Appendix: The Science of Climate Change

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Key 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 many 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. This warming is expected to continue.**

8. **Many other indicators of rising temperatures have been observed in the U.S. 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. **There have been observed trends in some types of extreme weather events, and these are 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 U.S.**

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 temperature change and on the 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.* The focus here is also 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.

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 (Karl et al. 2009), including the global climate assessments produced by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. National Academy of Sciences. This Appendix is consistent with the main chapter in providing a focus on the ongoing changes of climate in the United States. These changes are placed into a global context in the first few key messages, followed by an elaboration on the changes having the greatest impacts (and potential impacts) on the United States. Throughout the Appendix, there is more information on attribution, spatial and temporal detail, and physical mechanisms than could be covered within the length constraints of the main chapter.

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. We have attempted to identify the CMIP version in those instances when the source of the projections is unclear. (See Key Message 5 for more on these simulations and related emissions scenarios).

Key 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 is constantly changing over time. Without external forcing, changes are the result of complex interactions between the climate system's atmosphere, ocean, land surface, and living things. This natural variability is internal to (occurs within) the climate system. Internal variability of temperature on decadal time scales is quite small (less than 0.5°F)(Swanson et al. 2009) compared to the changes that can occur due to external forcers. External drivers that directly affect climate include natural phenomena, such as variations in the energy received from the Sun, as well as human-driven increases in carbon dioxide (CO_2) and other heat-trapping gases. Feedback mechanisms triggered by changes in the climate system are external drivers that indirectly affect climate by increasing or dampening an initial change.

The natural greenhouse effect is key to understanding how human activities can affect the Earth's climate. The greenhouse effect is a natural process, first discovered in 1824 and validated by observations in 1859. Heat-trapping gases, including water vapor, carbon dioxide, ozone, methane, and nitrous oxide, absorb some of the heat given off by the Earth's surface and lower atmosphere. They then radiate much of the energy back toward the surface, effectively trapping the heat inside the climate system. Without this natural greenhouse effect, the average surface temperature of the Earth would be about 60°F colder than it is today.

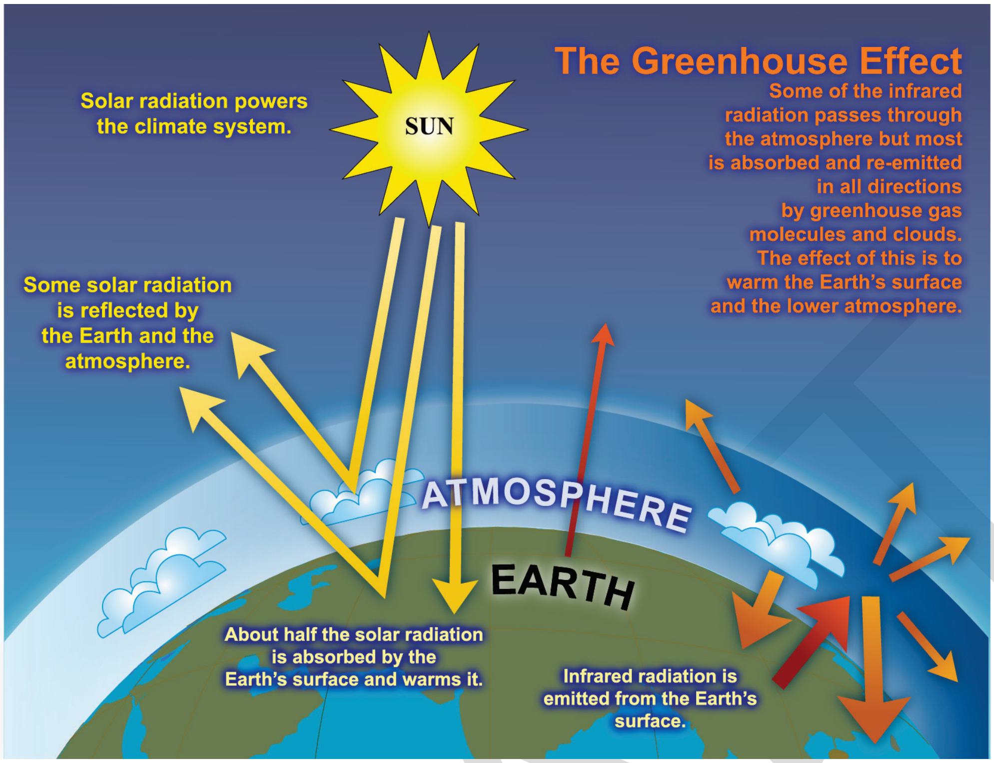


Figure 1: The Greenhouse Effect

Caption: Diagram illustrating the greenhouse effect. (Figure Source: IPCC 2007)

Water vapor is the single most important gas responsible for the natural greenhouse effect. However, the amount of water vapor in the atmosphere depends on temperature. This means that water vapor is a feedback, not a direct forcing on climate. Observational evidence shows that, in terms of direct forcing, carbon dioxide is the most important heat-trapping gas in the Earth's atmosphere (Lacis et al. 2010). This is because 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 account for between 26% and 33% of the total greenhouse effect (Schmidt et al. 2010). This is a range, rather than a single number, because some of the effects of water vapor overlap with those of other gases.

The concentrations of atmospheric CO_2 and other heat-trapping gases drive changes in the Earth's temperature, which in turn affects the levels of atmospheric water vapor and clouds that account for the remaining 66% to 80% of the greenhouse effect (Schmidt et al. 2010). Without the heat-trapping effects of carbon dioxide and the other greenhouse gases, climate simulations indicate that the greenhouse effect would not function, turning the Earth into a frozen ball of ice (Lacis et al. 2010).

Human activities are affecting the temperature of the Earth by altering the natural greenhouse effect. Burning fossil fuels (coal, oil, and natural gas), clearing of forests, and other human activities produce heat-trapping gases that build up in the atmosphere. This artificially intensifies the natural greenhouse effect, causing the planet to warm.

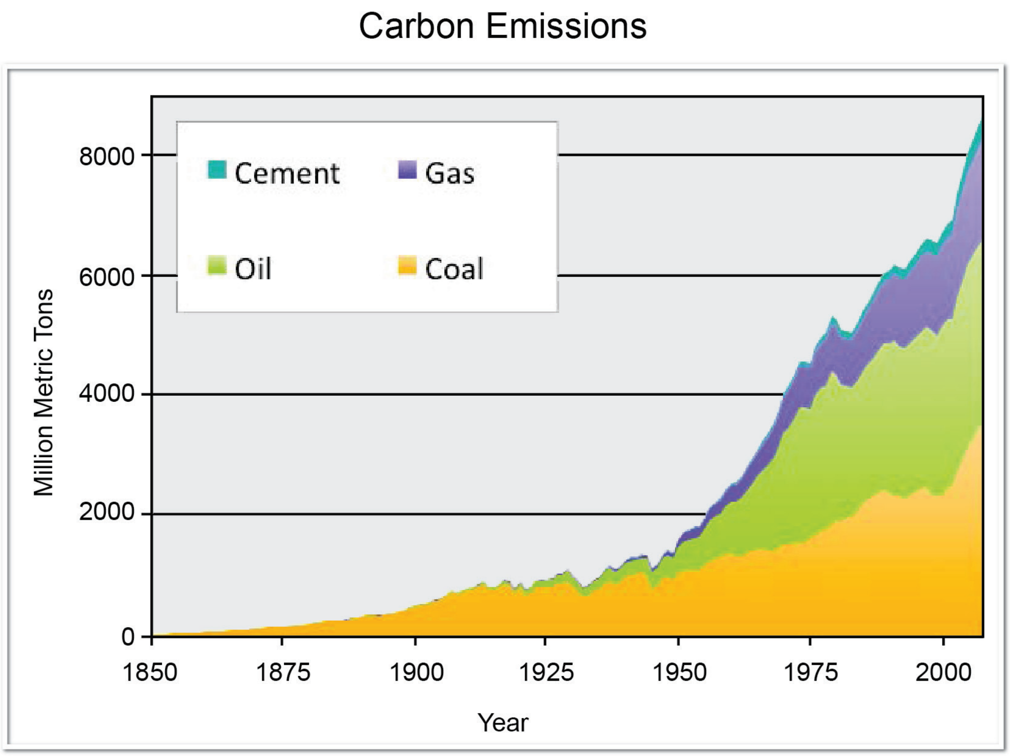


Figure 2: Carbon Emissions

Caption: Carbon emissions (in million metric tons) from burning coal, oil, and gas and producing cement, in units of million metric tons of carbon. (Source: Boden et al. 2010).

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 of other important greenhouse gases, including methane, nitrous oxide, and halocarbons, have also increased because of human activities. While the levels of these gases in the atmosphere are relatively small compared to 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 a contributor to climate change over the past 150 years or more.

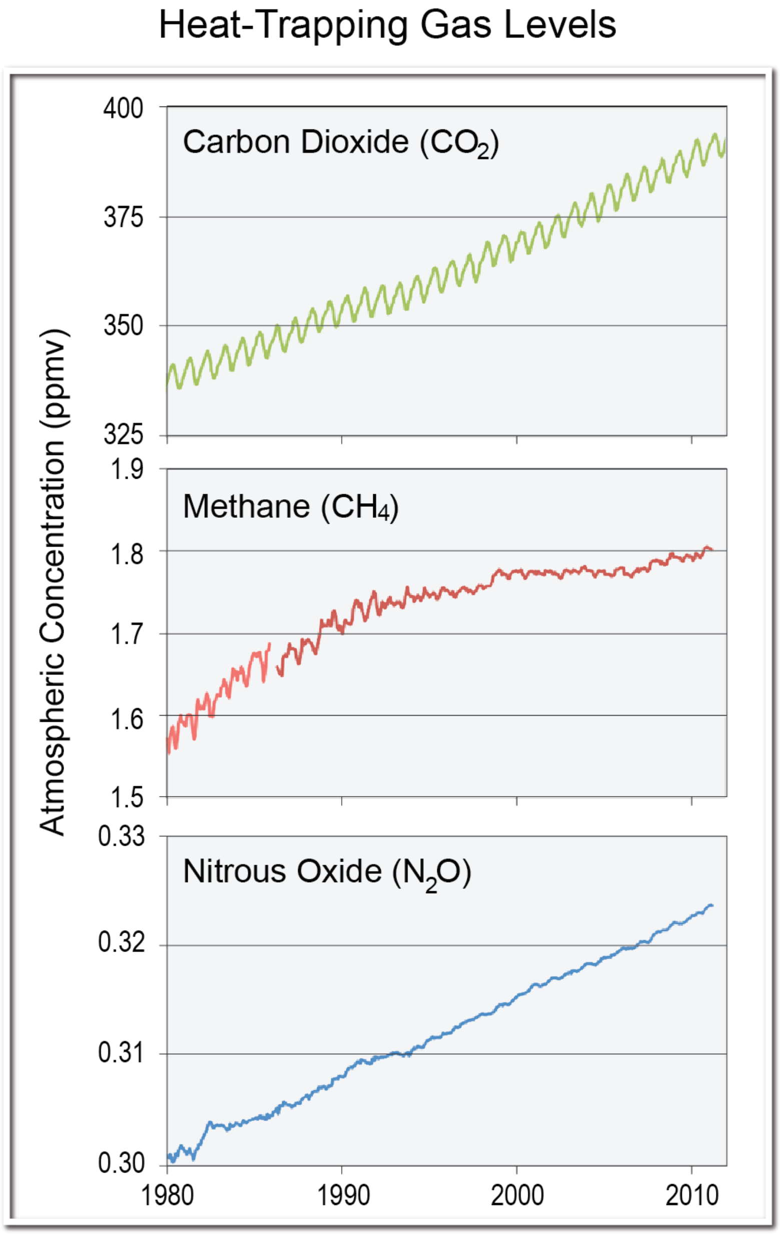


Figure 3: Heat-Trapping Gas Levels

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, or ppmv), respectively. Air sampling data from 1980 to the present show long-term increases due to human activities as well as short-term variations due to natural biogeochemical processes and seasonal vegetation growth. (Source: Khalil et al. 1993).

Carbon dioxide levels in the atmosphere are currently increasing at a rate of 0.5% per year. Atmospheric levels reached 392 parts per million in 2012, higher than anything the Earth has experienced in over a million years (the figure shows the ice core record for CO_2 levels over the last 800,000 years). Globally, over the past several decades, about 80% of carbon dioxide emissions from human activities came from burning fossil fuels, while about 20% came from deforestation and other agricultural practices. 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 stayed in the atmosphere, where carbon dioxide levels have increased by 40% relative to pre-industrial levels.

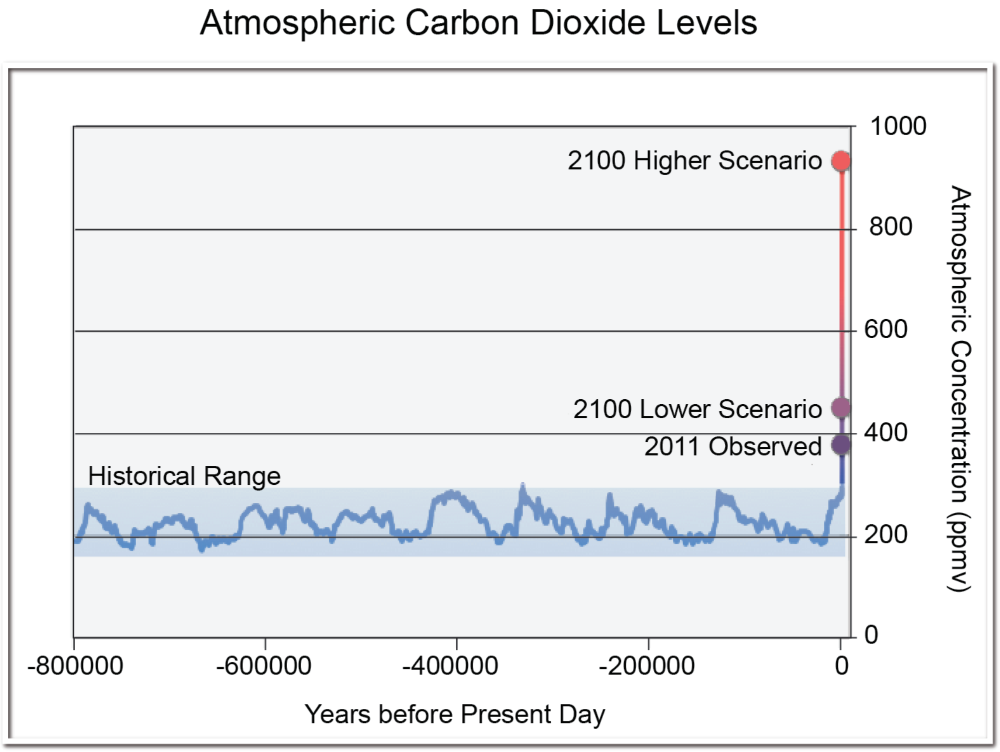


Figure 4: Atmospheric Carbon Dioxide Levels

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 cause atmospheric CO_2 levels 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 392 ppm, higher than any time in at least the last 800,000 years. By 2100, additional emissions from human activities are projected to increase CO_2 levels to 420 ppm under lower emissions (the RCP 2.6 scenario, which would require substantial emissions reductions) and 935 ppm under higher emissions (the RCP 8.5 scenario, which assumes continued increases in emissions). Historical composite CO_2 record based on measurements from EPICA Dome C (Sources: 664-800kyr, (Lüthi et al. 2008); 393-664 kyr, (Siegenthaler et al. 2005); 0-22 kyr, (Monnin et al. 2001) and Vostok (22-393 kyr, (Pépin 2001; Petit et al. 1999; Raynaud 2005); future projections from RCP 2.6 and 8.5 (Source: Meinshausen et al. 2011).

Methane levels in the atmosphere have increased mainly as a result of agriculture including raising livestock (which produce methane in their digestive tracts); mining coal, extraction and transport of natural gas, and other fossil fuel-related activities; and waste disposal including sewage and decomposing garbage in landfills. About 70% of the emissions of atmospheric methane now come from human activities. Atmospheric amounts of methane leveled off from 1999-2006 due to temporary decreases in both human and natural sources, 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. They have increased by about 20% relative to pre-industrial times.

Halocarbons are mostly man-made chemicals that have been manufactured to serve a specific purpose, from aerosol spray cans to refrigerant coolant. 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 international agreements 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 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% (Lamarque et al. 2005). Much higher increases have been observed in areas with high levels of air pollution, and lesser increases in remote locations where the air has remained relatively clean.

In addition to heat-trapping gases, human activities also produce tiny atmospheric particles, including dust and soot. For example, coal burning produces sulfur gases that form particles in the atmosphere. These sulfate particles reflect incoming sunlight away from the Earth, exerting a cooling influence on Earth's surface. Another type of particle, 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 and decrease the average size of cloud droplets when there is not enough water vapor compared to the number of particles available. This creates brighter clouds that reflect away energy from the Sun, resulting in an overall cooling effect. Particles that absorb energy encourage cloud droplets to evaporate by warming the atmosphere. Depending on their type, particles can either counteract 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. After a hundred years, about one third of the carbon dioxide emitted is still in the atmosphere. Methane lasts for approximately a decade before it is removed through chemical reactions. Particles, on the other hand, 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 be seen 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 (Shindell et al. 2012) examine various means for reducing near-term changes in climate, for example, by reducing emissions of methane and black carbon (soot).

In addition to emissions of greenhouse gases, air pollutants, and particles, human activities have also affected climate by changing the land surface. These types of 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 was 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 have had a net warming influence, but one that is much smaller than the human influence. Natural internal drivers of climate, such as El Niño events in the Pacific Ocean, have also influenced regional and global climate. Many 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, 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 2 to 3 years. These 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. 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.

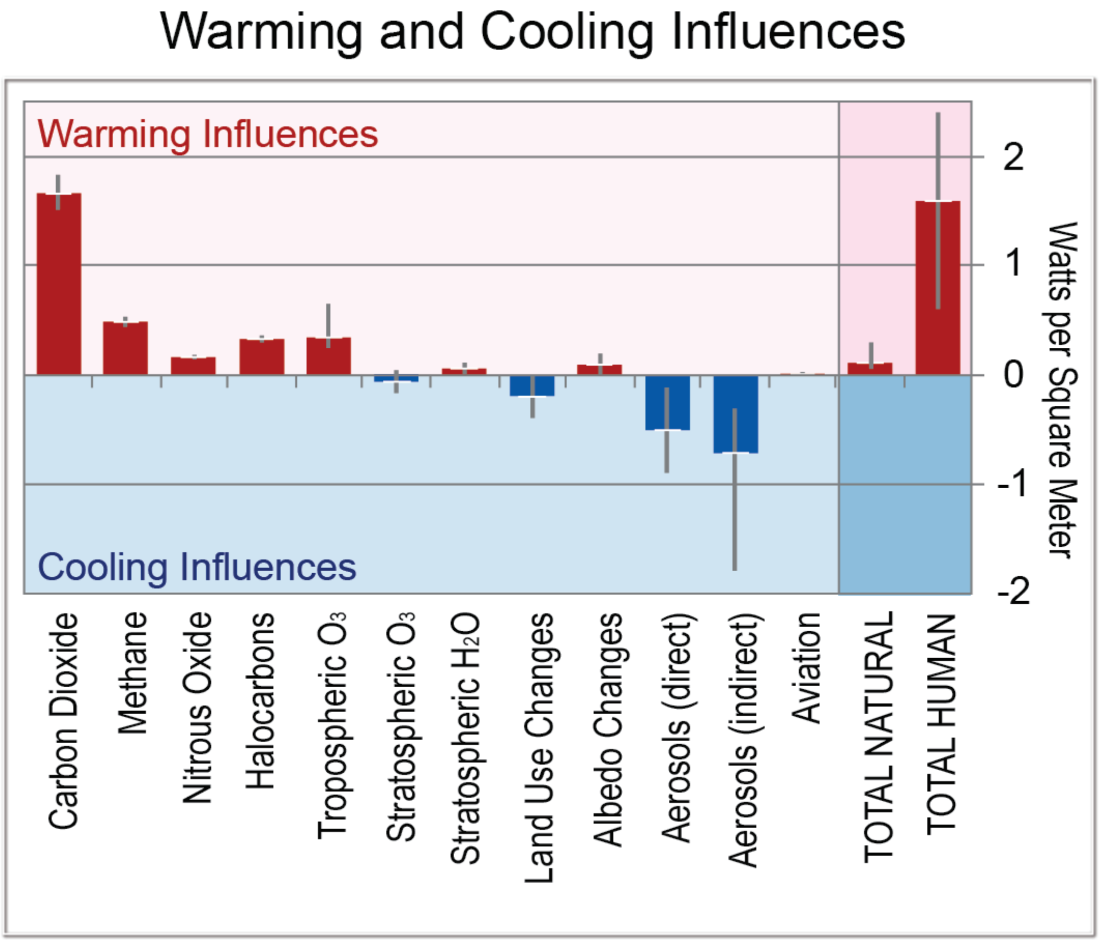


Figure 5: Warming and Cooling Influences

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 increase 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 so is not included here. The net effect is a strong warming, primarily from human activities. The thin lines on each bar show the range of uncertainty. (Forster 2007).

Key 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 assess changes in climate. 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, enough of these 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, subject to uncertainties inherent in algorithms and instrument calibrations. Climate "proxies" are biological or physical records ranging from tree rings to ice cores that correlate with aspects of climate, providing evidence that can stretch back to hundreds of thousands of years.

Development of Observing Capabilities

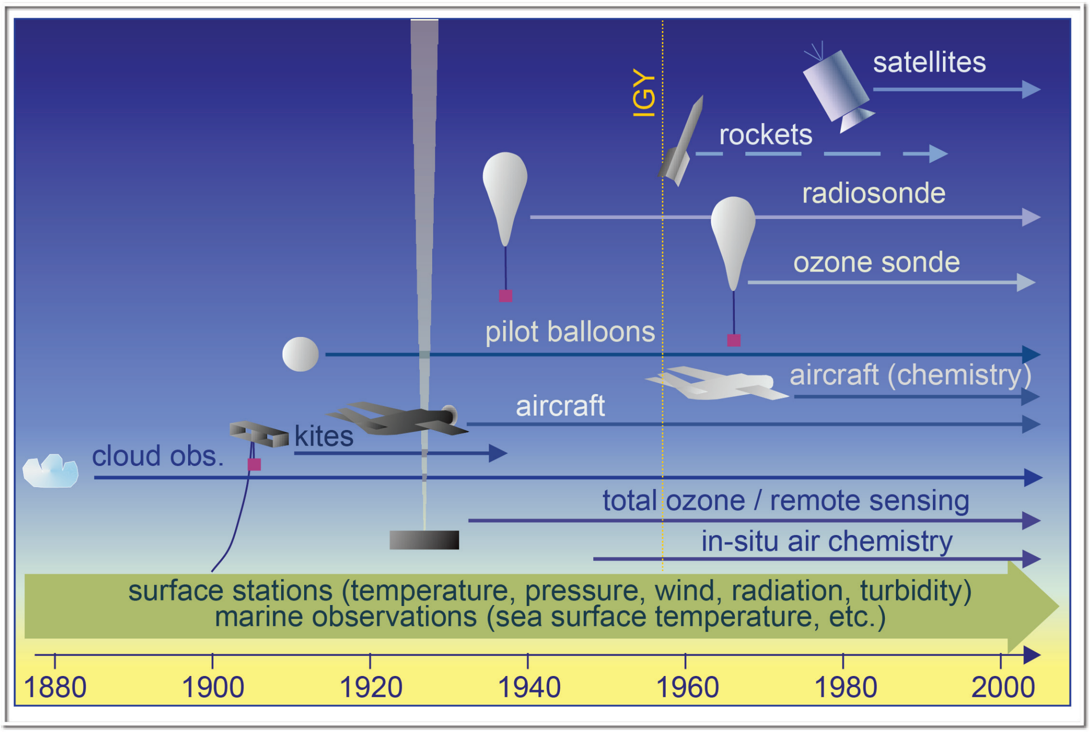


Figure 6: Development of Observing Capabilities

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

These diverse data 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 (Jones et al. 2012; Lawrimore et al. 2011; Rohde et al. 2012) and ocean (Kennedy et al. 2011; Smith and Reynolds 2002) as well as combined (Hansen et al. 2010; Morice 2012; Vose 2012). Each group takes a different approach, yet all agree that it is unequivocal that the planet is warming.

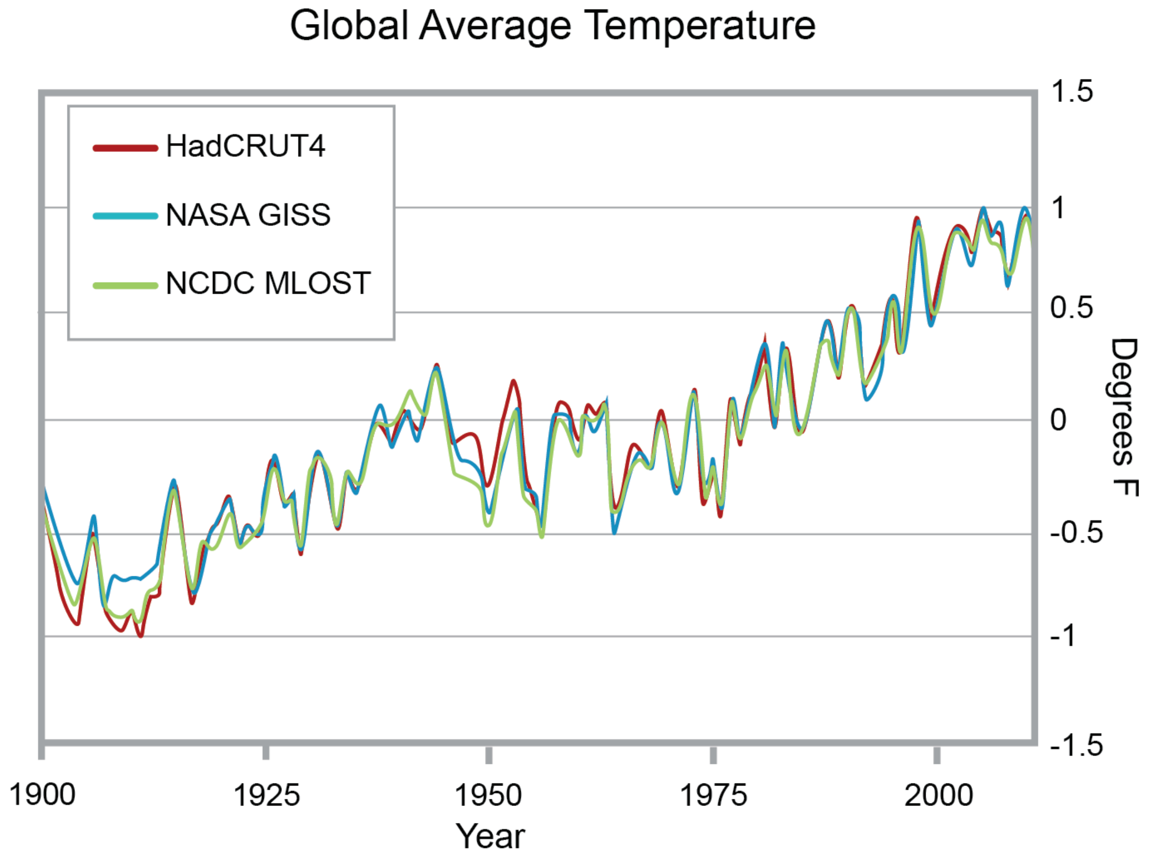


Figure 7: Global Average Temperature

Caption: Three different global surface temperature records all show increasing trends over the last century. The lines show annual average temperatures relative to the 1961-1990 average. Differences between the records, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. (Hansen et al. 2010; Morice 2012; Vose 2012)

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 and some parts of the U.S. Southeast, have even experienced cooling over the last century as a whole, though they have warmed over recent decades. Warming during the first half of the last century occurred mostly in the Northern Hemisphere. The last three decades have seen greater warming, particularly at high northern latitudes, and over land as compared to ocean.

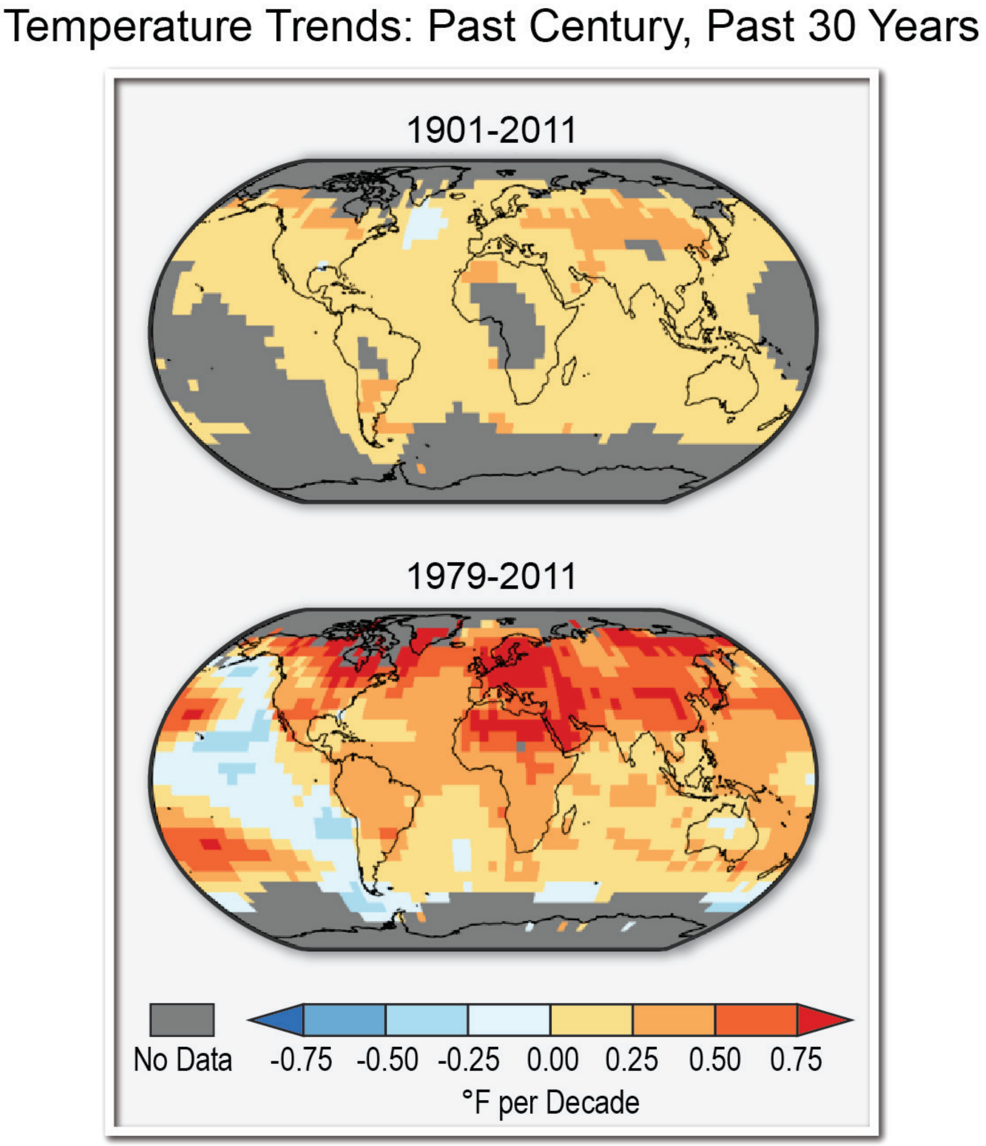


Figure 8: Temperature Trends: Past Century, Past 30 Years

Caption: Surface temperature trends for the period 1901-2011 (top) and 1979-2011 (bottom) from NCDC's surface temperature product (Vose 2012) .

Even if the surface temperature had never been measured, scientists could still conclude with high confidence that the global temperature has been rising because multiple lines of evidence all support this conclusion. Temperatures in the lower atmosphere and oceans have increased. Arctic sea ice, mountain glaciers, and Northern Hemisphere spring snow cover have all decreased. Sea level and near-surface humidity have increased. 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.

Ten Indicators of a Warming World

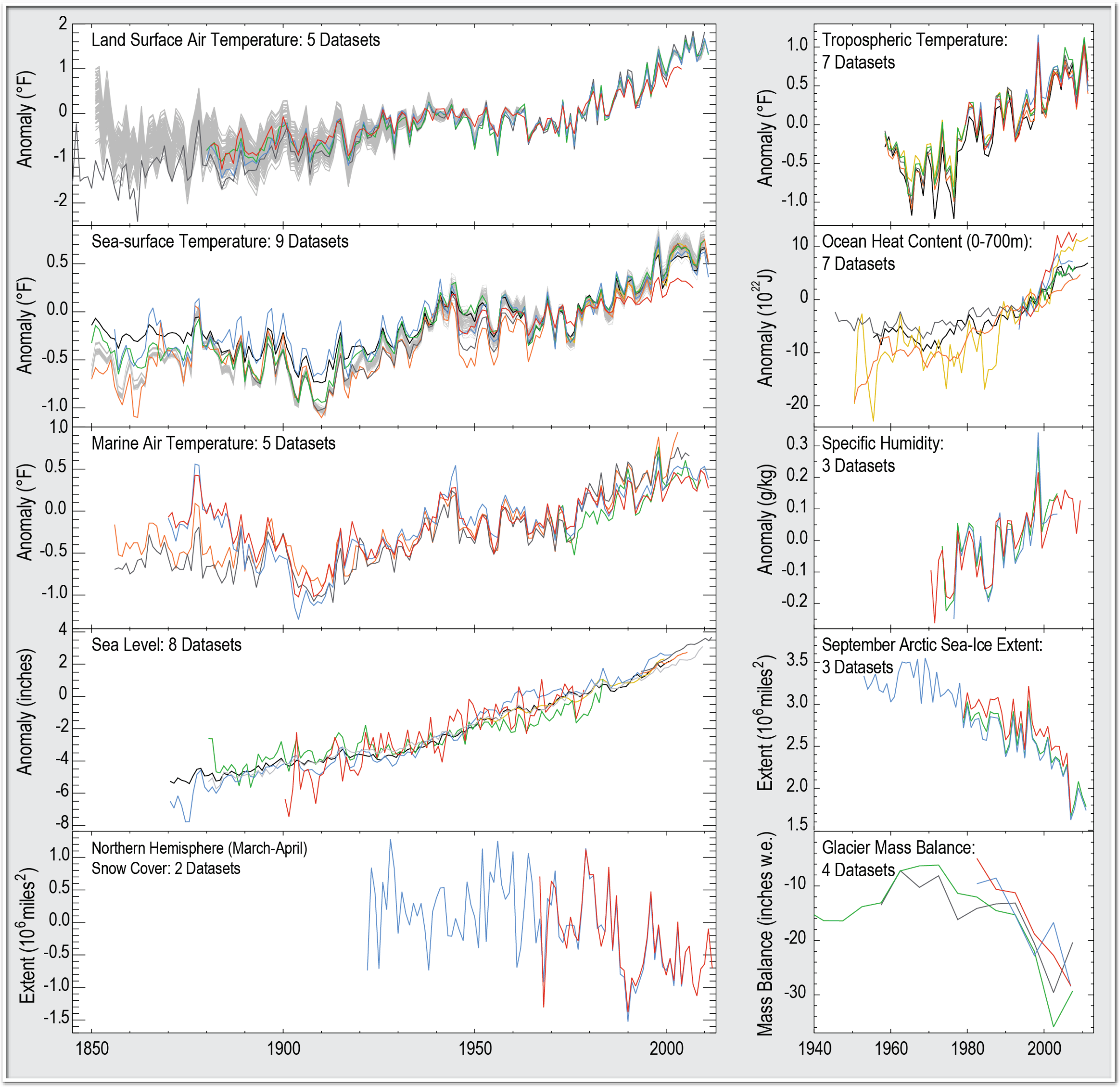


Figure 9: Ten Indicators of a Warming World

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 in the ways that would be expected in a warming world. Further details underpinning this diagram can be found at http://www.ncdc.noaa.gov/bams-state-of-the-climate/. Updated from (Kennedy et al. 2010).

Not all of the observed changes are directly related to temperature; some are related to the hydrological cycle. For example, there has been a slight increase in global average precipitation since 1900. However, there are strong geographic variations in this trend. 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 warming.

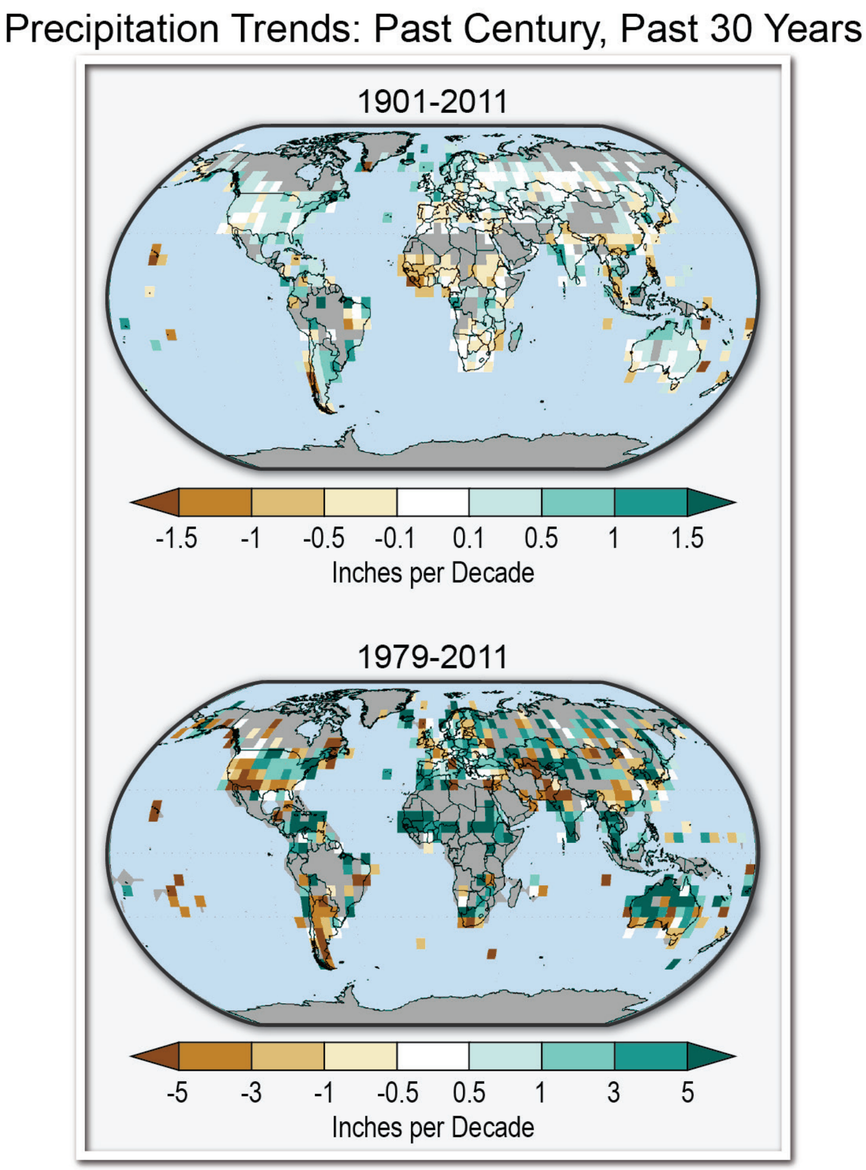


Figure 10: Precipitation Trends: Past Century, Past 30 Years

Caption: Global precipitation trends (inches per decade) for the period 1901-2011 (top) and 1979-2011 (bottom). (Figure source: NOAA NCDC)

Paleoclimate records based on climate proxies reveal that temperatures in the past have varied by about +/– 0.9°F over decadal time scales. Some periods in the past have been warmer, and others, cooler. However, the warming of the past 100 years is unusual relative to at least the past 2,000 years. Annual average global temperature during recent decades is at least as warm as the warmest interval of the past millennium globally, and continues to increase.

Key Message 3.

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

Today, average temperature, precipitation, and other aspects of climate are determined by a combination of human-induced changes and natural variations. 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, however, the human influence on climate can be either masked or augmented by natural variations over timescales of a decade or so. At regional and local scales, natural variations have an even larger effect.

Natural variations can drive increases or decreases in global and regional temperatures, as well as affect precipitation and drought patterns around the world. Over the long term (the past 10,000 to 30,000 years), however, the influence of internal natural variability on the Earth's climate system is negligible; in other words, over multiple decades the net effect of natural variability tends to sum to zero.

There are many modes of natural variability in the climate system. Most of them involve cyclical exchanges of heat and energy between the ocean and atmosphere and are manifested by recurring changes in sea surface temperatures, for example, or by surface pressure changes in the atmosphere. The largest and most well known of these 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 and 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. In the United States, 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 Pacific Northwest. El Niño conditions also tend to suppress Atlantic hurricane formation by increasing the amount of wind shear in the region where hurricanes form. The cool ENSO phase (usually called La Niña) is associated with dry conditions in the Central Plains, 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 variability such as ENSO can also affect global temperatures. In general, El Niño years tend to be warmer than average and La Niña, 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 nearly flat overall trend for the decade 1998-2007. Climate models can project the statistical behavior of these variations in temperature trends, but do not predict the exact timing of ENSO or other natural variations far into the future.

Natural modes of variability like ENSO are not necessarily stationary. For example, there appears to have been a shift in the pattern of ENSO in the mid-1970s, with the location of the warm water pool shifting from the eastern to the central Pacific. The frequency of natural variability can also change over time. Paleoclimate studies using tree rings show that ENSO activity over the last 100 years has been the highest in the last 500 years (Fowler et al. 2012) and both paleoclimate and modeling studies suggest that global temperature increases may interact with natural variability in ways that are difficult to predict.

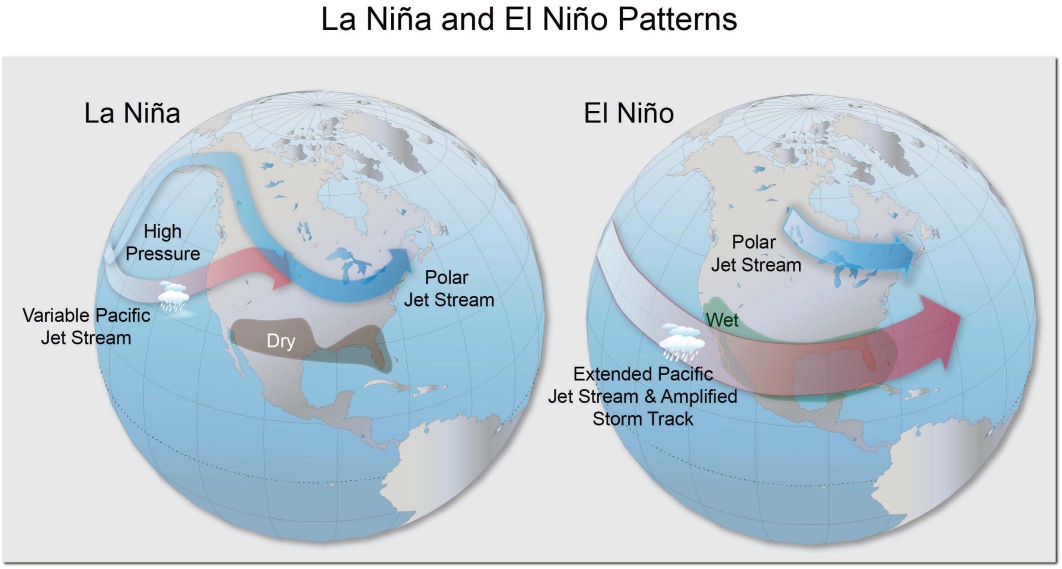


Figure 11: La Niña and El Niño Patterns

Caption: Typical January-March weather conditions and atmospheric circulation during El Niño events leads to unusually warm winter conditions in the northern U.S. and wetter than average conditions across the southern U.S. During La Niña, winters tend to be unusually cold through Alaska and western Canada, and dry throughout the southern (Figure source: NOAA)

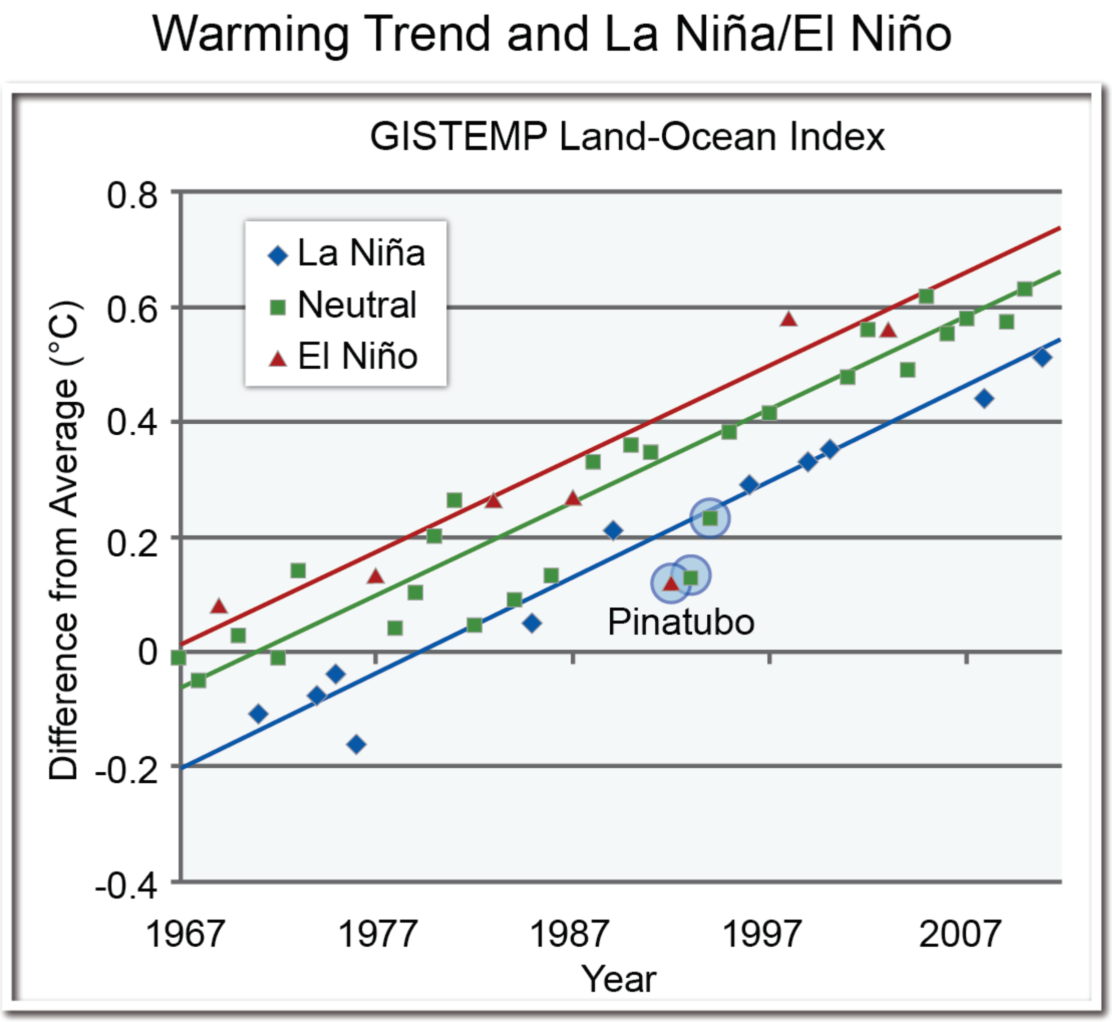


Figure 12: Warming Trend and El Niño/La Niña

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 ENSO event). When considering these sources of natural variability, all trends give 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 considered in the trends. Based on the NASA GISS temperature dataset (Morice 2012)

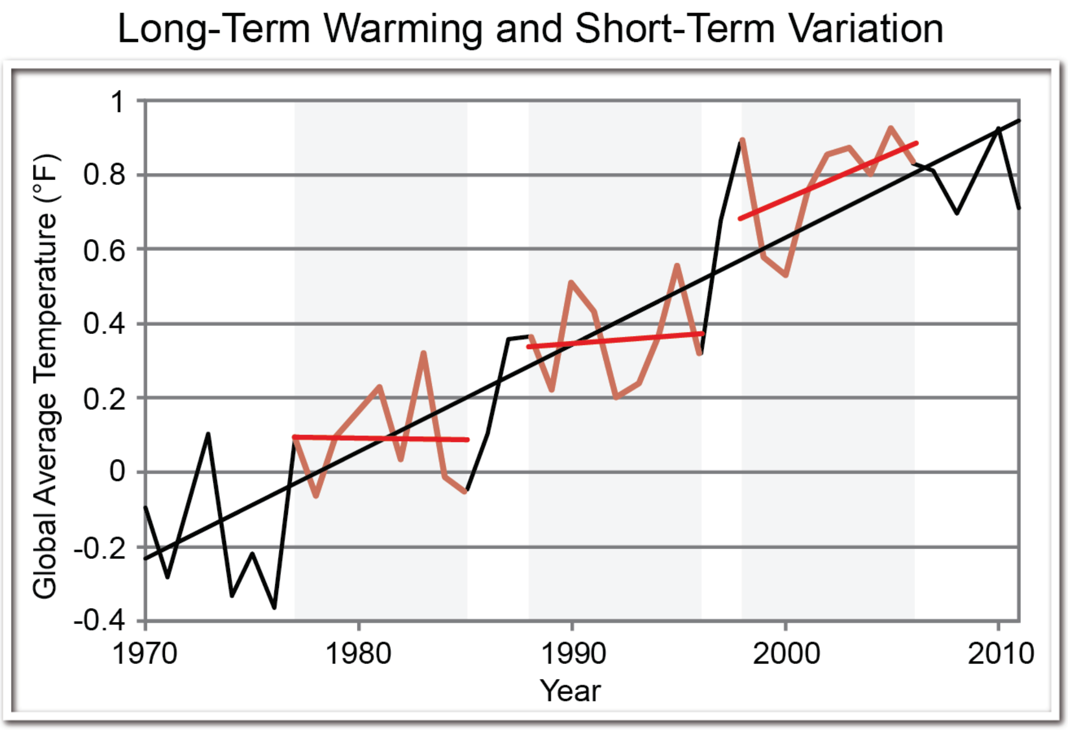


Figure 13: Long-Term Warming and Short-Term Variation

Caption: Observations of global mean surface air temperature show that although there can be short periods with little or even no significant upward trend (see for example the red trend lines in shaded areas for the periods 1977-1985, 1989-1996, and 1998-2006), global temperature continues to rise unabated over long-term climate timescales (black trend line). Source:

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 don't show much warming over that time period, though they have warmed in recent decades. Explanations include increased cloud cover and precipitation (Pan et al. 2004), increased small particles from coal burning, and natural factors related to forest re-growth (Portmann et al. 2009), decreased heat flux due to irrigation (Puma and Cook 2010), and multi-decade variability in North Atlantic and tropical Pacific sea surface temperatures (Kunkel et al. 2006; Meehl et al. 2012; Robinson et al. 2002).

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 (Meehl et al. 2012). 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. 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. Averaging (or compositing) of projections from different models smooths out the randomly occurring natural variations in the different models, leaving the signal of the externally forced changes.

Key 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, including 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 is responsible for the observed behavior.

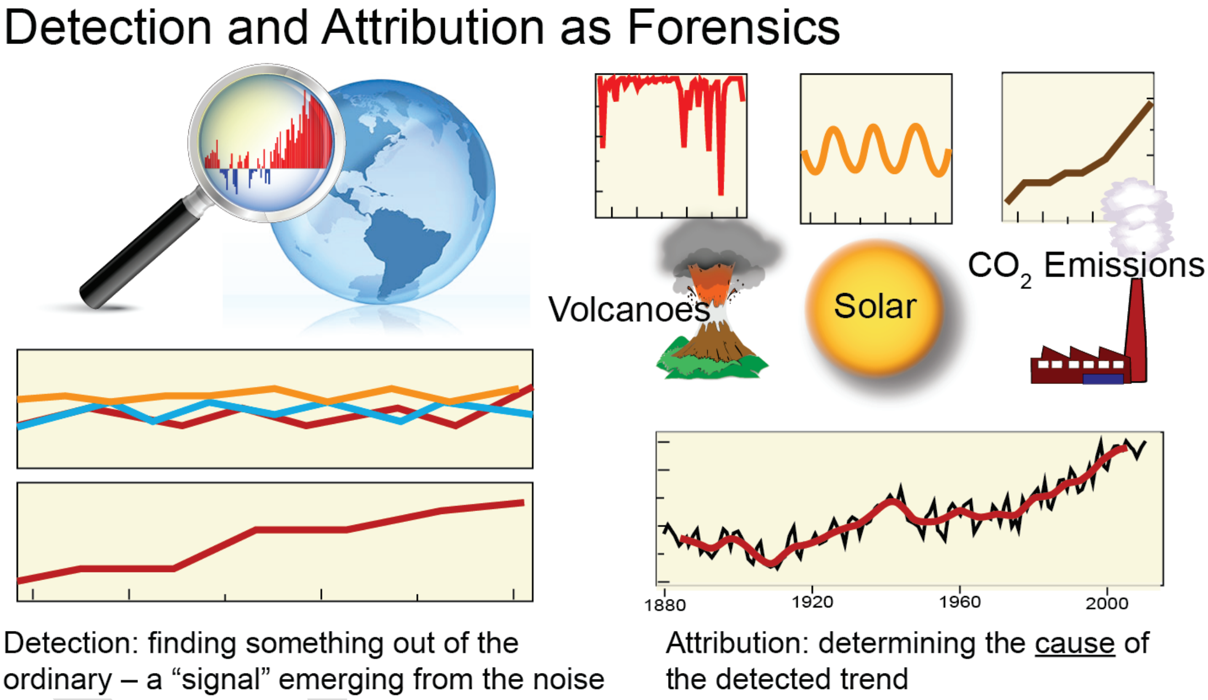


Figure 14: Detection and Attribution as Forensics

Caption: 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 particulates 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 behavior. 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 drivers (Stott et al. 2010). Most approaches consider changes in geographical patterns over time.

Climate simulations are used to test hypotheses regarding the causes of observed changes. First, simulations that include changes in both external natural and human drivers that may cause climate changes, such as increases in heat-trapping gases and changes in energy from the Sun, are used to characterize what effect those factors would have had. Then, simulations with no changes in external drivers, only changes in natural variability, are used to characterize what would be expected from normal internal variations in the climate.

Detection and attribution studies have been applied to a broad range of elements of the climate system and a number of specific extreme events that have occurred in recent years. Many published scientific studies have found that human influences are required to explain the observed changes in climate over the last half century. These changes include increases in surface temperatures (Jones and Stott 2011; Stott et al. 2010), changes in atmospheric vertical temperature profiles (Lott et al. 2012; Santer 2012), increases in ocean heat content (AchutaRao et al. 2007; AchutaRao et al. 2006), increasing atmospheric humidity (Santer et al. 2007; Willett et al. 2007), increases in intensity of precipitation (Min et al. 2011) and in runoff (Gedney et al. 2006), indirectly estimated through changes in ocean salinity (Durack et al. 2012), shifts in atmospheric circulation (Gillett and Stott 2009) and changes in a host of other indices (Stott et al. 2010). Taken together these paint a coherent picture of a planet whose climate is changing primarily as a result of human activities.

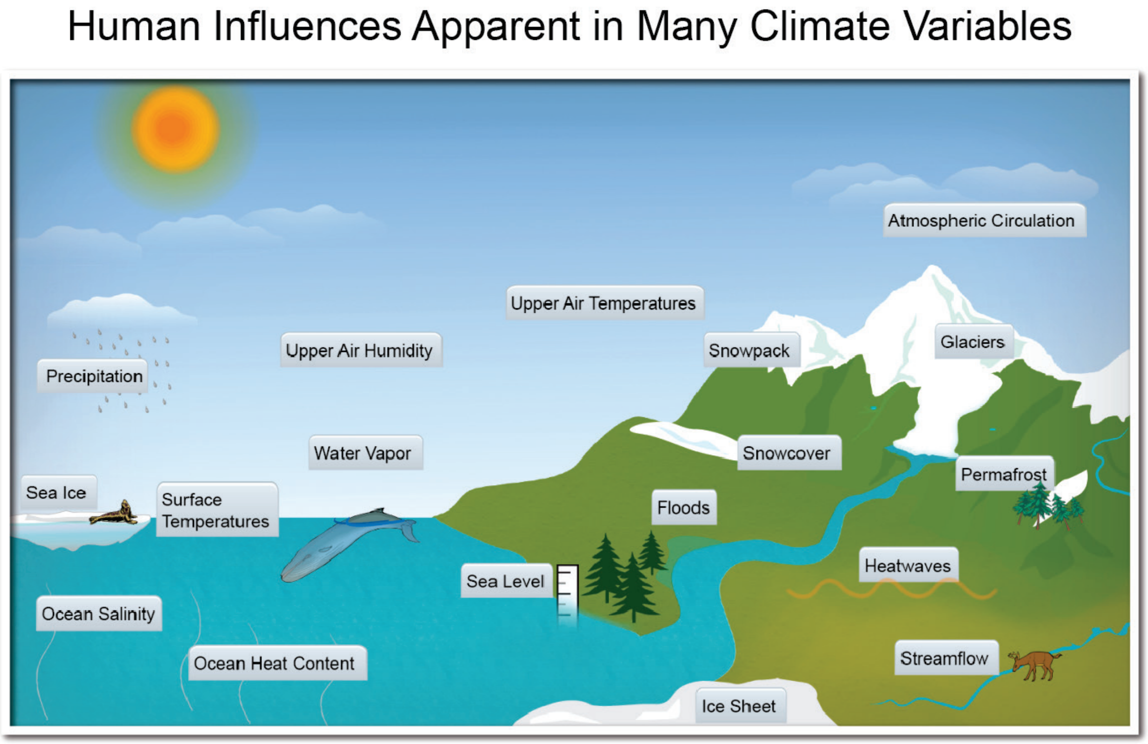


Figure 15: Human Influences Apparent in Many Climate Variables

Caption: Long-term trends and changes in extreme events are apparent for many aspects of the climate system. Scientific analyses can determine the extent to which these changes are attributable to human influences. (Figure source: NOAA NCDC)

Only Human Influence Can Explain Recent Warming

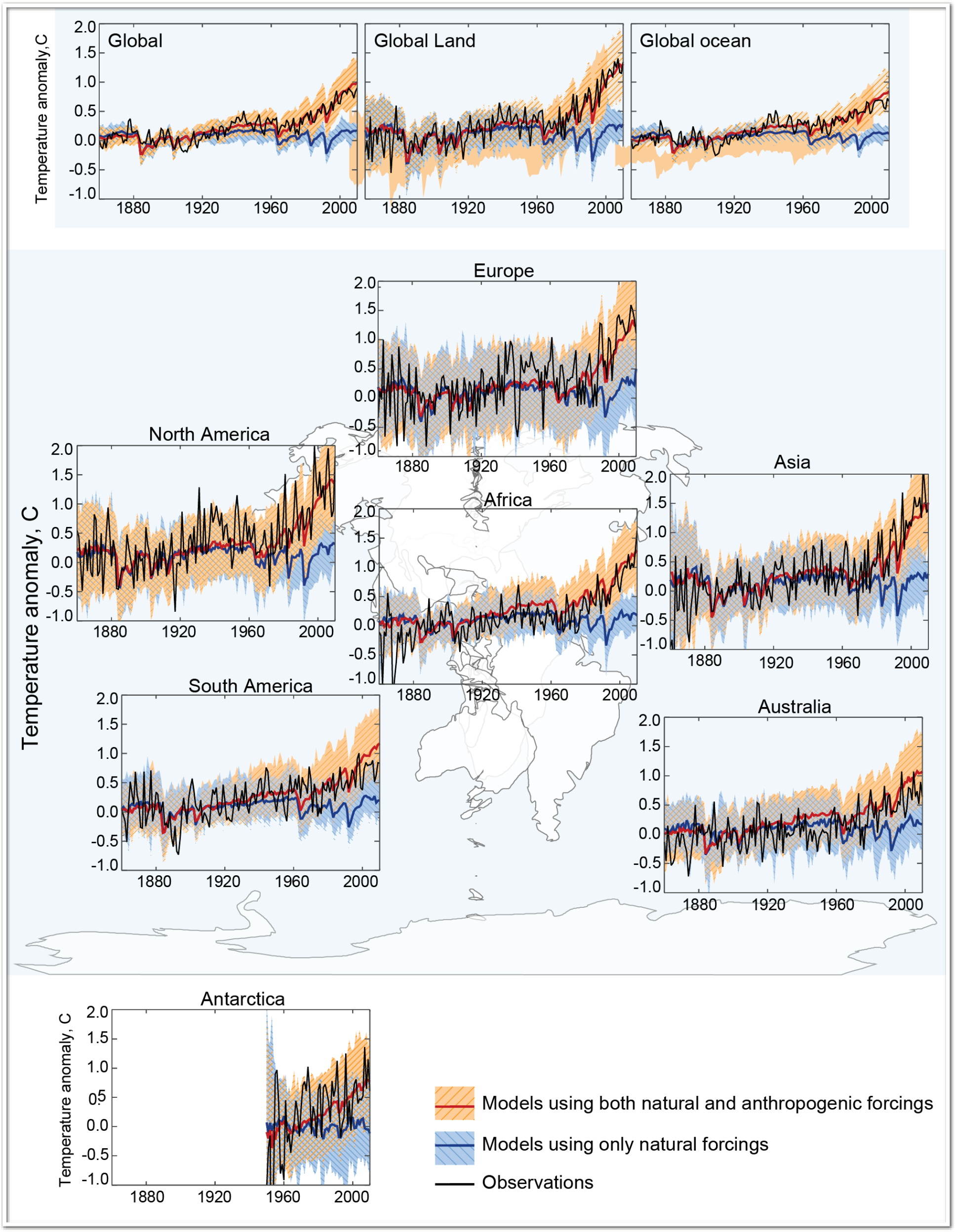


Figure 16: Only Human Influence Can Explain Recent Warming

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 observed changes in ten-year averages. The blue shading represents estimates from a broad range of climate simulations including solely natural (solar and volcanic) changes. The pink shading shows simulations including both the natural and human contributions. (Figure source: Jones et al. submitted)

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 (Allen 2011; Curry 2011; Trenberth 2011). 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 (Stott et al. 2011; Stott 2011) has been significantly altered by human influences on the climate system. Studies have concluded that there is a detectable human influence in recent heat waves in Europe (Christidis et al. 2012; Stott et al. 2004), Russia (Dole et al. 2011; Otto et al. 2012; Rahmstorf and Coumou 2011), and Texas (Hoerling et al. 2012 (submitted)) as well as flooding events in England and Wales (Pall et al. 2011), the timing and magnitude of snowmelt and resulting stream flow in some Western U.S. states (Barnett et al. 2008; Hidalgo et al. 2009; Pierce et al. 2008), and some specific events around the globe during 2011 (Peterson et al. 2012).

Key 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 over the past few centuries. Even if the net CO_2 emissions could be reduced to zero today, the human-induced perturbation to the global carbon cycle would persist for thousands of years (NRC 2011). Because global emissions of CO_2 and other heat-trapping gases continue to rise, exactly how much climate will change over this century and beyond depends primarily on two factors: 1) the amount of human activities and resulting emissions; and 2) how sensitive the climate is to those changes (the responsiveness of temperature to a change in radiative forcing).

Uncertainties in how the economy will evolve, where we'll be getting our energy from, or what our cities, our buildings, or our cars will look like, affect our ability to predict the future changes in climate. However, a series of plausible projections of what might happen, under a given set of assumptions, can and have been developed. These scenarios describe the future in terms of population, energy sources, technology, heat-trapping gas emissions, atmospheric levels of carbon dioxide, and/or global temperature change.

Some amount of future change is already inevitable due to past emissions of heat-trapping gases. The Earth's climate system, particularly the ocean, tends to lag the change in net incoming radiation by decades, and even centuries, in responding to changes in atmospheric composition. Even if all emissions of heat-trapping gases from human activity were suddenly stopped, a temperature increase of 0.5°F increase would occur (Matthews and Zickfeld 2012).

Over the next few decades, the greater part of the range 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. By the second half of the century, however, emissions scenario uncertainty (in other words, the net effect of human activities on the climate system) becomes increasingly dominant in determining the magnitude and patterns of future change, particularly for temperature-related aspects (Hawkins and Sutton 2009, 2011). Even though natural variability will still occur in the future, the majority of the difference between the future and present climates will be determined by choices that human society is making 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 even most regional temperatures and that these rising temperatures will increase with the magnitude of future emissions (see Figure 17 below and Figures 2.7 and 2.8 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; however, these are also projected to change as a result of the impacts of human activities on global 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 result 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) it would be relatively easy to calculate the change in global temperature that would result from a given increase in CO_2 levels. But a series of natural feedbacks within the Earth system act to amplify or diminish an initial change, adding uncertainty to the climate sensitivity. Some important feedbacks include:

- Clouds – Will warming increase or decrease cloudiness? Will the changes be to clouds that primarily reflect the Sun's energy, or clouds that trap even more heat within the Earth system?
- Albedo – 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?
- Carbon dioxide uptake 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?

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 as well as studies that look at climate changes in the distant past, can't 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 predicted from the greenhouse effect alone.

From a large number of independent datasets and analyses, it appears that the best estimate of climate sensitivity is about 5.4ºF (3ºC), with a likely range from 3.5ºF to 8ºF (for a doubling of the CO_2 concentration from preindustrial levels). This sensitivity 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 surface ocean temperature, and changes in cloud characteristics. The entire response of the climate system will not be 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 atmospheric CO_2 levels diverge.

As discussed previously in Key Message 3, interactions among various components of the Earth's system produce patterns of natural variability that can be chaotic, meaning that they are sensitive to the initial conditions of the climate system. These patterns can affect global and regional climate on time scales ranging from years to a decade or more. 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. In this report, all future projections are averaged over 20- to 30-year time periods.

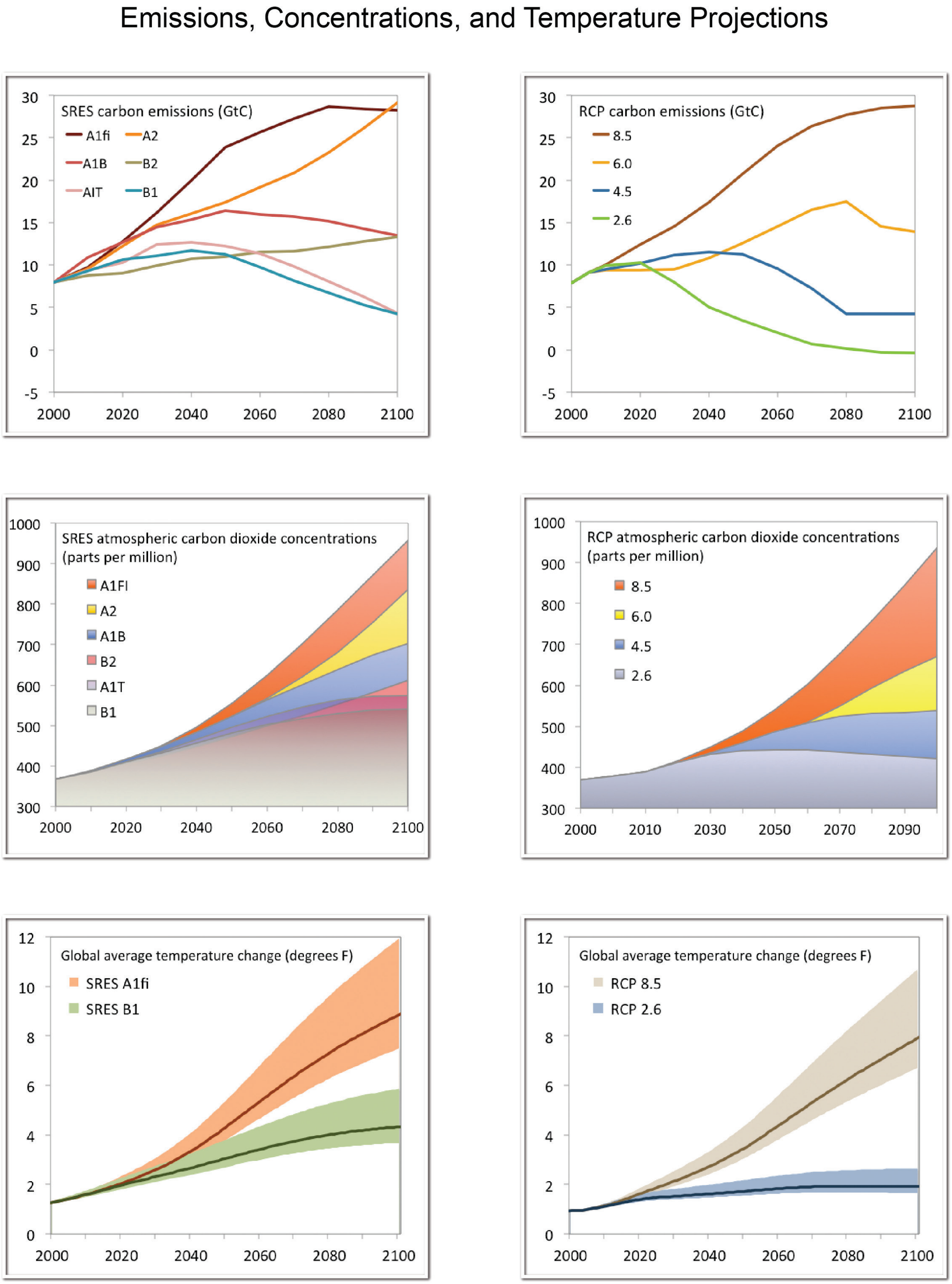


Figure 17: Emissions, Concentrations, and Temperature Projections

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). This figure compares SRES and RCP (top) annual carbon emissions (GtC), (middle) carbon dioxide equivalent levels in the atmosphere (ppm), and (bottom) resulting temperature change that would result from the best-guess (lines) and the likely range (shaded areas) of climate sensitivity (ºF). At the top end of the range, the older SRES scenarios are slightly higher. At the bottom end of the range, the RCP scenarios are much lower. This divergence is because RCP scenarios include the option of using policies to reduce carbon dioxide emissions, while SRES scenarios do not. (Data from CMIP3 and CMIP5)

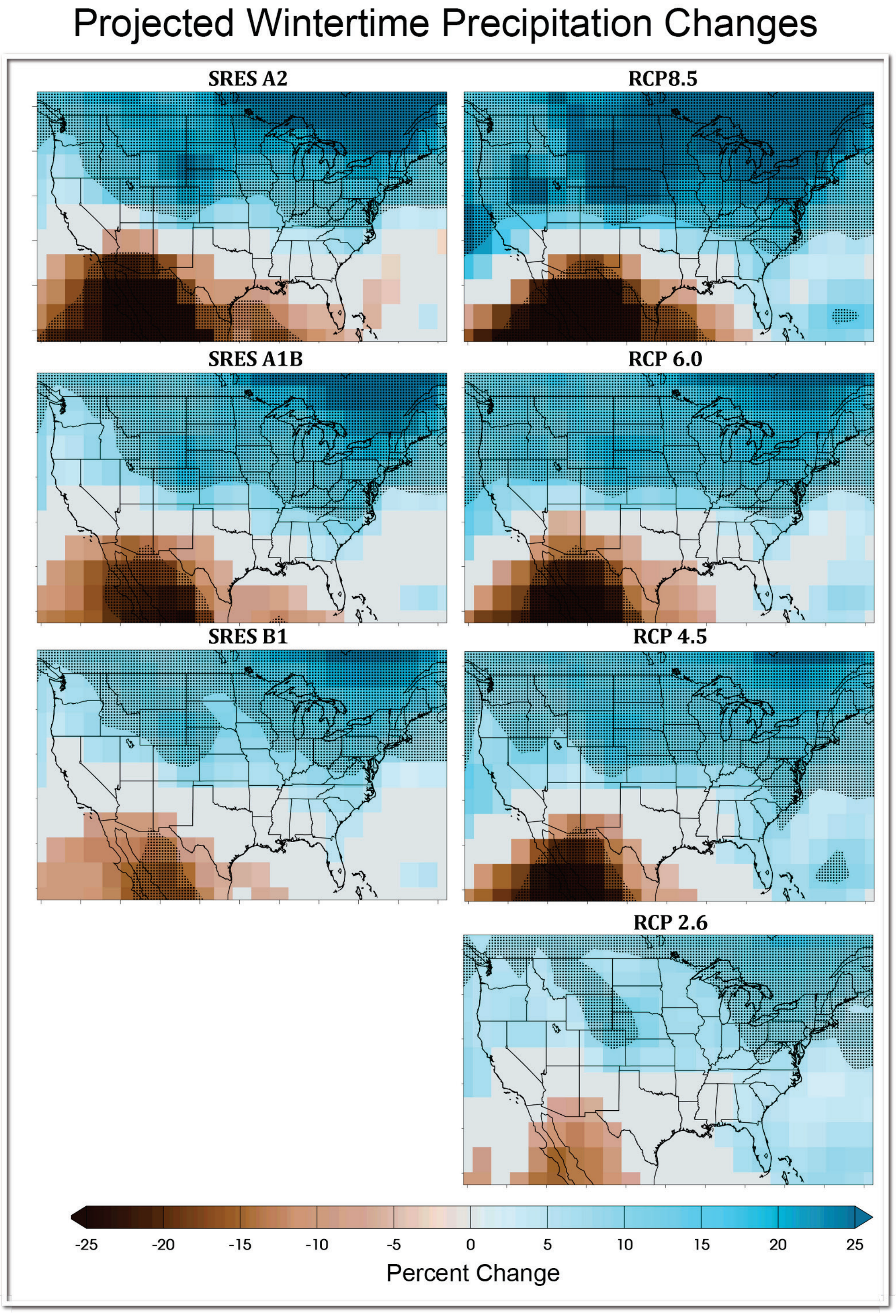


Figure 18: Projected Wintertime Precipitation Changes

Caption: Projected changes in wintertime precipitation at the end of this century (2071-2099) relative to the average for 1901-1960. 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. Teal indicates precipitation increases, and brown, decreases. Stippled areas indicate confidence that the projected changes are large and are consistently wetter or drier. Gray areas indicate confidence that the changes are small. 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 projection increase as the projected temperature increases. 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. Units: Percent. (Figure source: Michael Wehner, LBNL. Data from CMIP3 and CMIP5.).

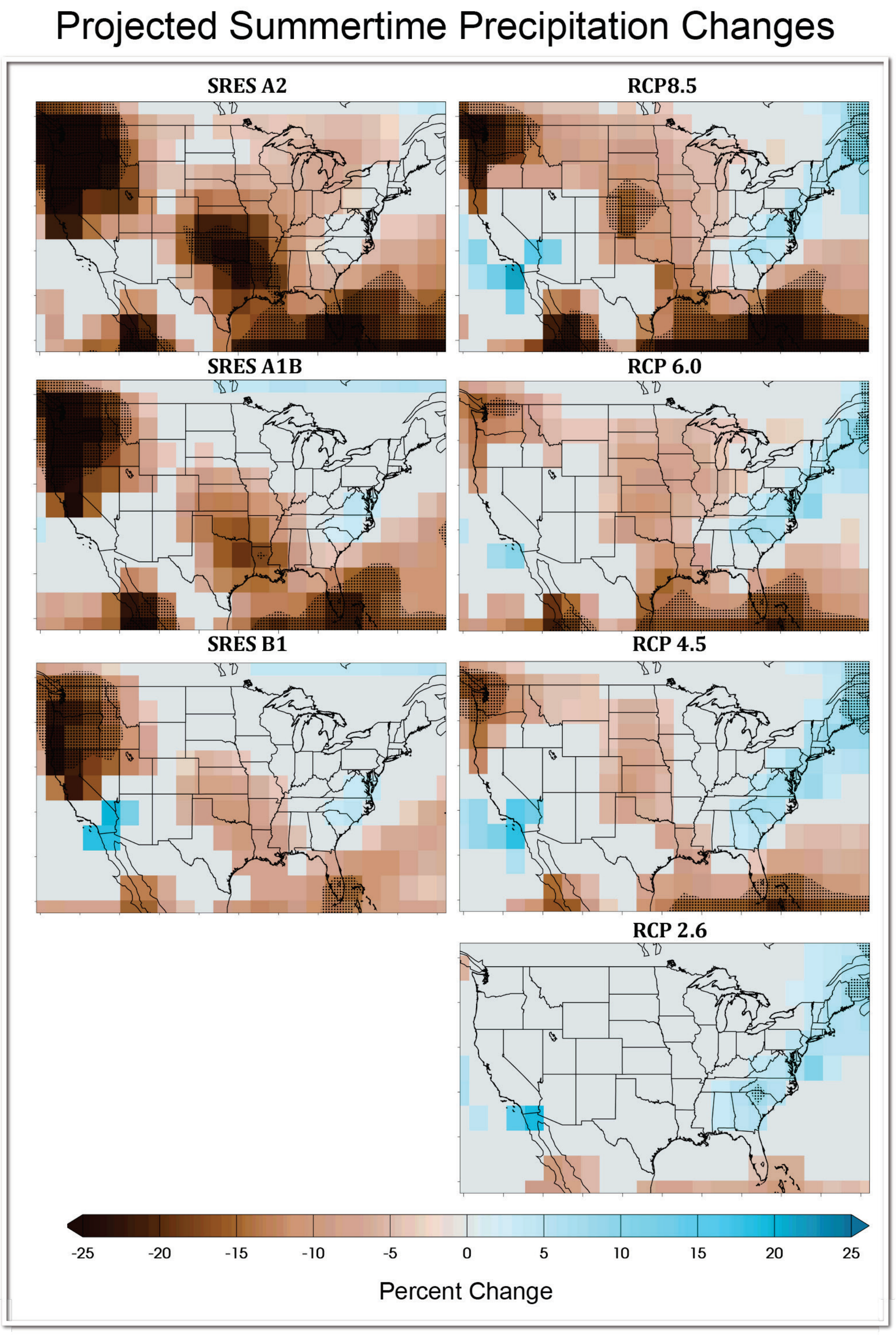


Figure 19: Projected Summertime Precipitation Changes

Caption: Projected changes in summertime precipitation at the end of this century (2071-2099) relative to the average for 1901-1960. 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. Teal indicates precipitation increases, and brown, decreases. Stippled areas indicate confidence that the projected changes are large and are consistently wetter or drier. Gray areas indicate confidence that the changes are small. 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: Michael Wehner, LBNL. Data from CMIP3 and CMIP5.)

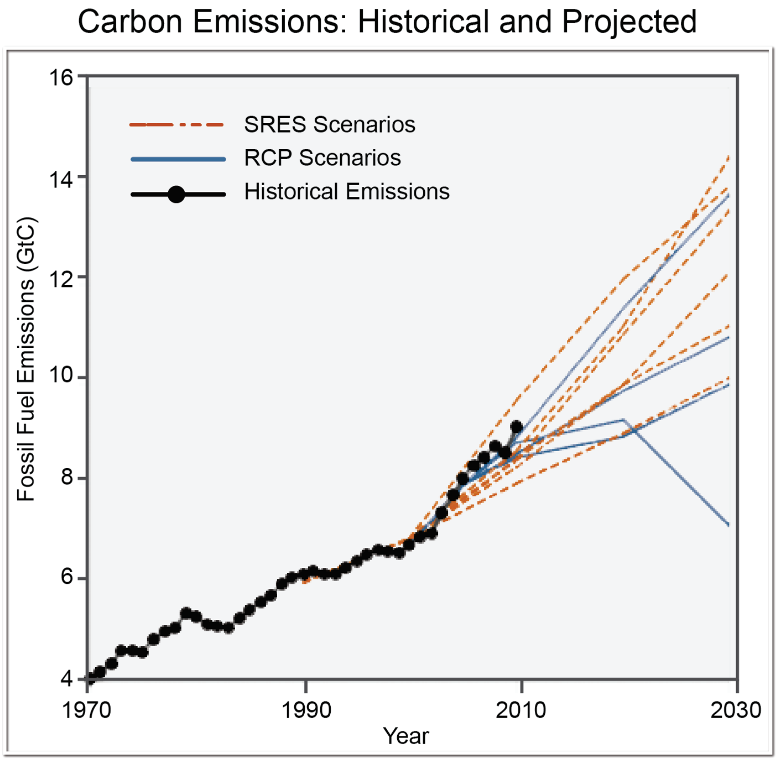


Figure 20: Carbon Emissions: Historical and Projected

Caption: Historical emissions of carbon from fossil fuel combustion and land-use change, including the combustion of coal, gas and oil and 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 fossil fuel consumption from 1970 to 2030. Source:

Key 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 many models, many clear trends emerge.

Climate scientists cannot create laboratory conditions that represent all the complexity of the earth system for performing experiments. Instead,, they 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.

Computational tools include models that simulate different parts of the climate system. The most sophisticated computational tools used by climate scientists are **general circulation models** (also referred to as "global climate models"), or GCMs. GCMs are mathematical models that simulate the physics, chemistry and, increasingly, the biology that influence the climate system. These are physical models, which are not based on statistical correlations, such as an observed relationship between global temperature and carbon dioxide. Rather, global climate models are built on the immutable equations of physics. These fundamental equations include the conservation of energy, mass, and momentum and how these properties are exchanged between different parts of the climate system.

Using these fundamental relationships, GCMs are able to simulate many important features of the Earth's climate system: the Jet Stream that circles the globe 30,000 feet up in the atmosphere; 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. These processes are simulated directly from the laws of physics and do not require any assumptions derived from fitting to observations or other data.

GCMs and other physical models are subject to two main types of uncertainty. First, because full 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 known, or because it is known but is not yet understood well enough to be modeled accurately. For example, GCMs 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 quite well enough understood yet to simulate accurately at the global scale. Observations of climate change in the distant past suggest there might be "tipping points" or mechanisms of abrupt changes in climate change that are not adequately understood.

Second, many processes occur in time and space at scales finer 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 science. These include small-scale physical processes such as cloud formation and precipitation, chemical reactions, and exchanges between the biosphere and atmosphere. For example, GCMs cannot model every single 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 GCM divided up the world into grid cells measuring more than 300 miles per side. Today, most GCMs 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.

Another way GCMs have improved is by incorporating 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 and 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 GCMs are what are known as earth system models, or ESMs. ESMs 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 (Randall 2007). However, all future simulations agree that both global and regional temperatures will increase over the coming century in response to increasing emissions of heat-trapping gases from human activities (IPCC 2007).

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 U.S. 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 up to 30 miles per grid cell. They are also subject to the same types of uncertainty as a global model: that of not including or correctly representing a physical process, as well as that of simulating processes that occur at smaller scales than the model can resolve. Regional climate models have additional uncertainty from how their boundaries are specified (frequency of updates 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 GCMs is available from the North American Regional Climate Change Program. These simulations are useful for examining certain impacts of global change 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 Key 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 based on a 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 biases, particularly in precipitation extremes, with larger amounts of climate change (Vrac et al. 2007). 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. Hence, 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 GCMs 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 approach (which consists of subtracting historical simulated values from future values, and adding the resulting "delta" to historical observations, as used in (NAST 2000) to complex clustering and neural network techniques that rival dynamical downscaling in their demand for computational resources and high-frequency GCM output (e.g., Kostopoulou and Jones 2007; Vrac et al. 2007). The delta approach is adequate for studies that are only interested in changes in seasonal or annual mean values. More complex methods must be used for studies that require information on how climate change may affect the frequency or timing of extreme events.

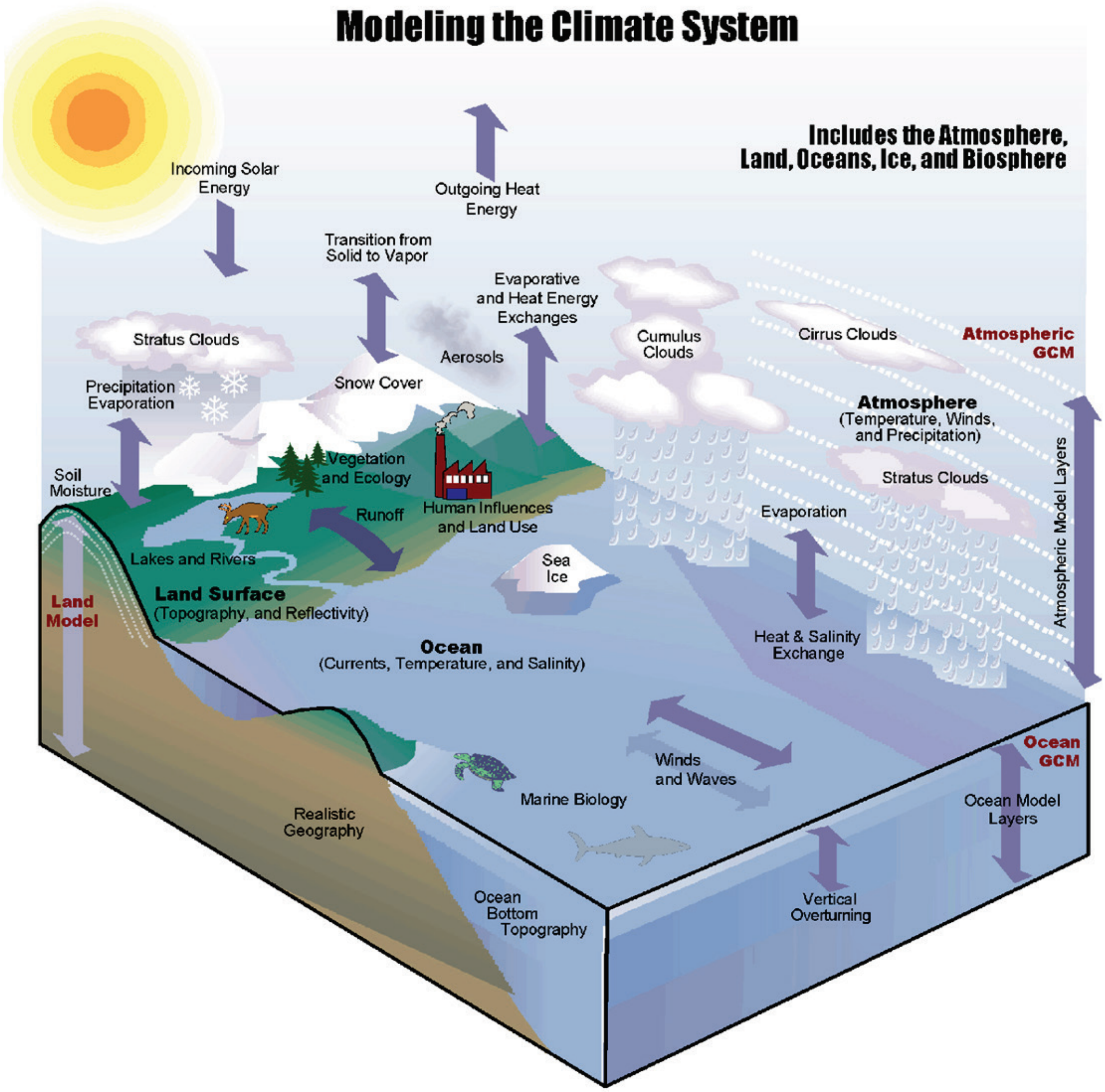


Figure 21: Modeling the Climate System

Caption: Some of the many processes that are often included in models of the Earth's climate system. (Figure source: UCAR)

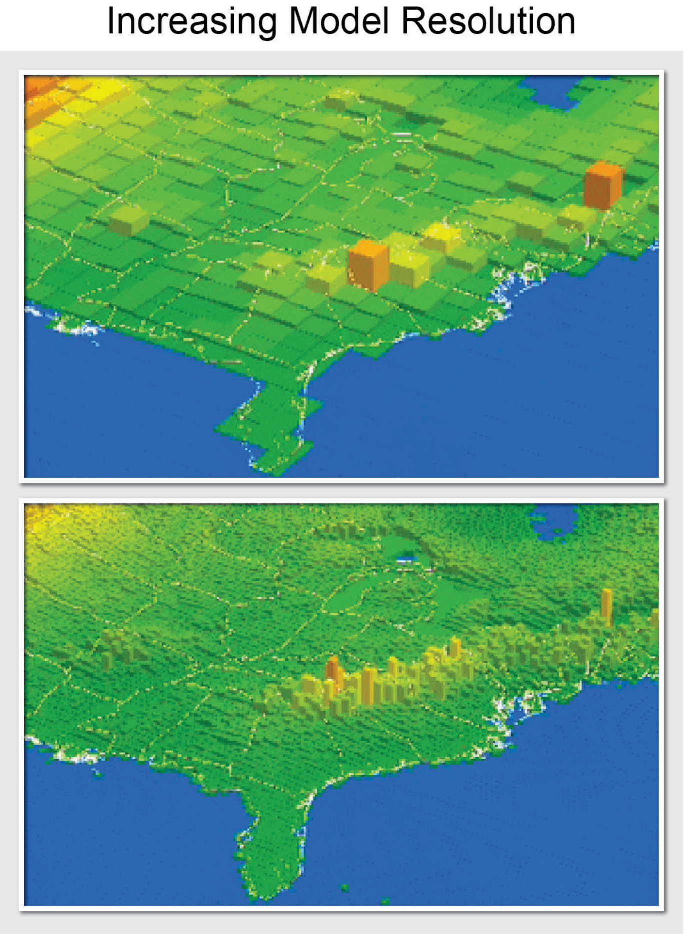


Figure 22: Increasing Model Resolution

Caption: Top) Illustration of the Eastern North American topography in a resolution of 110 km x 110 km. Bottom) Illustration of the Eastern North American topography in a resolution of 30 km x 30 km. Source:

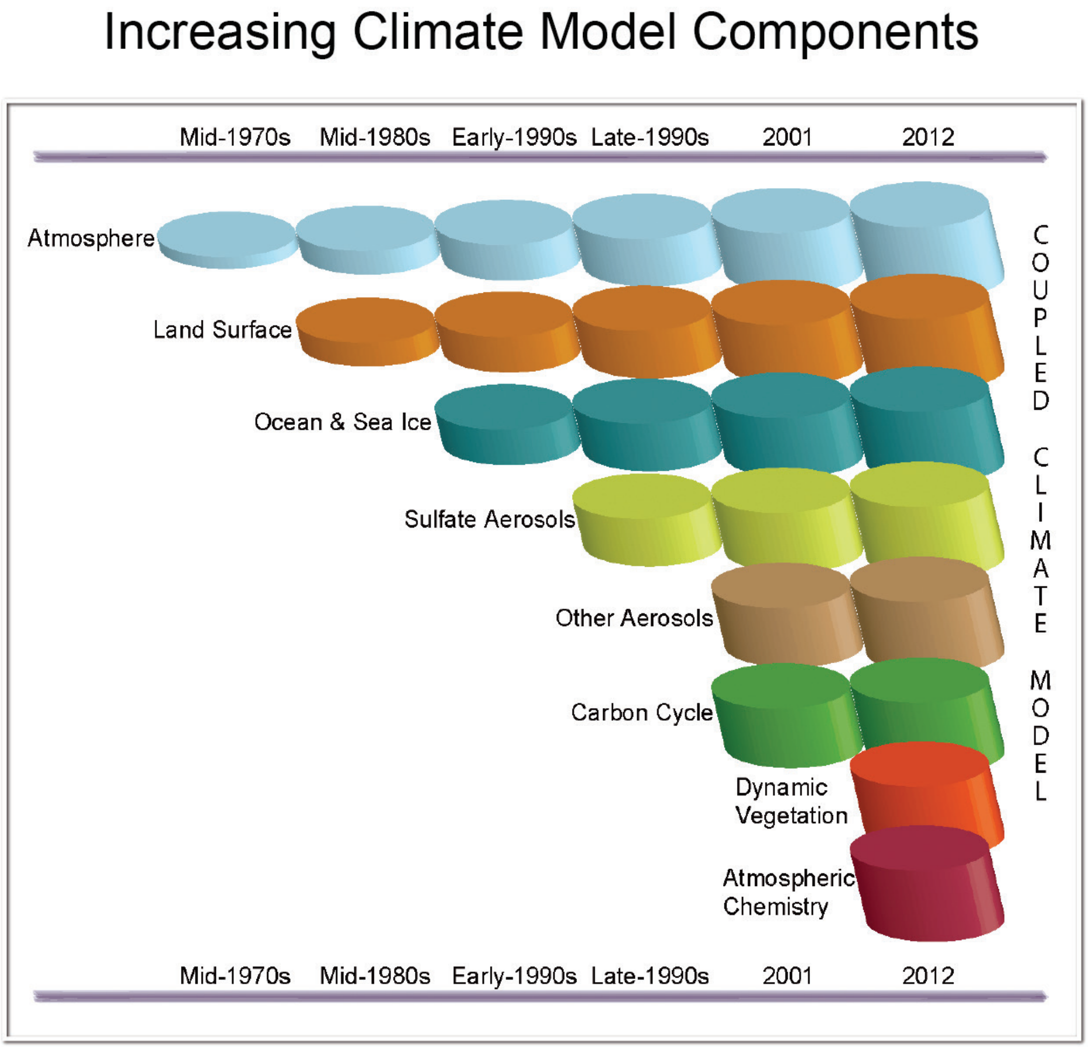


Figure 23: Increasing Climate Model Components

Caption: The development of climate models over the last 35 years showing how the different components are coupled into comprehensive climate models. Note that in the same time frame, the horizontal and vertical resolution has increased considerably and that ensembles with at least three independent experiments can now be considered as standard. (Source: IPCC)

Key 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. This warming is expected to continue.

Since the previous National Climate Assessment, there have been substantial advances in our understanding of the continental U.S. temperature records. Numerous studies have looked at many different aspects of the record (Fall et al. 2011; Hausfather et al. 2012 (submitted); Menne and Williams Jr 2009; Menne et al. 2009; Vose et al. 2012; Williams et al. 2012). These studies have increased confidence that the United States 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 (Karl et al. 1986; Williams et al. 2012). 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 (Quayle et al. 1991). Confounding this, as noted by a recent citizen science-effort, Surfacestations.org, the new instruments were often placed nearer buildings or other man-made structures. 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 (Fall et al. 2011; Menne et al. 2009; Williams et al. 2012).

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 (Diamond et al. submitted; Menne et al. 2009);
- Analyses to evaluate biases and uncertainties (Williams et al. 2012);
- Comparisons to a range of state-of-the-art meteorological data analyses (Vose et al. 2012); and
- In-depth analyses of the potential impacts of urbanization (Hausfather et al. 2012 (submitted))

These assessments indicate that the corrected data do not overestimate the rate of warming.

Because the average effect of these issues was to reduce recorded temperatures, adjusting for these issues tends to increase long-term warming trends. The impact is much larger for maximum temperature because the adjustments account for two distinct artificial cooling signals (that is, the change in observation time and 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 (McNider et al. 2012). In general, the uncorrected data exhibit more extreme trends as well as larger spatial variability; in other words, the adjustments have a smoothing effect.

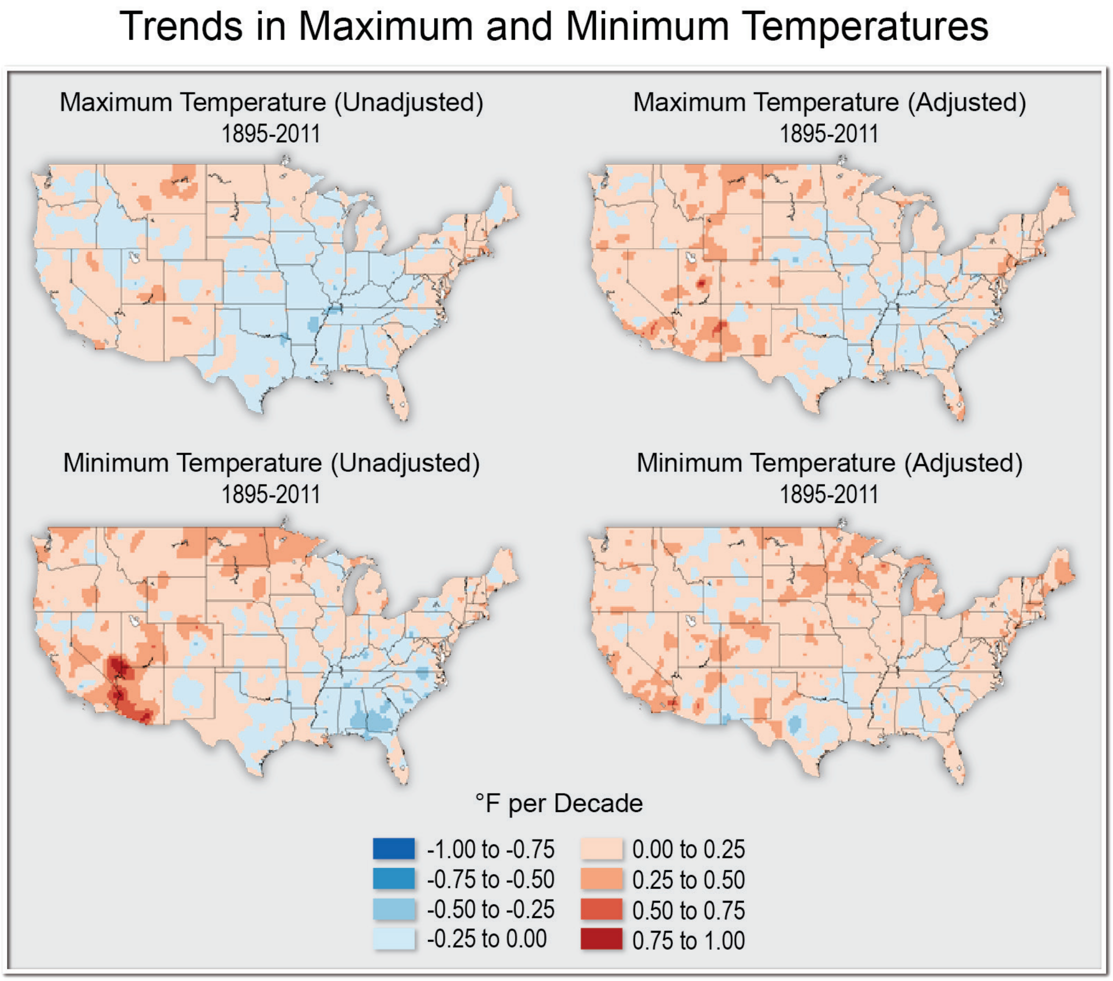


Figure 24: Trends in Maximum and Minimum Temperatures

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

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.

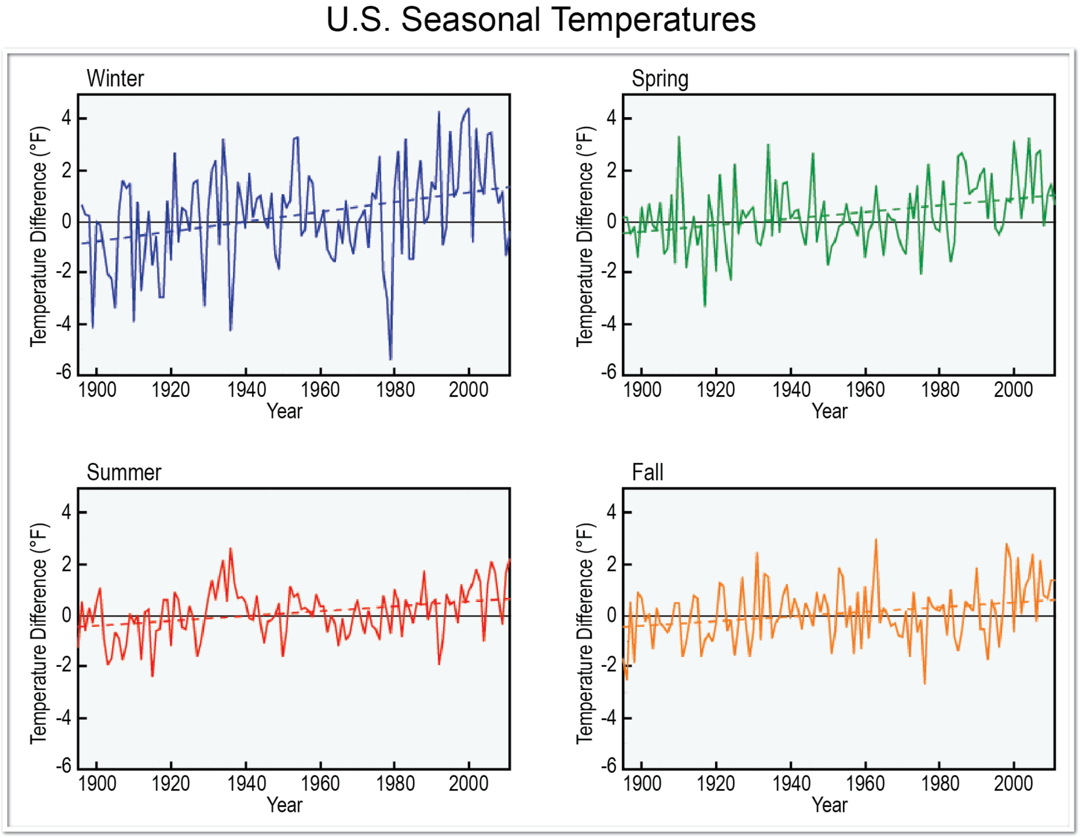


Figure 25: U.S. Seasonal Temperatures

Caption: Continental U.S. seasonal temperatures (relative to the 1901-1960 average, in °F) for winter (blue), spring (green), summer (red), and fall (orange) 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:Kunkel et al. 2012c)

Key Message 8.

Many other indicators of rising temperatures have been observed in the U.S. 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 (see Key Message 10 in Chapter 2). The annual average ice cover area for the Great Lakes has shown large year-to-year variability but has sharply declined over the last 30+ years (Wang et al. 2010). 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, including the 3 lowest ice extent winters of 1997-1998, 2001-2002, and 2005-2006. A reduction in ice leading to more open waters in winter raises concerns about possible increases in lake effect snowfall. However, future trends will depend on the air-water temperature differential.

Smaller lakes in other parts of the country show similar changes, which affect recreational and commercial activities of the surrounding communities. For example, the total duration of ice cover on Lake Mendota in Madison, WI has decreased from about 120 days in the late 1800s to less than 100 days in most years since 1990 (Magnuson 2010). Average dates of spring ice disappearance on Minnesota lakes show a trend toward earlier melting over the past 60 years or so.

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 (NOAA 2012). The summer drought of 2012 left Lakes Michigan and Ontario approximately one foot below their long-term averages. As noted in the previous National Climate Assessment (Karl et al. 2009), projected water level reductions 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 (Hayhoe et al. 2010). However, more recent studies have indicated that earlier approaches to computing evapotranspiration estimates from temperature may have overestimated evaporation losses (Lofgren et al. 2011). Moreover, accounting for land-atmosphere feedbacks further reduces the estimates of lake level declines (MacKay and Seglenieks 2012). The most recent estimates incorporating such feedbacks indicate water level decreases for the 2021-2050 period of approximately 1 inch for Lake Superior, 2 inches for Lake Michigan/Huron and 2.4 inches for Lake Erie (MacKay and Seglenieks 2012). However, the same study indicates increasing seasonal ranges of 2.7 inches for Lake Superior and 1.6 inches for Lakes Michigan/Huron and Erie. Projections of Great Lakes water levels represent evolving research and are still subject to considerable uncertainty.

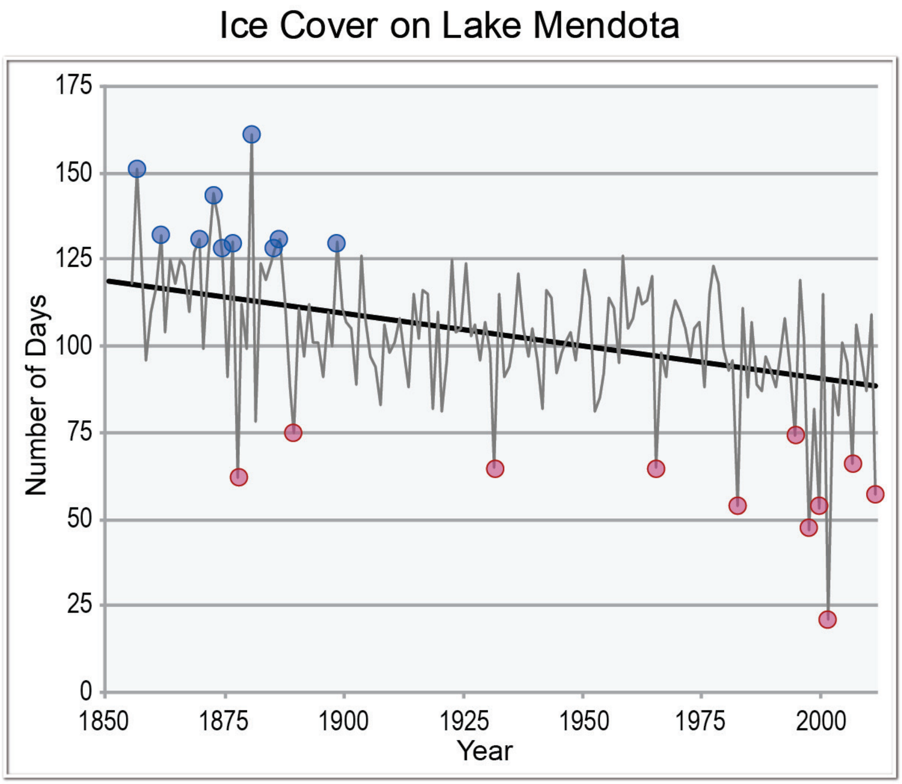


Figure 26: Ice Cover on Lake Mendota

Caption: The duration, or number of days, of ice cover on Lake Mendota, Wisconsin has decreased over time. The 10 longest and 11 shortest ice seasons are marked by blue and red circles, respectively. Seven of the 10 shortest ice cover seasons have occurred since 1980. Data from the Wisconsin State Climatology Office: Madison Lakes Ice Summary.

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 (http://www.erh.noaa.gov/btv/climo/lakeclose.shtml) shows that the lake now freezes approximately two weeks later than in the early 1800s and over a week later than 100 years ago. 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 three times in the 1800s and another four times between 1900 and 1950. It remained ice-free during 42% of the winters between 1951 and 1990. Since 1991, Lake Champlain has remained ice-free during 64% of the winters. One- to two-week advances of ice breakup dates and similar delays of freeze-up dates are also typical of lakes and rivers in Canada, Scandinavia, and northern Asia (IPCC 2007).

In the U.S. Southwest, there have been many indications of a changing climate over the last five decades: mountain snowpack decreased (as it did over western North America as a whole) (Mote et al. 2005), the dates of snowmelt runoff in California and across the West shifted to earlier in the year (Dettinger and Cayan 1995; Stewart et al. 2005), spring in the U. S. West began earlier (as indicated by shifts in the timing of plant blooms and spring snowmelt-runoff pulses) (Cayan et al. 2001), general shifts in western hydroclimatic seasons (Regonda et al. 2005), and trends toward more precipitation falling as rain instead of snow over the West (Knowles et al. 2006). 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 (Barnett et al. 2008).

Streamflow from Snowmelt Shifts to Earlier in Year

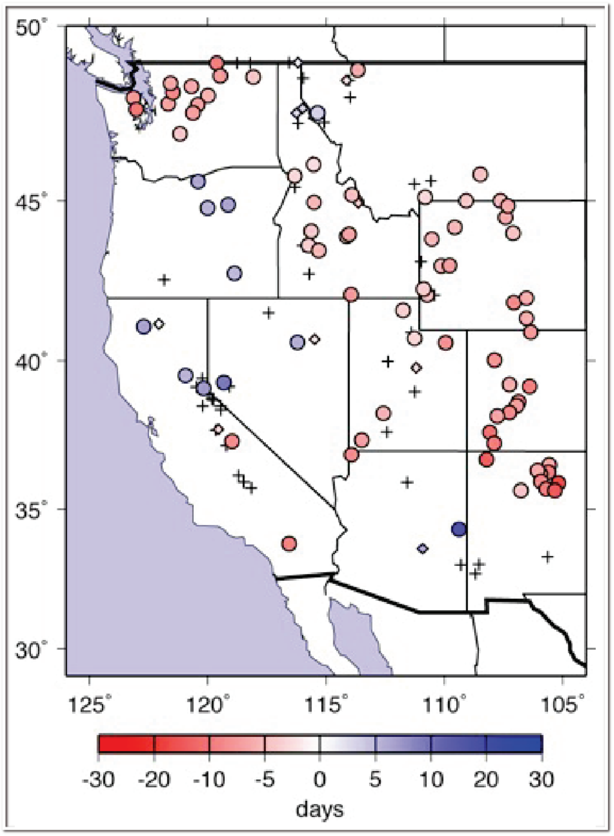


Figure 27: Streamflow from Snowmelt Shifts to Earlier in Year

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. 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, are indicated by red dots; locations where the annual flow is now arriving later are indicated by blue dots. 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).

Changing temperatures affect vegetation through the frost-free season length, the growing season length, and plant tolerance thresholds. 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 (Kunkel et al. 2004). 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 (National Audubon Society 2009) and a shift since the 1980s toward earlier first leaf dates for lilac and honeysuckle (EPA 2010)

Plant hardiness zones are determined primarily by the extremes of winter cold (Daly et al. 2010). While maps of plant hardiness have guided the selection of plants for both ornamental and agricultural purposes, these zones are subject to change as climate changes. Plant hardiness zones for the U.S. have recently been updated using the new climate normals (1981-2000), 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.

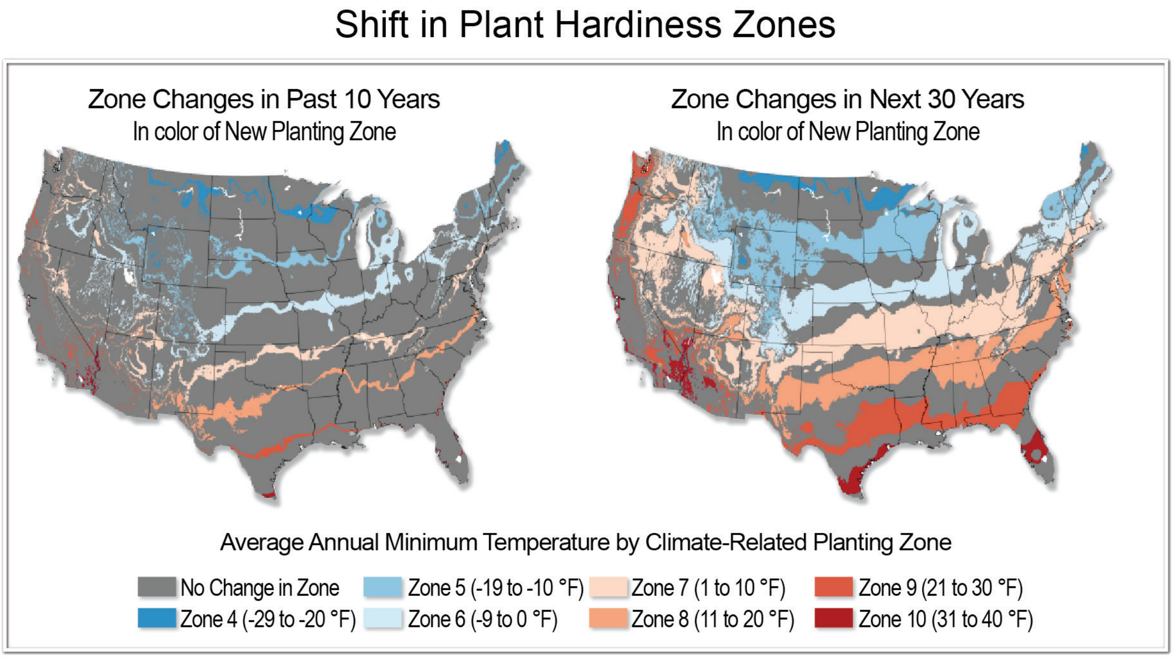


Figure 28: Shifts in Plant Hardiness Zones

Caption: The map on the left above 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 (map on right). (Figure source: NOAA)

Key Message 9.

There have been observed trends in some types of extreme weather events, and these are 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 across the U.S. Regional and global models project continued widespread increases in extreme precipitation over the continental U.S. and Alaska, consistent with these observed changes ((Wehner 2012). Precipitation events tend to be limited by available moisture. For the very rarest events, there is strong evidence from observations (Kunkel et al. 2012a) and models (Gutowski et al. 2008); (Li et al. 2011); (Wehner 2012) 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, DeAngelis et al. 2010; Groisman et al. 2012) and a shift in the number of El Niño events versus La Niña events.

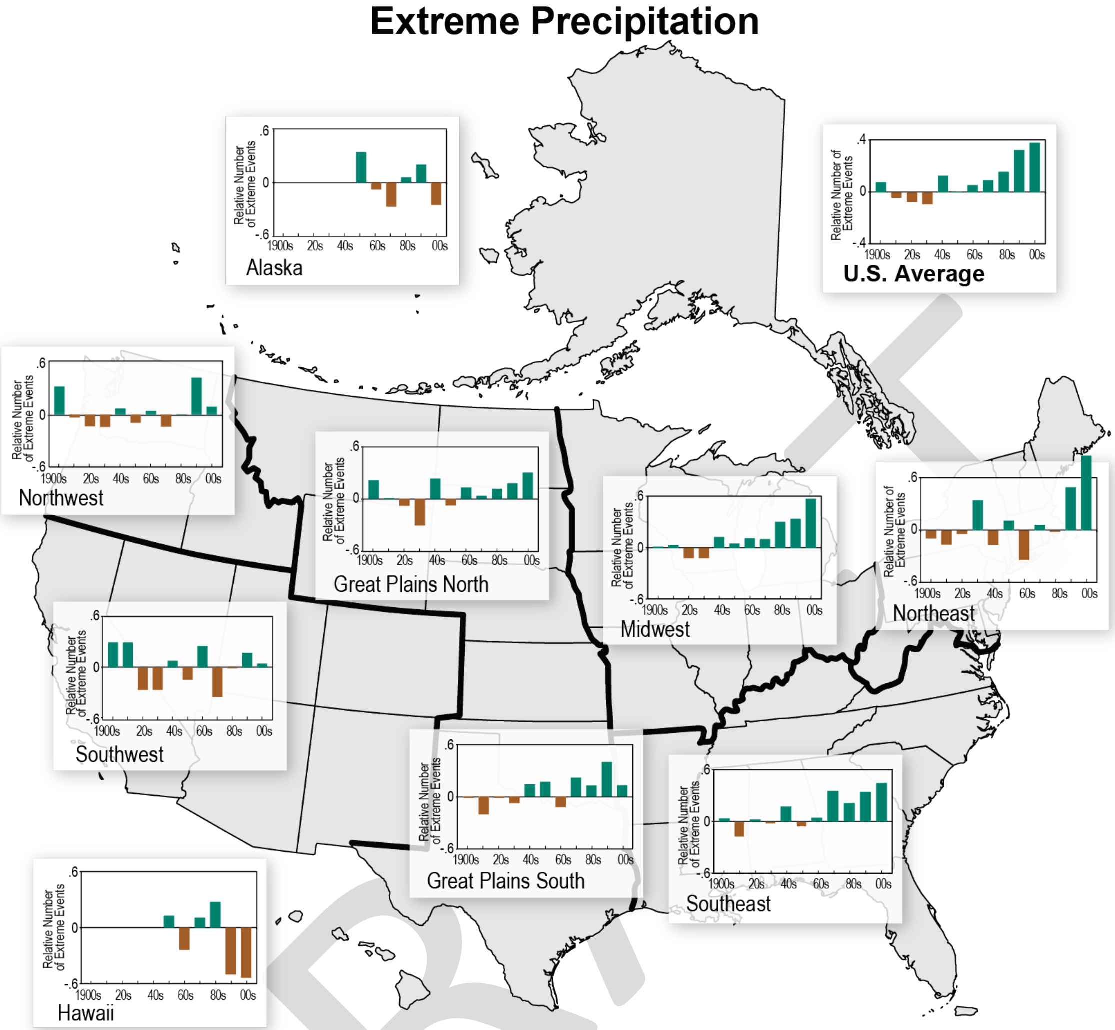


Figure 29: Extreme Precipitation

Caption: Heavy downpours are increasing nationally, with especially large increases in the Midwest and Northeast (Kunkel et al. 2012a). 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 11-year period of 2001-2011. Analysis based on 930 long-term, quality-controlled station records. (Figure source: NOAA NCDC / CICS-NC. Data from NOAA NCDC.)

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 (Kunkel et al. 2012b)).

There is also a northward shift in storms (Vose et al. 2012; Wang et al. 2009) which are often associated with extreme precipitation over the U.S. This shift is consistent with projections of a warming world (Bengtsson et al. 2009; Neu 2009). 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 (IPCC 2011) nor has any trend been identified in the number of U.S. landfalling hurricanes (Karl et al. 2009). Projections of future storm frequency suggest global numbers may slightly decrease (IPCC 2011). Two studies have found an upward trend in the number of extreme precipitation events associated with tropical cyclones (Knight and Davis 2009; Kunkel et al. 2010), but significant uncertainties remain (Groisman et al. 2012). 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 (Holland and Webster 2007; Landsea 2007; Mann et al. 2007b). The global satellite record shows a shift toward stronger tropical cyclones (IPCC 2011; Kossin et al. 2007), Elsner et al. (2008) but does not provide definitive evidence of a long-term trend. Nonetheless, there is a growing consensus based on our scientific understanding and very high resolution atmospheric modeling, that the strongest tropical cyclones, including Atlantic hurricanes, will become stronger in a warmer world (Emanuel 2000; Knutson et al. 2010).

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 (Kunkel et al. 2012a). Furthermore, since the phenomena are too small to be directly represented in climate models, future changes remain uncertain. (Peterson et al. 2012)

Key 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 U.S.

Temperature increases also increase evaporation rates (Peterson et al. 2012). The Palmer Drought Severity Index (PDSI) (Alley 1984; Palmer and Bureau 1965), 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 (Dai et al. 2004). 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. In fact, 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.

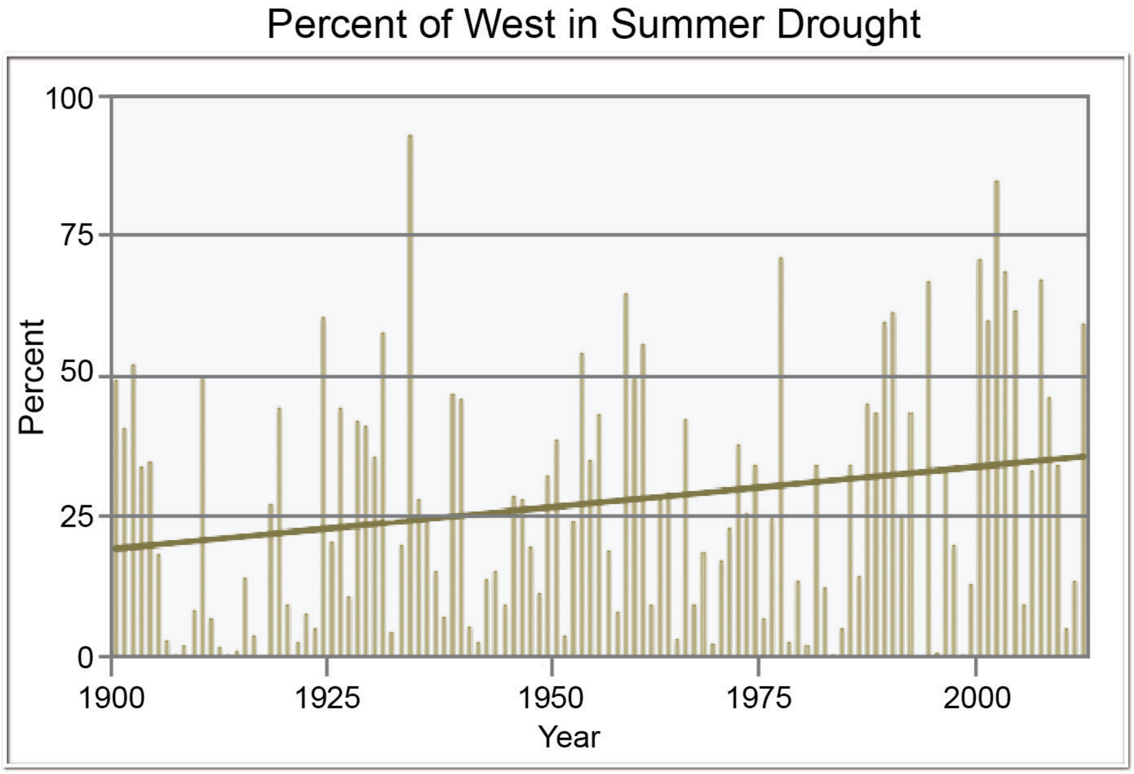


Figure 30: Percent of West in Summer Drought

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 (Brown et al. 2008; Littell et al. 2009; Schoennagel 2011; Westerling et al. 2003). For example, persistent drought conditions in the Southwest, combined with wildfire suppression and land management practices (Allen et al. 2002), 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 United States, while the area burned in the Southwest increased more than 300% relative to the area burned during the 1970s and early 1980s (Westerling et al. 2006).

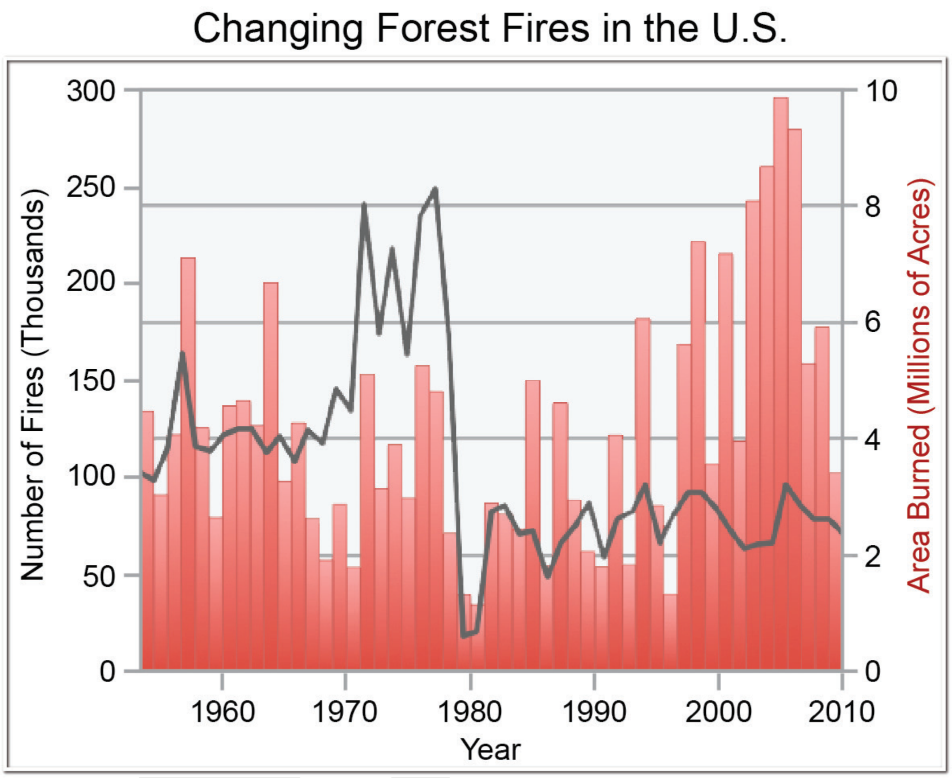


Figure 31: Changing Forest Fires in the U.S.

Caption: Although the average number of wildfires per year (black line) has decreased over time, the total area burned by wildfires (red 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 from the National Interagency Fire Center, for 1960 to 2011.

Future changes in 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 would be considered moderate to severe drought today (Wehner et al. 2011) . Despite its widespread usage, this index may be overly sensitive to future temperature increases. However, a direct examination of future soil moisture content projections also shows drying in most areas of the western U.S.

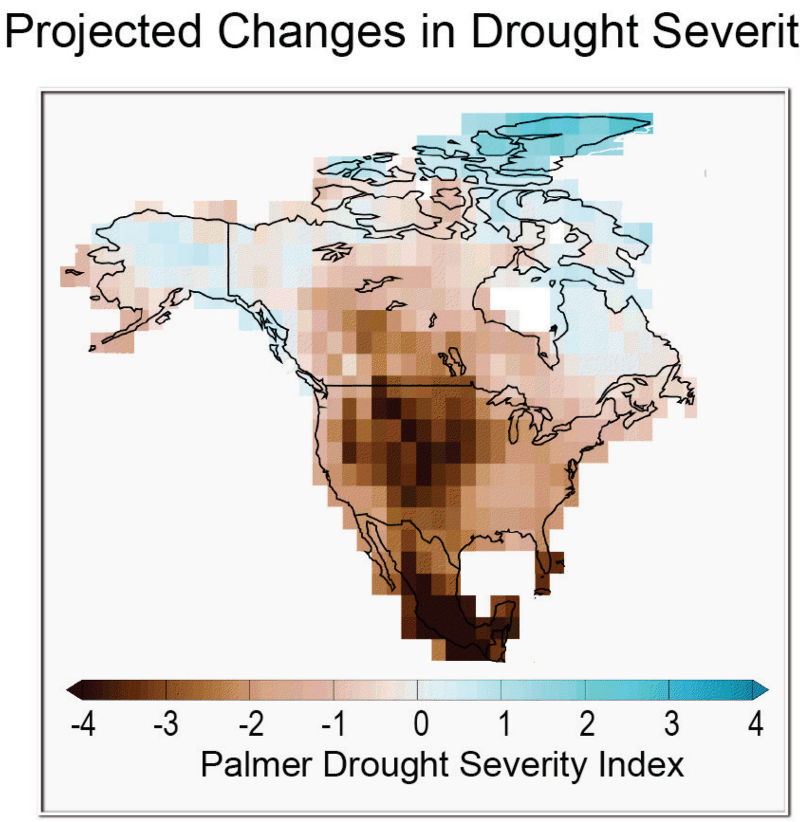


Figure 32: Projected Changes in Drought Severity

Caption: Projected Palmer Drought Severity Index at the end of this century from the CMIP3 models under the emissions scenario SRESA1B. Values less than –2 are termed by NOAA as “moderate drought,” less than –3 as “severe drought,” and less than –4 as “extreme drought”. (Wehner et al. 2011).

Provided fuels are available, 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 (Moritz et al. 2012). 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 (Spracklen et al. 2009). 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 (Westerling and Bryant 2008)).

Consecutive days with little or no precipitation can also reduce soil moisture. 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. Specifically, most of the western and southwestern U.S. is projected to experience statistically significant increases in the annual maximum number of consecutive dry days, up to 26 days above present-day values for parts of southern California and Arizona. The only sizeable area with statistically significant decreases in consecutive dry days is the north-central U.S.

Key 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.

A changing climate is affecting the Arctic on land and sea. Increasing temperatures and associated impacts are apparent throughout the Arctic, especially 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 (Meier et al. 2012), 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 (Kinnard et al. 2011). The fact that winter ice extent has declined less than summer ice extent (see Ch. 3: Our Changing Climate, Key Message 10) is indicative of a trend toward only seasonal 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 (Overland and Wang 2009). 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 (Francis and Vavrus 2012). 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.

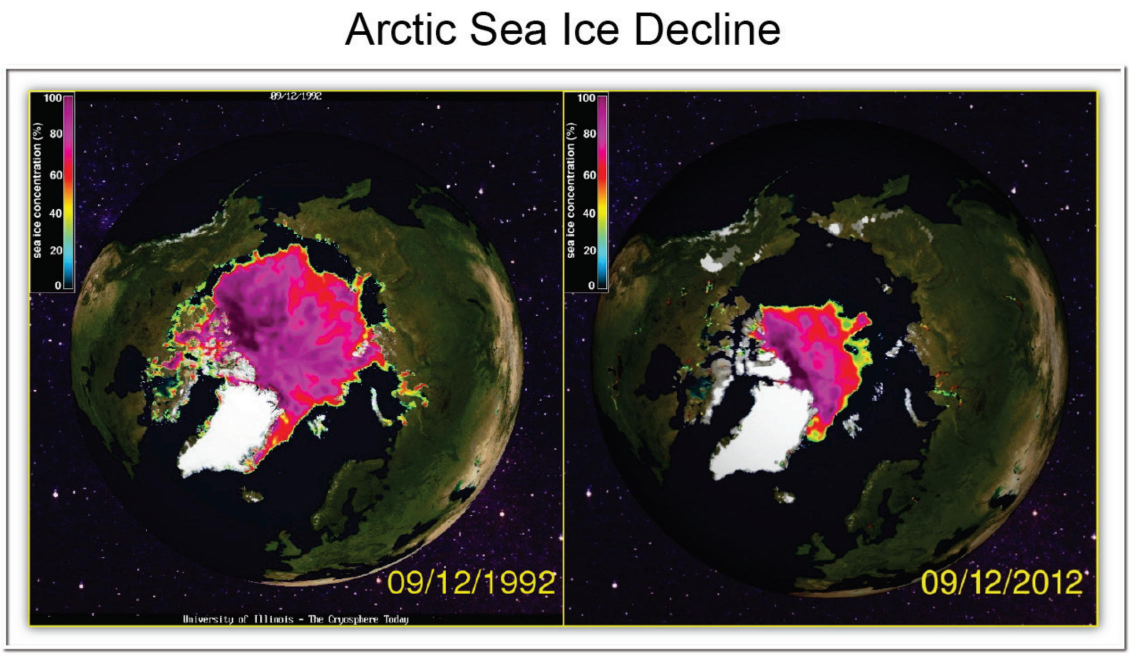


Figure 33: Arctic Sea Ice Decline

Caption: The spatial extent of Arctic sea ice cover in September has decreased substantially in the past two decades. The reduction of September extent from 1992 (left) to 2012 (right) has been nearly 50%. (Figure source: University of Illinois, The Cryosphere Today)

On land, changes in permafrost provide compelling indicators of climate change 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, as well as potentially causing infrastructure and environmental damages.

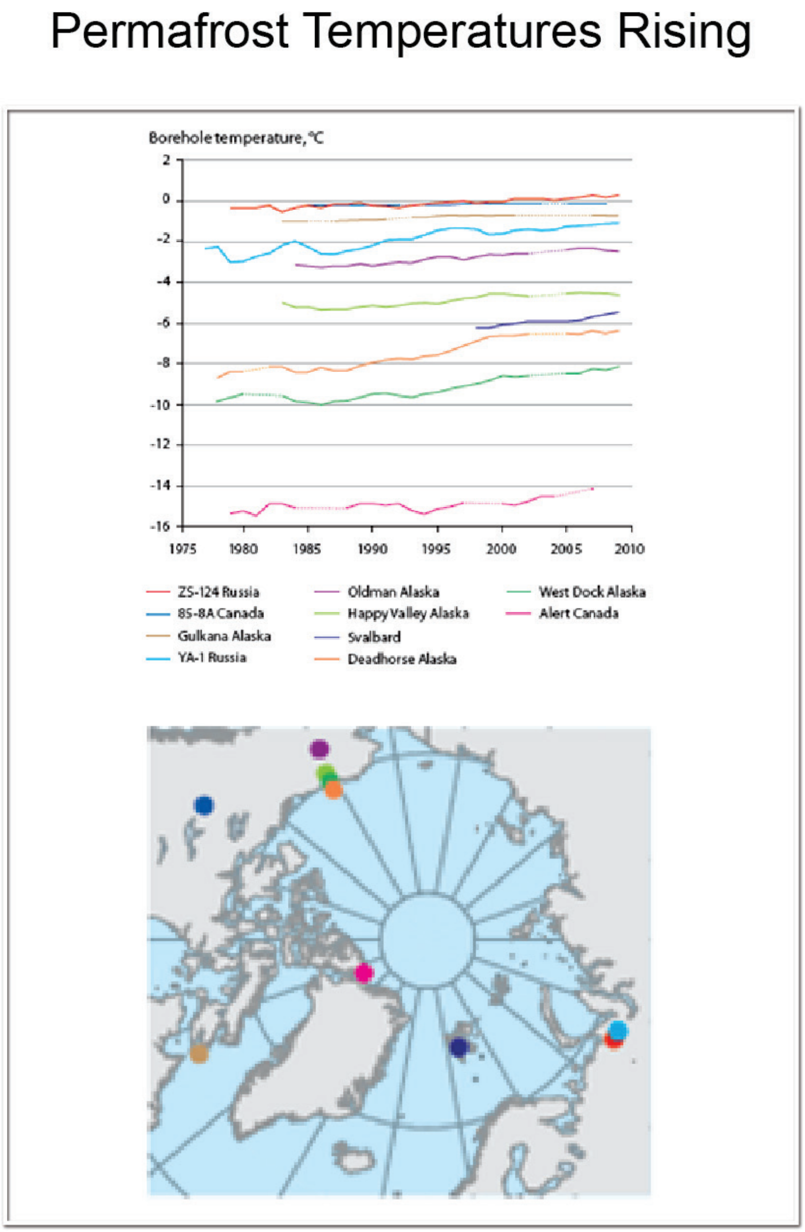


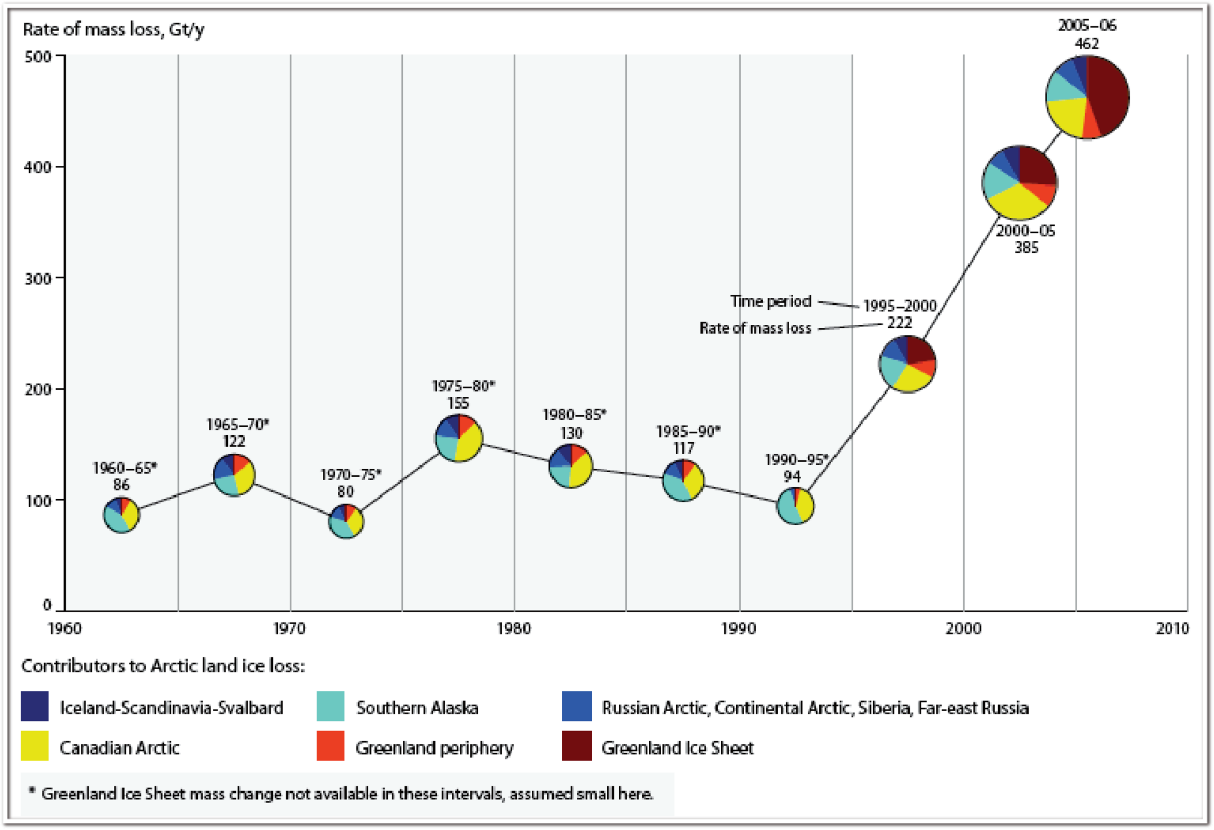
Figure 34: Permafrost Temperatures Rising

Caption: Ground temperatures at depths between 10 and 20 meters for boreholes across the circumpolar northern permafrost regions (Callaghan and Johansson 2012; Romanovsky et al. 2010).

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 (Callaghan and Johansson 2012). 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.

Glaciers are retreating 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 (Cogley 2009; Romanovsky et al. 2010).

Melting of Arctic Land-based Ice



* Greenland Ice Sheet mass change not available in these intervals, assumed small here.

Figure 35: 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 from (Cogley 2009).

Projections of future mass loss by glaciers and small ice caps indicate a continuation of current trends, although these projections are based on only 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 warming will outweigh the effects of increases in snowfall. The regions from which the contributions to sea level are projected to be largest are the Canadian Arctic, Alaska, and the Russian Arctic (Arctic Monitoring and Assessment Programme 2011).

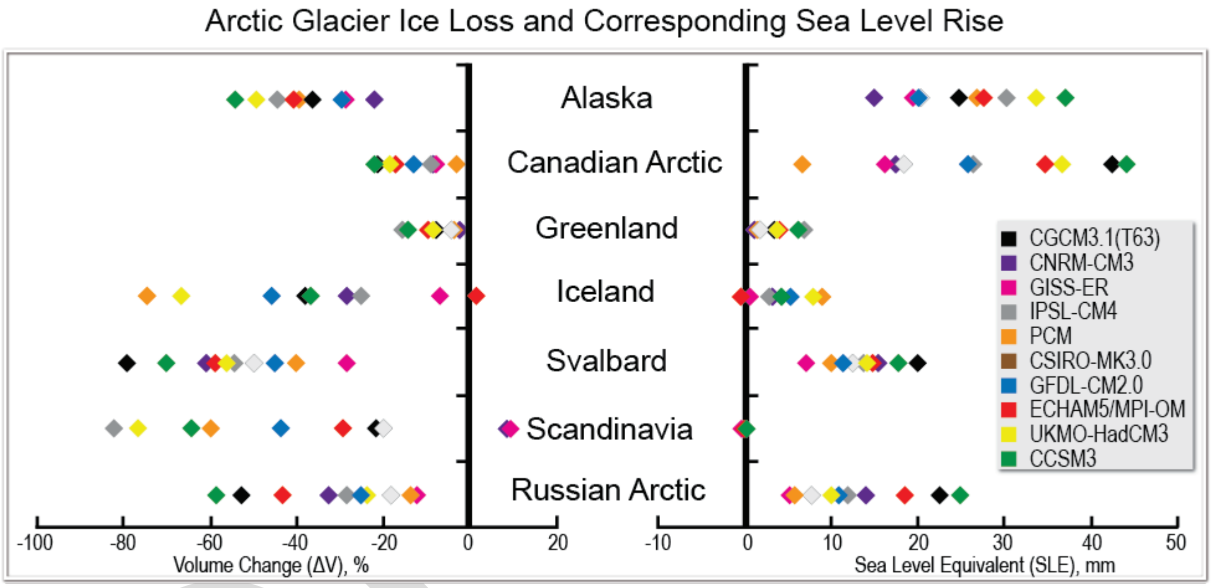


Figure 36: Arctic Glacier Ice Loss and Corresponding Sea Level Rise

Caption: Projections of fractional volume change and the equivalent sea level rise by 2100 for seven geographical 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). Negative volume changes (-%) represent a net loss of ice (left), and corresponding contributions to sea level rise (right) (Radić and Hock 2011).

Key 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 temperature change and on the ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.

Rising sea levels are one of the hallmarks of a warming planet. They will also be one of the major impacts of human-caused global warming on both human society and the natural environment.

Global sea level increases are primarily caused by one 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 winds up warming the oceans (Church et al. 2011). 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 0.59 +/– 0.20 millimeters per year since 1992, with Greenland's contribution being more than double that of Antarctica (Shepherd et al. 2012). 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 that most coastlines will see higher waters. The rates of sea level rise along individual coastlines, however, remain 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 and 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 (Bromirski et al. 2011).

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 (Ivins et al. 2007). 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.

Future projections of sea levels along U.S. coastlines also require information about distant sources of sea level rise, such as loss of ice from the great ice sheets on Greenland and

Antarctica. These continents hold enough ice to raise global sea levels by more than 200 feet if they were to melt completely. While this is 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 (Willis and Church 2012). 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 (Chen et al. 2009; Khan et al. 2010).

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 (Strauss et al. 2012). Although sea level rise is often thought of as causing a slow inundation, the most immediate impacts of sea level rise are to increase 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.

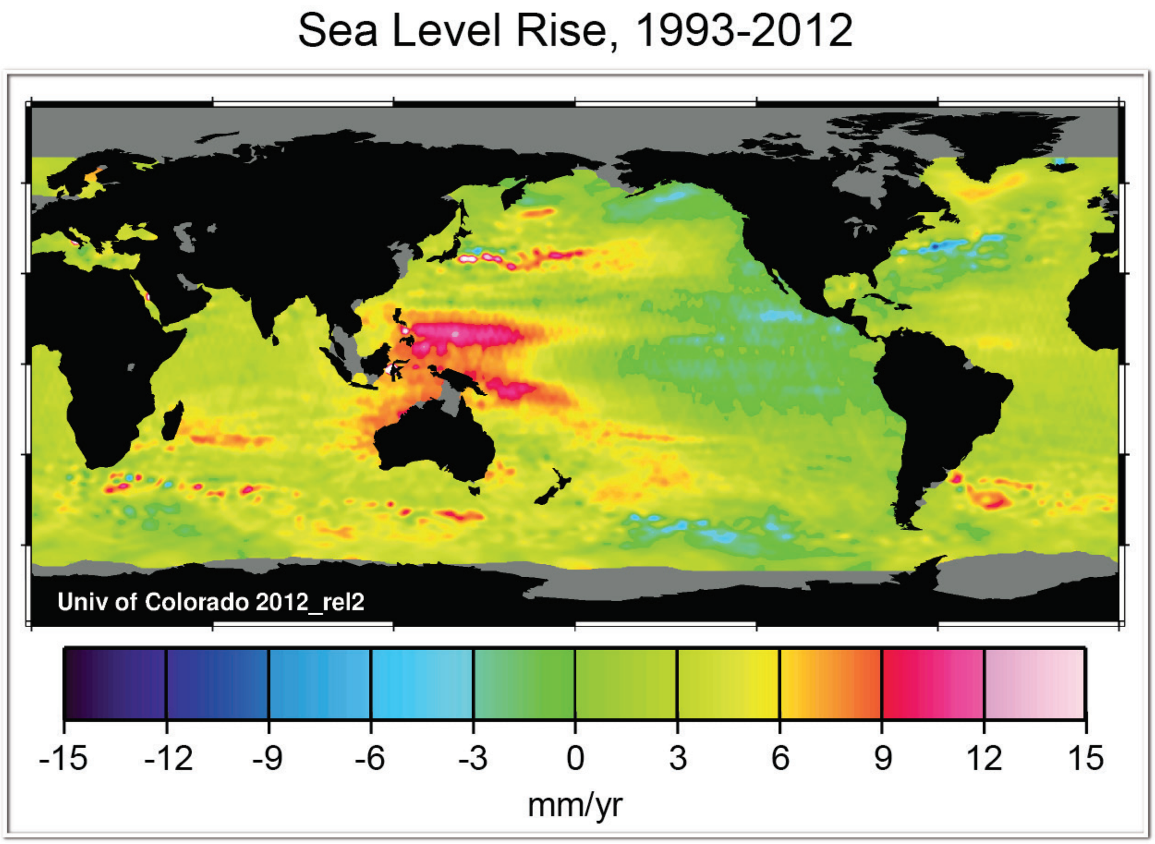


Figure 37: Sea Level Rise, 1993-2012

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 (Nerem et al. 2010).

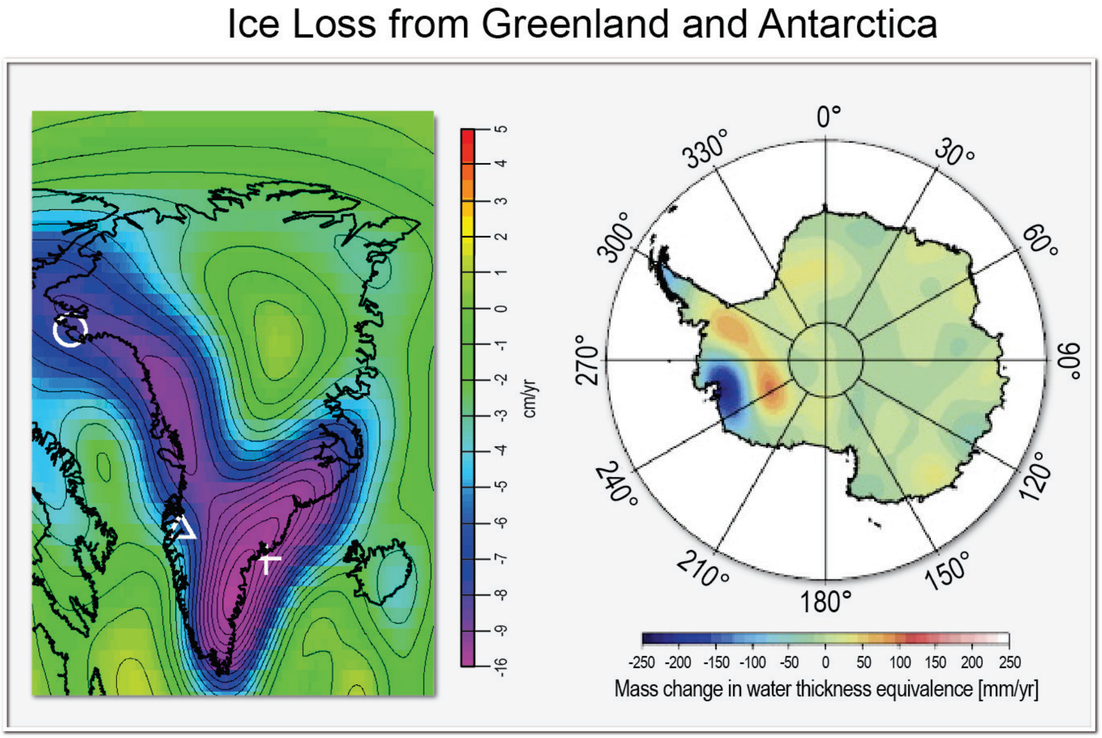


Figure 38: Ice Loss from Greenland and Antarctica

Caption: (left) rate of ice mass loss from Greenland (Khan et al. 2010). (right) rate of ice mass loss from Antarctica (Chen et al. 2009). The GRACE (Gravity Recovery and Climate Experiment) satellites measure changes in the pull of gravity over these two continents. As they lose ice to the oceans, the gravitational pull of Greenland and Antarctica is reduced. GRACE has now proven that both of the major ice sheets are currently contributing to global sea level rise due to ice loss.

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