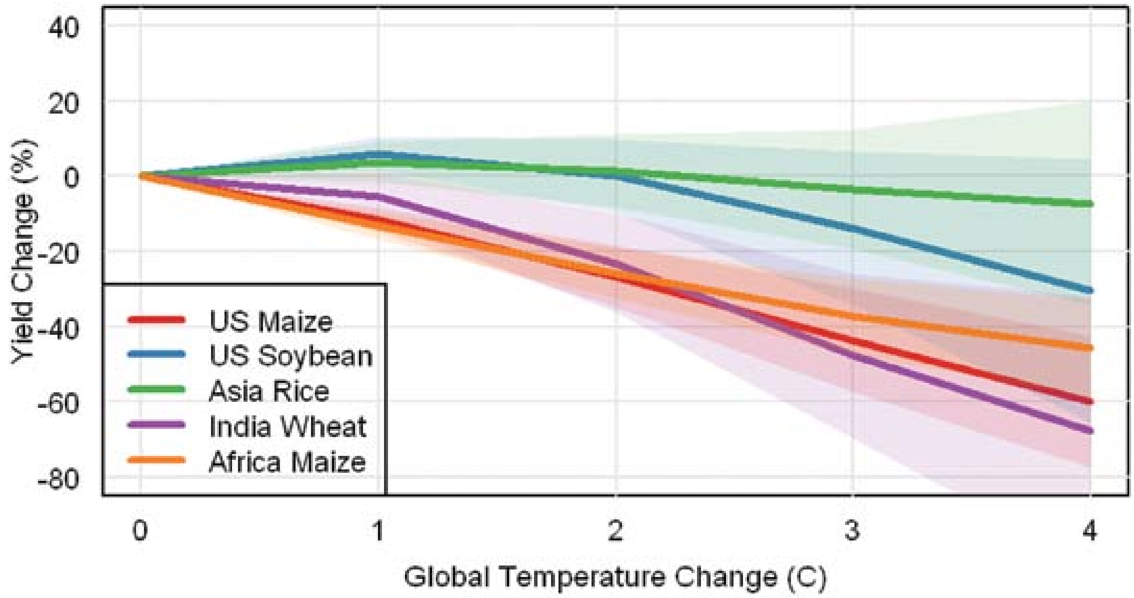


FIGURE 13. Yields of corn in the United States and Africa, and wheat in India, are projected to drop by 5-15% per degree of global warming. This figure shows projected changes in yield as a function of average global temperature increase for those crops as well as for U.S. soybeans and Asian rice. The expected impacts on crop yield are from both warming and carbon dioxide increases, assuming no crop adaptation. Solid lines show best estimates, and shaded regions show ranges of projections. Values of global temperature change are relative to the preindustrial value; current global temperatures are roughly 0.7°C (1.3°F) above that value.

Climate's effect on human health is mixed with many other influences, making it difficult to quantify the net risks of climate change. Some insights have been gained, though. For example:

• In recent decades, heat and cold have killed about three times as many people as all other natural disasters combined. As global temperatures rise, the risk of heat-related illnesses and deaths should rise, while the risk of cold-related illnesses and deaths should drop.

• In contrast to earlier findings, insect-borne disease may not change dramatically in prevalence but may shift location, with the ranges of malaria and other diseases moving toward some areas but away from others.

• Recent studies have highlighted the risks to human health from changes in air and water quality. Ground-level ozone, a lung irritant that may trigger asthma in children, could increase in cities around the world as temperatures increase, assuming that the pollutants leading to low-level ozone are not reduced. Intensified rainfall will challenge drainage systems and boost the risk of water contamination. Recent increases in the length of the pollen season may also boost the incidence of allergies, although this is an evolving area of research.

WHAT DOES IT MEAN?

The U.S. Corn Belt is projected to experience a loss of 11% corn production per degree of warming, while at the same time global cereal demand is expected to rise by roughly 1.2% per year. That means that farmers would have to work every year to overcome shortfalls that would, under today's conditions, take 9 years to materialize.

Increases in the Duration of Heat Waves

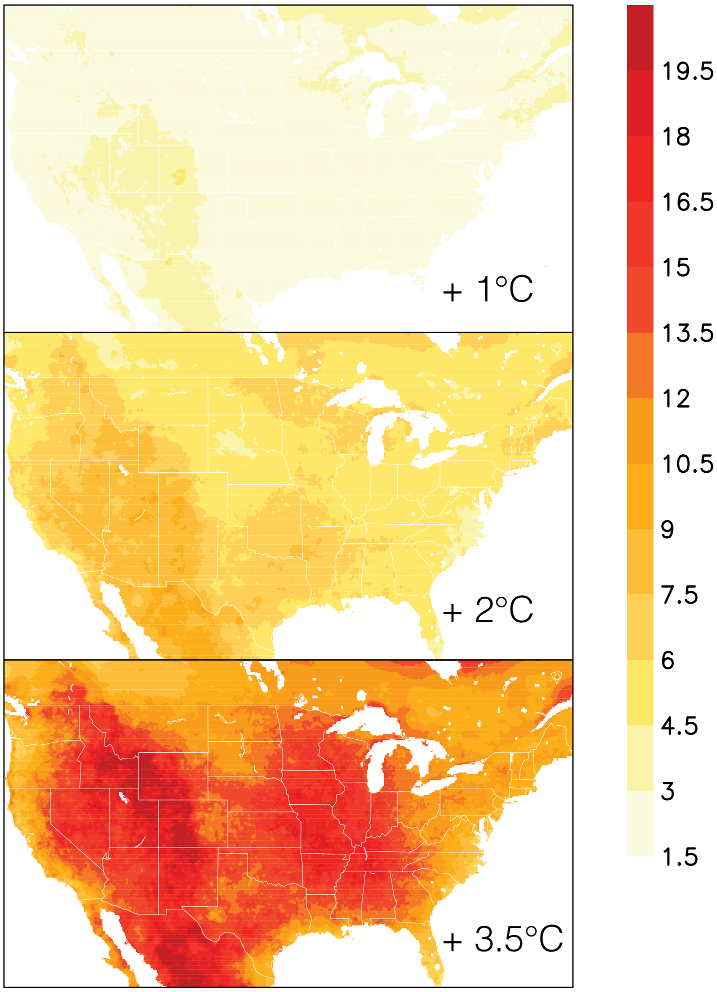


FIGURE 14. Heat waves are expected to last longer as the average global temperature increases. Values shown are the changes in the heat-wave-duration-index, measured in days. The index is defined as the longest period each year with at least 5 consecutive days in which daily high temperatures are at least 5°C above the climatological (1961-1990) average for that same calendar day. Projected changes are for 20-year periods during which average global temperature increased by 1°C, 2°C, and 3.5°C, respectively, relative to the 1961-1979 average.

Coastlines and infrastructure

- **At a mean sea-level rise of 0.5 meters (20 inches), coastal flooding becomes a threat to 5-200 million people**
- **The Arctic experiences major changes affecting infrastructure, including a shorter land transportation season and longer marine transportation season**
- **Risk of extreme temperature, precipitation and storms that impact infrastructure increases**
- **Demand increases for air conditioning and decreases for winter heating**

Global population growth is largely centered in coastal cities, many of which may soon be at risk from sea-level rise. However, quantifying the future threat posed to particular coastlines by rising seas and floods is very challenging. Many nonclimatic factors are involved, and the risks will vary greatly from one location to the next. Moreover, infrastructure damage is often triggered by extreme events rather than gradual change. There are some clear "hot spots," particularly in large urban areas on coastal deltas, including those of the Mississippi, Nile, Ganges, and Mekong rivers (see Figure 16). Risks to these areas may accelerate if global mean sea level (relative to 1980-1999 average levels) rises beyond 0.3 meters (12 inches), which is expected later this century. At the same time, much can be done to change infrastructure and reduce risk, although it is difficult to make broad-based estimates of vulnerability and potential adaptation costs on coastal infrastructure.

If mean sea level rises by 0.5 meters (20 inches) relative to a 1990 baseline, coastal flooding could affect anywhere from 5-200 million people. Up to 4 million people could be permanently displaced as erosion could claim more than 250,000 square kilometers of wetland and dryland (98,000 square miles, an area the size of Oregon). Migra-

“Hot Spots” of Vulnerability to Sea-Level Rise

FIGURE 15. Although it is very difficult to quantify the future threat posed by rising seas and floods to all coastal populations, several “hot spots” can be identified. Large urban areas on coastal deltas, including those of the Mississippi, Nile, Ganges, and Mekong rivers, are highlighted. This map shows the relative vulnerability of coastal deltas to sea-level rise that exacerbates natural and human induced subsidence and amplifies the surge intensities of coastal storms. Larger dots indicate populations that could be displaced by 2050 if current sea-level trends continue.

tions are already occurring in towns along the coast of Alaska, where reductions in sea ice and melting permafrost allow waves to batter and erode the shoreline.

Many U.S. urban areas are considering a range of adaptations to the risk of increased flooding on and near coastlines. Proposals being explored include large-scale water diversion from the highly developed Sacramento–San Joaquin Delta in California, which lies below sea level, and flood-protection barricades in the New York area, a technique already employed near London, St. Petersburg, and Venice.

The use and availability of energy will also be affected by climate change in several ways. Demand for air conditioning is expected to continue to grow in many areas worldwide as temperatures rise, which poses the risk for electricity shortages related to peak demand. Hydropower, which accounts for most electricity in South America and northern Europe, is vulnerable to rainfall and snowfall variations: every 1% change in precipitation produces about a 1% change in power generation. However, projecting future climate effects on hydropower is limited by uncertainties in projecting precipitation changes on a local and regional scale.

Global population growth is largely centered in coastal cities, many of which may soon be at risk from sea-level rise.

Streamflow and fire

- **Streamflow decreases by 5-10% per degree of warming in some river basins, including the Arkansas and the Rio Grande**
- **Average area burned by wildfire per year in parts of western United States increases by two to four times per degree of warming**

In many areas, streamflow is critical to the availability of water. Although each human needs only about 5 liters (1.3 gallons) of water per day for survival, the average daily per-capita water use varies from about 10 liters (2.6 gallons) in Africa to 200 liters (53 gallons) per day in the United States. About 90% of all water use worldwide is for agriculture.

During a year's time, streamflow generally equals runoff—the amount of water from snow or rain that flows into rivers and creeks. However, it is not a straightforward task to convert runoff to streamflow in climate modeling. The most common technique is to feed the output from global-model projections of climate into a separate model that depicts smaller-scale river-basin hydrology. In other cases, global models have been used to directly project runoff based on modeled rainfall and snowfall. Though limited by the resolution of global models, this technique has been shown to be useful for larger river basins.

By using the second technique—direct analysis of runoff from global climate models used in the Fourth Assessment Report (AR4) from the IPCC—we find that future runoff is likely to decrease throughout most of the United States, except for parts of the Northwest and Northeast, with particularly sharp drops in the Southwest. This generally occurs because enhanced evaporation from warming outweighs any potential runoff gain from increases in precipitation. These decreases in U.S. runoff are similar across most of the IPCC scenarios, and they grow at roughly a linear pace within the range of 1-2°C of global warming. Globally, streamflow in many temperate river basins outside Eurasia is likely to decrease, especially in arid and semiarid regions.

Rising temperatures and increased evaporation can also be expected to boost the risk of fire in some regions. In general, forests that are already fire-prone, such as the evergreen forests of the western United States and Canada, should become even more vulnerable to fire as temperatures warm. At the same time, areas dominated by shrubs and grasses, such as parts of the U.S. Southwest, may see a reduction in fire over time. In these regions, a wet year can boost fire risk the following

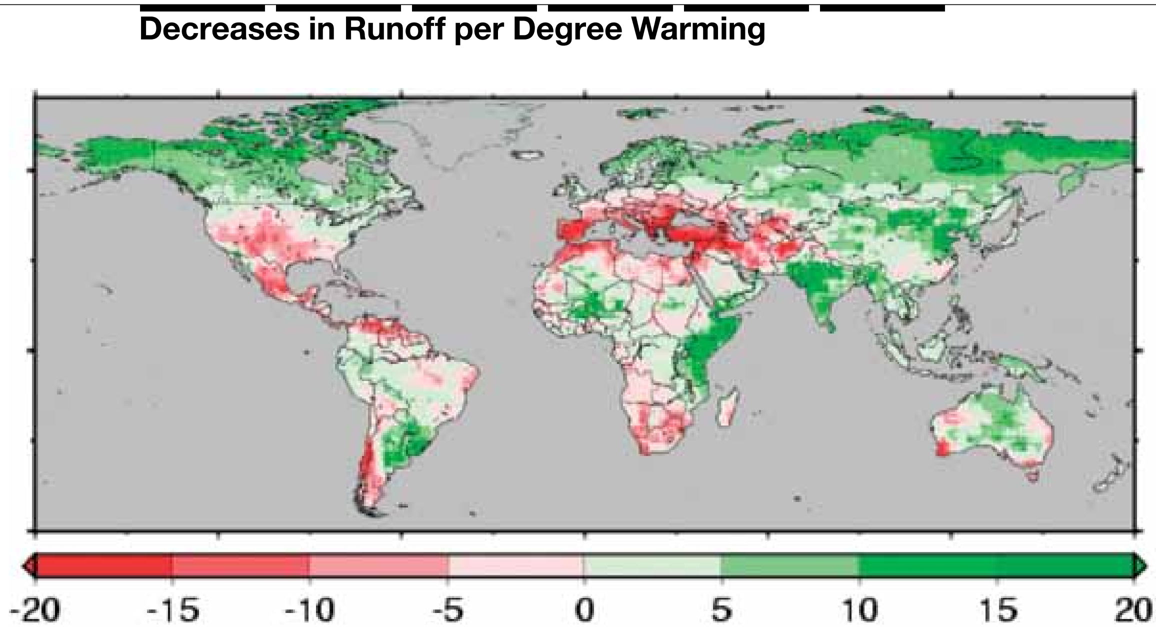


FIGURE 16. Enhanced evaporation due to warming is projected to decrease the amount of runoff—the water flowing into rivers and creeks—in many parts of the United States. Runoff is a key index of the availability of fresh water. The figure shows the percent median change in runoff per degree of global warming, relative to the period from 1971 to 2000.

Increased Risk of Fire

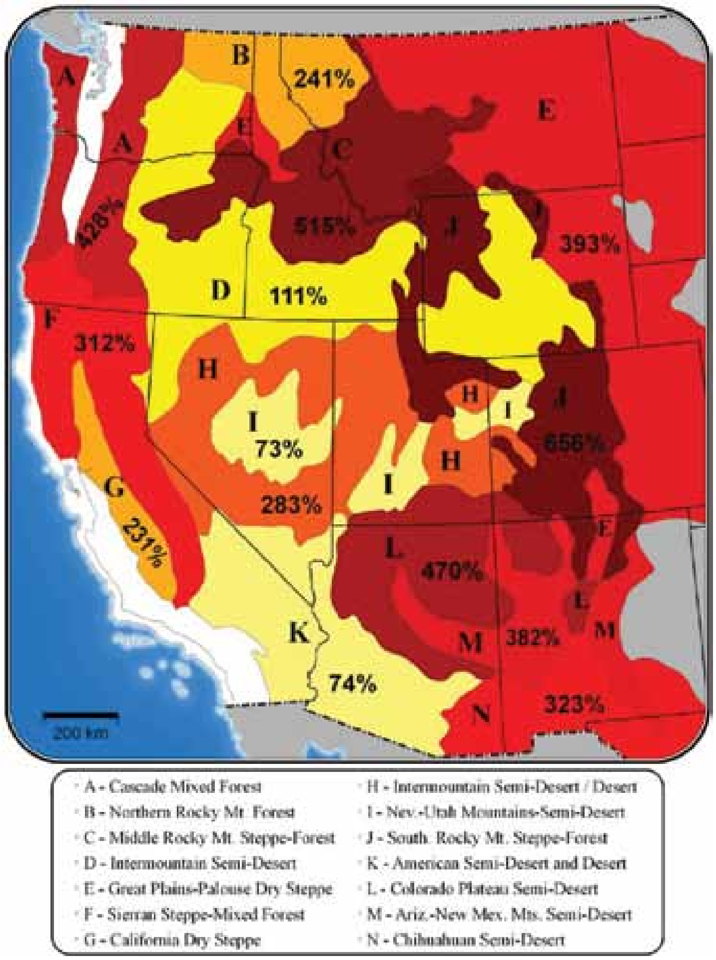


FIGURE 17. Rising temperatures and increased evaporation are expected to increase the risk of fire in many regions of the West. This figure shows the percent increase in burned areas in the U.S. West, one of the places most at risk for fire increases, for a 1°C increase in global average temperatures, relative to the median area burned during 1950-2003.

year, as shrubs and grasses die out. Even as warmer temperatures favorable to drying enhance the risk of fire in forests, similar changes could cause shrublands and grasslands to wither into deserts, eliminating large-scale fires. In this case, the potential societal benefits from a decrease in fire would be countered by the loss of existing ecosystems.

Quantitative depictions of changes in fire risk remain challenging, because most global models do not yet allow ecosystems to evolve in response to change in climate. In addition, models can vary widely in their depiction of precipitation change across small regions, and this has a direct effect on projected fire risk.

Land and ocean ecosystems

- **Individual land species experience shifts in timing of flowers and breeding cycles, in geographic ranges, and in population**
- **Disturbances arise from changes in the frequency and timing of fire, pests, and disease**
- **Forest processes shift, including nutrient cycling, transpiration, and respiration**
- **Shifts occur in the geographic ranges and die-off rates of some ocean species**
- **Corals and mollusks experience declining calcification rates and corals exhibit more frequent bleaching events**
- **Nutrient availability shifts in coastal upwelling zones**
- **Zones of depleted oxygen (dead zones) become larger and longer-lasting**

Whether marine or terrestrial, all organisms attempt to acclimate to a changing environment or else move to a more favorable location. Climate change threatens to push some species beyond their abilities to adapt or move.

The ranges of countless land-based plants and animals are hemmed in by human development, yet many species are responding to climate change during the past few decades in other ways. A variety of plants are blooming earlier in the spring, and some birds, mammals, fish, and insects are migrating earlier, while other species are altering their seasonal breeding and hatching patterns. Global analyses show that, among species experiencing such shifts, these behaviors occurred an average of 5 days earlier per decade from 1970 to 2000. Shifts in the timing of one species relative to others can disrupt patterns of feeding, pollination, and other key aspects of food webs.

Climate change could also affect physiology and genetics, although few studies have examined these potential links. The body structures of woodrats and other species have been found to change in response to natural climate shifts in the past, and one recent study found a mosquito species with genetic changes apparently linked to climate change.

In general, species most at risk of extinction are found in small numbers across small areas, with pressures such as poaching also at work. Global warming could team with these risk factors to threaten temperature-dependent species who cannot reach a cool refuge, such as those living on islands or mountaintops where warming is under way. Warming could also have a unique impact on tropical rainforests (which are already being depleted by development), because even a small warming could lead to temperatures completely beyond the range of some rainforest species.

In the ocean, circulation changes will be a key driver of ecosystem impacts. Satellite data show that increased vertical stratification between warm surface waters and cooler, deeper waters—a trend expected to grow with climate change in many areas—separates near-surface marine life from nutrients below, which reduces primary productivity (the total amount of marine life) over a period of years. Vertical mixing in the oceans should decrease across the tropics and subtropics, reducing primary productivity there, while mixing and productivity could increase in temperate and polar waters, especially with expected losses in sea ice. At the same time, ocean warming will continue to push the ranges of many marine species poleward.

Changing ocean chemistry will bring other impacts. Warmer waters should lead to a decline in subsurface oxygen, boosting the risk of areas of hypoxia and associated "dead zones," where species high on the food chain are largely absent. Ocean acidification will threaten many species over time, especially mollusks and coral reefs. Not all life forms will suffer: some types of phytoplankton and other photosynthetic organisms may benefit from increases in CO_2, and laboratory studies of crustaceans show both increased and decreased calcification rates in response to elevated CO_2.

Effects on the Ocean Food Web

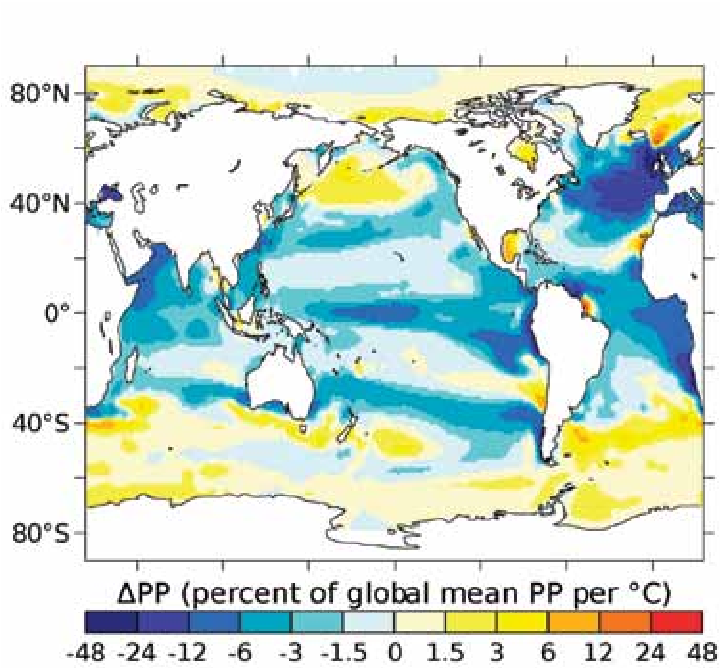


FIGURE 18. The growth of marine phytoplankton, the base of the ocean food web, will be reduced over time because of warmer temperatures, which create a greater distance between warmer surface waters and cooler deep waters, separating upper marine life from nutrients found in deep water. The figure shows changes in phytoplankton growth (vertically integrated annual mean primary production, or PP), expressed as the percentage difference between 2090-2099 and 1860-1869 per 1°C of global warming.

A number of key climate changes and impacts for the next few decades and centuries can now be estimated for different levels of warming. Because many impacts increase proportionally with global temperature, we now have increased confidence in how global warming levels of 1°C, 2°C, 3°C, and so forth affect such phenomena as precipitation, extreme heat, streamflow, sea ice, crop yields, coral bleaching, and sea level. This provides scientific support for evaluating the impact of different stabilization targets.

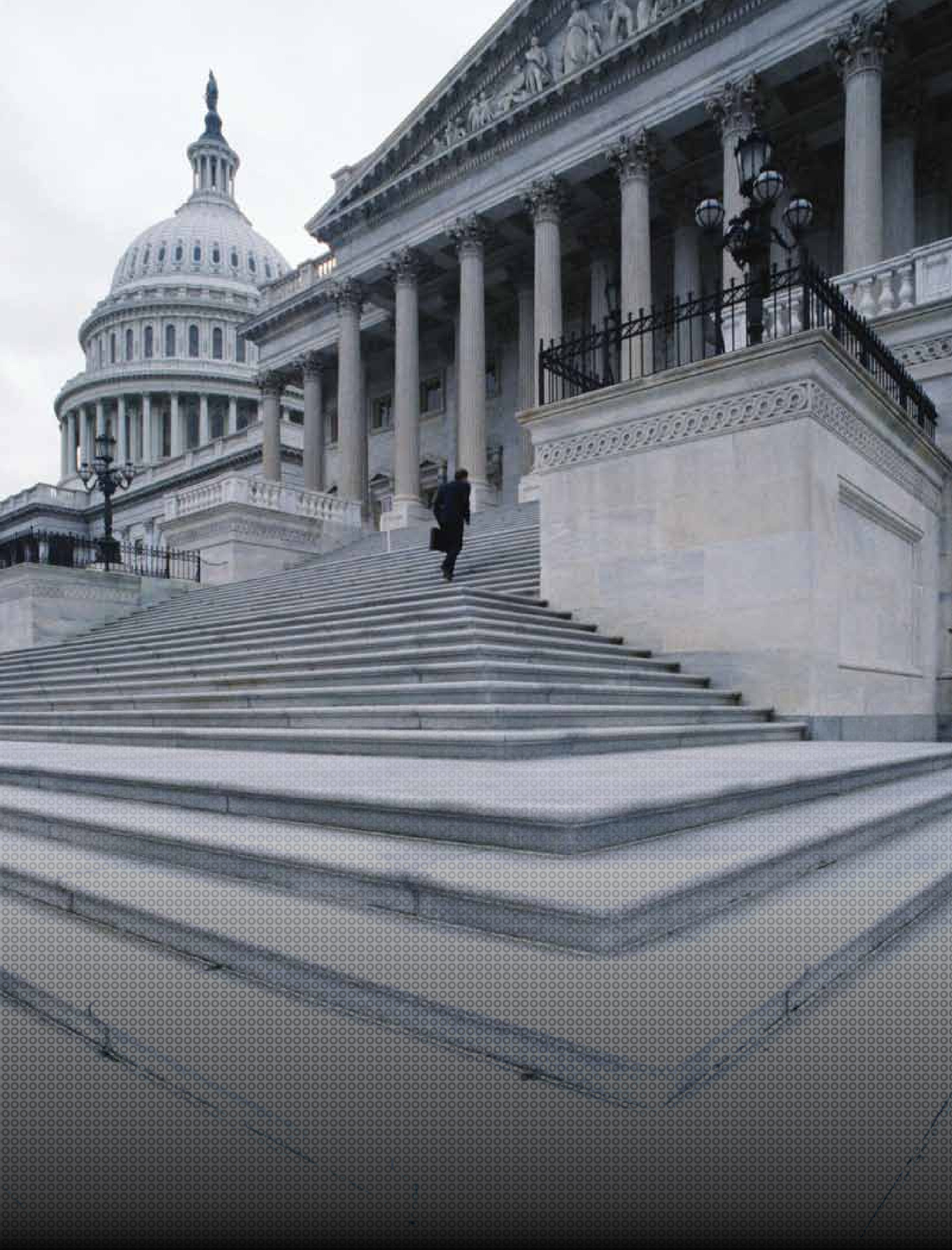
The cumulative carbon framework, another recent development, provides further guidance. Many longer-term impacts over this century and beyond depend more on how much carbon is eventually emitted than on when emissions occur. Policies that address both short- and long-term impacts could therefore be crafted with attention to the total amount of emissions, climate changes, impacts, and associated uncertainties over decades to come. This implies that emission pathways over the next several decades should be considered not only for their possible short-term benefits, but also for their role in influencing cumulative emissions—and thus eventual climate change—much further into the future.

using science to inform choices

Some climate changes and impacts are currently understood only in a qualitative manner; they cannot be quantified as a function of stabilization targets. This does not imply that they are negligible. Some of these impacts, such as species changing their ranges or behaviors, could in fact grow to become the dominant risks posed by human-produced climate change.

Those who create policies to address emissions growth must also determine what is an "acceptable" level of warming as well as an acceptable level of risk. These are inherently value judgments that can be guided but not determined by physical science. Not everyone has the same tolerance for risk or the same values, and societies vary in the resources they devote to ensuring the safety and well-being of their citizens and ecosystems.

Responding to climate change and associated variability could become increasingly more difficult and expensive across developed and developing countries alike. This report provides scientific information that should help policymakers evaluate the expected impacts of choices and consequences of stabilization targets over the short and long term.



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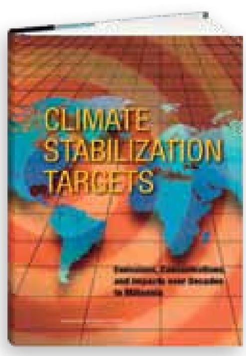
ABOUT THIS REPORT

The National Academies appointed the committee of experts listed below to address a specific task requested by the Energy Foundation and the U.S. Environmental Protection Agency. The members volunteered their time for this activity. The report, *Climate Stabilization Targets: Emissions, Concentrations, and Impacts Over Decades to Millennia,* represents the committee's consensus view in response to the requested task. The report was peer-reviewed.

EXPERT CONSENSUS REPORT

Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations: Susan Solomon (*Chair*), National Oceanic and Atmospheric Administration; **David Battisti**, University of Washington, Seattle; **Scott Doney**, Woods Hole Oceanographic Institution; **Katharine Hayhoe**, Texas Tech University; **Isaac M. Held**, National Oceanic and Atmospheric Administration; **Dennis P. Lettenmaier**, University of Washington, Seattle; **David Lobell**, Stanford University; **Damon Matthews**, Concordia University, Montreal; **Raymond Pierrehumbert**, University of Chicago; **Marilyn Raphael**, University of California, Los Angeles; **Richard Richels**, Electric Power Research Institute, Inc., Washington, DC; **Terry L. Root**, Stanford University; **Konrad Steffen**, University of Colorado, Boulder; **Claudia Tebaldi**, Climate Central, Vancouver; **Gary W. Yohe**, Wesleyan University; **Toby Warden** (Study Director), **Lauren Brown** (Research Associate), National Research Council.

This booklet was written by Robert Henson and prepared by the National Research Council based on the report.



For more information, contact the Board on Atmospheric Sciences and Climate at (202) 334-2744 or visit http://dels.nas.edu/basc. Copies of *Climate Stabilization Targets: Emissions, Concentrations, and Impacts Over Decades to Millennia* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; www.nap.edu.

At a time when responding to climate change is one of the nation's most complex endeavors, reports from the National Research Council provide objective analyses in support of policymakers and stakeholders. These reports are produced by committees of leading scientists and other experts convened by the Board on Atmospheric Sciences and Climate and numerous other entities within the National Research Council.