Appendix 3: Climate Science

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Supplemental Messages

1. **Although climate changes in the past have been caused by natural factors, human activities are now the dominant agents of change. Human activities are affecting climate through increasing atmospheric levels of heat-trapping gases and other substances, including particles.**

2. **Global trends in temperature and many other climate variables provide consistent evidence of a warming planet. These trends are based on a wide range of observations, analyzed by many independent research groups around the world.**

3. **Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere interactions, influences global and regional temperature and precipitation over timescales ranging from months up to a decade or more.**

4. **Human-induced increases in atmospheric levels of heat-trapping gases are the main cause of observed climate change over the past 50 years. The “fingerprints” of human-induced change also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.**

5. **Past emissions of heat-trapping gases have already committed the world to a certain amount of future climate change. How much more the climate will change depends on future emissions and the sensitivity of the climate system to those emissions.**

6. **Different kinds of physical and statistical models are used to study aspects of past climate and develop projections of future change. No model is perfect, but many of them provide useful information. By combining and averaging multiple models, many clear trends emerge.**

7. **Scientific understanding of observed temperature changes in the U.S. has greatly improved, confirming that the U.S. is warming as expected in response to global climate change.**

8. **Many other indicators of rising temperatures have been observed in the United States. These include reduced lake ice, glacier retreat, earlier melting of snowpack, reduced lake levels, and a longer growing season. These and other indicators are expected to continue to reflect higher temperatures.**

9. **Trends in some types of extreme weather events have been observed in recent decades, consistent with rising temperatures. These include increases in: heavy precipitation nationwide, especially in the Midwest and Northeast; heat waves, especially in the West; and the intensity of Atlantic hurricanes. These trends are expected to continue. Research on climate changes' effects on other types of extreme events continues.**

10. **Drought and fire risk are increasing in many regions as temperatures and evaporation rates rise. The greater the future warming, the more these risks will increase, potentially affecting the entire United States.**

11. **Summer Arctic sea ice extent, volume, and thickness have declined rapidly, especially north of Alaska. Permafrost temperatures are rising and the overall amount of permafrost is shrinking. Melting of land- and sea-based ice is expected to continue with further warming.**

12. **Sea level is already rising at the global scale and at individual locations along the U.S. coast. Future sea level rise depends on the amount of warming and ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.**

Appendix: The Science of Climate Change

This Appendix provides further information and discussion on climate science beyond that presented in the chapter Our Changing Climate. Like the chapter, the Appendix focuses on the observations, model simulations, and other analyses that explain what is happening to climate at the national and global scales, why these changes are occurring, and how climate is projected to change throughout this century. In the Appendix, however, more information is provided on attribution, spatial and temporal detail, and physical mechanisms than could be covered within the length constraints of the main chapter.

As noted in the main chapter, changes in climate, and the nature and causes of these changes, have been comprehensively discussed in a number of other reports, including the 2009 assessment: Global Climate Change Impacts in the United States[1] and the global assessments produced by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. National Academy of Sciences. This Appendix provides an updated discussion of global change in the first few supplemental messages, followed by messages focusing on the changes having the greatest impacts (and potential impacts) on the United States. The projections described in this Appendix are based, to the extent possible, on the CMIP5 model simulations. However, given the timing of this report relative to the evolution of the CMIP5 archive, some projections are necessarily based on CMIP3 simulations. (See Supplemental Message 5 for more on these simulations and related future scenarios).

Supplemental Message 1.

Although climate changes in the past have been caused by natural factors, human activities are now the dominant agents of change. Human activities are affecting climate through increasing atmospheric levels of heat-trapping gases and other substances, including particles.

The Earth's climate has long been known to change in response to natural external forcings. These include variations in the energy received from the Sun, volcanic eruptions, and changes in the Earth's orbit, which affects the distribution of sunlight across the world. The Earth's climate is also affected by factors that are internal to the climate system, which are the result of complex interactions between the atmosphere, ocean, land surface, and living things (see Supplemental Message 3). These internal factors include natural modes of climate system variability, such as the El Niño Southern Oscillation.

Natural changes in external forcings and internal factors have been responsible for past climate changes. At the global scale, over multiple decades, the impact of external forcings on temperature far exceeds that of internal variability (which is less than 0.5°F[2]). At the regional scale, and over shorter time periods, internal variability can be responsible for much larger changes in temperature and other aspects of climate. Today, however, the picture is very different. Although natural factors still affect climate, human activities are now the primary cause of the current warming: specifically, human activities that increase atmospheric levels of carbon dioxide (CO_2) and other heat-trapping gases and various particles that, depending on the type of particle, can have either a heating or cooling influence on the atmosphere.

The greenhouse effect is key to understanding how human activities affect the Earth's climate. As the sun shines on the Earth, the Earth heats up. The Earth then re-radiates this heat back to space. Some gases, including water vapor (H_2O), carbon dioxide (CO_2), ozone (O_3), methane (CH_4), and nitrous oxide (N_2O), absorb some of the heat given off by the Earth's surface and lower atmosphere. These heat-trapping gases then radiate energy back toward the surface, effectively trapping some of the heat inside the climate system. This greenhouse effect is a natural process, first recognized in 1824 by the French mathematician and physicist Joseph Fourier[3] and confirmed by British scientist John Tyndall in a series of experiments starting in 1859.[4] Without this natural greenhouse effect (but assuming the same albedo, or reflectivity, as today), the average surface temperature of the Earth would be about 60°F colder.

Today, however, the natural greenhouse effect is being artificially intensified by human activities. Burning fossil fuels (coal, oil, and natural gas), clearing forests, and other human activities produce heat-trapping gases. These gases accumulate in the atmosphere, as natural removal processes are unable to keep pace with increasing emissions. Increasing atmospheric levels of CO_2, CH_4, and N_2O (and other gases and some types of particles like soot) from human activities increase the amount of heat trapped inside the Earth system. For this reason, we refer to these gases as "heat-trapping gases" throughout this assessment. This human-caused intensification of the greenhouse effect is the primary cause of observed warming in recent decades.

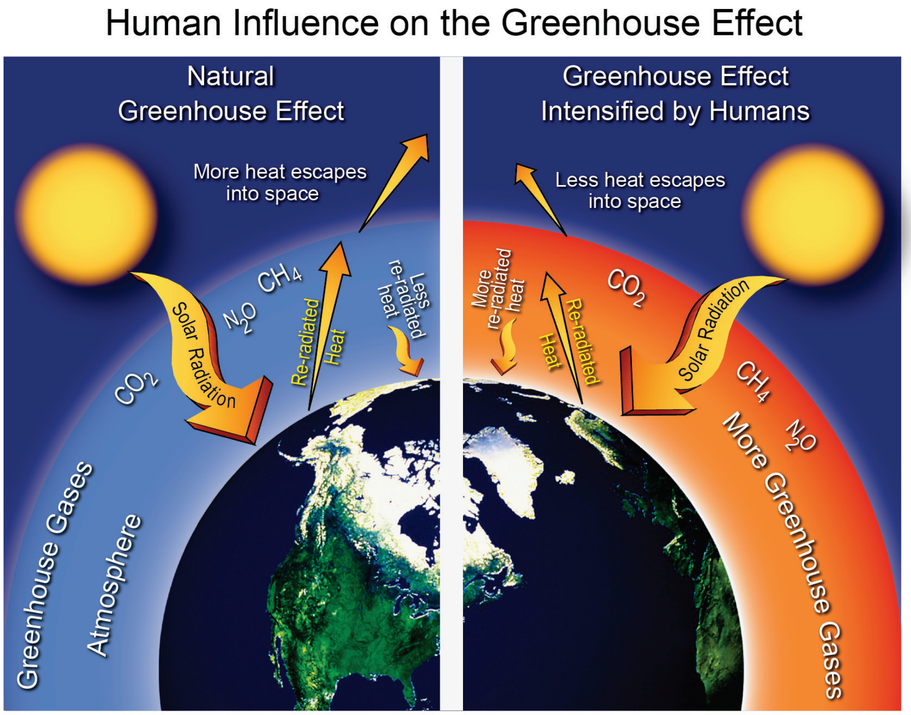


Figure 1: Human Influence on the Greenhouse Effect

Caption: Left: A stylized representation of the natural greenhouse effect. Most of the sun's radiation reaches the Earth's surface. Naturally occurring heat-trapping gases, including water vapor, carbon dioxide, methane, and nitrous oxide, do not absorb the short-wave energy from the Sun but do absorb the long-wave energy re-radiated from the Earth, keeping the planet much warmer than it would be otherwise. **Right**: In this stylized representation of the human-intensified greenhouse effect, human activities, predominantly the burning of fossil fuels (coal, oil, and gas), are increasing levels of carbon dioxide and other heat-trapping gases, increasing the natural greenhouse effect and thus Earth's temperature. (Figure source: modified from National Park Service).[5]

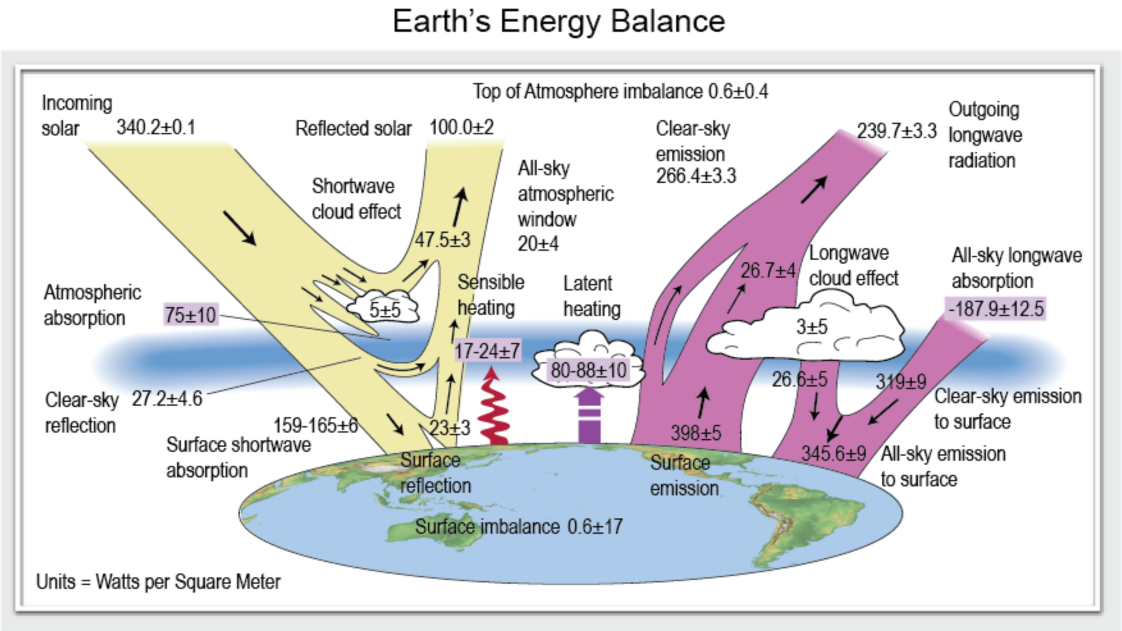


Figure 2: Earth's Energy Balance

Caption: This figure summarizes results of measurements taken from satellites of the amount of energy coming in to and going out of Earth's climate system. It demonstrates that our scientific understanding of how the greenhouse effect operates, is, in fact, accurate, based on real world measurements. (Figure source: modified from Stephens et al. 2012^{6}).

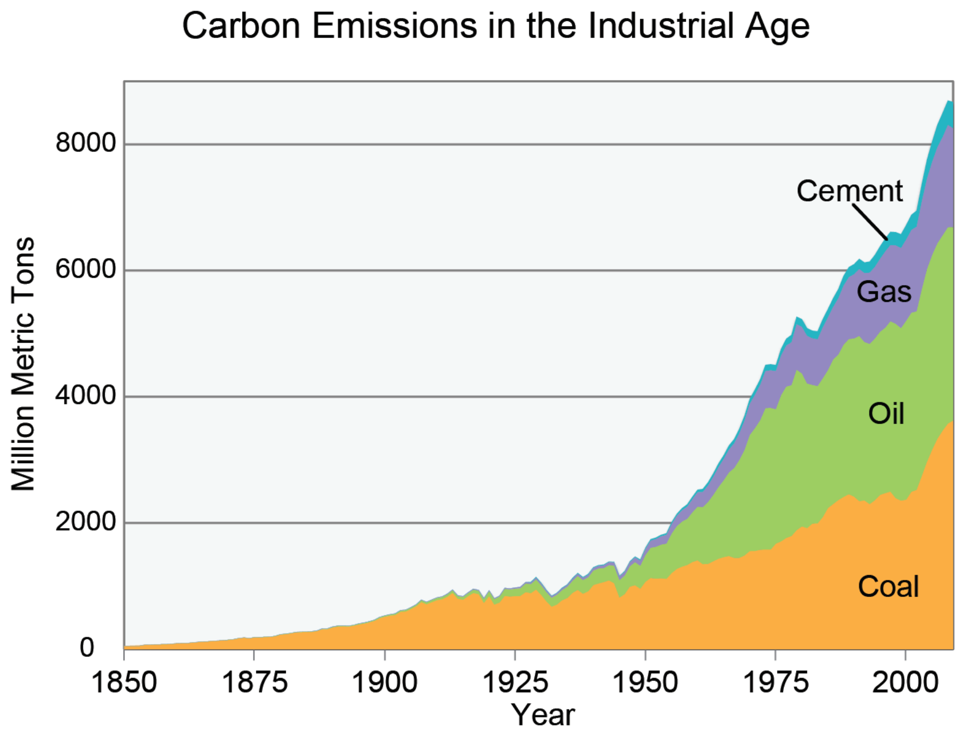


Figure 3: Carbon Emissions in the Industrial Age

Caption: Global carbon emissions from burning coal, oil, and gas and producing cement (1850-2009). These emissions account for about 80% of the total emissions of carbon from human activities, with land-use changes (like cutting down forests) accounting for the other 20% in recent decades (Data from Boden et al. 2012[7]).

Carbon dioxide has been building up in the Earth's atmosphere since the beginning of the industrial era in the mid-1700s. Emissions and atmospheric levels, or concentrations, of other important heat-trapping gases, including methane, nitrous oxide, and halocarbons, have also increased because of human activities. While the atmospheric concentrations of these gases are relatively small compared to those of molecular oxygen or nitrogen, their ability to trap heat is extremely strong. The human-induced increase in atmospheric levels of carbon dioxide and other heat-trapping gases is the main reason the planet has warmed over the past 50 years and has been an important factor in climate change over the past 150 years or more.

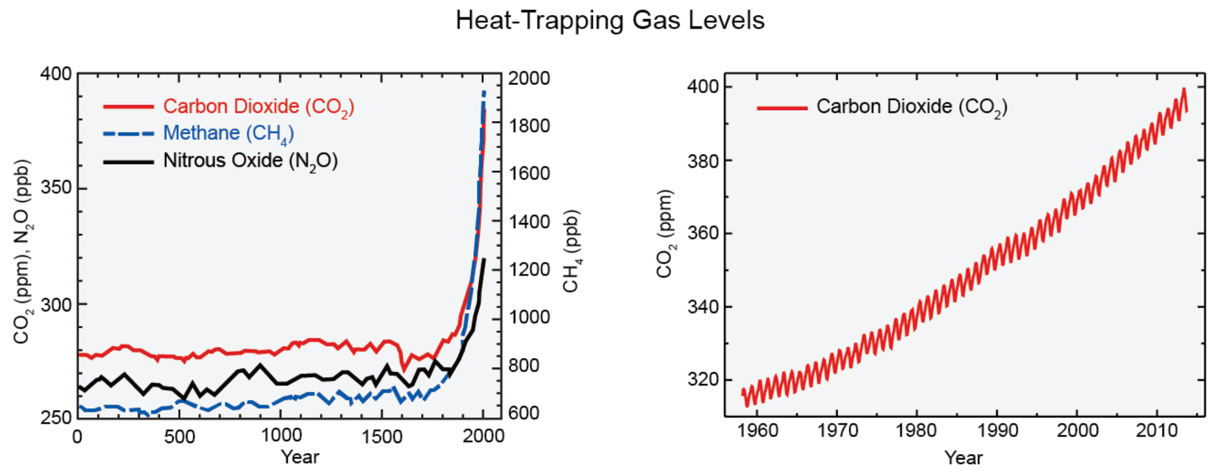


Figure 4: Heat-Trapping Gas Levels

Caption: Present-day atmospheric levels of carbon dioxide, methane, and nitrous oxide are notably higher than their pre-industrial averages of 280, 0.7, and 0.27 parts per million (by volume), respectively (left). Air sampling data from 1958 to 2013 show long-term increases due to human activities as well as short-term variations due to natural biogeochemical processes and seasonal vegetation growth (right). (Figure sources: (left) Forster et al. 2007; (right) Scripps Institution of Oceanography and NOAA Earth Systems Research Laboratory).

Carbon dioxide levels in the atmosphere are currently increasing at a rate of 0.5% per year. Atmospheric levels measured at Mauna Loa in Hawai'i and at other sites around the world reached 400 parts per million in 2013, higher than the Earth has experienced in over a million years. Globally, over the past several decades, about 78% of carbon dioxide emissions has come from burning fossil fuels, 20% from deforestation and other agricultural practices, and 2% from cement production. Some of the carbon dioxide emitted to the atmosphere is absorbed by the oceans, and some is absorbed by vegetation. About 45% of the carbon dioxide emitted by human activities in the last 50 years is now stored in the oceans and vegetation. The remainder has built up in the atmosphere, where carbon dioxide levels have increased by more than 40% relative to pre-industrial levels.

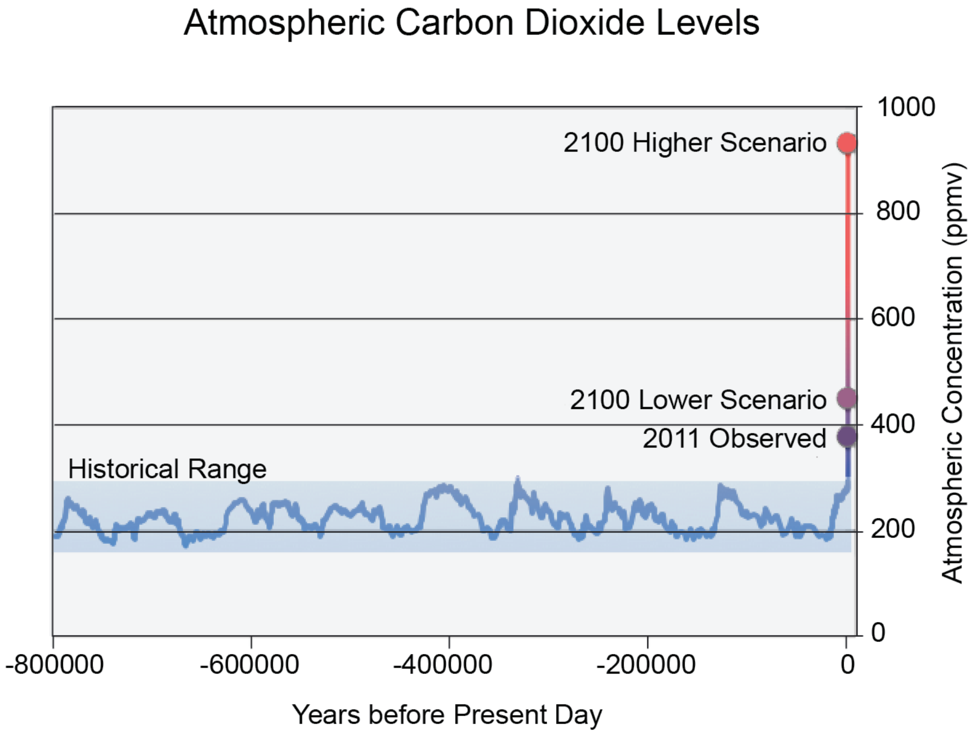


Figure 5: Atmospheric Carbon Dioxide Levels

Caption: Air bubbles trapped in an Antarctic ice core extending back 800,000 years document the atmosphere's changing carbon dioxide concentration. Over long periods, natural factors have caused atmospheric CO_2 concentrations to vary between about 170 to 300 parts per million (ppm). As a result of human activities since the Industrial Revolution, CO_2 levels have increased to 400 ppm, higher than any time in at least the last one million years. By 2100, additional emissions from human activities are projected to increase CO_2 levels to 420 ppm under a very low scenario, which would require immediate and sharp emissions reductions (RCP 2.6,) and 935 ppm under a higher scenario, which assumes continued increases in emissions (RCP 8.5). This figure shows the historical composite CO_2 record based on measurements from EPICA (European Project for Ice Coring in Antarctica) Dome C. (Data from Lüthi et al. 2008[8] (664-800 thousand years [kyr] ago); Siegenthaler et al. 2005[9] (393-664 kyr ago); Vostok (22-393 kyr ago [Pépin 2001; Petit et al. 1999; Raynaud 2005] [10]); and Monnin et al. 2001[11] (0-22 kyr ago); and Meinshausen et al. 2011[12] (future projections from RCP 2.6 and 8.5).

Methane levels in the atmosphere have increased due to human activities, including: agriculture, with livestock producing methane in their digestive tracts, and rice farming producing it via bacteria that live in the flooded fields; mining coal, extraction and transport of natural gas, and other fossil fuel-related activities; and waste disposal including sewage and decomposing garbage in landfills. On average, about 55% to 65% of the emissions of atmospheric methane now come from human activities.[13,14] Atmospheric concentrations of methane leveled off from 1999-2006 due to temporary decreases in both human and natural sources,[13,14] but have been increasing again since then. Since preindustrial times, methane levels have increased by 250% to their current levels of 1.85 ppm.

Other greenhouse gases produced by human activities include ***nitrous oxide, halocarbons, and ozone.*** Nitrous oxide levels are increasing, primarily as a result of fertilizer use and fossil fuel burning. The concentration of nitrous oxide has increased by about 20% relative to pre-industrial times.

Halocarbons are manufactured chemicals produced to serve specific purposes, from aerosol spray propellants to refrigerant coolants. One type of halocarbon, long-lived chlorofluorocarbons (CFCs), was used extensively in refrigeration, air conditioning, and for various manufacturing purposes. However, in addition to being powerful heat-trapping gases, they are also responsible for depleting stratospheric ozone. Atmospheric levels of CFCs are now decreasing due to actions taken by countries under the Montreal Protocol, an international agreement designed to protect the ozone layer. As emissions and atmospheric levels of halocarbons continue to decrease, their effect on climate will also shrink. However, some of the replacement compounds are hydrofluorocarbons (HFCs), which are potent heat-trapping gases, and their concentrations are increasing.

Over 90% of the ozone in the atmosphere is in the stratosphere, where it protects the Earth from harmful levels of ultraviolet radiation from the Sun. In the lower atmosphere, however, ozone is an air pollutant and also an important heat-trapping gas. Upper-atmosphere ozone levels have decreased because of human emissions of CFCs and other halocarbons. However, lower-atmosphere ozone levels have increased because of human activities, including transportation and manufacturing. These produce what are known as ozone precursors: air pollutants that react with sunlight and other chemicals to produce ozone. Since the late 1800s, average levels of ozone in the lower atmosphere have increased by more than 30%.[15] Much higher increases have been observed in areas with high levels of air pollution, and smaller increases in remote locations where the air has remained relatively clean.

Human activities can also produce tiny atmospheric particles, including dust and soot. For example, coal burning produces sulfur gases that form particles in the atmosphere. These sulfur-containing particles reflect incoming sunlight away from the Earth, exerting a cooling influence on Earth's surface. Another type of particle, composed mainly of soot or black carbon, absorbs incoming sunlight and traps heat in the atmosphere, warming the Earth.

In addition to their direct effects, these particles can affect climate indirectly by changing the properties of clouds. Some encourage cloud formation because they are ideal surfaces on which water vapor can condense to form cloud droplets. Some can also increase the number but decrease the average size of cloud droplets when there is not enough water vapor compared to the number of particles available, thus creating brighter clouds that reflect energy from the sun away from the Earth, and resulting in an overall cooling effect. Particles that absorb energy encourage cloud droplets to evaporate by warming the atmosphere. Depending on their type, increasing amounts of particles can either offset or increase the warming caused by increasing levels of greenhouse gases. At the scale of the planet, the net effect of these particles is to offset between 20% and 35% of the warming caused by heat-trapping gases.

The effects of all of these greenhouse gases and particles on the Earth's climate depend in part on how long these gases and particles remain in the atmosphere. Human-induced emissions of carbon dioxide have already altered atmospheric levels in ways that will persist for thousands of years. About one-third of the carbon dioxide emitted in any given year remains in the atmosphere 100 years later. However, the impact of past human emissions of carbon dioxide on the global carbon cycle will endure for tens of thousands of years. Methane lasts for approximately a decade before it is removed through chemical reactions. Particles, on the other hand, only remain in the atmosphere anywhere from a few days to several weeks. This means that the effects of any human actions to reduce particle emissions can show results nearly immediately. It may take decades, however, before the results of human actions to reduce long-lived greenhouse gas emissions can be observed. Some recent studies[16] examine various means for reducing near-term changes in climate, for example, by reducing emissions of short-lived gases like methane and particles like black carbon (soot). These approaches are being explored as ways to reduce the rate of short-term warming while more comprehensive approaches to reducing carbon dioxide emissions (and hence the rate of long-term warming) are being implemented.

In addition to emissions of greenhouse gases, air pollutants, and particles, human activities have also affected climate by changing the land surface. These changes include cutting and burning forests, replacing natural vegetation with agriculture or cities, and large-scale irrigation. These transformations of the land surface can alter how much heat is reflected or absorbed by the surface, causing local and even regional warming or cooling. Globally, the net effect of these changes has probably been a slight cooling influence over the past 100 years.

Considering all known natural and human drivers of climate since 1750, a strong net warming from long-lived greenhouse gases produced by human activities dominates the recent climate record. This warming has been partially offset by increases in atmospheric particles and their effects on clouds. Two important natural external drivers also influence climate: the sun and volcanic eruptions. Since 1750, these natural external drivers are estimated to have had a small net warming influence, one that is much smaller than the human influence. Natural internal climate variations, such as El Niño events in the Pacific Ocean, have also influenced regional and global climate. Several other modes of internal natural variability have been identified, and their effects on climate are superimposed on the effects of human activities, the sun, and volcanoes.

During the last three decades, direct observations indicate that the sun's energy output has decreased slightly. The two major volcanic eruptions of the past 30 years have had short-term cooling effects on climate, lasting two to three years. Thus, natural factors cannot explain the warming of recent decades; in fact, their net effect on climate has been a slight cooling influence over this period. In addition, the changes occurring now are very rapid compared to the major changes in climate over at least the last several thousand years.

It is not only the direct effects from human emissions that affect climate. These direct effects also trigger a cascading set of feedbacks that cause indirect effects on climate – acting to increase or dampen an initial change. For example, water vapor is the single most important gas responsible for the natural greenhouse effect. Together, water vapor and clouds account for between 66% and 80% of the natural greenhouse effect.[17] However, the amount of water vapor in the atmosphere depends on temperature; increasing temperatures increase the amount of water vapor. This means that the response of water vapor is an internal feedback, not an external forcing of the climate.

Observational evidence shows that, of all the external forcings, an increase in atmospheric CO_2 concentration is the most important factor in increasing the heat-trapping capacity of the atmosphere. Carbon dioxide and other gases, such as methane and nitrous oxide, do not condense and fall out of the atmosphere, whereas water vapor does (for example, as rain or snow). Together, heat-trapping gases other than water vapor account for between 26% and 33% of the total greenhouse effect,[17] but are responsible for most of the changes in climate over recent decades. This is a range, rather than a single number, because some of the absorption effects of water vapor overlap with those of the other important gases. Without the heat-trapping effects of carbon dioxide and the other non-water vapor greenhouse gases, climate simulations indicate that the greenhouse effect would not function, turning the Earth into a frozen ball of ice.[18]

The average conditions and the variability of the Earth's climate are critical to all aspects of human and natural systems on the planet. Human society has become increasingly complex and dependent upon the climate system and its behavior. National and global infrastructures, economies, agriculture, and ecosystems are adapted to the present climate state, which from a geologic timescale perspective has been remarkably stable for the past several thousand years. Any significant perturbation, in either direction, would have substantial impacts upon both human society and the natural world. The magnitude of the human influence on climate and the rate of change raise concerns about the ability of ecosystems and human systems to successfully adapt to future changes.

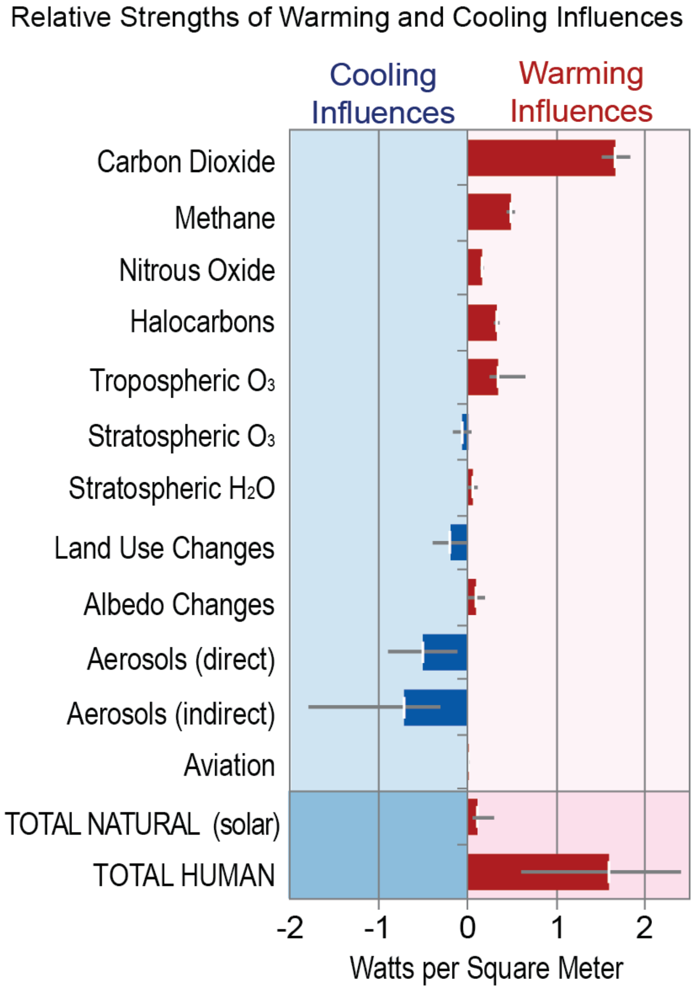


Figure 6: Relative Strengths of Warming and Cooling Influences

Caption: Different factors have exerted a warming influence (red bars) or a cooling influence (blue bars) on the planet. The warming or cooling influence of each factor is measured in terms of the change in radiative forcing in watts per square meter by 2005 relative to 1750. This figure includes all the major human-induced factors as well as the sun, the only major natural factor with a long-term effect on climate. The cooling effect of individual volcanoes is also natural, but is relatively short-lived and so is not included here. Aerosols refer to tiny particles, with their direct effects including, for example, the warming influence of back carbon (soot) and cooling influence of sulfate particles from coal burning. Indirect effects of aerosols include their effect on clouds. The net radiative influence from natural and human influences is a strong warming, predominantly from human activities. The thin lines on each bar show the range of uncertainty. (Figure source: adapted from Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2.20 (A). Cambridge University Press.)[14]

Supplemental Message 2.

Global trends in temperature and many other climate variables provide consistent evidence of a warming planet. These trends are based on a wide range of observations, analyzed by many independent research groups around the world.

There are many types of observations that can be used to detect changes in climate and determine what is causing these changes. Thermometer and other instrument-based surface weather records date back hundreds of years in some locations. Air temperatures are measured at fixed locations over land and with a mix of predominantly ship- and buoy-based measurements over the ocean. By 1850, a sufficiently extensive array of land-based observing stations and ship-borne observations had accumulated to begin tracking global average temperature. Measurements from weather balloons began in the early 1900s, and by 1958 were regularly taken around the world. Satellite records beginning in the 1970s provide additional perspectives, particularly for remote areas such as the Arctic that have limited ground-based observations. Satellites also provided new capabilities for mapping precipitation and upper air temperatures. Climate "proxies" – biological or physical records ranging from tree rings to ice cores that correlate with aspects of climate – provide further evidence of past climate that can stretch back hundreds of thousands of years.

Development of Observing Capabilities

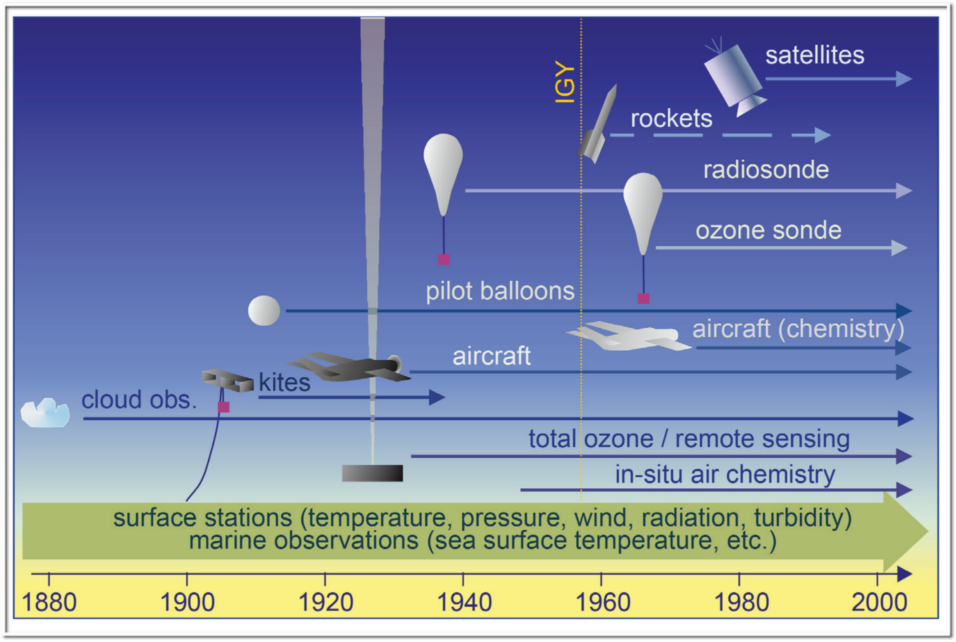


Figure 7: Development of Observing Capabilities

Caption: Changes in the mix and increasing diversity of technologies used to observe climate (IGY is the International Geophysical Year). (Figure source: adapted from Brönnimann et al. 2007[19]).

These diverse datasets have been analyzed by scientists and engineers from research teams around the world in many different ways. The most high-profile indication of the changing climate is the surface temperature record, so it has received the most attention. Spatial coverage, equipment, methods of observation, and many other aspects of the measurement record have changed over time, so scientists identify and adjust for these changes. Independent research groups have looked at the surface temperature record for land[20] and ocean[21] as well as land and ocean combined.[22,23] Each group takes a different approach, yet all agree that it is unequivocal that the planet is warming.

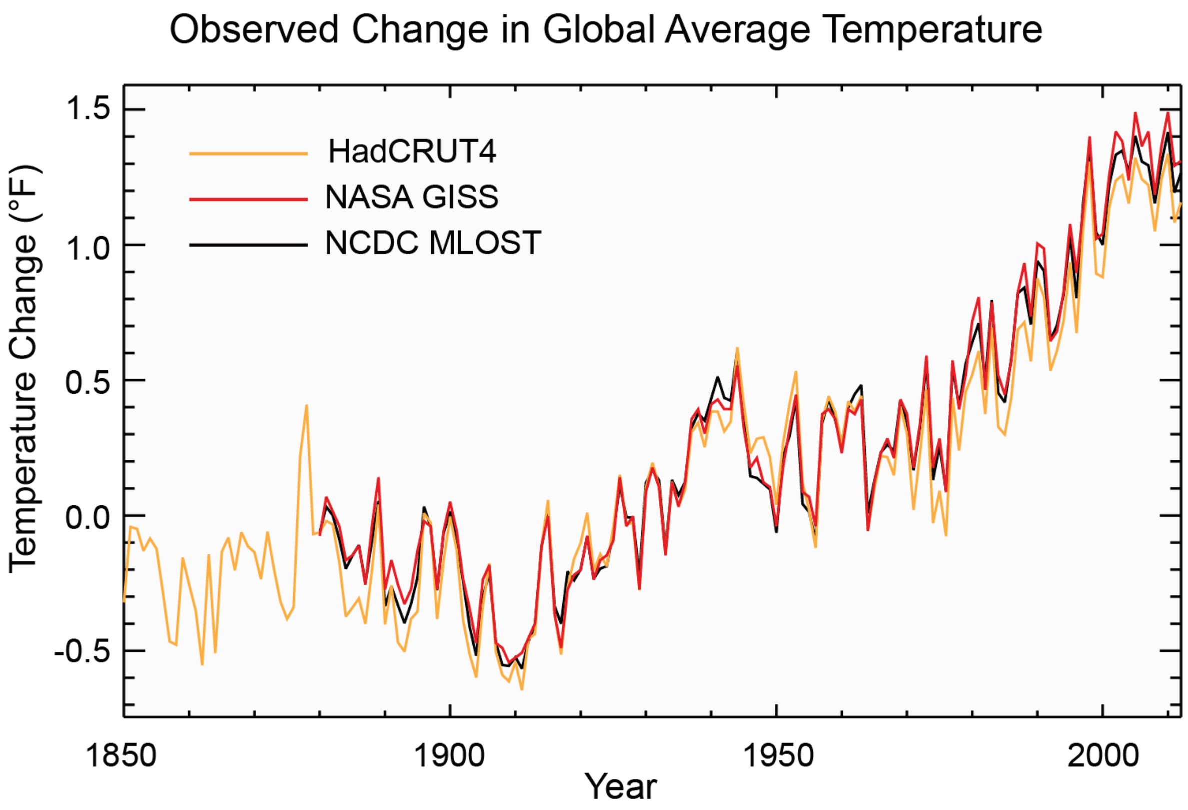


Figure 8: Observed Change in Global Average Temperature

Caption: Three different global surface temperature records all show increasing trends over the last century. The lines show annual differences in temperature relative to the 1901-1960 average. Differences among data sets, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. (Figure source: NOAA NCDC / CICS-NC).

There has been widespread warming over the past century. Not every region has warmed at the same pace, however, and a few regions, such as the North Atlantic Ocean (Figure 9) and some parts of the U.S. Southeast (Figure 2.7 in Ch. 2: Our Changing Climate), have even experienced cooling over the last century as a whole, though they have warmed over recent decades. This is due to the stronger influence of internal variability over smaller geographic regions and shorter time scales, as mentioned in Supplemental Message 1 and discussed in more detail in

Supplemental Message 3. Warming during the first half of the last century occurred mostly in the Northern Hemisphere. The last three decades have seen greater warming in response to accelerating increases in heat-trapping gas concentrations, particularly at high northern latitudes, and over land as compared to ocean.

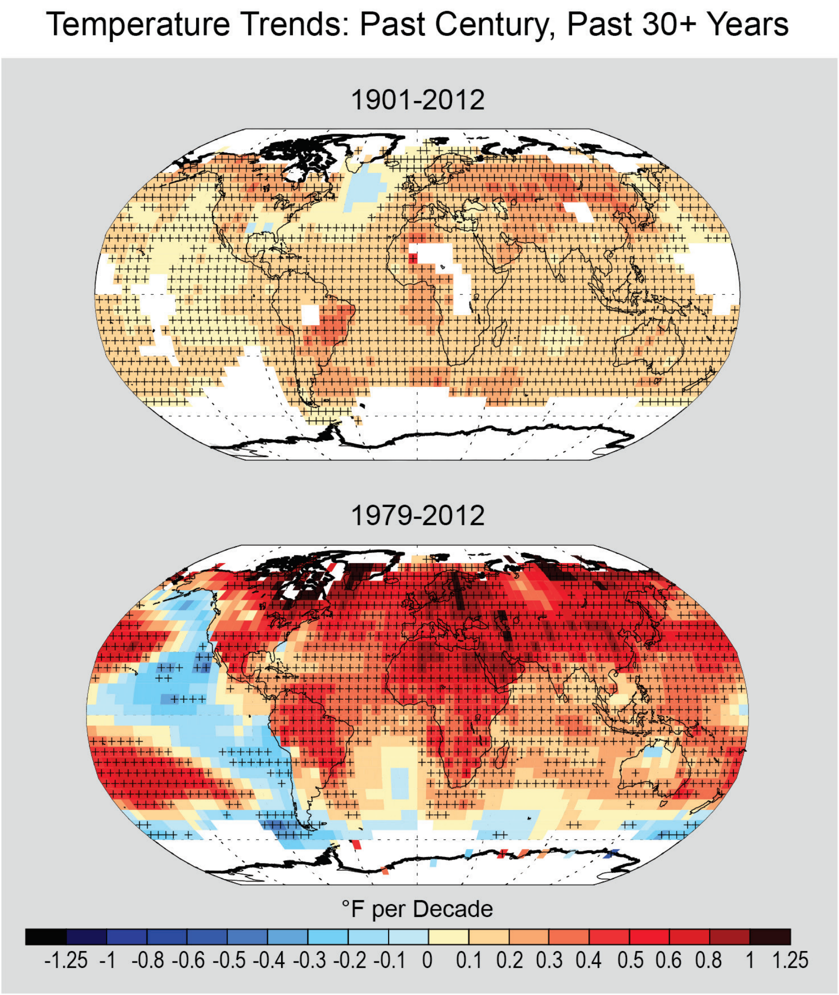


Figure 9: Temperature Trends: Past Century, Past 30+ Years

Caption: Surface temperature trends for the period 1901-2012 (top) and 1979-2012 (bottom) from NCDC's surface temperature product. The relatively coarse resolution of these maps does not capture the finer details associated with mountains, coastlines, and other small-scale effects. (Figure source: updated from Vose et al. 2012[23]).

Even if the surface temperature had never been measured, scientists could still conclude with high confidence that the global temperature has been increasing because multiple lines of evidence all support this conclusion. Temperatures in the lower atmosphere and oceans have increased, as have sea level and near-surface humidity. Arctic sea ice, mountain glaciers, and Northern Hemisphere spring snow cover have all decreased. As with temperature, multiple research groups have analyzed each of these indicators and come to the same conclusion: all of these changes paint a consistent and compelling picture of a warming world.

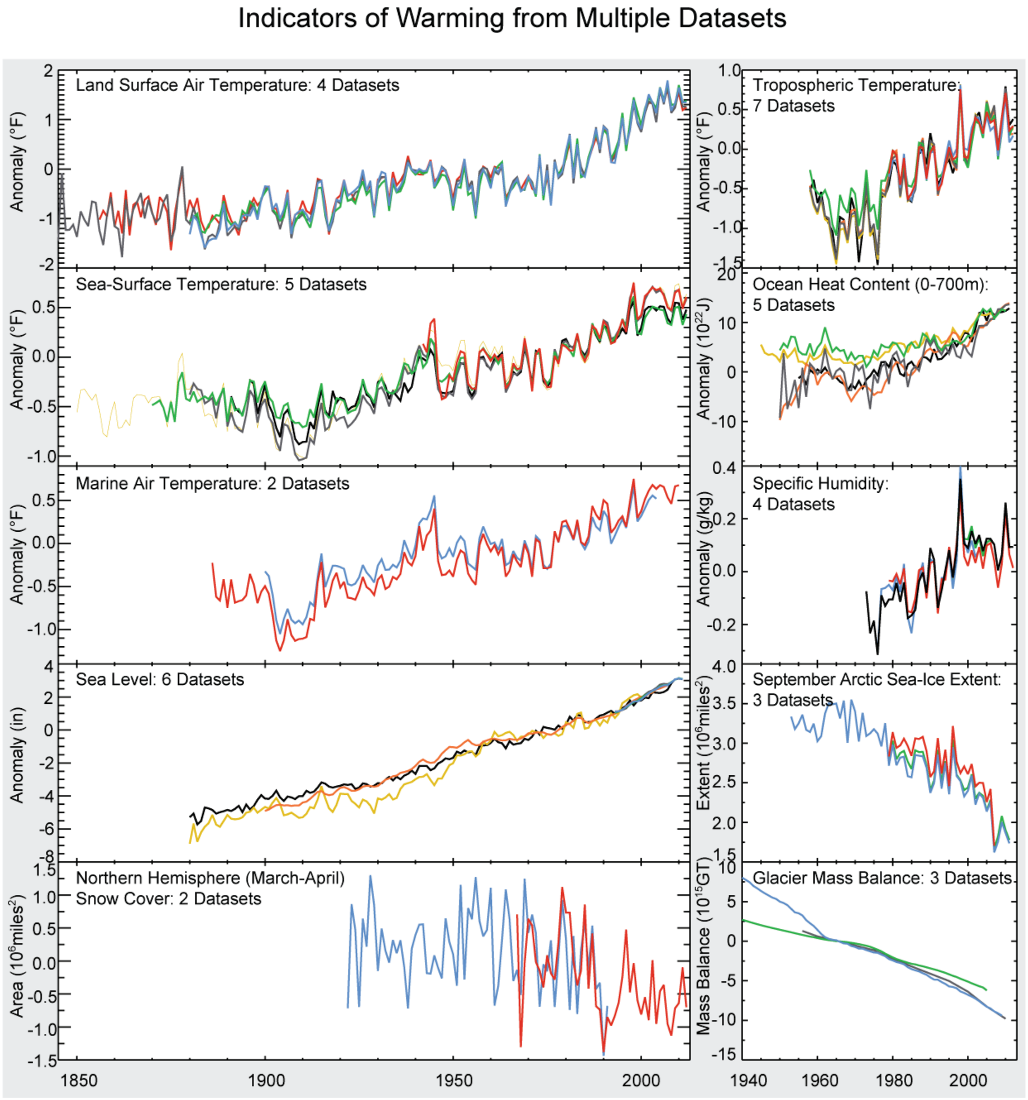
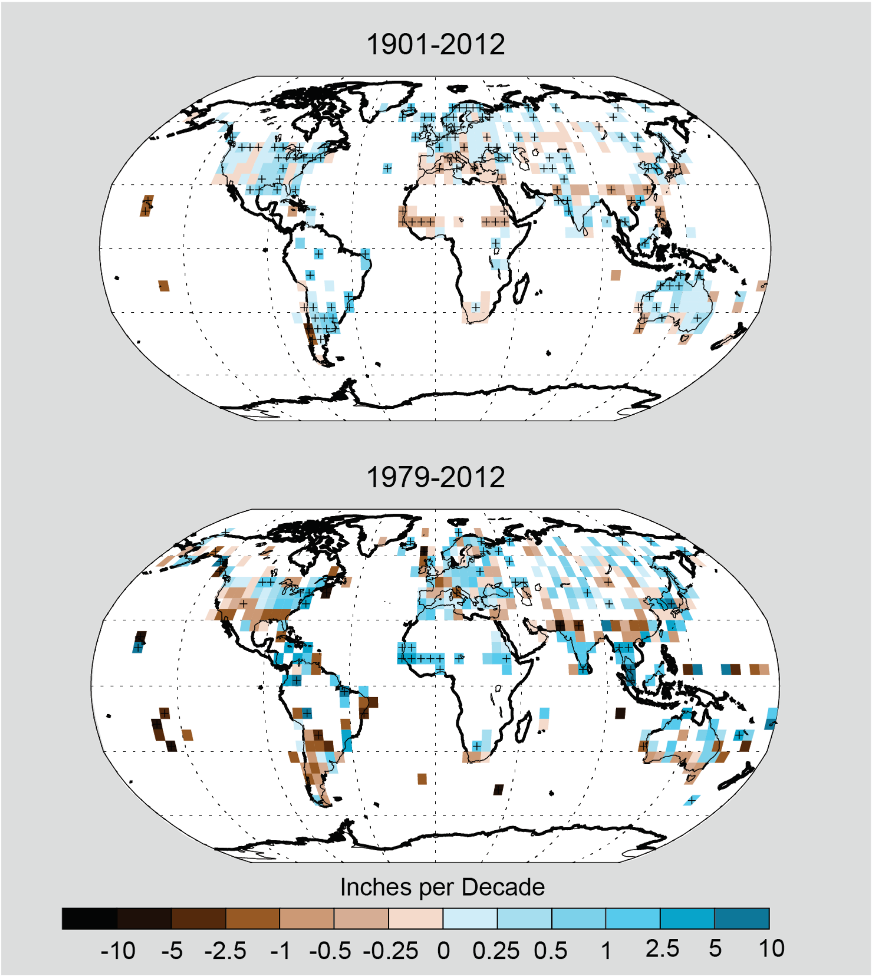


Figure 10: Indicators of Warming from Multiple Data Sets

Caption: Observed changes, as analyzed by many independent groups in different ways, of a range of climate indicators. All of these are in fact changing as expected in a warming world. Further details underpinning this diagram can be found at http://www.ncdc.noaa.gov/bams-state-of-the-climate/. (Figure source: updated from Kennedy et al. 2010[24]).

Not all of the observed changes are directly related to temperature; some are related to the hydrological cycle (the way water moves cyclically among land, ocean, and atmosphere). Precipitation is perhaps the most societally relevant aspect of the hydrological cycle and has been observed over global land areas for over a century. However, spatial scales of precipitation are small (it can rain several inches in Washington, D.C., but not a drop in Baltimore) and this makes interpretation of the point-measurements difficult. Based upon a range of efforts to create global averages, it is likely that there has been little change in globally averaged precipitation since 1900. However, there are strong geographic trends including a likely increase in precipitation in Northern Hemisphere mid-latitude regions taken as a whole. In general, wet areas are getting wetter and dry areas are getting drier, consistent with an overall intensification of the hydrological cycle in response to global warming.


Annual Precipitation Trends: Past Century, Past 30+ Years

1901-2012

1979-2012

Figure 11: Precipitation Trends: Past Century, Past 30+ Years

Caption: Global precipitation trends for the period 1901-2012 (top) and 1979-2012 (bottom). (Figure source: NOAA NCDC / CICS-NC).

Analyses of past changes in climate during the period before instrumental records (referred to as paleoclimate) allow current changes in atmospheric composition, sea level, and climate (including extreme events), as well as future projections, to be placed in a broader perspective of past climate variability. A number of different reconstructions of the last 1,000 to 2,000 years (for example,[25,26]) give a consistent picture of Northern Hemisphere temperatures, and in a few cases, global temperatures, over that time period. The analyses in the Northern Hemisphere indicate that the 1981 to 2010 period (and therefore the last decade) was the warmest of at least the last 1,300 years and probably much longer.[27,28] A reconstruction going back 11,300 years ago[29] suggests that the last decade was warmer than at least 72% of global temperatures since the end of the last ice age 20,000 years ago. The observed warming of the last century has also apparently reversed a long-term cooling trend at mid-to high latitudes of the Northern Hemisphere throughout the last 2,000 years.

Other analyses of past climates going back millions of years indicate that past periods with high levels (400 ppm or greater) of CO_2 were associated with temperatures much higher than today's and with much higher sea levels.[30]

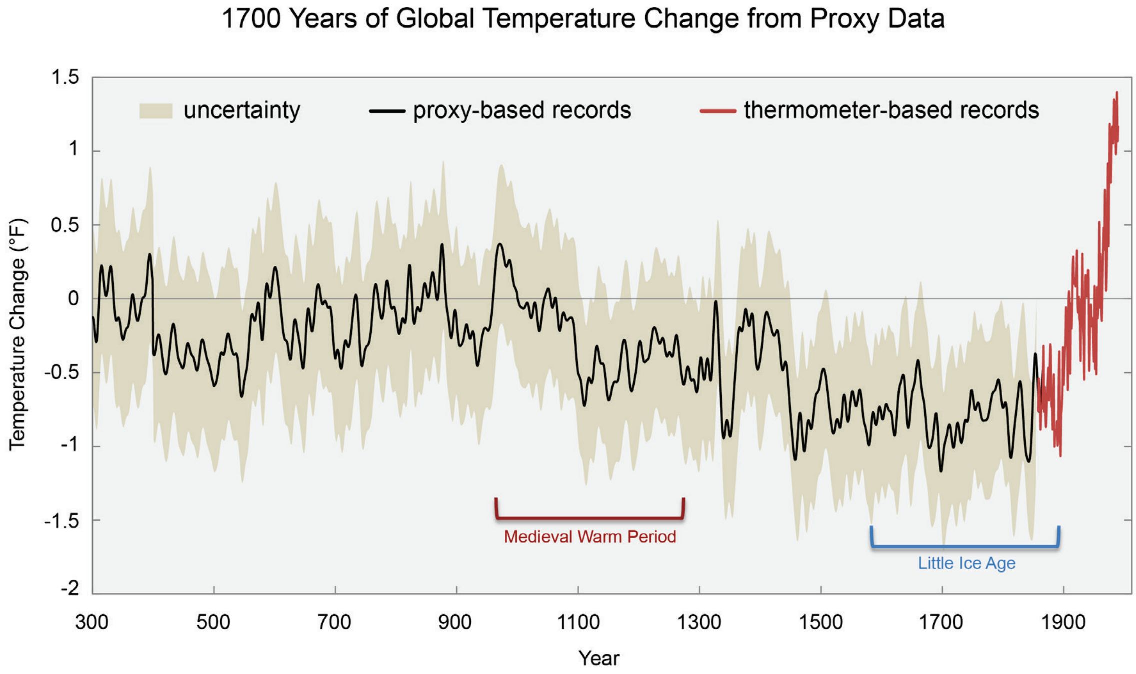


Figure 12: 1700 years of Global Temperature from Proxy Data

Caption: Changes in the temperature of the Northern Hemisphere from surface observations (in red) and from proxies (in black; uncertainty range represented by shading) relative to 1961-1990 average temperature. These analyses suggest that current temperatures are higher than seen globally in at least the last 1700 years, and that the last decade (2001 to 2010) was the warmest decade on record. (Figure source: adapted from Mann et al. 2008[26]).

Supplemental Message 3.

Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere interactions, influences global and regional temperature and precipitation over timescales ranging from months up to a decade or more.

Natural variations internal to the Earth's climate system can drive increases or decreases in global and regional temperatures, as well as affect precipitation and drought patterns around the world. Today, average temperature, precipitation, and other aspects of climate are determined by a combination of human-induced changes superimposed on natural variations in both internal and external factors such as the sun and volcanoes (see Supplemental Message 1). The relative magnitudes of the human and natural contributions to temperature and climate depend on both the time and spatial scales considered. The magnitude of the effect humans are having on global temperature specifically, and on climate in general, has been steadily increasing since the Industrial Revolution. At the global scale, the human influence on climate can be either masked or augmented by natural internal variations over timescales of a decade or so (for example, [31]). At regional and local scales, natural variations have an even larger effect. Over longer periods of time, however, the influence of internal natural variability on the Earth's climate system is negligible; in other words, over periods longer than several decades, the net effect of natural variability tends to sum to zero.

There are many modes of natural variability within the climate system. Most of them involve cyclical exchanges of heat and energy between the ocean and atmosphere. They are manifested by recurring changes in sea surface temperatures, for example, or by surface pressure changes in the atmosphere. While many global climate models are able to simulate the spatial patterns of ocean and atmospheric variability associated with these modes, they are less able to capture the chaotic variability in the timescales of the different modes.[32]

The largest and most well-known mode of internal natural variability is the El Niño/Southern Oscillation or ENSO. This natural mode of variability was first identified as a warm current of ocean water off the coast of Peru, accompanied by a shift in pressure between two locations on either side of the Pacific Ocean. Although centered in the tropical Pacific, ENSO affects regional temperatures and precipitation around the world by heating or cooling the lower atmosphere in low latitudes, thereby altering pressure gradients aloft. These pressure gradients, in turn, drive the upper-level winds and the jet stream that dictates patterns of mid-latitude weather, as shown in Figure 13. In the U.S., for example, the warm ENSO phase (commonly referred to as El Niño) is usually associated with heavy rainfall and flooding in California and the Southwest, but decreased precipitation in the Northwest.[33] El Niño conditions also tend to suppress Atlantic hurricane formation by increasing the amount of wind shear in the region where hurricanes form.[34] The cool ENSO phase (usually called La Niña) is associated with dry conditions in the Central Plains,[35] as well as a more active Atlantic hurricane season. Although these and other conditions are typically associated with ENSO, no two ENSO events are exactly alike.

Natural modes of variability such as ENSO can also affect global temperatures. In general, El Niño years tend to be warmer than average and La Niña years, cooler. The strongest El Niño event recorded over the last hundred years occurred in 1998. Superimposed on the long-term increase in global temperatures due to human activities, this event caused record high global temperatures. After 1998, the El Niño event subsided, resulting in a slowdown in the temperature increase since 1998. Overall, however, years in which there are El Niño, La Niña, or neutral conditions all show similar long-term warming trends in global temperature (see Figure 14).

Natural modes of variability like ENSO are not necessarily stationary. For example, there appears to have been a shift in the pattern and timing of ENSO in the mid-1970s, with the location of the warm water pool shifting from the eastern to the central Pacific and the frequency of events increasing. Paleoclimate studies using tree rings show that ENSO activity over the last 100 years has been the highest in the last 500 years,[36] and both paleoclimate and modeling studies suggest that global temperature increases may interact with natural variability in ways that are difficult to predict. Climate models can simulate the statistical behavior of these variations in temperature trends. For example, models can project whether some phenomena will increase or decrease in frequency, but cannot predict the exact timing of particular events far into the future.

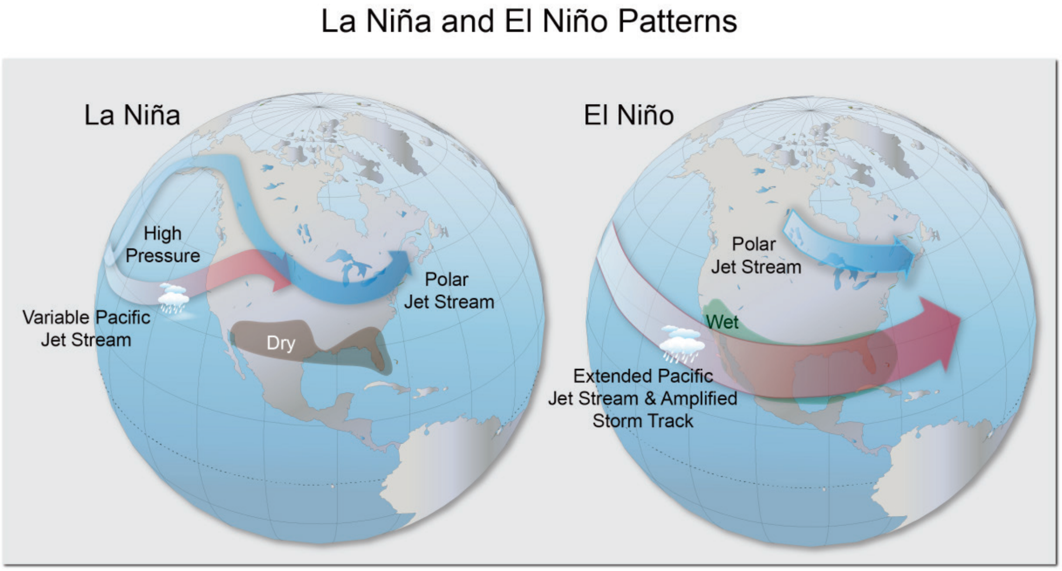


Figure 13: La Niña and El Niño Patterns

Caption: Typical January-March weather conditions and atmospheric circulation (jet streams shown by red and blue arrows) during La Niña and El Niño conditions. Cloud symbols show areas that are wetter than normal. During La Niña, winters tend to be unusually cold in Alaska and western Canada, and dry throughout the southern United States. El Niño leads to unusually warm winter conditions in the northern U.S. and wetter than average conditions across the southern U.S. (Figure source: NOAA).

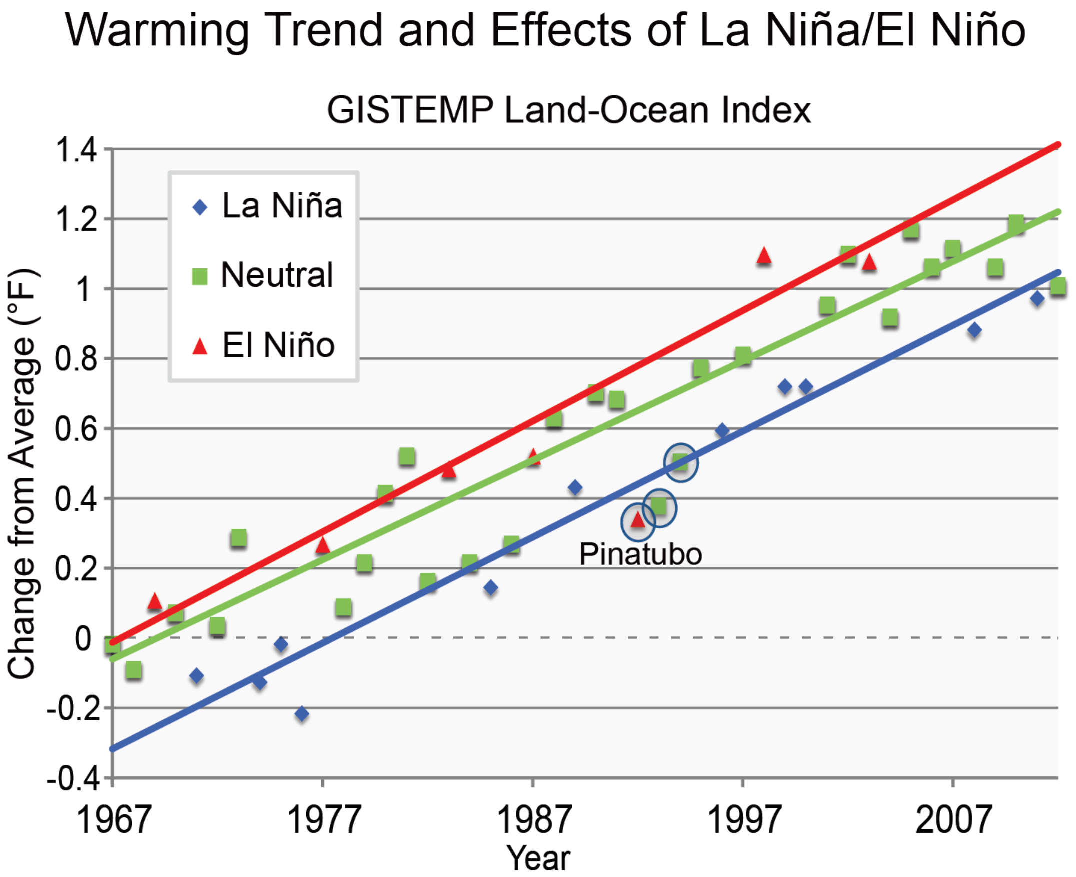


Figure 14: Warming Trend and Effects of El Niño/La Niña

Caption: Trends in globally and annually averaged temperature when considering whether it was an El Niño year, a La Niña year, or a neutral year (no El Niño or La Niña event). The average global temperature is 0.4ºF higher in El Niño years than in La Niña years. However, all trends show the same significant increase in temperature over the past 45 years. The years for the short-term cooling effect following the Mt. Pinatubo volcanic eruption are not included in the trends. (Figure source: adapted from John Nielsen-Gammon 2012.[37] Data from NASA GISS temperature dataset[38] and Climate Prediction Center Niño 3.4 index[39]).

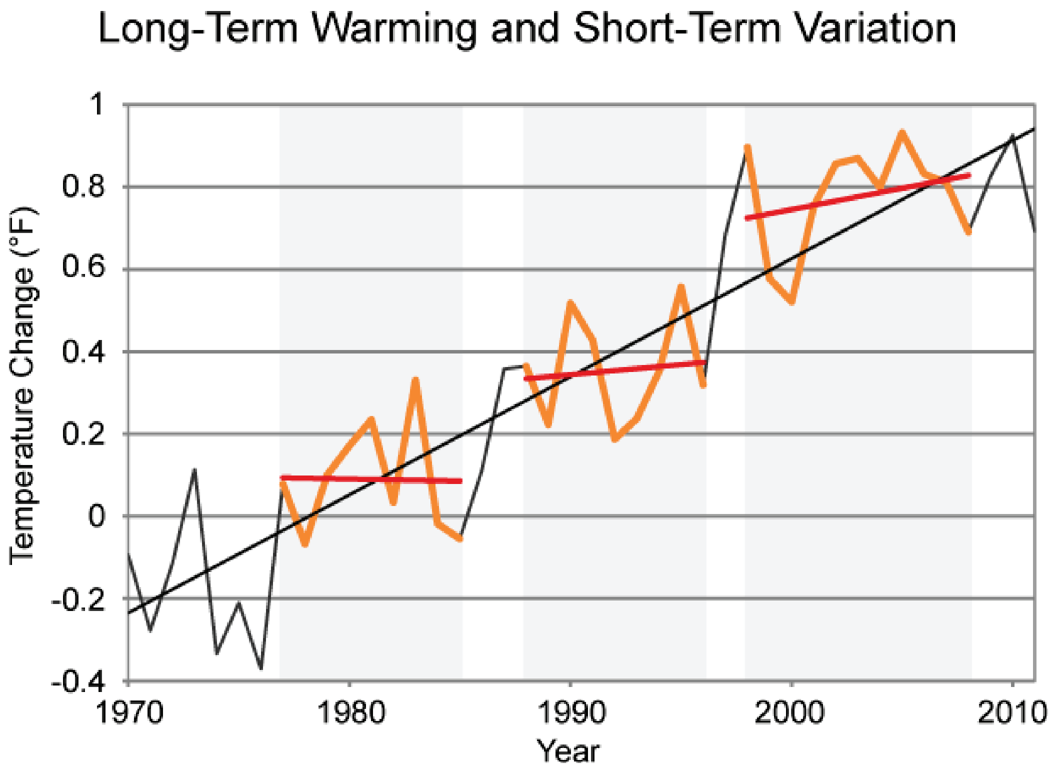


Figure 15: Long-Term Warming and Short-Term Variation

Caption: Observations of global mean surface air temperature show that although there can be short periods with little or even no significant upward trend (red trend lines in shaded areas), global temperature continues to rise unabated over long-term climate timescales (black trend line). The recent period, 1998-2012, is another example of a short-term pause embedded in the underlying warming trend. The differences between short-term trends and the underlying (long-term) trend are often associated with modes of natural variability such as El Niño and La Niña that redistribute heat between the ocean and atmosphere. (Data from NOAA NCDC).

There are other natural modes of variability in the climate system. For example, the North Atlantic Oscillation is frequently linked to variations in winter snowfall along the Atlantic seaboard. The Pacific Decadal Oscillation was first identified as a result of its effect on the Pacific salmon harvest. The influence of these and other natural variations on global temperatures is generally less than ENSO, but local influences may be large.

A combination of natural and human factors explains regional "warming holes" where temperatures actually decreased for several decades in the middle to late part of the last century at a few locations around the world. In the U.S., for example, the Southeast and parts of the Great Plains and Midwest regions did not show much warming over that time period, though they have warmed in recent decades. Explanations include increased cloud cover and precipitation,[40] increased small particles from coal burning, natural factors related to forest re-growth,[41] decreased heat flux due to irrigation,[42] and multi-decade variability in North Atlantic and tropical Pacific sea surface temperatures.[43,44] The importance of tropical Pacific and Atlantic sea surface temperatures on temperature and precipitation variability over the central U.S. has been particularly highlighted by many studies. Over the next few decades, as the multi-decadal tropical Pacific Ocean cycle continues its effect on sea surface temperatures, the U.S. Southeast could warm at a rate that is faster than the global average.[44]

At the global scale, natural variability will continue to modify the long-term trend in global temperature due to human activities, resulting in greater and lesser trends over relatively short time scales. Interactions among various components of the Earth's climate system produce patterns of natural variability that can be chaotic, meaning that they are sensitive to the initial conditions of the climate system. Global climate models simulate natural variability with varying degrees of realism, but the timing of these random variations differs among models and cannot be expected to coincide with those of the actual climate system. Over climatological time periods, however, the net effect of natural internal variability on the global climate tends to average to zero. For example, there can be warmer years due to El Niño (such as 1998) and cooler years due to La Niña (such as 2011), but over multiple decades the net effect of natural variability on uncertainty in global temperature and precipitation projections is small.

Averaging (or compositing) of projections from different models smooths out the randomly occurring natural variations in the different models, leaving a clear signal of the long-term externally forced changes in climate, not weather. In this report, all future projections are averaged over 20- to 30-year time periods.

Supplemental Message 4.

Human-induced increases in atmospheric levels of heat-trapping gases are the main cause of observed climate change over the past 50 years. The “fingerprints” of human-induced change also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.

Determining the causes of climate changes is a field of research known as “detection and attribution.” *Detection* involves identifying a climate trend or event (for instance, long-term surface air temperature trends, or a particularly extreme heat wave) that is strikingly outside the norm of natural variations in the climate system. Similar to conducting forensic analysis on evidence from a crime scene, *attribution* involves considering the possible causes of an observed event or change, and identifying which factor(s) are responsible.

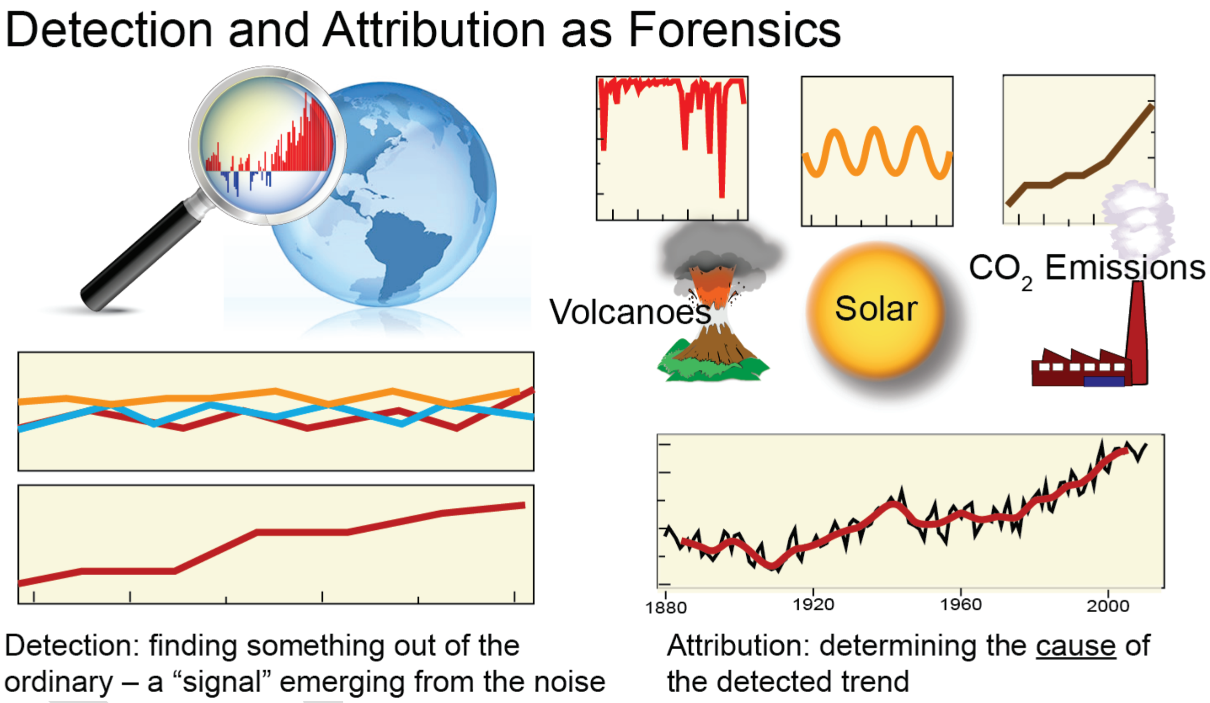


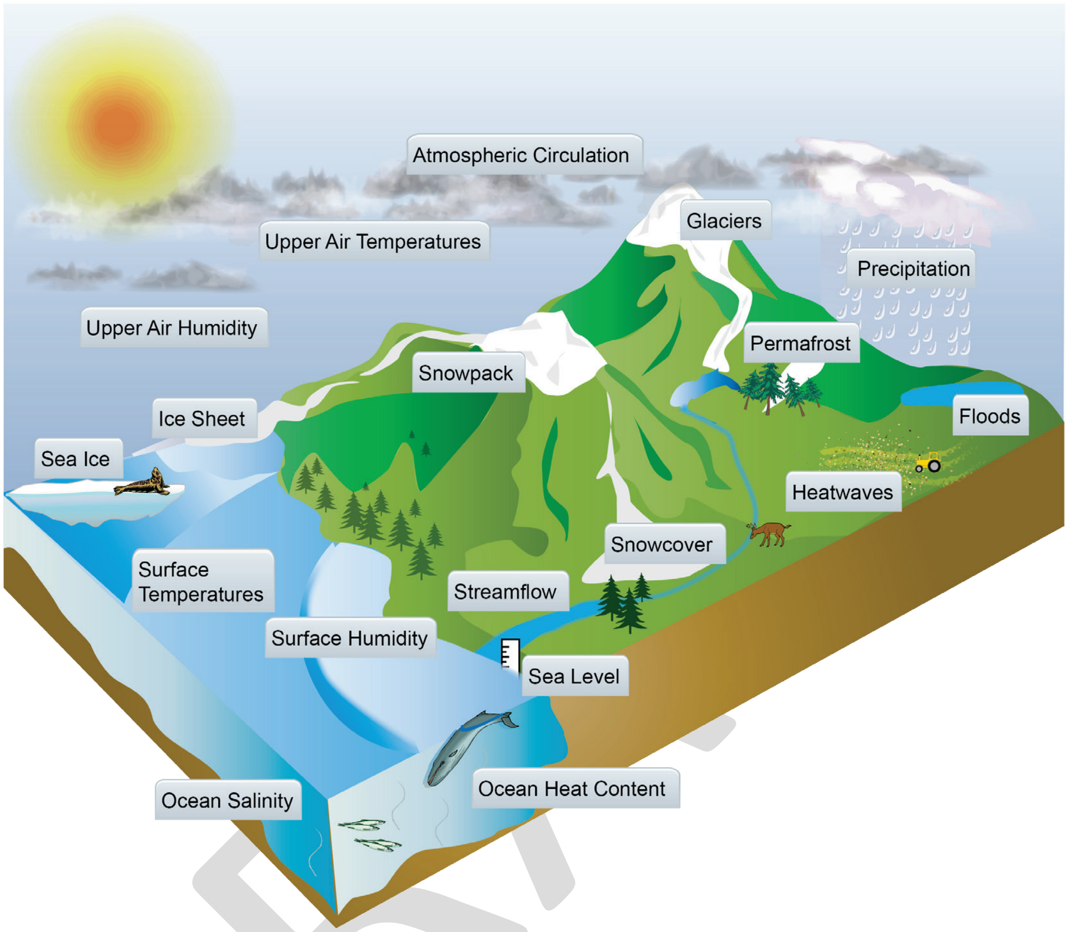
Figure 16: Detection and Attribution as Forensics

Caption: Simplified image of the methodology that goes into detection and attribution of climate changes. The natural factors considered usually include changes in the sun’s output and volcanic eruptions, as well as natural modes of variability such as El Niño and La Niña. Human factors include the emissions of heat-trapping gases and particles as well as clearing of forests and other land-use changes. (Figure source: NOAA NCDC).

Detection and attribution studies use statistical analyses to identify the causes of observed changes in temperature, precipitation, and other aspects of climate. They do this by trying to match the complex “fingerprint” of the observed climate system behavior to a set of simulated changes in climate that would be caused by different forcings.[45] Most approaches consider not only global but also regional patterns of changes over time.

Climate simulations are used to test hypotheses regarding the causes of observed changes. First, simulations that include changes in both natural and human forcings that may cause climate changes, such as changes in energy from the sun and increases in heat-trapping gases, are used to characterize what effect those factors would have had working together. Then, simulations with no changes in external forcings, only changes due to natural variability, are used to characterize what would be expected from normal internal variations in the climate. The results of these simulations are compared to observations to see which provides the best match for what has really occurred.

Detection and attribution studies have been applied to study a broad range of changes in the climate system as well as a number of specific extreme events that have occurred in recent years. These studies have found that human influences are the only explanation for the observed changes in climate over the last half-century. Such changes include increases in surface temperatures,[45,46] changes in atmospheric vertical temperature profiles,[47] increases in ocean heat content,[48] increasing atmospheric humidity,[49] increases in intensity of precipitation[50] and in runoff,[51] indirectly estimated through changes in ocean salinity,[52] shifts in atmospheric circulation,[53] and changes in a host of other indices.[45] Taken together these paint a coherent picture of a planet whose climate is changing primarily as a result of human activities.



Human Influences Apparent in Many Aspects of the Changing Climate

Figure 17: Human Influences Apparent in Many Aspects of the Changing Climate

Caption: Figure shows examples of the many aspects of the climate system in which changes have been formally attributed to human emissions of heat-trapping gases and particles by studies published in peer-reviewed science literature. For example, observed changes in surface air temperature at both the global and continental levels, particularly over the past 50 years or so, cannot be explained without including the effects of human activities. While there are undoubtedly many natural factors that have affected climate in the past and continue to do so today, human activities are the dominant contributor to recently observed climate changes. (Figure source: NOAA NCDC).

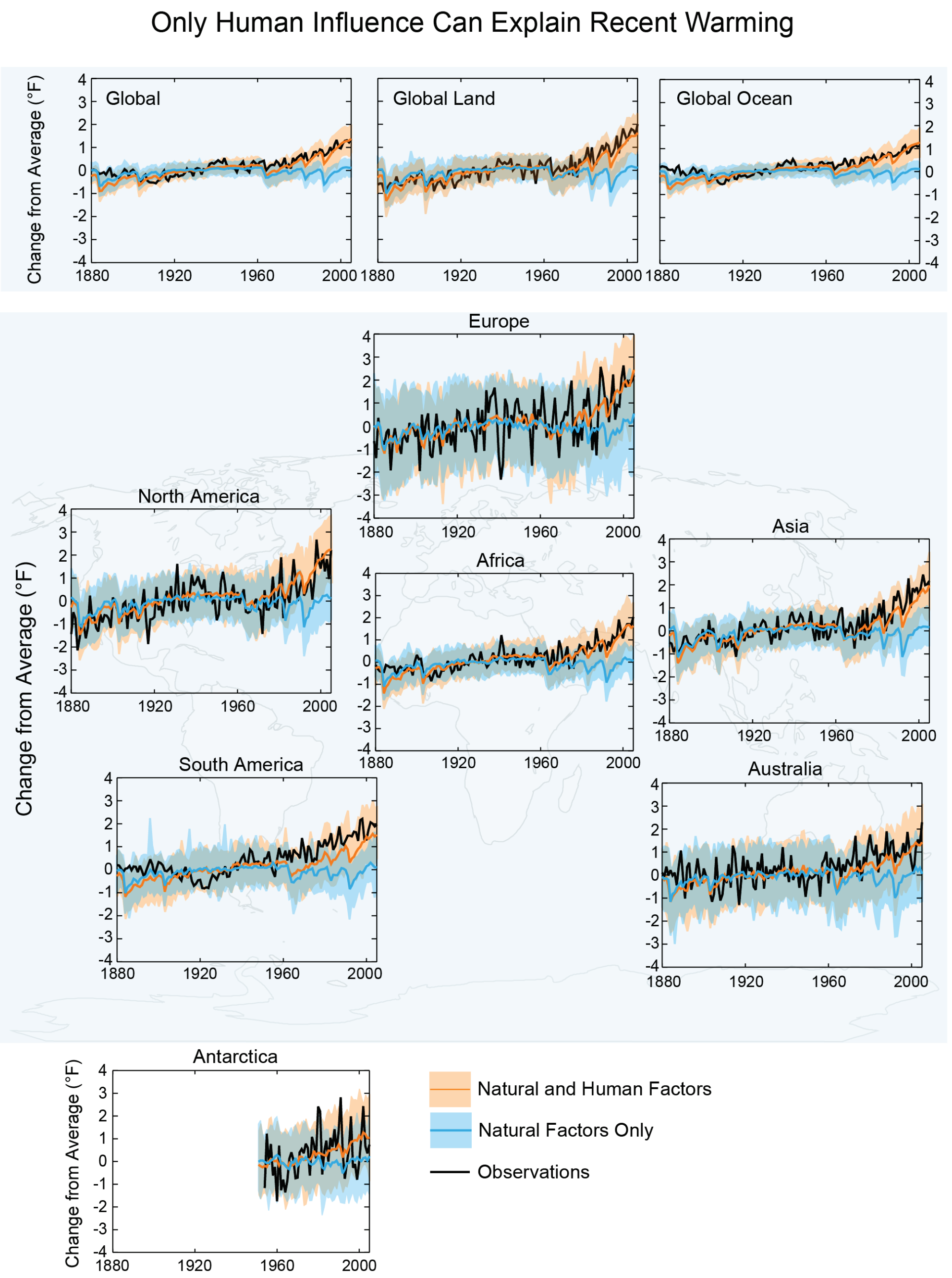


Figure 18: Only Human Influence Can Explain Recent Warming

Caption: Changes in surface air temperature at the continental and global scales can only be explained by the influence of human activities on climate. The black line depicts the annually averaged observed changes. The blue shading shows climate model simulations that include the effects of natural (solar and volcanic) forcing only. The orange shading shows climate model simulations that include the effects of both natural and human contributions. These analyses demonstrate that the observed changes, both globally and on a continent-by-continent basis, are caused by the influence of human activities on climate. (Figure source: updated from Jones et al. 2013).[54]

Detection and attribution of specific events is more challenging than for long-term trends as there is less data, or evidence, available from which to draw conclusions. Attribution of extreme events is especially scientifically challenging.[55] Many extreme weather and climate events observed to date are within the range of what could have occurred naturally, but the probability, or odds, of some of these very rare events occurring[56] has been significantly altered by human influences on the climate system. For example, studies have concluded that there is a detectable human influence in recent heat waves in Europe,[57] Russia,[58] and Texas[59] as well as flooding events in England and Wales,[60] the timing and magnitude of snowmelt and resulting streamflow in some western U.S. states,[61,62] and some specific events around the globe during 2011.[63]

Supplemental Message 5.

Past emissions of heat-trapping gases have already committed the world to a certain amount of future climate change. How much more the climate will change depends on future emissions and the sensitivity of the climate system to those emissions.

A certain amount of climate change is already inevitable due to the build-up of CO_2 in the atmosphere from human activities, most of it since the Industrial Revolution. A decrease in temperature would only be expected if there was an unexpected decrease in natural forcings, such as a reduction in the power of the sun. The Earth's climate system, particularly the ocean, tends to lag behind changes in atmospheric composition by decades, and even centuries, due to the large heat capacity of the oceans and other factors. Even if all emissions of the relevant gases and particles from human activity suddenly stopped, a temperature increase of 0.5°F still would occur over the next few decades,[64] and the human-induced changes in the global carbon cycle would persist for thousands of years.[65]

Global emissions of CO_2 and other heat-trapping gases continue to rise. How much climate will change over this century and beyond depends primarily on: 1) human activities and resulting emissions; and 2) how sensitive the climate is to those changes (that is, the response of global temperature to a change in radiative forcing caused by human emissions). Uncertainties in how the economy will evolve, what types of energy will be used, or what our cities, buildings, or cars will look like in the future all limit scientists' ability to predict the future changes in climate. Scientists can, however, develop scenarios – plausible projections of what might happen, under a given set of assumptions. These scenarios describe possible futures in terms of population, energy sources, technology, heat-trapping gas emissions, atmospheric levels of carbon dioxide, and/or global temperature change.

Over the next few decades, the greater part of the range (or uncertainty) in projected global and regional change is the result of natural variability and scientific limitations in our ability to model and understand the Earth's climate system (natural variability is discussed in Supplemental Message 3 and scientific or model uncertainty in Supplemental Message 6). By the second half of the century, however, scenario uncertainty (that is, uncertainty about what will be the level of emissions from human activities) becomes increasingly dominant in determining the magnitude and patterns of future change, particularly for temperature-related aspects.[66] Even though natural variability will continue to occur, most of the difference between present and future climates will be determined by choices that society makes today and over the next few decades. The further out in time we look, the greater the influence of human choices on the magnitude of future change.

For temperature, it is clear that increasing emissions from human activities will drive consistent increases in global and most regional temperatures and that these rising temperatures will increase with the magnitude of future emissions (see Figure 19 and Figures 2.8 and 2.9 in Ch. 2: Our Changing Climate). Uncertainty in projected temperature change is generally smaller than uncertainty in projected changes in precipitation or other aspects of climate.

Future climate change also depends on climate sensitivity, generally summarized as the response of global temperature to a doubling of CO_2 levels in the atmosphere relative to pre-industrial levels of 280 parts per million. If the only impact of increasing atmospheric CO_2 levels were to amplify the natural greenhouse effect (as CO_2 levels increase, more of the Earth's heat is absorbed by the atmosphere before it can escape to space, as discussed in Supplemental Message 1), it would be relatively easy to calculate the change in global temperature that would result from a given increase in CO_2 levels. However, a series of feedbacks within the Earth's climate system act to amplify or diminish an initial change, adding some uncertainty to the precise climate sensitivity. Some important feedbacks include:

- Clouds – Will warming increase or decrease cloudiness? Will the changes be to lower altitude clouds that primarily reflect the sun's energy, or higher clouds that trap even more heat within the Earth system?
- Albedo (reflectivity) – How quickly will bright white reflective surfaces, such as snow and ice, that reflect most of the sun's energy, melt, and be replaced by a dark ocean or land area that absorbs most of the sun's energy? How will vegetation changes caused by climate change alter surface reflectivity?
- Carbon dioxide absorption by the ocean and the biosphere – Will the rate of uptake increase in the future, helping to remove human emissions from the atmosphere? Or will it decrease, causing emissions to build up even faster than they are now?

Feedbacks are particularly important in the Arctic, where rising temperatures melt ice and snow, exposing relatively dark land and ocean, which absorb more of the sun's energy, heating the region even further. Rising temperatures also thaw permafrost, releasing carbon dioxide and methane trapped in the previously frozen ground into the atmosphere, where they further amplify the greenhouse effect (see Supplemental Message 1). Both of these feedbacks act to further amplify the initial warming due to human emissions of carbon dioxide and other heat-trapping gases.

Together, these and other feedbacks determine the long-term response of the Earth's temperature to an increase in carbon dioxide and other emissions from human activities. Past observations, including both recent measurements and studies that look at climate changes in the distant past, cannot tell us precisely how sensitive the climate system will be to increasing emissions of heat-trapping gases if we are starting from today's conditions. They can tell us, however, that the net effect of these feedbacks will be to increase, not diminish, the direct warming effect. In other words, the climate system will warm by more than would be expected from the greenhouse effect alone.

Quantifying the effect of these feedbacks on global and regional climate is the subject of ongoing data collection and active research. As noted above, one measure used to study these effects is the equilibrium climate sensitivity, which is an estimate of the temperature change that would result, once the climate had reached an equilibrium state, as a result of doubling the CO_2 concentration from preindustrial levels. The equilibrium climate sensitivity (for a doubling of the CO_2 concentration from preindustrial levels) has long been estimated to be in the range of 2.7°F to 8.1°F. The 2007 IPCC AR4 [14] refined this range based on more recent evidence to conclude that the value is likely to be in the range 3.6°F to 8.1°F, with a most probable value of about 5.4°F, based upon multiple observational and modeling constraints, and that it is very unlikely to be less than 2.7°F. Climate sensitivities determined from a variety of evidence agree well with this range, including analyses of past paleoclimate changes.[67,68] This is substantially greater than the increase in temperature from just the direct radiative effects of the CO_2 increase (around 2°F).

Some recent studies have suggested that climate sensitivities are at the higher end of this range (such as Fusillo and Trenberth, 2012), while others have suggested values at the lower end of the range (Hargeaves et al. 2012; Lewis 2013; Libardoni and Forest 2011, 2013; Lindzen and Choi, 2011; Ring et al., 2012; Schmittner et al. 2011). Some recent studies have even suggested that the climate sensitivity may be less than 2.7°F based on analyses of recent temperature trends (Lewis 2013). However, analyses based on recent temperature trends are subject to significant uncertainties in the treatment of natural variability,[68] the effects of volcanic eruptions,[69] and the effects of recent accelerated penetration of heat to the deep ocean.[70]

Sometimes, the equilibrium climate sensitivity is confused with the transient climate response, defined as the temperature change for a 1% per year CO_2 increase, and calculated using the difference between the start of the experiment and a 20-year period centered on the time of CO_2 doubling. This value is generally smaller than the equilibrium climate sensitivity because of the slow rate at which heat transfers between the oceans and the atmosphere due to transient heat uptake of the ocean. The transient climate response is better constrained than the equilibrium climate sensitivity.[14] It is very likely larger than 1.8°F and very unlikely to be greater than 5.4°F. This transient response includes feedbacks that respond to global temperature change over timescales of years to decades. These “fast” feedbacks include increases in atmospheric water vapor, reduction of ice and snow, warming of the ocean surface, and changes in cloud characteristics. The entire response of the climate system will not be fully seen until the deep ocean comes into balance with the atmosphere, a process that can take thousands of years.

Combining the uncertainty due to climate sensitivity with the uncertainty due to human activities produces a range of future temperature changes that overlap over the first half of this century, but begins to separate over the second half of the century as emissions and atmospheric CO_2 levels diverge.

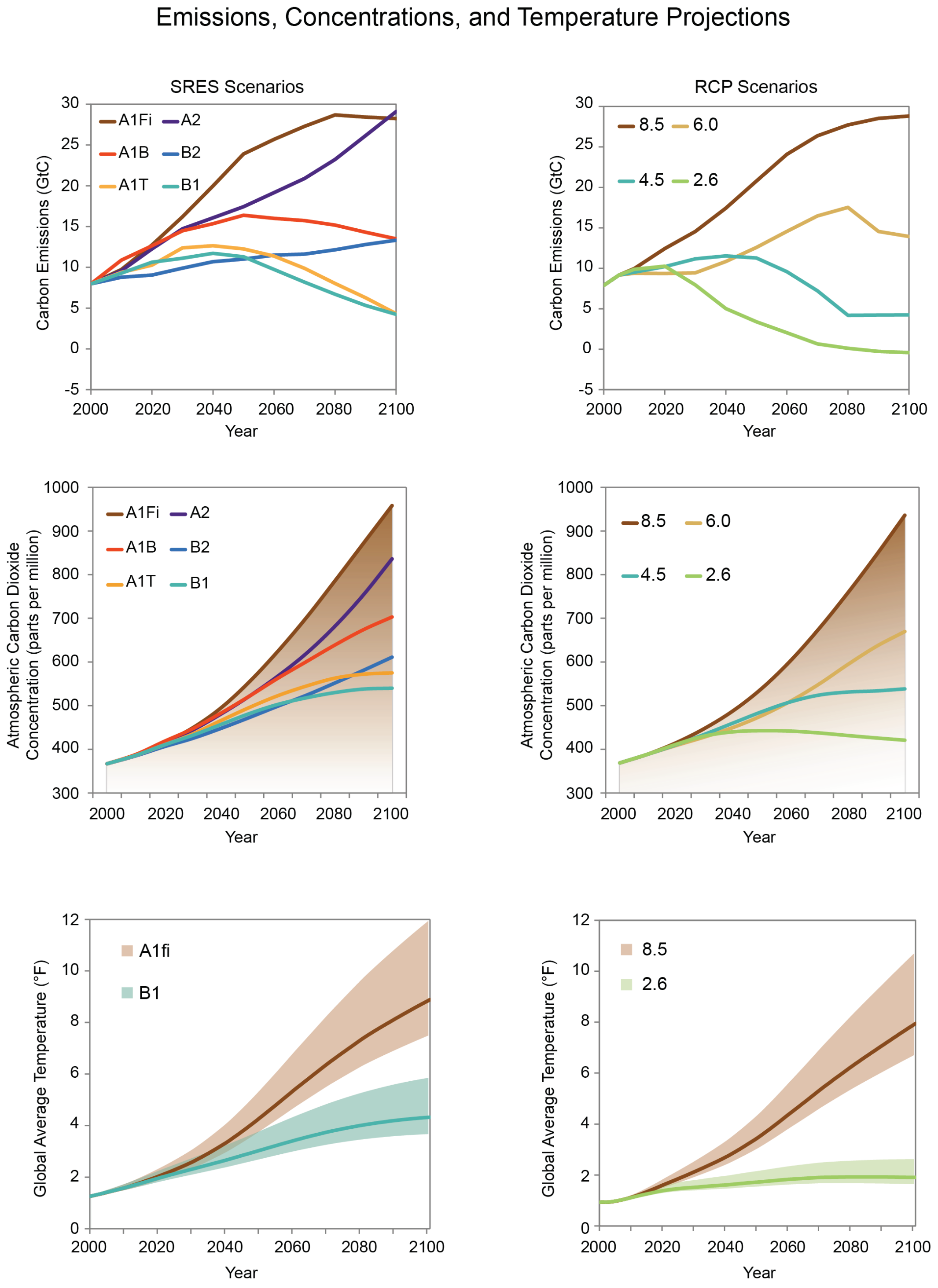


Figure 19: Emissions, Concentrations, and Temperature Projections

Caption: Two families of scenarios are commonly used for future climate projections: the 2000 Special Report on Emission Scenarios (SRES, left) and the 2010 Representative

Concentration Pathways (RCP, right). The SRES scenarios are named by family (A1, A2, B1, B2), where each family is designed around a set of consistent assumptions: for example, a world that is more integrated or more divided. In contrast, the RCP scenarios are simply numbered according to the change in radiative forcing (from +2.6 to +8.5 watts per square meter) that results by 2100. This figure compares SRES and RCP annual carbon emissions (top), carbon dioxide equivalent levels in the atmosphere (middle), and temperature change that would result from the central estimate (lines) and the likely range (shaded areas) of climate sensitivity (bottom). At the top end of the range, the older SRES scenarios are slightly higher. Comparing carbon dioxide concentrations and global temperature change between the SRES and RCP scenarios, SRES A1fI is similar to RCP 8.5; SRES A1B to RCP 6.0 and SRES B1 to RCP 4.5. The RCP 2.6 scenario is much lower than any SRES scenario because it includes the option of using policies to achieve net negative carbon dioxide emissions before end of century, while SRES scenarios do not. (Data from CMIP3 and CMIP5).

Projected Annually-Averaged Temperature Change

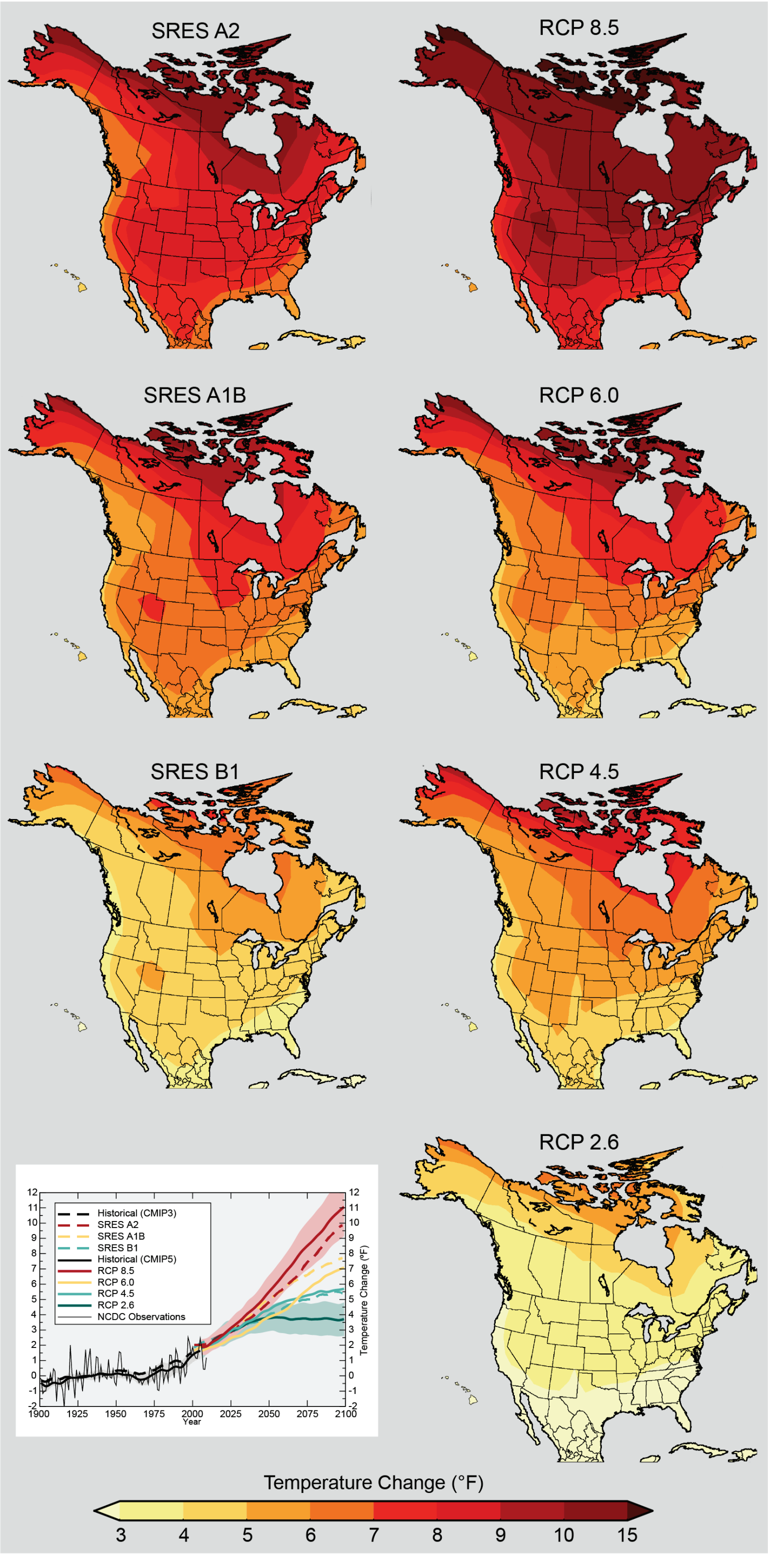
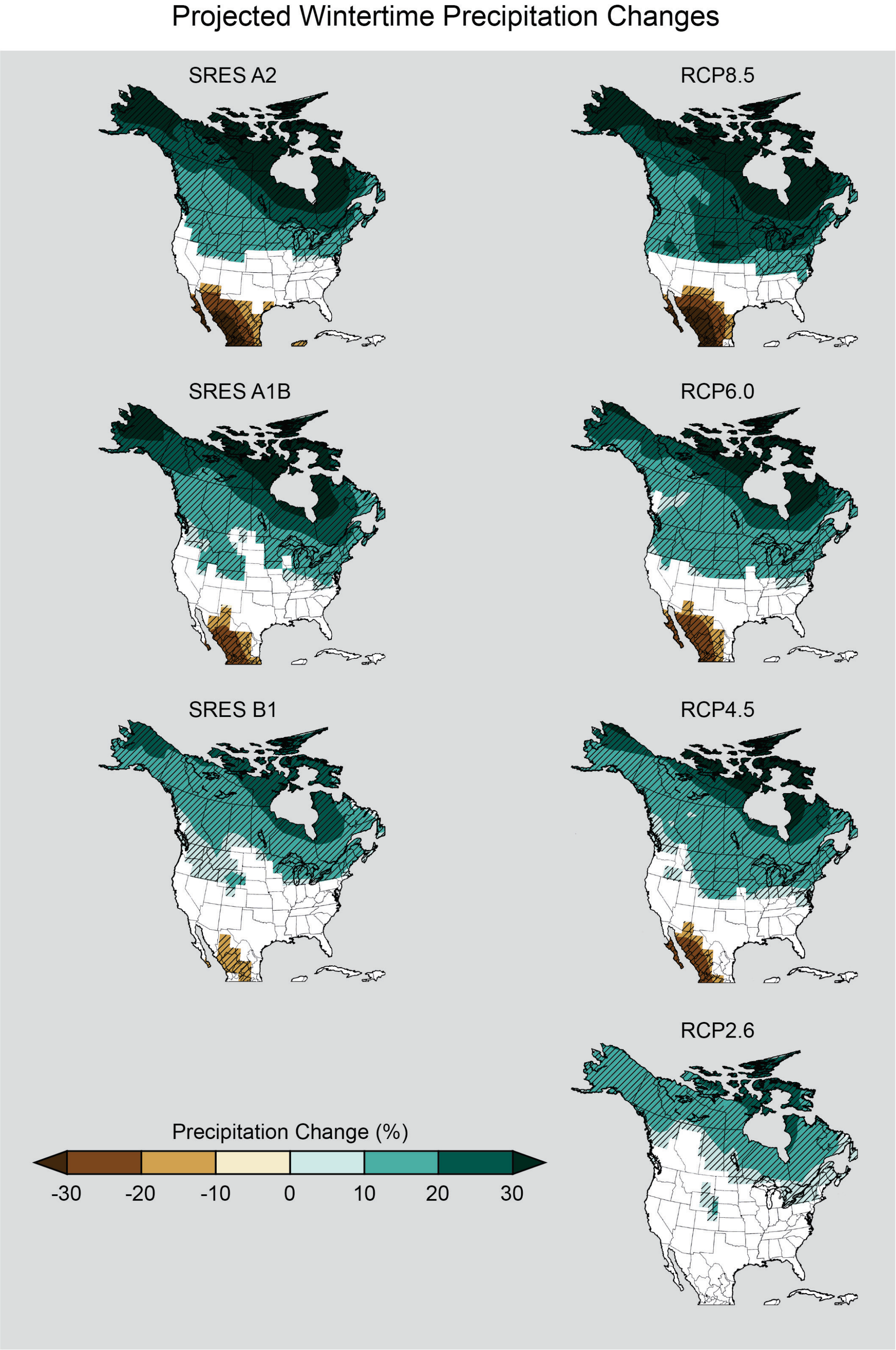


Figure 20: Projected Annually-Averaged Temperature **C**hange

Caption: Projected change in surface air temperature at the end of this century (2071-2099) relative to the end of the last century (1970-1999). The older generation of models (CMIP3) and SRES emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. The scenarios are described under Supplemental Message 5 and in Figure 19. Differences between the old and new projections are mostly a result of the differences in the scenarios of the emission of heat-trapping gases rather than the increased complexity of the new models. None of the new scenarios are exactly the same as the old ones, although at the end of the century SRES B1 and RCP 4.5 are roughly comparable, as are SRES A1B and RCP 6.0. (Figure source: NOAA NCDC / CICS-NC).



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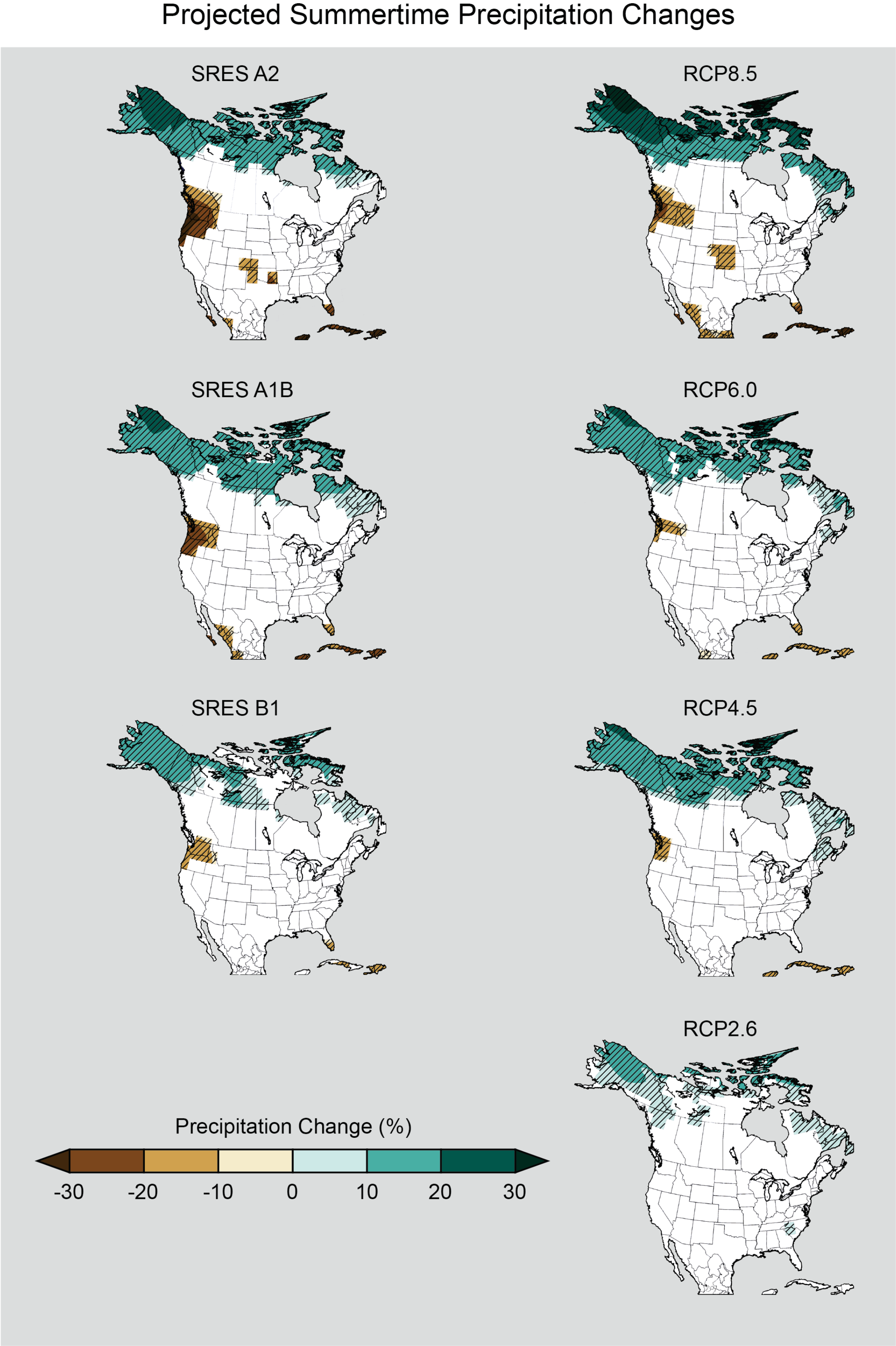
2 **Figure 21:** Projected Wintertime Precipitation Changes

Caption: Projected changes in wintertime precipitation at the end of this century (2071-2099) relative to the average for 1970-1999. The older generation of models (CMIP3) and emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. In both sets of projections, the northern parts of the U.S. (and Alaska) become wetter. Increases in both the amount of precipitation change and the confidence in the projections go up as the projected temperature rises. In the farthest northern parts of the U.S., much of the additional winter precipitation will still fall as snow. This is not likely to be the case farther south. (Figure source: NOAA NCDC / CICS-NC).


Projected Summertime Precipitation Changes
SRES A2
RCP8.5
SRES A1B
RCP6.0
SRES B1
RCP4.5
RCP2.6
Precipitation Change (%)
-30
-20
-10
0
10
20
30

1

Figure 22: Projected Summertime Precipitation Changes

Caption: Projected changes in summertime precipitation toward the end of this century (2071-2099) relative to the average for 1970-1999. The older generation of models (CMIP3) and emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate confidence that the changes are not projected to be larger than could be expected from natural variability. In most of the contiguous U.S., decreases in summer precipitation are projected, but not with as much confidence as the winter increases. When interpreting maps of temperature and precipitation projections, readers are advised to pay less attention to small details and greater attention to the large-scale patterns of change. (Figure source: NOAA NCDC / CICS-NC).

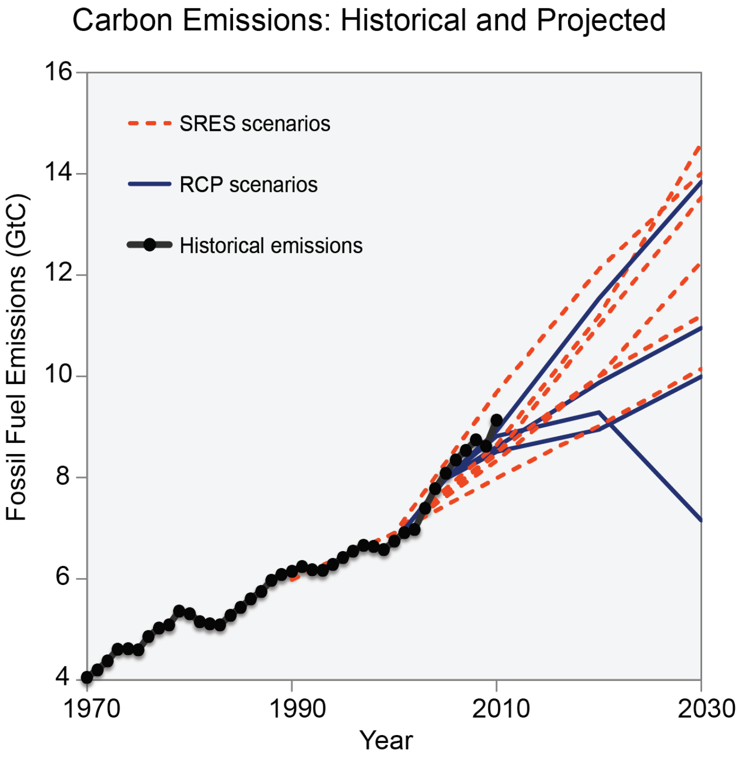


Figure 23: Carbon Emissions: Historical and Projected

Caption: Historical emissions of carbon from fossil fuel (coal, oil, and gas) combustion and land-use change (such as deforestation) have increased over time. The growth rate was nearly three times greater during the 2000s as compared to the 1990s. This figure compares the observed historical (black dots) and projected future SRES (orange dashed lines) and RCP (blue solid lines) carbon emissions from 1970 to 2030. (Data from Boden et al. 2011[71] plus preliminary values for 2009 and 2010 based on BP statistics and U.S. Geological Survey cement data).

Supplemental Message 6.

Different kinds of physical and statistical models are used to study aspects of past climate and develop projections of future change. No model is perfect, but many of them provide useful information. By combining and averaging multiple models, many clear trends emerge.

Climate scientists use a wide range of observational and computational tools to understand the complexity of the Earth's climate system and to study how that system responds to external forces, including the effect of humans on climate. Observational tools are described in Supplemental Message 2.

Computational tools include models that simulate different parts of the climate system. The most sophisticated computational tools used by climate scientists are **global climate models** (previously referred to as "general circulation models"), or GCMs. GCMs are mathematical models that simulate the physics, chemistry, and, increasingly, the biology that influence the climate system. GCMs are built on fundamental equations of physics that include the conservation of energy, mass, and momentum, and how these are exchanged among different parts of the climate system. Using these fundamental relationships, the models generate many important features that are evident in the Earth's climate system: the jet stream that circles the globe 30,000 feet above the Earth's surface; the Gulf Stream and other ocean currents that transport heat from the tropics to the poles; and even, when the models can be run at a fine enough spatial resolution to capture these features, hurricanes in the Atlantic and typhoons in the Pacific.

GCMs and other physical models are subject to two main types of uncertainty. First, because scientific understanding of the climate system is not complete, a model may not include an important process. This could be because that process is not yet recognized, or because it is known but is not yet understood well enough to be modeled accurately. For example, the models do not currently include adequate treatments of dynamical mechanisms that are important to melting ice sheets. The existence of these mechanisms is known, but they are not yet well enough understood to simulate accurately at the global scale. Also, observations of climate change in the distant past suggest there might be "tipping points" or mechanisms of abrupt changes in climate change, such as shifts in ocean circulation, that are not adequately understood.[72] These are discussed further in Appendix 4: FAQ T.

Second, many processes occur at finer temporal and spatial (time and space) scales than models can resolve. Models instead must approximate what these processes would look like at the spatial scale that the model can resolve using empirical equations, or parameterizations, based on a combination of observations and scientific understanding. Examples of important processes that must be parameterized in climate models include turbulent mixing, radiational heating/cooling, and small-scale physical processes, such as cloud formation and precipitation, chemical reactions, and exchanges between the biosphere and atmosphere. For example, these models cannot represent every raindrop. However, they can simulate the total amount of rain that would fall over a large area the size of a grid cell in the model. These approximations are usually derived from a limited set of observations and/or higher resolution modeling and may not hold true for every location or under all possible conditions.

GCMs are constantly being enhanced as scientific understanding of climate improves and as computational power increases. For example, in 1990, the average model divided up the world into grid cells measuring more than 300 miles per side. Today, most models divide the world up into grid cells of about 60 to 100 miles per side, and some of the most recent models are able to run short simulations with grid cells of only 15 miles per side. Supercomputer capabilities are the primary limitation on grid cell size. Newer models also incorporate more of the physical processes and components that make up the Earth's climate system. The very first global climate models were designed to simulate only the circulation of the atmosphere. Over time, the ocean, clouds, land surface, ice, snow, and other features were added one by one. Most of these features were new modules that were developed by experts in those fields and then added into an existing GCM framework. Today, there are more than 35 GCMs created and maintained by more than 20 modeling groups around the world. Some of the newest models are known as Earth System Models, or ESMs, which include all the previous components of a typical GCM, but also incorporate modules that represent additional aspects of the climate system, including agriculture, vegetation, and the carbon cycle.

Some models are more successful than others at reproducing observed climate and trends over the past century,[73] or the large-scale dynamical features responsible for creating the average climate conditions over a certain region (such as the Arctic[74] or the Caribbean[75]). Evaluation of models' success often depends on the variable or metric being considered in the analysis, with some models performing better than others for certain regions or variables.[76] However, all future simulations agree that both global and regional temperatures will increase over this century in response to increasing emissions of heat-trapping gases from human activities.[14]

Differences among model simulations over several years to several decades arise from natural variability (as discussed in Supplemental Message 3) as well as from different ways models characterize various small-scale processes. Averaging simulations from multiple models removes the effects of randomly occurring natural variations. The timing of natural variations is largely unpredictable beyond several seasons (although such predictability is an active research area). For this reason, model simulations are generally averaged (as the last stage in any analysis) to make it easier to discern the impact of external forcing (both human and natural). The effect of averaging on the systematic errors depends on the extent to which models have similar errors or offsetting errors.

Despite their increasing resolution, most GCMs cannot simulate fine-scale changes at the regional to local scale. For that reason, **downscaling** is often used to translate GCM projections into the high-resolution information required as input to impact analyses. There are two types of models commonly used for downscaling: dynamical and statistical.

Dynamical downscaling models are often referred to as regional climate models since they include many of the same physical processes that make up a global climate model, but simulate these processes at higher resolution and over a relatively small area, such as the Northwest or Southeast United States. At their boundaries, regional climate models use output from GCMs to simulate what is going on in the rest of the world. Regional climate models are computationally intensive, but provide a broad range of output variables including atmospheric circulation, winds, cloudiness, and humidity at spatial scales ranging from about 6 to 30 miles per grid cell. They are also subject to the same types of uncertainty as a global model, such as not fully resolving physical processes that occur at even smaller scales. Regional climate models have additional uncertainty related to how often their boundary conditions are updated and where they are defined. These uncertainties can have a large impact on the precipitation simulated by the models at the local to regional scale. Currently, a limited set of regional climate model simulations based on one future scenario and output from five CMIP3 GCMs is available from the North American Regional Climate Change Assessment Program (these are the "NARCCAP" models used in some sections of this report). These simulations are useful for examining certain impacts over North America. However, they do not encompass the full range of uncertainty in future projections due to both human activities and climate sensitivity described in Supplemental Message 5.

Statistical downscaling models use observed relationships between large-scale weather features and local climate to translate future projections down to the scale of observations. Statistical models are generally very effective at removing errors in historical simulated values, leading to a good match between the average (multi-decadal) statistics of observed and statistically downscaled climate at the spatial scale and over the historical period of the observational data used to train the statistical model. However, statistical models are based on the key assumption that the relationship between large-scale weather systems and local climate will remain constant over time. This assumption may be valid for lesser amounts of change, but could lead to errors, particularly in precipitation extremes, with larger amounts of climate change.[77] Statistical models are generally flexible and less computationally demanding than regional climate models. A number of databases provide statistically downscaled projections for a continuous period from 1960 to 2100 using many global models and a range of higher and lower future scenarios (for example, the U.S. Geological Survey database described by Maurer et al. 2007[78]).[79,80] Statistical downscaling models are best suited for analyses that require a range of future projections that reflect the uncertainty in emission scenarios and climate sensitivity, at the scale of observations that may already be used for planning purposes.

Ideally, climate impact studies could use both statistical and dynamical downscaling methods. Regional climate models can directly simulate the response of regional climate processes to global change, while statistical models can better remove any biases in simulations relative to observations. However, rarely (if ever) are the resources available to take this approach. Instead, most assessments tend to rely on one or the other type of downscaling, where the choice is based on the needs of the assessment. If the study is more of a sensitivity analysis, where using one or two future simulations is not a limitation, or if it requires many climate variables as input, then regional climate modeling may be more appropriate. If the study needs to resolve the full range of projected changes under multiple models and scenarios, or is more constrained by practical resources, then statistical downscaling may be more appropriate. However, even within statistical downscaling, selecting an appropriate method for any given study depends on the questions being asked. The variety of techniques ranges from a simple "delta" (change or difference) approach (subtracting historical simulated values from future values, and adding the resulting delta to historical observations, as used in the first national climate assessment[81] to complex clustering and neural network techniques that rival dynamical downscaling in their demand for computational resources and high-frequency model output (for example, [77,82]). The delta approach is adequate for studies that are only interested in changes in seasonal or annual average temperature. More complex methods must be used for studies that require information on how climate change may affect the frequency or timing of precipitation and climate extremes.

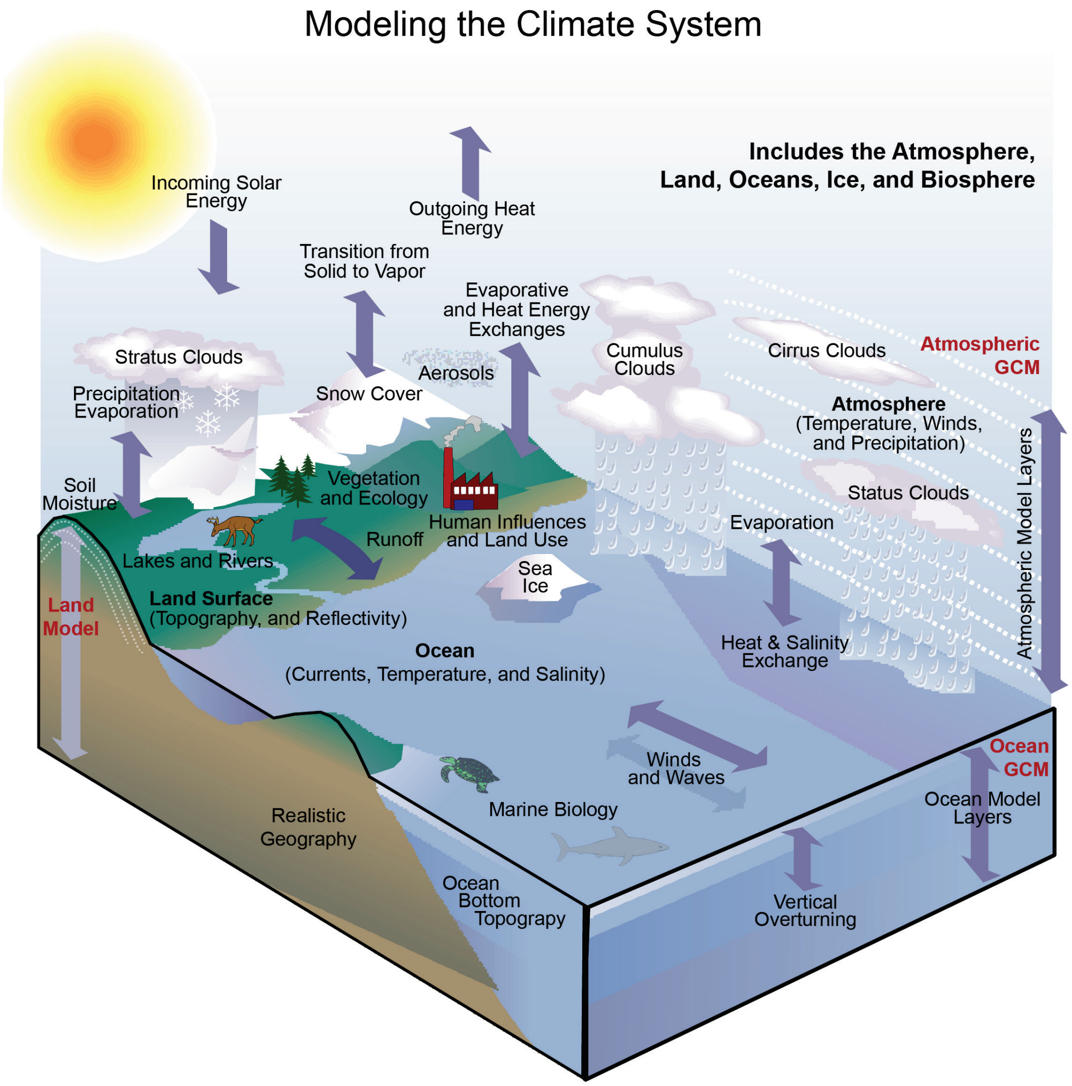
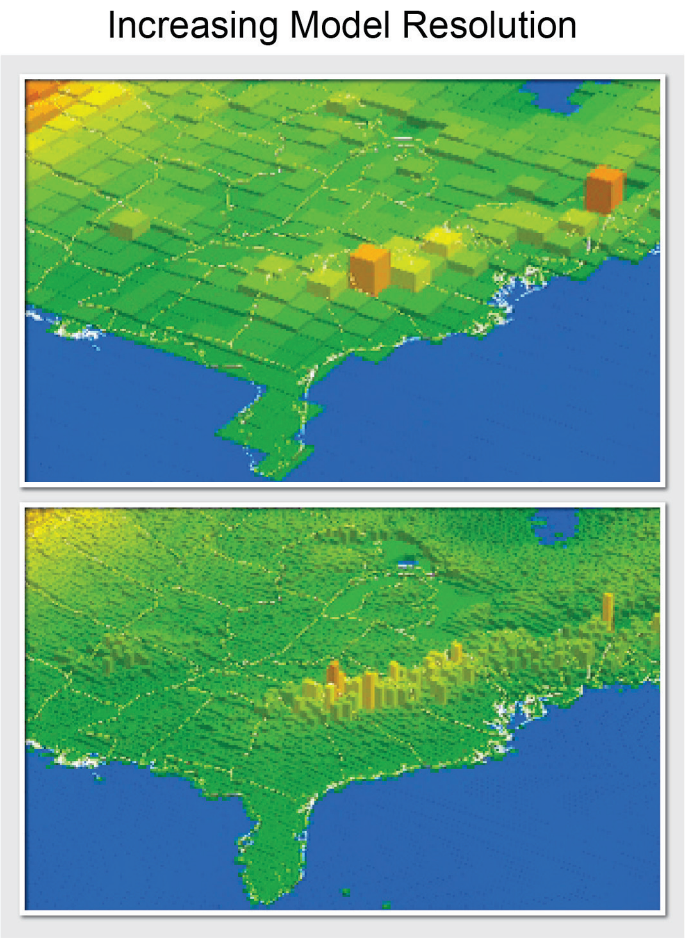


Figure 24: Modeling the Climate System

Caption: Some of the many processes often included in models of the Earth's climate system. (Figure source: Karl and Trenberth 2003).



Increasing Model Resolution

Figure 25: Increasing Model Resolution

Caption: Top: Illustration of the eastern North American topography in a resolution of 68 x 68 miles (110 x 110 km). Bottom: Illustration of the eastern North American topography in a resolution of 19 x 19 miles (30 x 30 km).

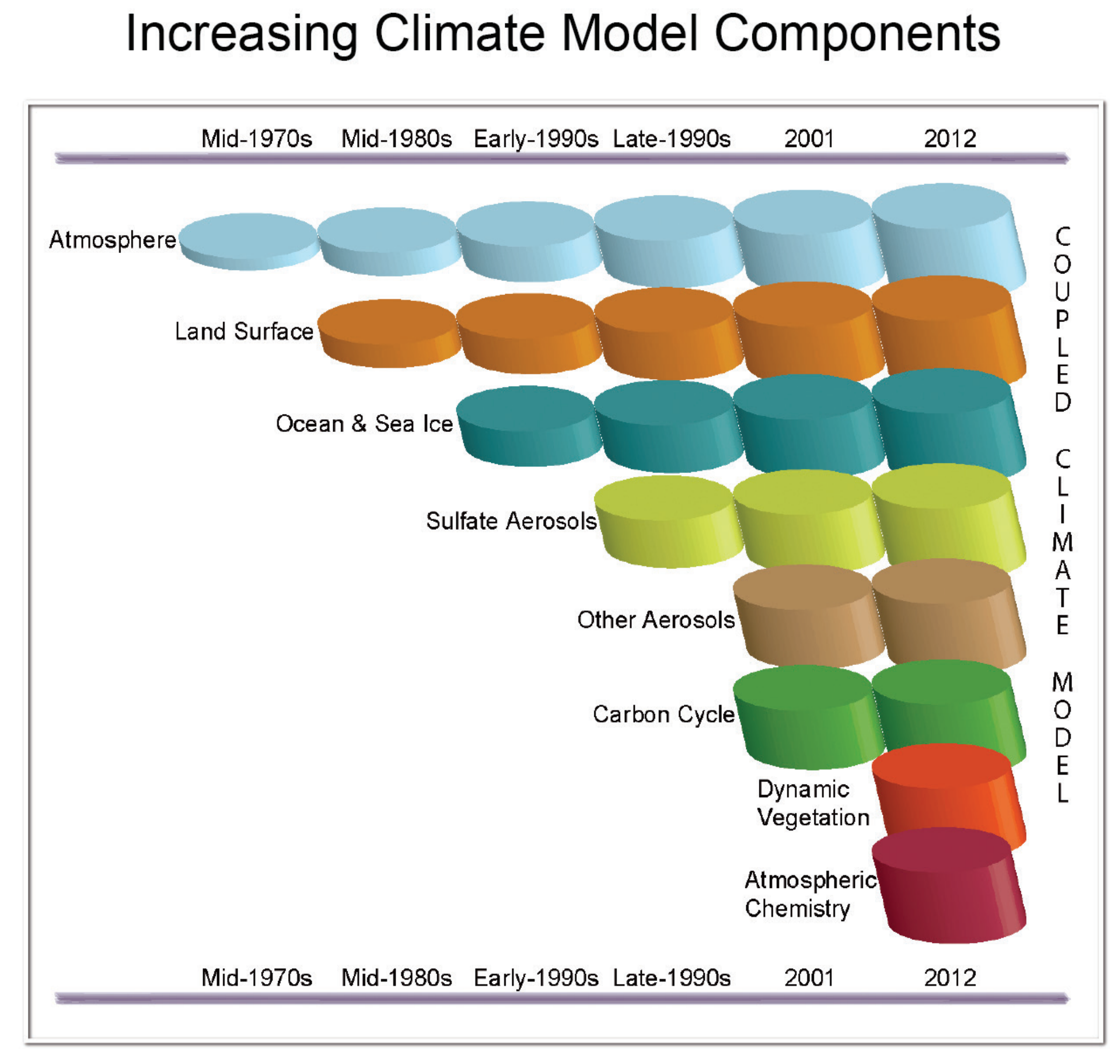


Figure 26: Increasing Climate Model Components

Caption: The development of climate models over the last 35 years showing how the different components are coupled into comprehensive climate models. Volume of each element depicts changes over time in the level of sophistication of the model component. Note that both the horizontal and vertical resolution has increased considerably over the time period shown in the figure. Timeframes for most CMIP3 and CMIP5 simulations were 2003-2005 and 2010-2012, respectively. (Figure source: adapted from IPCC 2013).

Supplemental Message 7.

Scientific understanding of observed temperature changes in the U.S. has greatly improved, confirming that the U.S. is warming as expected in response to global climate change.

There have been substantial recent advances in our understanding of the continental U.S. temperature records. Numerous studies have looked at many different aspects of the record.[27,83,84,85,86,87] These studies have increased confidence that the U.S. is warming, and refined estimates of how much.

Historical temperature data are available for thousands of weather stations. However, for a variety of practical and often unavoidable reasons, there have been frequent changes to individual stations and to the network as a whole. Two changes are particularly important. The first is a widespread change in the time at which observers read their thermometers. Second, most stations now use electronic instruments rather than traditional glass thermometers.

Extensive work has been done to document the effect of these changes on historical temperatures. For example, the change from afternoon to morning observations resulted in systematically lower temperatures for both maximum and minimum, artificially cooling the U.S. temperature record by about 0.5°F.[87,88] The change in instrumentation was equally important but more complex. New electronic instruments generally recorded higher minimum temperatures, yielding an artificial warming of about 0.25°F, and lower maximum temperatures, resulting in an artificial cooling of about 0.5°F. This has been confirmed by extended period side-by-side instrument comparisons.[89] Confounding this, as noted by a recent citizen science effort, the new instruments were often placed nearer buildings or other man-made structures.[90] Analyses of the changes in siting indicate that this had a much smaller effect than the change in instrumentation across the network as a whole.[83,85,87]

Extensive work has been done to develop statistical adjustments that carefully remove these and other non-climate elements that affect the data. To confirm the efficacy of the adjustments, several sensitivity assessments have been undertaken. These include:

- a comparison with the U.S. Climate Reference Network;[85,91]
- analyses to evaluate biases and uncertainties;[87]
- comparisons to a range of state-of-the-art meteorological data analyses;[86] and
- in-depth analyses of the potential impacts of urbanization.[84]

These assessments agree that the corrected data do not overestimate the rate of warming. Rather, because the average effect of these issues was to reduce recorded temperatures, adjusting for these issues tends to reveal a larger long-term warming trend. The impact is much larger for maximum temperature as compared to minimum temperature because the adjustments account for two distinct artificial cooling signals: the change in observation time and the change in instrumentation. The impact is smaller for minimum temperature because the artificial signals roughly offset one another (the change in observation time cooling the record, the change in instrumentation warming the record). Even without these adjustments, however, both maximum and minimum temperature records show increases over the past century.

Geographically, maximum temperature has increased in most areas except in parts of the western Midwest, northeast Great Plains, and the Southeast regions. Minimum temperature exhibits the same pattern of change with a slightly greater area of increases. The causes of these slight differences between maximum and minimum temperature are a subject of ongoing research.[92] In general, the uncorrected data exhibit more extreme trends as well as larger spatial variability; in other words, the adjustments have a smoothing effect.

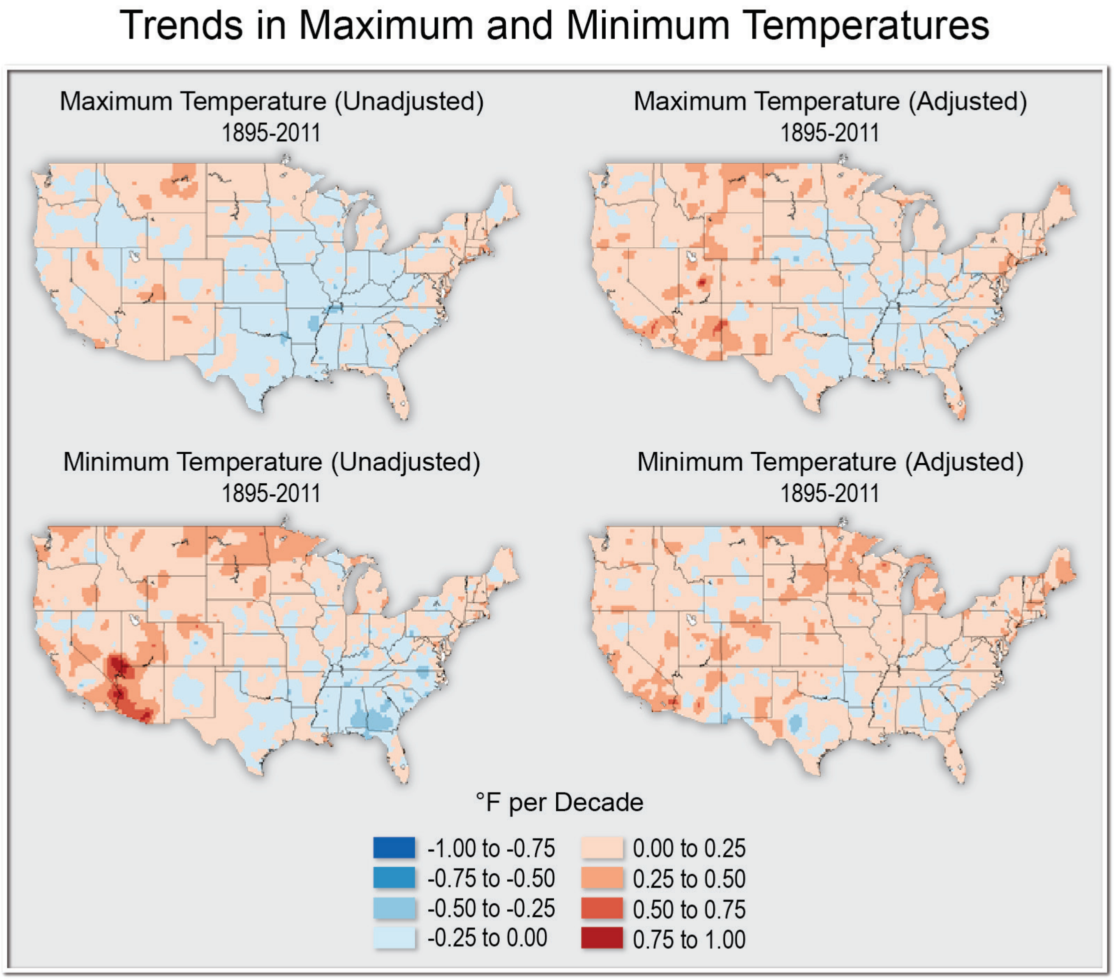


Figure 27: Trends in Maximum and Minimum Temperatures

Caption: Geographic distribution of linear trends in the U.S. Historical Climatology Network for the period 1895-2011. (Figure source: updated from Menne et al. 2009).

The corrected temperature record also confirms that U.S. average temperature is increasing in all four seasons. The heat that occurred during the Dust Bowl era is prominent in the summer record. The warmest summer on record was 1936, closely followed by 2011. However, twelve of the last fourteen summers have been above average. Temperatures during the other seasons have also generally been above average in recent years.

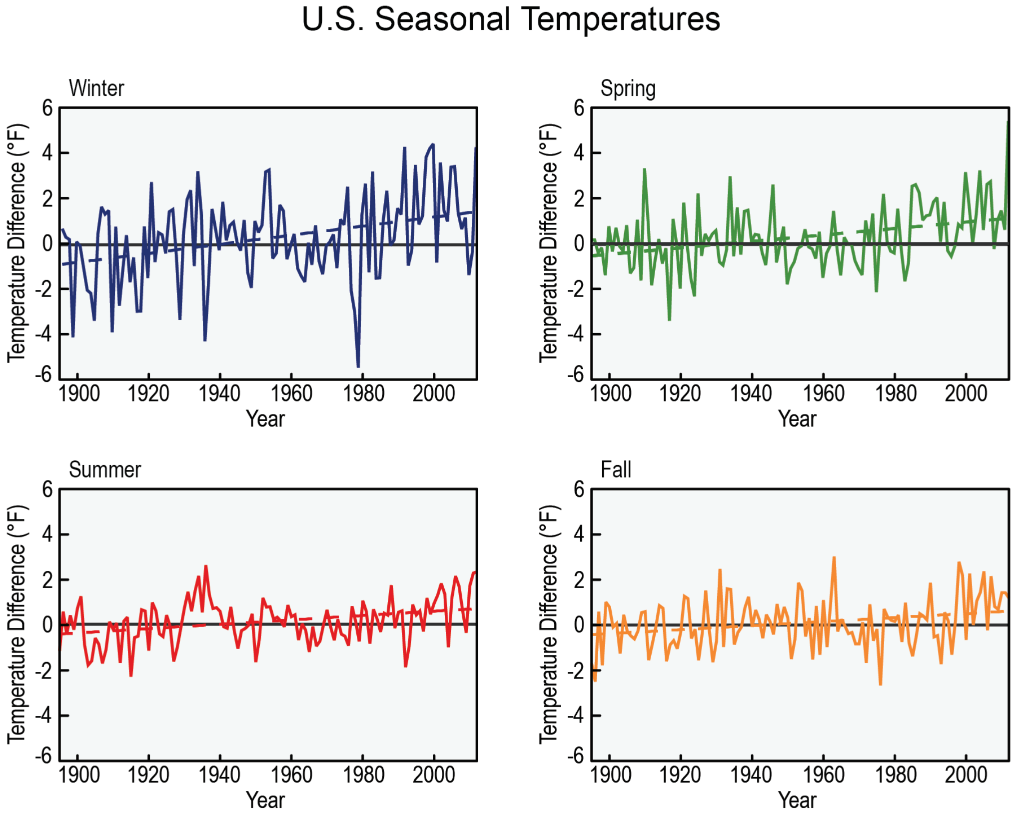


Figure 28: U.S. Seasonal Temperatures

Caption: Continental U.S. seasonal temperatures (relative to the 1901-1960 average) for winter, spring, summer, and fall all show evidence of increasing trends. Dashed lines show the linear trends. Stronger trends are seen in winter and spring as compared to summer and fall. (Figure source: updated from Kunkel et al. 2013).[93]

Supplemental Message 8.

Many other indicators of rising temperatures have been observed in the United States. These include reduced lake ice, glacier retreat, earlier melting of snowpack, reduced lake levels, and a longer growing season. These and other indicators are expected to continue to reflect higher temperatures.

While surface air temperature is the most widely cited measure of climate change, other aspects of climate that are affected by temperature are often more directly relevant to both human society and the natural environment. Examples include shorter duration of ice on lakes and rivers, reduced glacier extent, earlier melting of snowpack, reduced lake levels due to increased evaporation, lengthening of the growing season, and changes in plant hardiness zones. Changes in these and many other variables are consistent with the recent warming over much of the United States. Taken as a whole, these changes provide compelling evidence that increasing temperatures are affecting both ecosystems and human society.

Striking decreases in the coverage of ice on the Great Lakes have occurred over the last few decades (see Ch 2: Our Changing Climate, Key Message 11). The annual average ice cover area for the Great Lakes, which typically shows large year-to-year variability, has sharply declined over the last 30+ years.[94] Based on records covering the winters of 1972-1973 through 2010-2011, 12 of the 19 winters prior to 1991-1992 had annual average ice cover greater than 20% of the total lake area while 15 of the 20 winters since 1991-1992 have had less than 20% of the total lake area covered with ice. This includes the three lowest ice extent winters of 1997-1998, 2001-2002, and 2005-2006. A reduction in ice leading to more open water in winter raises concerns about possible increases in lake effect snowfall, although future trends will also depend on the difference between local air and water temperatures.

Smaller lakes in other parts of the country show similar changes. For example, the total duration of ice cover on Lake Mendota in Madison, Wisconsin, has decreased from about 120 days in the late 1800s to less than 100 days in most years since 1990.[95] Average dates of spring ice disappearance on Minnesota lakes show a trend toward earlier melting over the past 60 years or so. These changes affect the recreational and commercial activities of the surrounding communities.

A long-term record of the ice-in date (the first date in winter when ice coverage closes the lake to navigation) on Lake Champlain in Vermont shows that the lake now freezes approximately two weeks later than in the early 1800s and over a week later than 100 years ago.[96] Later ice-in dates are an indication of higher lake temperatures, as it takes longer for the warmer water to freeze in winter. Prior to 1950, the absence of winter ice cover on Lake Champlain was rare, occurring just three times in the 1800s and four times between 1900 and 1950. By contrast, it remained ice-free during 42% of the winters between 1951 and 1990, and since 1991, Lake Champlain has remained ice-free during 64% of the winters. One- to two-week advances of ice breakup dates and similar length delays of freeze-up dates are also typical of lakes and rivers in Canada, Scandinavia, and northern Asia.[14]

While shorter durations of lake ice enhance navigational opportunities during winter, decreasing water levels in the Great Lakes present risks to navigation, especially during the summer. Water levels on Lakes Superior, Michigan, and Ontario have been below their long-term (1918-2008) averages for much of the past decade.[97] The summer drought of 2012 left Lakes Michigan and Ontario approximately one foot below their long-term averages. As noted in the second national climate assessment,[1] projected water level reductions for this century in the Great Lakes range from less than a foot under lower-emission scenarios to between 1 and 2 feet under higher emission scenarios, with the smallest changes projected for Lake Superior and the largest change projected for Lakes Michigan and Huron.[79] A notable feature is the large range (several feet) of water level projections among models.[98] More recent studies have indicated that earlier approaches to computing evapotranspiration estimates from temperature may have overestimated evaporation losses.[99] Accounting for land-atmosphere feedbacks may further reduce the estimates of lake level declines.[100] These recent studies, along with the large spread in models, indicate that projections of Great Lakes water levels represent evolving research and are still subject to considerable uncertainty.

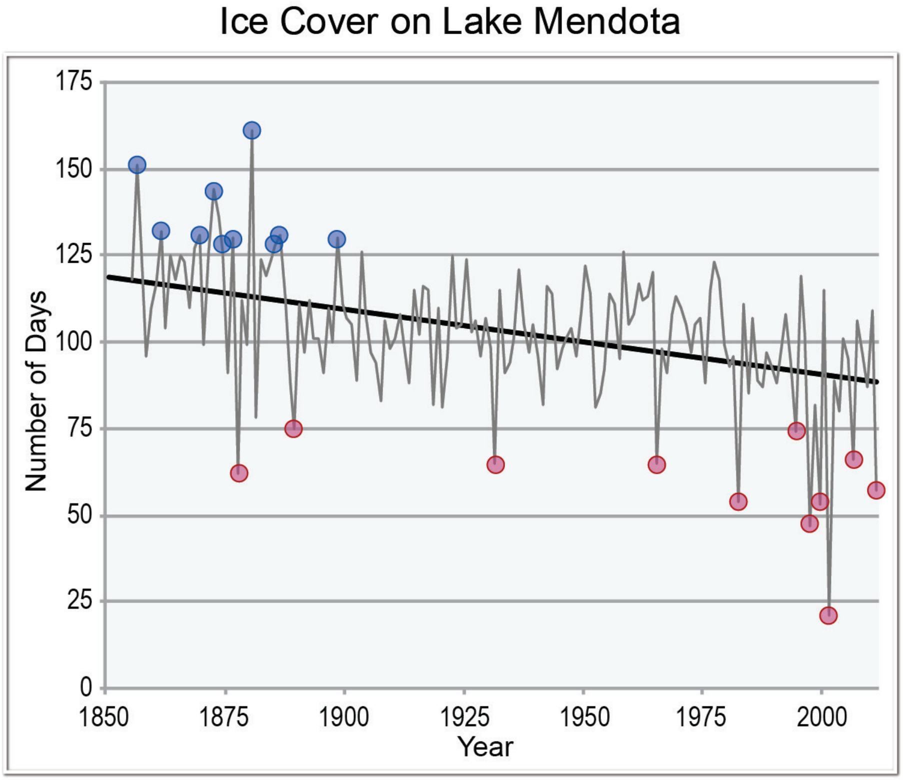


Figure 29: Ice Cover on Lake Mendota

Caption: The duration, or number of days, of ice cover on Lake Mendota, Wisconsin has decreased over time. The 10 longest ice seasons are marked by blue circles, and the 11 shortest ice seasons are marked by red circles. Seven of the 10 shortest ice cover seasons have occurred since 1980. (Figure source: Kunkel et al. 2013[101]).

In the U.S. Southwest, indications of a changing climate over the last five decades include decreases in mountain snowpack,[102] earlier dates of snowmelt runoff,[103,104] earlier onset of spring (as indicated by shifts in the timing of plant blooms and spring snowmelt-runoff pulses),[105] general shifts in western hydroclimatic seasons,[106] and trends toward more precipitation falling as rain instead of snow over the West.[107] The ratio of precipitation falling as rain rather than snow, the amount of water in snowpack, and the timing of peak stream flow on snowmelt-fed rivers all changed as expected with warming over the past dozen years, relative to the last century baselines.[61]

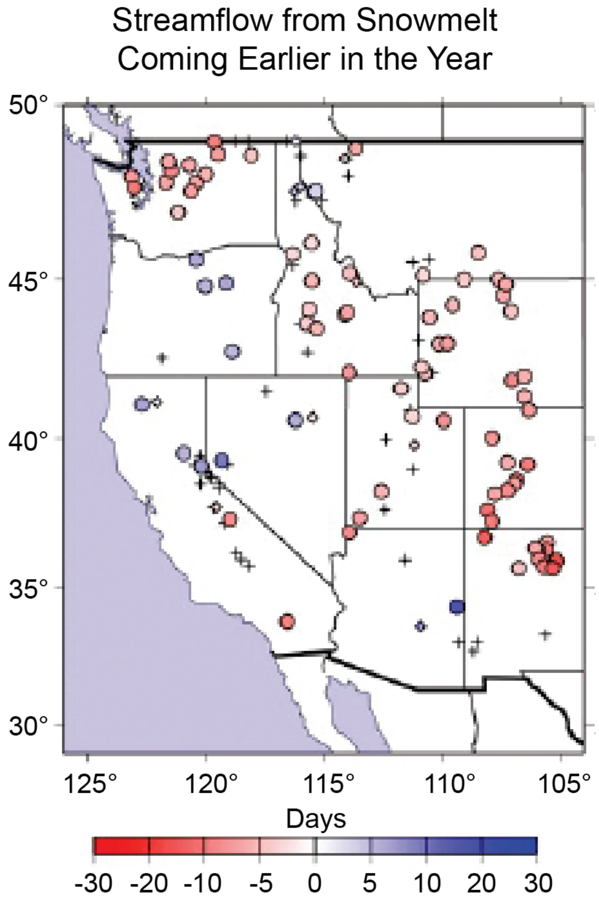


Figure 30: Streamflow from Snowmelt Coming Earlier in the Year

Caption: At many locations in the western U.S., the timing of streamflow in rivers fed by snowpack is shifting to earlier in the year. Red dots indicate stream gauge locations where half of the annual flow is now arriving anywhere from 5 to 20 days earlier each year for 2001-2010, relative to the 1951-2000 average. Blue dots indicate locations where the annual flow is now arriving later. Crosses indicate locations where observed changes are not statistically different from the past century baseline at 90% confidence levels, diamonds indicate gauges where the timing difference was significantly different at 90% confidence, and dots indicate gauges where timing was different at 95% confidence level. (Updated from Stewart et al. 2005).[104]

Changing temperatures affect vegetation through lengthening of the frost-free season and the corresponding growing season, and changing plant tolerance thresholds. The U.S. average frost-free season length (defined as the number of days between the last and first occurrences of 32°F in spring and autumn, respectively) increased by about two weeks during the last century.[108] The increase was much greater in the western than in the eastern United States. Consistent with the recent observed trends in frost-free season length, the largest projected changes in growing season length are in the mountainous regions of the West, while smaller changes are projected for the Midwest, Northeast, and Southeast. Related plant and animal changes include a northward shift in the typical locations of bird species[109] and a shift since the 1980s toward earlier first leaf dates for lilac and honeysuckle.[110]

Plant hardiness zones are determined primarily by the extremes of winter cold.[111] Maps of plant hardiness have guided the selection of plants for both ornamental and agricultural purposes, and these zones are changing as climate warms. Plant hardiness zones for the U.S. have recently been updated using the new climate normals (1981-2010), and these zones show a northward shift by up to 100 miles relative to the zones based on the older (1971-2000) normals. Even greater northward shifts, as much as 200 miles, are projected over the next 30 years as warming increases. Projected shifts are largest in the major agricultural regions of the central U.S.

Evidence of a warming climate across the U.S. is based on a host of indicators: hydrology, ecology, and physical climate. Most of these are changing in ways consistent with increasing temperatures, and are expected to continue to change in the future as a result of ongoing increases in human-induced heat-trapping gas emissions.

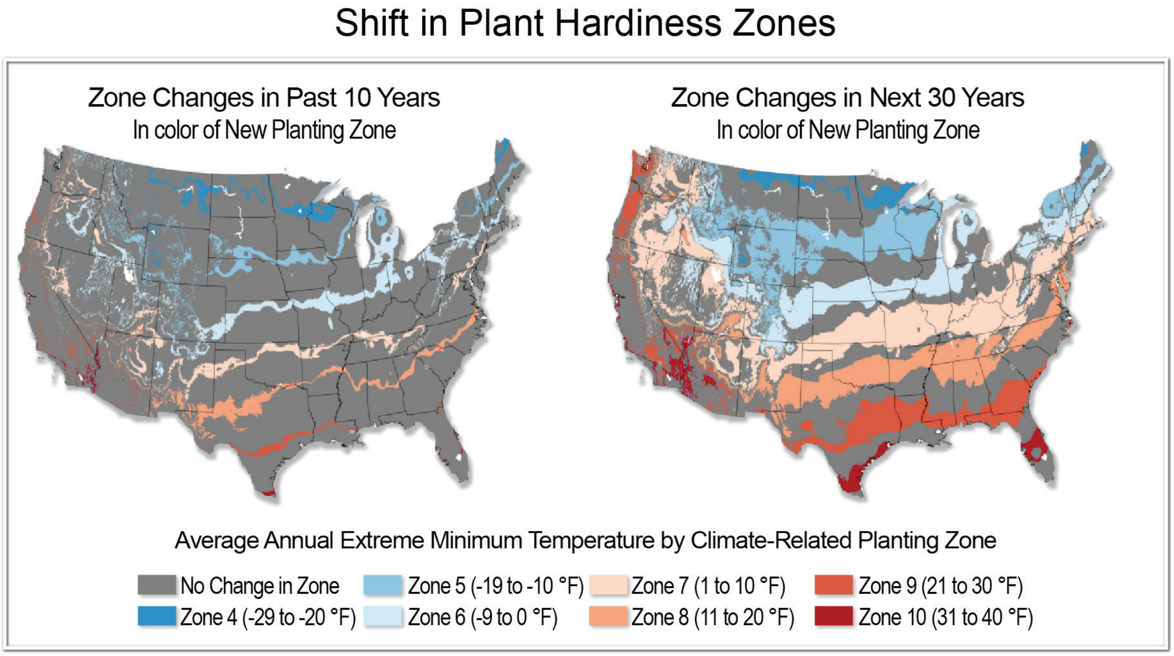


Figure 31: Shifts in Plant Hardiness Zones

Caption: The map on the left shows the change in Plant Hardiness Zones calculated from those based on the 1971-2000 climate to those based on the 1981-2010 climate. Even greater changes are projected over the next 30 years (right). (Figure source: NOAA).

Supplemental Message 9.

Trends in some types of extreme weather events have been observed in recent decades, consistent with rising temperatures. These include increases in: heavy precipitation nationwide, especially in the Midwest and Northeast; heat waves, especially in the West; and the intensity of Atlantic hurricanes. These trends are expected to continue. Research on climate changes' effects on other types of extreme events continues.

High impact, large-scale extreme events are complex phenomena involving various factors that can often create a "perfect storm." Such extreme weather occurs naturally. However, the influence of human activities on global climate is altering the frequency and/or severity of many of these events.

Observations show that heavy downpours have already increased nationally. Regional and global models project increases in extreme precipitation for every U.S. region.[112] Precipitation events tend to be limited by available moisture. For the heaviest, most rare events, there is strong evidence from observations[113] and models[112,114] that higher temperatures and the resulting moister atmosphere are the main cause of these observed and projected increases. Other factors that may also have an influence on observed U.S. changes in extreme precipitation are land-use changes (for example, changes in irrigation[115,116]) and a shift in the number of El Niño events versus La Niña events.

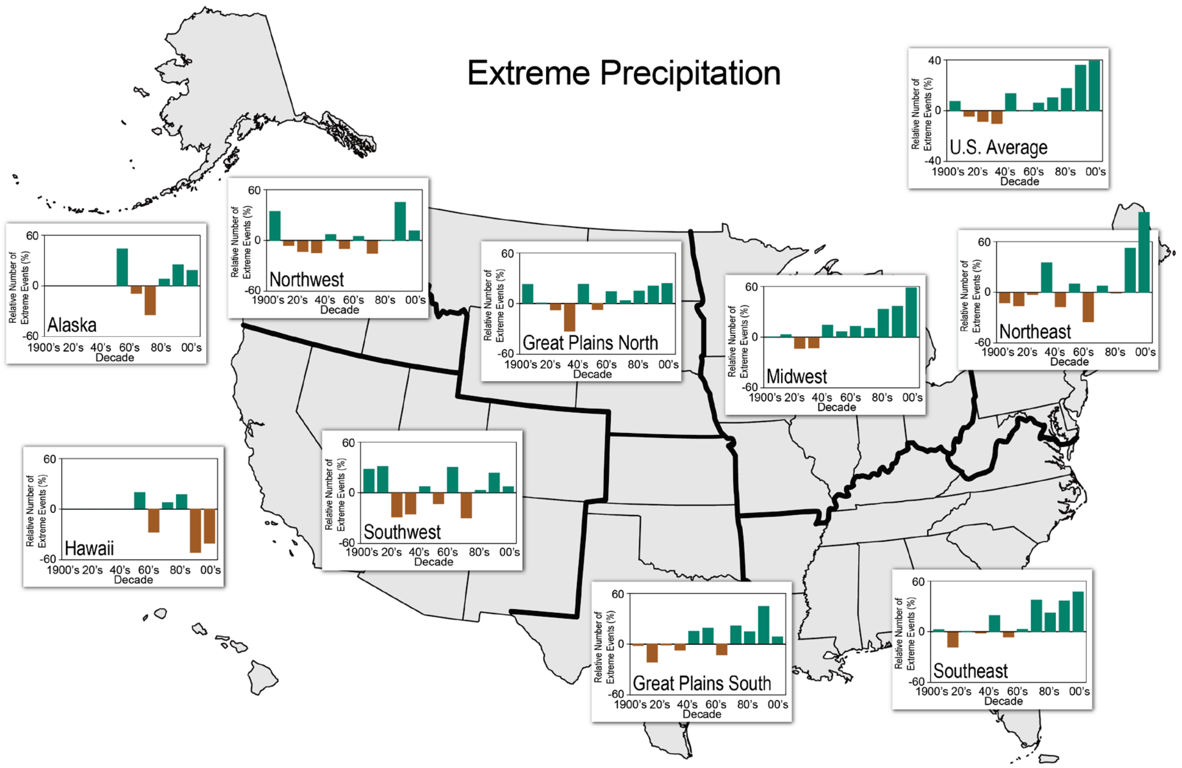


Figure 32: Extreme Precipitation

Caption: Heavy downpours are increasing nationally, with especially large increases in the Midwest and Northeast.[93] Despite considerable decadal-scale natural variability, indices such as this one based on 2-day precipitation totals exceeding a threshold for a 1-in-5-year occurrence exhibit a greater than normal occurrence of extreme events since 1991 in all U.S. regions except Alaska and Hawaii. Each bar represents that decade's average, while the far right bar in each graph represents the average for the 12-year period of 2001-2012. Analysis based on 726 long-term, quality- controlled station records. This figure is a regional expansion of the national index in Figure 2.16 of Chapter 2. (Figure source: updated from Kunkel et al. 2013[93]).

Climate change can also alter the characteristics of the atmosphere in ways that affect weather patterns and storms. In the mid-latitudes, where most of the continental U.S. is located, there is an increasing trend in extreme precipitation in the vicinity of fronts associated with mid-latitude storms (also referred to as extra-tropical [outside the tropics] cyclones[117]). There is also a northward shift in storms over the U.S.[118] that are often associated with extreme precipitation. This shift is consistent with projections of a warming world.[119] No change in mid-latitude storm intensity or frequency has been detected.

In the tropics, the most important types of storms are tropical cyclones, referred to as hurricanes when they occur in the Atlantic Ocean. Over the 40 years of satellite monitoring, there has been a shift toward stronger hurricanes in the Atlantic, with fewer category 1 and 2 hurricanes and more category 4 and 5 hurricanes. There has been no significant trend in the global number of tropical cyclones[120] nor has any trend been identified in the number of U.S. landfalling hurricanes.[1] Two studies have found an upward trend in the number of extreme precipitation events associated with tropical cyclones,[121] but significant uncertainties remain.[116] A change in the number of Atlantic hurricanes has been identified, but interpreting its significance is complicated both by multi-decadal natural variability and the reliability of the pre-satellite historical record.[122] The global satellite record shows a shift toward stronger tropical cyclones,[120,123] but does not provide definitive evidence of a long-term trend. Nonetheless, there is a growing consensus based on scientific understanding and very high resolution atmospheric modeling that the strongest tropical cyclones, including Atlantic hurricanes, will become stronger in a warmer world.[124]

The number of heat waves has been increasing in recent years. On a decadal basis, the decade of 2001-2010 had the second highest number since 1901 (first is the 1930s). This trend has continued in 2011 and 2012, with the number of intense heat waves being almost triple the long-term average. Regionally, the Northwest, Southwest, and Alaska had their highest number of heat waves in the 2000s, while the 1930s were the highest in the other regions (note that the Alaskan time series begins in the 1950s). For the number of intense cold waves, the national-average value was highest in the 1980s and lowest in the 2000s. The lack of cold waves in the 2000s was prevalent throughout the contiguous U.S. and Alaska. Climate model simulations indicate that the recent trends toward increasing frequency of heat waves and decreasing frequency of cold waves will continue in the future.

The data on the number and intensity of severe thunderstorm phenomena (including tornadoes, thunderstorm winds, and hail) are not of sufficient quality to determine whether there have been historical trends.[113] This scarcity of high quality data, combined with the fact that these phenomena are too small to be directly represented in climate models,[125] makes it difficult to project how these storms might change in the future.

Supplemental Message 10.

Drought and fire risk are increasing in many regions as temperatures and evaporation rates rise. The greater the future warming, the more these risks will increase, potentially affecting the entire United States.

Temperature increases increase evaporation rates, which (all else remaining equal) would be expected to lead to increased drying.[125] The Palmer Drought Severity Index (PDSI),[126] a widely used indicator of dryness that incorporates both precipitation and temperature-based evaporation estimates, does not show any trend for the U.S. as a whole over the past century.[127] However, drought intensity and frequency have been increasing over much of the West, especially during the last four decades. In the Southeast, western Great Lakes, and southern Great Plains, droughts have increased during the last 40 years, but do not show an increase when examined over longer periods encompassing the entire last century. In the Southwest, drought has been widespread since 2000; the average value of the PDSI during the 2000s indicated the most severe average drought conditions of any decade. The severity of recent drought in the Southwest reflects both the decade's low precipitation and high temperatures.

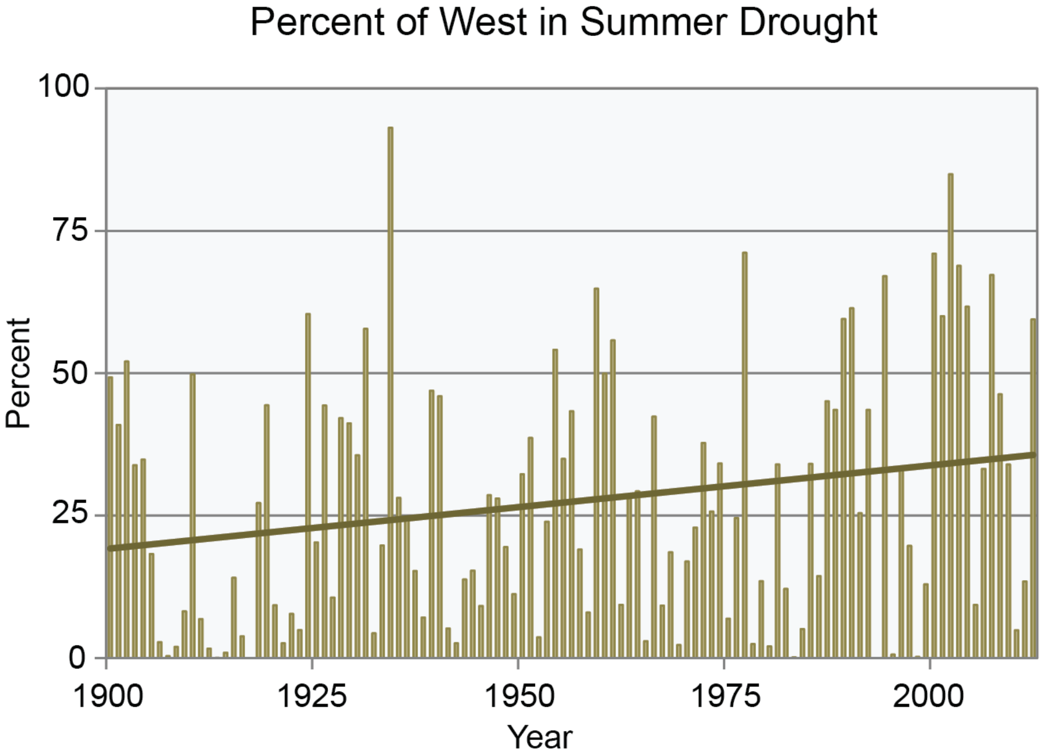


Figure 33: Percent of West in Summer Drought

Caption: The area of the western U.S. in moderately to extremely dry conditions during summer (June-July-August) varies greatly from year to year but shows a long-term increasing trend from 1900 to 2012. (Data from NOAA NCDC State of the Climate Drought analysis).

Seasonal and multi-year droughts affect wildfire severity.[128] For example, persistent drought conditions in the Southwest, combined with wildfire suppression and land management practices,[129] have contributed to wildfires of unprecedented size since 2000. Five western states (Arizona, Colorado, Utah, California, and New Mexico) have experienced their largest fires on record at least once since 2000. Much of the increase in fires larger than 500 acres occurred in the western U.S., and the area burned in the Southwest increased more than 300% relative to the area burned during the 1970s and early 1980s.[130]

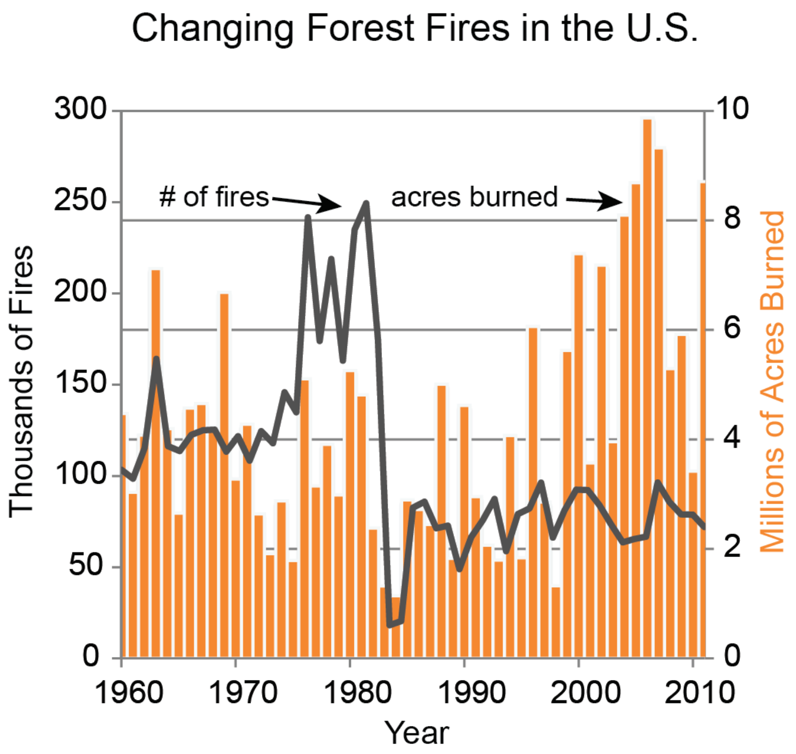


Figure 34: Changing Forest Fires in the U.S.

Caption: Although the average number of wildfires per year (black line) has decreased over time, the total area burned by wildfires (orange bars) in the continental U.S. (primarily in the western states) has nearly doubled since 2000 relative to the long-term 1960-1999 average (data shown are for 1960-2011). (Data from the National Interagency Fire Center).

Droughts on a duration and scale that affect agriculture are projected to increase in frequency and severity in this century due to higher temperatures. Projections of the Palmer Drought Severity Index at the end of this century indicate that the normal state for most of the nation will be what is considered moderate to severe drought today.[131,132] The PDSI is used by several states for monitoring drought and for triggering certain actions.[133] It is also one component of the U.S. Drought Monitor (http://droughtmonitor.unl.edu/current.html). The closely related Palmer Hydrological Index is the most important component of Drought Monitors objective long-term blend indicator (http://www.cpc.ncep.noaa.gov/products/predictions/tools/edb/lbfinal.gif), which is used by the U.S. Department of Agriculture to identify counties that are eligible to participate in certain Federal government drought relief programs. The U.S. Drought Monitor is also used by some states for similar purposes.

Despite its widespread usage, this index may be overly sensitive to future temperature increases.[134] As temperatures increase during this Century, these PDSI-based monitoring tools may over-estimate the intensity of drought during anomalous warm periods, so statutory adjustments to these tools may be warranted. However, the projection of increased drought risk is reinforced by a direct examination of future soil moisture content projections, which reveals substantial drying in most areas of the western U.S (Ch. 2: Our Changing Climate, Key Message 3).

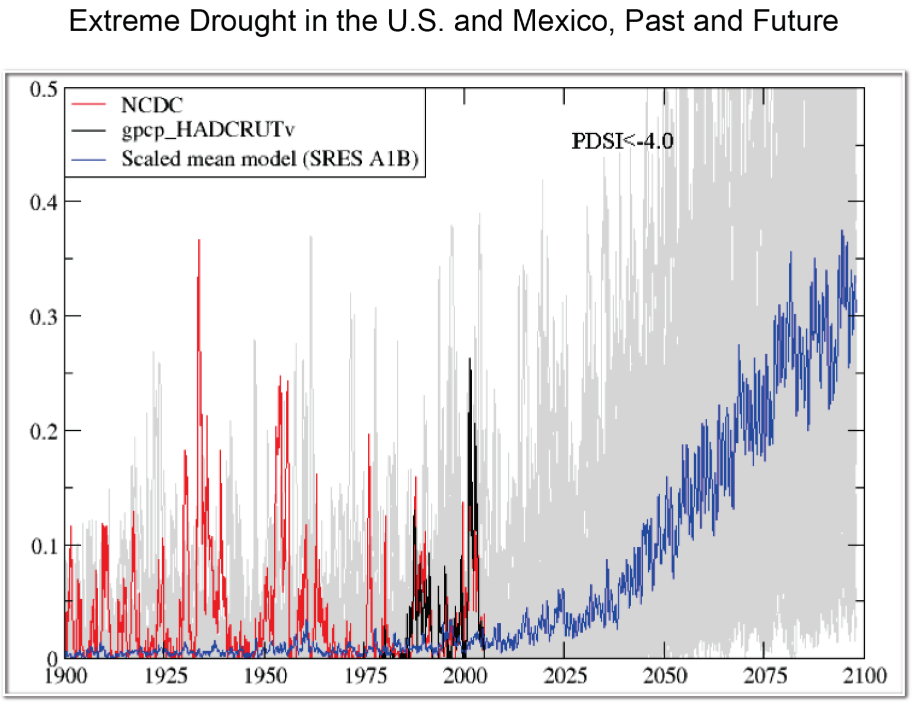


Figure 35: Extreme Drought in the U.S. and Mexico, Past and Future

Caption: The fractional areal extent of the contiguous U.S. and Mexico in extreme drought according to projections of the Palmer Drought Severity Index under an intermediate emissions scenario (SRES A1B, in between the B1 and A2 scenarios used elsewhere in this report) (Ch. 2: Our Changing Climate, Key Message 3; Climate Science Appendix, Supplemental Message 5). The Palmer Drought Severity Index is the most widely used measure of drought, although it is more sensitive to temperature than other drought indices and may over-estimate the magnitude of drought increases. The red line is based on observed temperature and precipitation. The blue line is from the average of 19 different climate models. The gray lines in the background are individual results from over 70 different simulations from these models. These results suggest an increasing probability of agricultural drought over this century throughout most of the U.S. (Figure source: Wehner et al. 2011[132]).

Provided the wood and ground litter has dried out, the area of forest burned in many mid-latitude areas, including the western U.S., may increase substantially as temperature and evapotranspiration increase, exacerbating drought.[135] Under even relatively modest amounts of warming, significant increases in area burned are projected in the Sierra Nevada, southern Cascades, and coastal California; in the mountains of Arizona and New Mexico; on the Colorado Plateau; and in the Rocky Mountains.[136] Other studies, examining a broad range of climate change and development scenarios, find increases in the chance of large fires for much of northern California's forests.[137]

Long periods of consecutive days with little or no precipitation also can lead to drought. The average annual maximum number of consecutive dry days are projected to increase for the higher emissions scenarios in areas that are already prone to little precipitation by mid-century and increase thereafter (Ch. 2: Our Changing Climate, Key Message 5). Much of the western and southwestern U.S. is projected to experience statistically significant increases in the annual maximum number of consecutive dry days, on average up to 10 days above present-day values for parts of the contiguous U.S. by the end of this century under high emissions scenarios. Hence, some years are projected to experience substantially longer dry seasons.

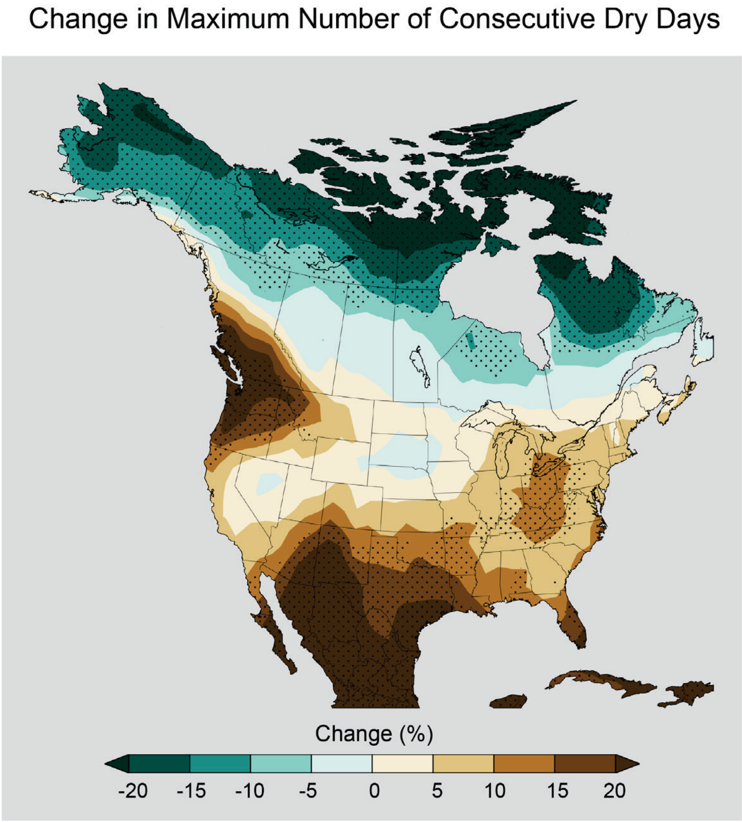


Figure 36. Change in Maximum Number of Consecutive Dry Days

Caption: Change in the number of consecutive dry days (days receiving less than 0.04 inches (1 mm) of precipitation) at the end of this century (2081-2100) relative to the end of last century (1980-1999) under the higher scenario, RCP8.5. Stippling indicates areas where changes are consistent among at least 80% of the 25 models used in this analysis. (Ch. 2: Our Changing Climate, Key Message 3; Climate Science Appendix, Supplemental Message 5). (Figure source: NOAA NCDC / CICS-NC).

Supplemental Message 11.

Summer Arctic sea ice extent, volume, and thickness have declined rapidly, especially north of Alaska. Permafrost temperatures are rising and the overall amount of permafrost is shrinking. Melting of land- and sea-based ice is expected to continue with further warming.

Increasing temperatures and associated impacts are apparent throughout the Arctic, including Alaska. Sea ice coverage and thickness, permafrost on land, mountain glaciers, and the Greenland Ice Sheet all show changes consistent with higher temperatures.

The most dramatic decreases in summer sea ice have occurred along the northern coastline of Alaska and Russia. Since the satellite record began in 1979, September (summer minimum) sea ice extent has declined by 13% per decade in the Beaufort Sea and 32% per decade in the Chukchi Sea,[138] leaving the Chukchi nearly ice-free in the past few Septembers. Longer-term records based on climate proxies suggest that pan-Arctic ice extent in summer is the lowest it has been in at least the past 1,450 years.[139] Winter ice extent has declined less than summer ice extent (see Ch. 2: Our Changing Climate, Key Message 11), indicative of a trend toward seasonal-only (as opposed to year-round) ice cover, which is relatively thin and vulnerable to melt in the summer. Recent work has indicated that the loss of summer sea ice may be affecting the atmospheric circulation in autumn and early winter. For example, there are indications that a weakening of sub-polar westerly winds during autumn is an atmospheric response to a warming of the lower troposphere of the Arctic.[140] Extreme summer ice retreat also appears to be increasing the persistence of associated mid-latitude weather patterns, which may lead to an increased probability of extreme weather events that result from prolonged conditions, such as drought, flooding, cold spells, and heat waves.[141] However, the combination of interannual variability and the small sample of years with extreme ice retreat make it difficult to identify a geographically consistent atmospheric response pattern in the middle latitudes.

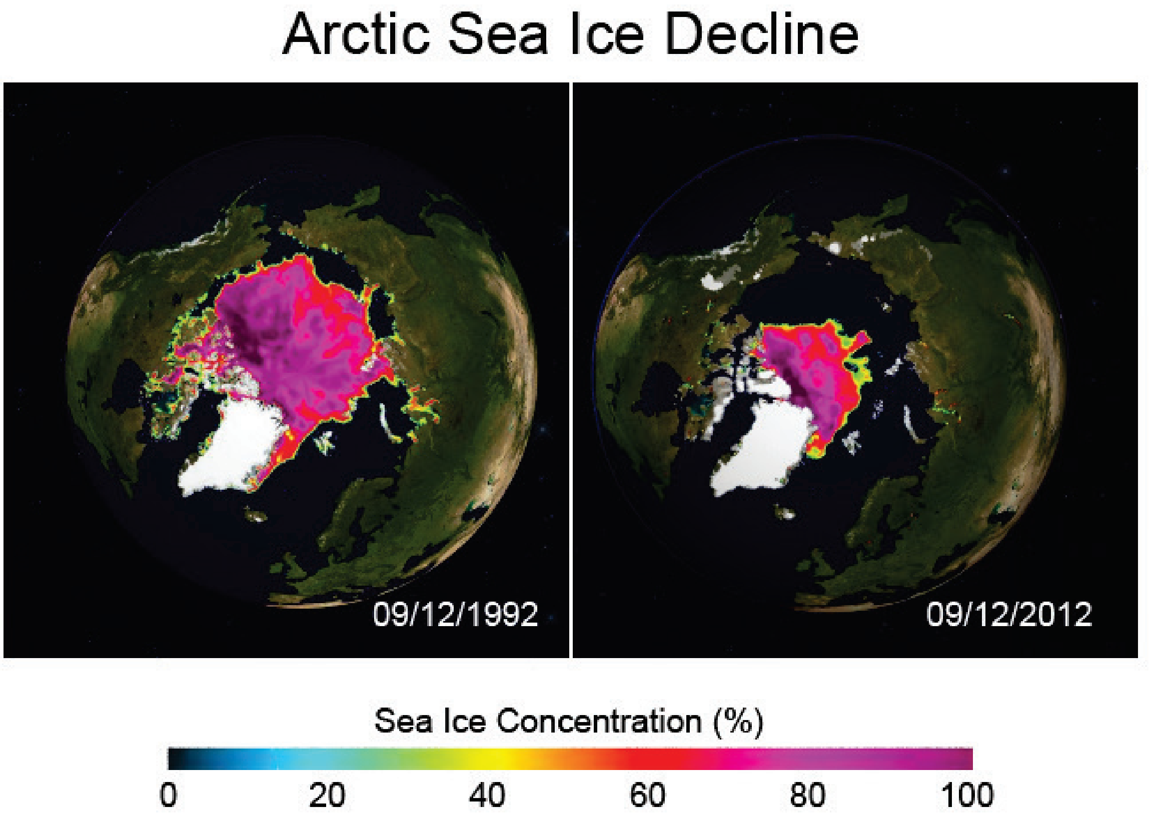


Figure 37: Arctic Sea Ice Decline

Caption: The spatial extent of Arctic sea ice cover in September has decreased substantially in the past two decades, as shown in this pair of satellite images depicting sea ice concentrations. The reduction of September sea ice extent from 1992 (left) to 2012 (right) has been nearly 50%, or about 1.2 million square miles (3 million square kilometers), which is nearly one-third the area of the contiguous United States. (Figure source: University of Illinois, The Cryosphere Today[142]).

On land, changes in permafrost provide compelling indicators of a warming climate as they tend to reflect long-term average changes in climate. Borehole measurements are particularly useful as they provide information from levels below about 10-meter depth where the seasonal cycle becomes negligible. Increases in borehole temperatures over the past several decades are apparent at various locations, including Alaska, northern Canada, Greenland, and northern Russia. The increases are about 3.6°F at the two stations in northern Alaska (Deadhorse and West Dock). In northern Alaska and northern Siberia where permafrost is cold and deep, thaw of the entire permafrost layer is not imminent. However, in the large areas of discontinuous permafrost of Russia, Alaska, and Canada, average annual temperatures are sufficiently close to freezing that permafrost thaw is a risk within this century. Thawing of permafrost can release methane into the atmosphere, amplifying warming (see Supplemental Message 5), as well as potentially causing infrastructure and environmental damages.

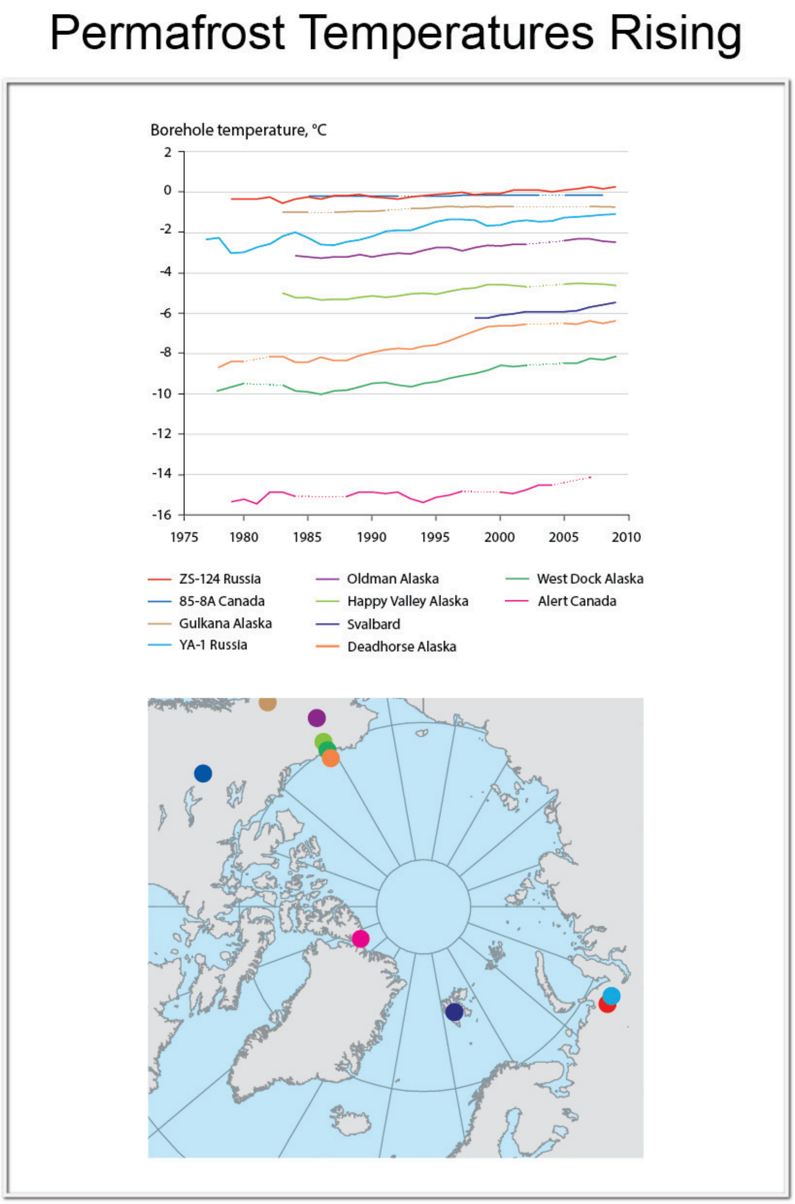


Figure 38: Permafrost Temperatures Rising

Caption: Ground temperatures at depths between 33 and 66 feet (10 and 20 meters) for boreholes across the circumpolar northern permafrost regions (Figure source: AMAP 2011[143]).

There is evidence that the active layer (the near-surface layer of seasonal thaw, typically up to three feet deep) may be thickening in many areas of permafrost, including in northern Russia and Canada.[144] Permafrost thaw in coastal areas increases the vulnerability of coastlines to erosion by ocean waves, which in turn are exacerbated by the loss of sea ice from coastal areas affected by storms.

Increased melt is reducing both the mass and areal extent of glaciers over much of the Northern Hemisphere. Over the past decade, the contribution to sea level rise from glaciers and small ice caps (excluding Greenland) has been comparable to the contributions from the Greenland Ice Sheet.[145]

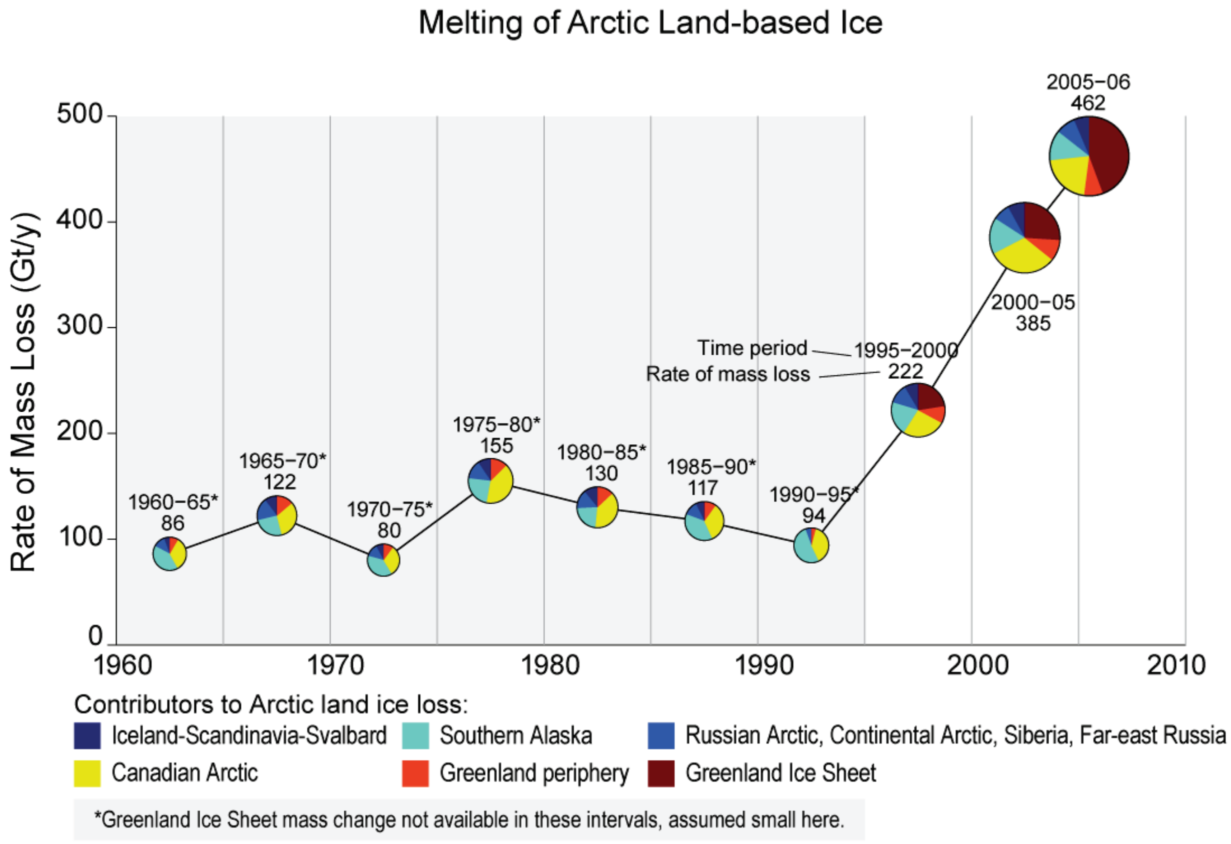


Figure 39: Melting of Arctic Land-based Ice

Caption: Inputs of freshwater to the ocean from mountain glaciers, small ice caps, and the Greenland Ice Sheet have increased dramatically in the past two decades. The size of the circles in the figure is proportional to the five-year average freshwater contributions to the ocean from melting of land-based ice. The coloring indicates the relative contributions from the Greenland Ice Sheet (brown) and mountain glaciers from the Greenland periphery (orange), Iceland-Scandinavia-Svalbard (dark blue), the Canadian Arctic (yellow), southern Alaska (light blue), and the Russian Arctic (medium blue). The largest contributions from mountain glaciers have been from the Canadian Arctic and southern Alaska. Note that contributions from mass changes of the Greenland Ice Sheet are not available prior to the mid-1990s, but they are assumed to have been small during this earlier period because annual snow accumulation was in approximate balance with annual meltwater discharge. (Figure source: AMAP 2011).[143]

Projections of future mass loss by glaciers and small ice caps indicate a continuation of current trends, although these projections are based only on the changes in temperature and precipitation projected by global climate models; they do not include the effects of dynamical changes (for example, glacier movement). While there is a wide range among the projections derived from different global climate models, the models are consistent in indicating that the effects of melting will outweigh the effects of increases in snowfall. The regions from which the contributions to sea level rise are projected to be largest are the Canadian Arctic, Alaska, and the Russian Arctic.[143]

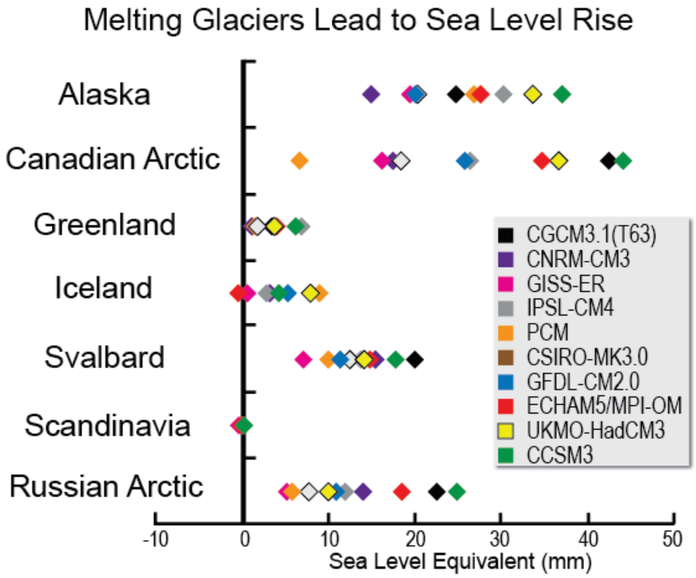


Figure 40: Melting Glaciers Lead to Sea Level Rise

Caption: Projections of contributions to sea level rise by 2100 for seven regions that include all Arctic glaciers. Projections are based on temperature and precipitation simulated by ten different global climate models from CMIP3. For each region, the estimates are shown in different colors corresponding to the ten different models (inset box). (Figure source: adapted from Radić and Hock 2011[146]).

Supplemental Message 12.

Sea level is already rising at the global scale and at individual locations along the U.S. coast. Future sea level rise depends on the amount of warming and ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.

The rising global average sea level is one of the hallmarks of a warming planet. It will also be one of the major impacts of human-caused global warming on both human society and the natural environment.

Global sea level is increasing as a result of two different processes. First, the oceans absorb more than 90% of the excess heat trapped by human interference with the climate system, and this warms the oceans.[147] Like mercury in a thermometer, the warmer ocean water expands, contributing to global sea level rise. Second, the warmer climate also causes melting of glaciers and ice sheets. This meltwater eventually runs off into the ocean and contributes to sea level rise as well. A recent synthesis of surface and satellite measurements of the ice sheets shows that the rate at which the Greenland and Antarctic ice sheets contribute to sea level rise has been increasing rapidly and has averaged 0.02 inches (plus or minus 0.008) inches per year since 1992, with Greenland's contribution being more than double that of Antarctica.[148] In addition, local sea level change can differ from the global average sea level rise due to changes in ocean currents, local land movement, and even changes in the gravitational pull of the ice sheets and changes in the Earth's rotation.

There is high confidence that global sea level will continue to rise over this century and beyond, and that most coastlines will see higher water levels. The rates of sea level rise along individual coastlines are difficult to predict as they can vary depending on the region. For example, globally averaged sea level has risen steadily by about 2.4 inches over the past two decades. But during that time, many regions have seen much more rapid rise while some have experienced falling sea levels. These complicated patterns are caused by changes in ocean currents and movement of heat within the oceans. Many of these patterns are due in part to natural, cyclic changes in the oceans. On the west coast of the United States, sea level has fallen slightly since the early 1990s. Recent work suggests that a natural cycle known as the Pacific Decadal Oscillation has counteracted most or all of the global sea level signal there. This means that in coming decades the west coast is likely to see faster than average sea level rise as this natural cycle changes mode.[149]

Along any given coastline, determining the rate of sea level rise is complicated by the fact that the land may be rising or sinking. Along the Gulf Coast, for example, local geological factors including extraction of oil, natural gas, and water from underground reservoirs are causing the land to sink, which could increase the effect of global sea level rise by several inches by the end of this century.[150] In some other locations, coastlines are rising as they continue to rebound from glaciation during the last glacial maximum. Predicting the future of any single coastline requires intimate knowledge of the local geology as well as the processes that cause sea levels to change at both the local and global scale.

Greenland and Antarctica hold enough ice to raise global sea levels by more than 200 feet if they were to melt completely. While this is very unlikely over at least the next few centuries, studies suggest that meltwater from ice sheets could contribute anywhere from several inches to 4.5 feet to global sea levels by the end of this century.[151] Because their behavior in a warming climate is still very difficult to predict, these two ice sheets are the biggest wildcards for potential sea level rise in the coming decades. What is certain is that these ice sheets are already responding to the warming of the oceans and the atmosphere. Satellites that measure small changes in the gravitational pull of these two regions have proven that both Greenland and Antarctica are currently losing ice and contributing to global sea level rise.[152]

In the United States, an estimated 5 million people currently live within 4 feet of current high tide lines, which places them at increasing risk of flooding in the coming decades.[153] Although sea level rise is often thought of as causing a slow inundation, the most immediate impacts of sea level rise are increases in high tides and storm surges. A recent assessment of flood risks in the United States found that the odds of experiencing a "100-year flood" are on track to double by 2030.

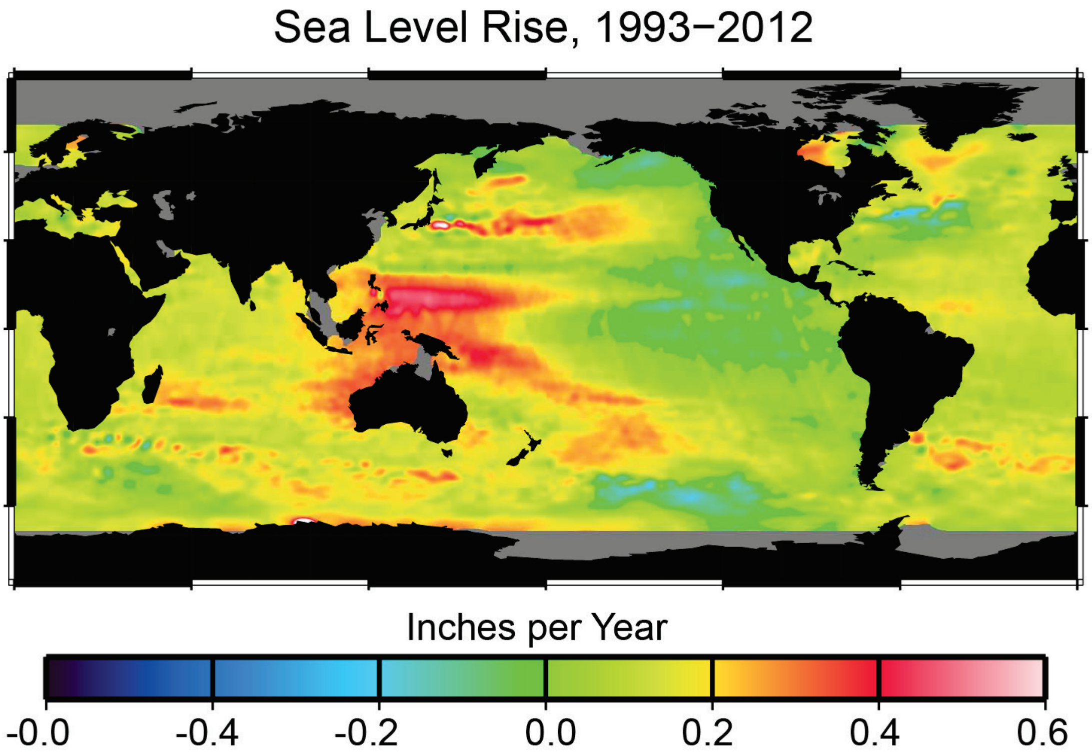


Figure 41: Sea Level Rise, 1993-2012

Caption: The patterns of sea level rise between 1993 and 2012 as measured by satellites. The complicated patterns are a reminder that sea levels do not rise uniformly.[154] (Figure source: University of Colorado, Sea Level Research Group).

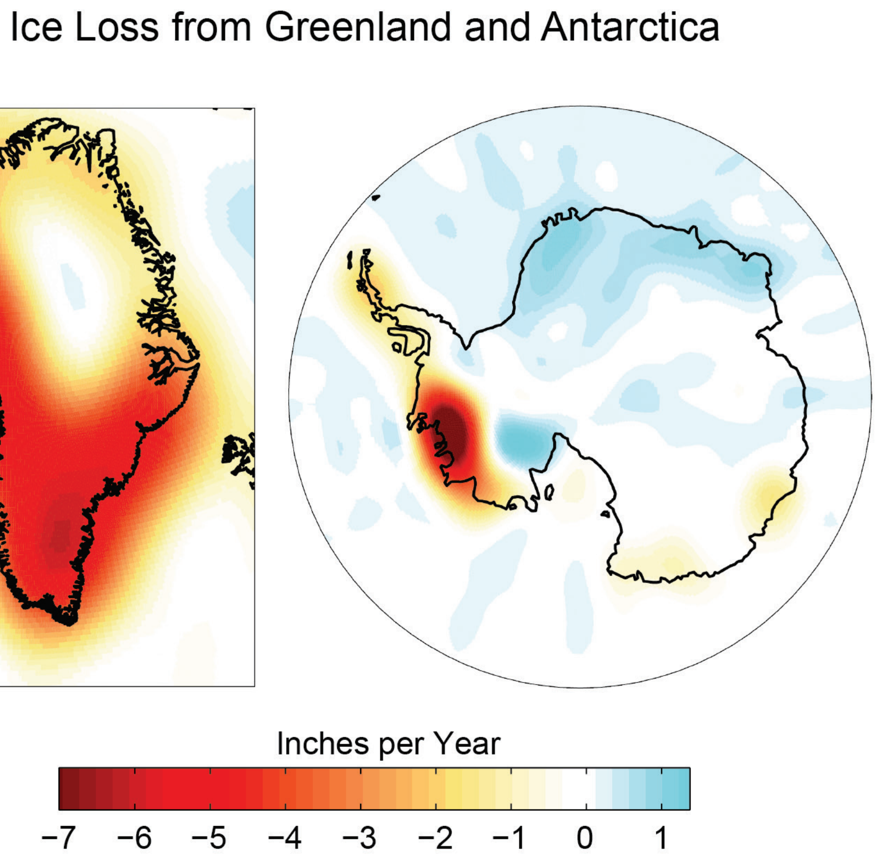


Figure 42: Ice Loss from Greenland and Antarctica

Caption: Rate of ice mass loss from Greenland (left) and Antarctica (right) from 2003 to 2012. The GRACE (Gravity Recovery and Climate Experiment) satellites measure changes in the pull of gravity over these two regions. As they lose ice to the oceans, the gravitational pull of Greenland and Antarctica is reduced. Analyses of GRACE data have now proven that both of the major ice sheets are currently contributing to global sea level rise due to ice loss. Over the periods plotted here, Greenland lost enough ice to raise sea level at a rate of 0.028 inches per year (0.72 mm/yr), and Antarctica lost ice at a rate that caused 0.0091 inches of sea level rise per year (0.24 mm/yr). (Figure source: (left) NASA Jet Propulsion Laboratory; (right) updated from Ivins et al. 2013[155]).

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