United States Environmental Protection Agency

Climate Change Indicators in the United States, 2014

Third Edition

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Contents

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Introduction

The Earth's climate is changing. Temperatures are rising, snow and rainfall patterns are shifting, and more extreme climate events—like heavy rainstorms and record high temperatures—are already taking place. Scientists are highly confident that many of these observed changes can be linked to the climbing levels of carbon dioxide and other greenhouse gases in our atmosphere, which are caused by human activities.

The **climate change indicators** in this report look at the composition of the atmosphere, fundamental measures of climate, and the extent to which several climate-sensitive aspects of the oceans, snow and ice, human health, society, and ecosystems are changing. Together, these indicators present compelling evidence that climate change is happening now in the United States and around the world.

HOW IS THE CLIMATE CHANGING?

Since the Industrial Revolution began in the 1700s, people have added a significant amount of greenhouse gases into the atmosphere, largely by burning fossil fuels to generate electricity, heat and cool buildings, and power vehicles—as well as by clearing forests. The major greenhouse gases that people have added to the atmosphere are carbon dioxide, methane, nitrous oxide, and fluorinated gases. When these gases are emitted into the atmosphere, many remain there for long time periods, ranging from a decade to thousands of years. Past emissions affect our atmosphere in the present day; current and future emissions will continue to increase the levels of these gases in our atmosphere for the foreseeable future.

"Greenhouse gases" got their name because they trap heat (energy) in the lower part of the atmosphere (see "The Greenhouse Effect" on p. 4). As more of these gases are added to the atmosphere, more heat is trapped. This extra heat leads to higher air temperatures near the Earth's surface, alters weather patterns, and raises the temperature of the oceans.

These observed changes affect people and the environment in important ways. For example, sea levels are rising, glaciers are melting, and plant and animal life cycles are changing. These types of changes can bring about fundamental disruptions in ecosystems, affecting plant and animal populations, communities, and biodiversity. Such changes can also affect society and traditional ways of life for

WHY USE INDICATORS?

One important way to track and communicate the causes and effects of climate change is through the use of indicators. An indicator represents the state or trend of certain environmental or societal conditions over a given area and a specified period of time. For example, long-term measurements of temperature in the United States and globally are used as an indicator to track and better understand the effects of changes in the Earth's climate.

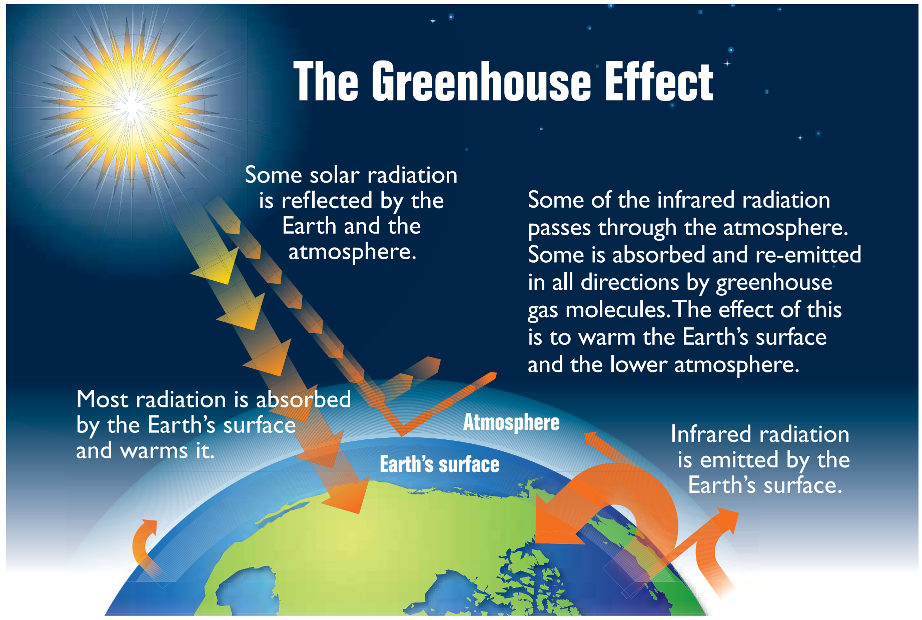
HOW DO THE INDICATORS RELATE TO CLIMATE CHANGE?

All of the indicators in this report relate to either the causes or effects of climate change. Some indicators show trends that can be more directly linked to human-induced climate change than others. Collectively, the trends depicted in these indicators provide important evidence of "what climate change looks like."

WHAT IS CLIMATE CHANGE?

Climate change refers to any substantial change in measures of climate (such as temperature or precipitation) lasting for an extended period (decades or longer). Climate change may result from natural factors and processes or from human activities.

Global warming is a term often used interchangeably with the term "climate change," but they are not entirely the same thing. Global warming refers to an average increase in the temperature of the atmosphere near the Earth's surface. Global warming is just one aspect of global climate change, though a very important one.



certain communities, including where people can live, what kinds of crops are most viable, and what kinds of businesses can thrive in certain areas.

Although the climate is continually changing, not every climate change indicator will show a smooth pattern of steady change. The Earth is a complex system, and there will always be natural variations from one year to the next—for example, a very warm year followed by a colder year. The Earth's climate also goes through other natural cycles that can play out over a period of several years or even decades. Individual years or even individual decades can deviate from the long-term trend.[1] Thus, EPA's indicators present trends for as many years as the underlying data allow.

ABOUT THIS REPORT

EPA publishes this report to communicate information about the science and impacts of climate change, assess trends in environmental quality, and inform decision-making. *Climate Change Indicators in the United States, 2014*, is the third edition of a report first published by the U.S. Environmental Protection Agency (EPA) in 2010 and updated in 2012. This report presents 30 indicators to help readers understand observed long-term trends related to the causes and effects of climate change, the significance of these changes, and their possible consequences for people, the environment, and society. Although each indicator has a connection to climate change, this report is not intended to identify the extent to which a certain indicator is driving climate change, nor the relative role of climate change in *causing* a trend in an observed indicator. Connections between human activities, climate change, and observed indicators are explored in more detail elsewhere in the scientific literature.

This report and the accompanying detailed technical documentation have been designed to ensure that the science and underlying peer-reviewed data supporting the indicators are presented and documented transparently. This report consists of peer-reviewed, publicly available data from a number of government agencies, academic institutions, and other organizations. EPA also received feedback from scientists, researchers, and communications experts in nongovernmental and private sectors. This feedback helped to inform the content and new features of this 2014 report. The entire report, including its technical support document, was peer-reviewed by independent technical experts.

About the Indicators in This Report

The indicators in this report were chosen using a set of criteria that considered usefulness, data quality, and relevance to climate change. The report is a compilation of key data sets for communication purposes; in addition to being published here, these data sets have been published in the scientific literature and in other government or academic reports.

Trends relevant to climate change are best viewed at broad geographic scales and over long time horizons, rather than at localized scales or over a few years or a season. The indicators in this report are based on historical records that go back in time as far as possible without sacrificing data quality. Most of the indicators in this report focus on the United States. However, some include global trends to provide context or a basis for comparison, or because they are intrinsically global in nature, such as atmospheric concentrations of greenhouse gases, which are influenced by global activities. The geographic extent and timeframe that each indicator represents largely depend on data availability and the nature of what is being measured.

All of the indicators discussed in this report relate to either the causes or effects of climate change. Some indicators are directly linked to human activities that cause climate change, such as Global Greenhouse Gas Emissions. Changes depicted by other indicators, such as U.S. and Global Temperature, have been confidently linked with the increase in greenhouse gases caused by human activity. Some of the trends in other indicators, such as Wildfires, although consistent with what one would expect in a warming climate, cannot yet be firmly attributed to human-induced climate change for various reasons (for example, limitations in the historical data, or other factors in addition to climate change that may influence the trend). A few indicators do not yet show any significant trend over the period for which data are available.

A Roadmap to the Report

The indicators are divided into six chapters: Greenhouse Gases, Weather and Climate, Oceans, Snow and Ice, Health and Society, and Ecosystems. Some chapters also include a "Community Connection" or "A Closer Look" feature that highlights a specific region, data record, or area of interest. Each indicator features five elements:

- One or more graphics depicting changes over time. Some indicators consist of a single metric, while others present multiple metrics (for example, the Drought indicator shows two different ways of calculating drought).
- Key points about what the indicator shows.
- Background on how the indicator relates to climate change.
- Information about how the indicator was developed.
- Important notes concerning interpretation of the indicator.

EPA has compiled an accompanying **technical support document** containing more detailed information about each indicator, including data sources, data collection methods, calculations, statistical considerations, and sources of uncertainty. This document also describes EPA's approach and criteria for selecting indicators for the report. This information is available on EPA's website at: www.epa.gov/climatechange/indicators.

Additional resources that can provide readers with more information appear at the end of the report (see Climate Change Resources on p. 98).

WHO IS THIS REPORT FOR?

Climate Change Indicators in the United States, 2014, is written with the primary goal of informing readers' understanding of climate change. It is also designed to be useful for the public, scientists, analysts, decision-makers, educators, and others who can use climate change indicators as a tool for:

- Effectively communicating relevant climate science information in a sound, transparent, and easy-to-understand way.
- Assessing trends in environmental quality, factors that influence the environment, and effects on ecosystems and society.
- Informing science-based decision-making.

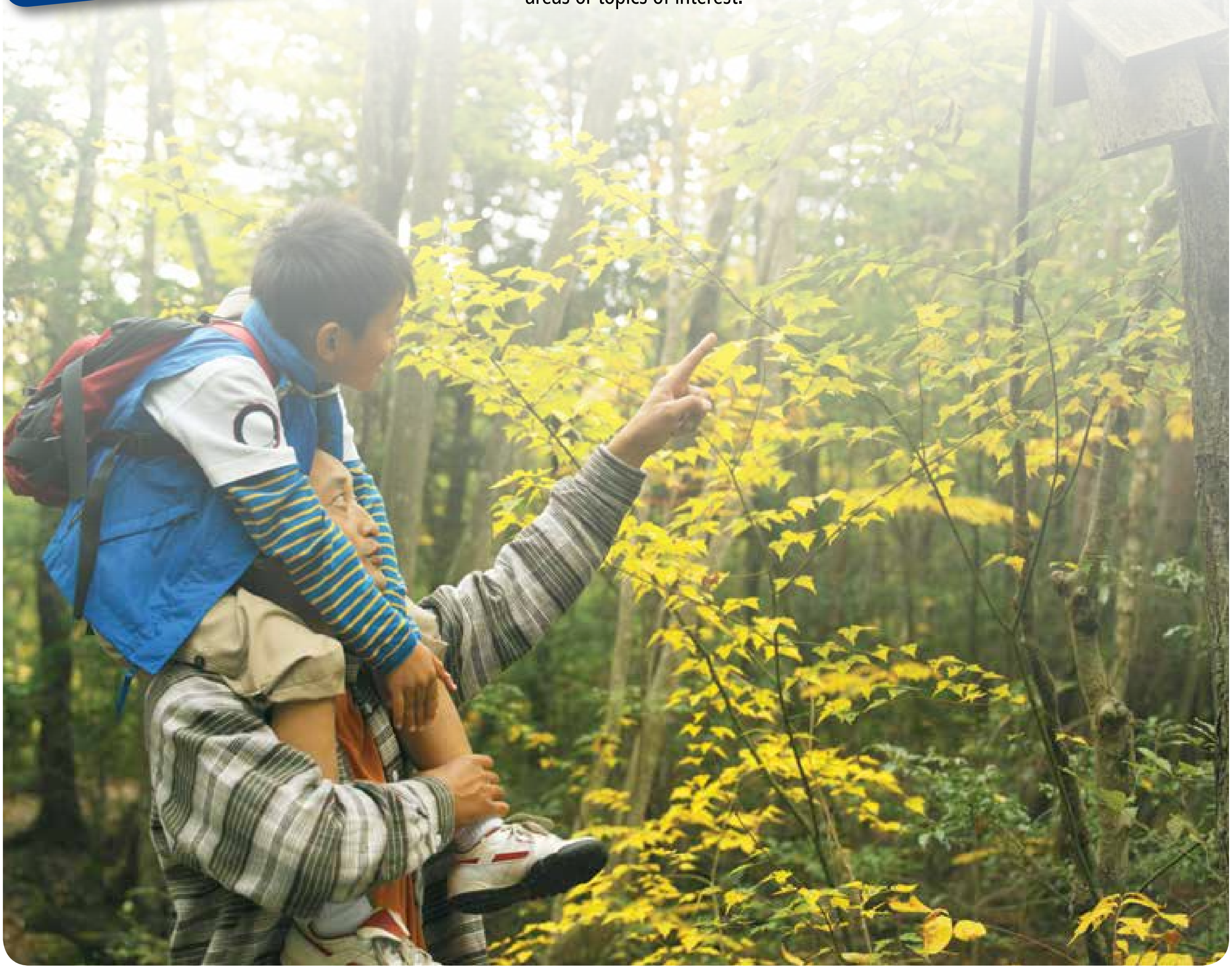
LOOKING AHEAD

Indicators of climate change are expected to become even more numerous and to depict even clearer trends in the future. EPA will continue to work in partnership with coordinating bodies, such as the U.S. Global Change Research Program, and with other agencies, organizations, and individuals to collect and communicate useful data and to inform policies and programs based on this knowledge. As new and more comprehensive indicator data become available, EPA will continually update the indicators presented in this report.

WHAT'S NEW IN 2014?

The 2014 report reflects the following new features and changes:

- **Four new indicators: Heating and Cooling Degree Days, Lyme Disease, Wildfires**, and **Great Lakes Water Levels and Temperatures**. These additions provide further evidence of climate change and its effects on people, society, and ecosystems.
- **Expanded indicators: Atmospheric Concentrations of Greenhouse Gases** was expanded to cover global concentrations of ozone, and **Climate Forcing** was expanded to show the influence of ozone and other short-lived climate forcers. New metrics were added to the **High and Low Temperatures** and **Streamflow** indicators. Maps were added to **Sea Surface Temperature** and **Leaf and Bloom Dates** to show how changes over time vary by region.
- **Updated indicators:** Nearly all indicators have been updated with additional years of data that have become available since the last report.
- **"Community Connection" and "A Closer Look" content:** Four chapters highlight observed data for particular areas to provide a local or regional perspective on relevant topics. The data for these features meet the same data quality criteria as EPA's national indicators, but are focused on highlighting specific, more localized areas or topics of interest.



Understanding Greenhouse Gases

MAJOR GREENHOUSE GASES ASSOCIATED WITH HUMAN ACTIVITIES

The major greenhouse gases emitted into the atmosphere are carbon dioxide, methane, nitrous oxide, and fluorinated gases (see the table below). Some of these gases are produced almost entirely by human activities; others come from a combination of natural sources and human activities.

Many of the major greenhouse gases can remain in the atmosphere for tens to hundreds of years after being released. They become globally mixed in the lower part of the atmosphere, called the troposphere (the first several miles above the Earth's surface), reflecting the combined contributions of emissions sources worldwide from the past and present. Due to this global mixing, concentrations of these gases will be fairly similar no matter where in the world they are measured.

Some other substances have much shorter atmospheric lifetimes (i.e., less than a year) but are still relevant to climate change. Important short-lived substances that affect the climate include water vapor, ozone in the troposphere, pollutants that lead to ozone formation, and aerosols (atmospheric particles) such as black carbon and sulfates. Water vapor, tropospheric ozone, and black carbon contribute to warming, while other aerosols produce a cooling effect.

Several factors determine how strongly a particular greenhouse gas will affect the Earth's climate. One factor is the length of time that the gas remains in the atmosphere. A second factor is each gas's unique ability to absorb energy. By considering both of these factors, scientists calculate a gas's global warming potential, which measures how much a given amount of the greenhouse gas is estimated to contribute to global warming over a specific period of time (for example, 100 years) after being emitted. For purposes of comparison, global warming potential values are calculated in relation to carbon dioxide, which is assigned a global warming potential equal to 1. The table below describes sources, lifetimes, and global warming potentials for several important long-lived greenhouse gases.

GASES AND SUBSTANCES INCLUDED IN THIS REPORT

This report focuses on most of the major, well-mixed greenhouse gases that contribute to the vast majority of warming of the climate. It also includes certain substances with shorter atmospheric lifetimes (i.e., less than a year) that are relevant to climate change. In addition to several long-lived greenhouse gases, the **Atmospheric Concentrations of Greenhouse Gases** indicator tracks concentrations of ozone in the layers of the Earth's atmosphere, while Figure 2 of the **Climate Forcing** indicator shows the influence of a variety of short-lived substances.

Major Long-Lived Greenhouse Gases and Their Characteristics

Greenhouse gas	How it's produced	Average lifetime in the atmosphere	100-year global warming potential
Carbon dioxide	Emitted primarily through the burning of fossil fuels (oil, natural gas, and coal), solid waste, and trees and wood products. Changes in land use also play a role. Deforestation and soil degradation add carbon dioxide to the atmosphere, while forest regrowth takes it out of the atmosphere.	see below*	1
Methane	Emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and agricultural practices and from the anaerobic decay of organic waste in municipal solid waste landfills.	12 years	28
Nitrous oxide	Emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste.	121 years	265
Fluorinated gases	A group of gases that contain fluorine, including hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride, among other chemicals. These gases are emitted from a variety of industrial processes and commercial and household uses, and do not occur naturally. Sometimes used as substitutes for ozone-depleting substances such as chlorofluorocarbons (CFCs).	A few weeks to thousands of years	Varies (the highest is sulfur hexafluoride at 23,500)

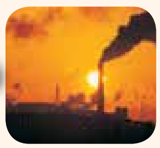
This table shows 100-year global warming potentials, which describe the effects that occur over a period of 100 years after a particular mass of a gas is emitted. Global warming potentials and lifetimes come from the Intergovernmental Panel on Climate Change's Fifth Assessment Report.[1]

** Carbon dioxide's lifetime cannot be represented with a single value because the gas is not destroyed over time, but instead moves among different parts of the ocean–atmosphere–land system. Some of the excess carbon dioxide will be absorbed quickly (for example, by the ocean surface), but some will remain in the atmosphere for thousands of years, due in part to the very slow process by which carbon is transferred to ocean sediments.*

Summary of Key Points

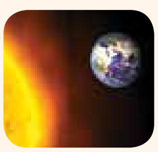
Greenhouse Gases

U.S. Greenhouse Gas Emissions. In the United States, greenhouse gas emissions caused by human activities increased by 5 percent from 1990 to 2012. However, since 2005, total U.S. greenhouse gas emissions have decreased by 10 percent. Carbon dioxide accounts for most of the nation's emissions and most of the increase since 1990. Electricity generation is the largest source of greenhouse gas emissions in the United States, followed by transportation. Emissions per person have decreased slightly in the last few years.



Global Greenhouse Gas Emissions. Worldwide, net emissions of greenhouse gases from human activities increased by 35 percent from 1990 to 2010. Emissions of carbon dioxide, which account for about three-fourths of total emissions, increased by 42 percent over this period. As with the United States, the majority of the world's emissions result from electricity generation, transportation, and other forms of energy production and use.

Atmospheric Concentrations of Greenhouse Gases. Concentrations of carbon dioxide and other greenhouse gases in the atmosphere have increased since the beginning of the industrial era. Almost all of this increase is attributable to human activities. Historical measurements show that current levels of many greenhouse gases are higher than any levels recorded for hundreds of thousands of years, even after accounting for natural fluctuations.



Climate Forcing. Climate forcing refers to a change in the Earth's energy balance, leading to either a warming or cooling effect. An increase in the atmospheric concentrations of greenhouse gases produces a positive climate forcing, or warming effect. From 1990 to 2013, the total warming effect from greenhouse gases added by humans to the Earth's atmosphere increased by 34 percent. The warming effect associated with carbon dioxide alone increased by 27 percent.

Weather & Climate

U.S. and Global Temperature. Average temperatures have risen across the contiguous 48 states since 1901, with an increased rate of warming over the past 30 years. Seven of the top 10 warmest years on record have occurred since 1998. Average global temperatures show a similar trend, and the top 10 warmest years on record worldwide have all occurred since 1998. Within the United States, temperatures in parts of the North, the West, and Alaska have increased the most.

High and Low Temperatures. Many extreme temperature conditions are becoming more common. Since the 1970s, unusually hot summer temperatures have become more common in the United States, and heat waves have become more frequent—although the most severe heat waves in U.S. history remain those that occurred during the "Dust Bowl" in the 1930s. Record-setting daily high temperatures have become more common than record lows. The decade from 2000 to 2009 had twice as many record highs as record lows.

U.S. and Global Precipitation. Total annual precipitation has increased in the United States and over land areas worldwide. Since 1901, precipitation has increased at an average rate of 0.5 percent per decade in the contiguous 48 states and 0.2 percent per decade over land areas worldwide. However, shifting weather patterns have caused certain areas, such as Hawaii and parts of the Southwest, to experience less precipitation than usual.

Heavy Precipitation. In recent years, a higher percentage of precipitation in the United States has come in the form of intense single-day events. Nationwide, nine of the top 10 years for extreme one-day precipitation events have occurred since 1990. The occurrence of abnormally high annual precipitation totals (as defined by the National Oceanic and Atmospheric Administration) has also increased.

Drought. Average drought conditions across the nation have varied since records began in 1895. The 1930s and 1950s saw the most widespread droughts, while the last 50 years have generally been wetter than average. However, specific trends vary by region. A more detailed index developed recently shows that between 2000 and 2013, roughly 20 to 70 percent of the United States experienced drought at any given time, but this index has not been in use for long enough to compare with historical drought patterns.

A Closer Look: Temperature and Drought in the Southwest. The southwestern United States is particularly sensitive to changes in temperature and thus vulnerable to drought, as even a small decrease in water availability in this already arid region can threaten natural systems and society.

Tropical Cyclone Activity. Tropical storm activity in the Atlantic Ocean, the Caribbean, and the Gulf of Mexico has increased during the past 20 years. Increased storm intensity is closely related to variations in sea surface temperature in the tropical Atlantic. However, changes in observation methods over time make it difficult to know for sure whether a long-term increase in storm activity has occurred. Records collected since the late 1800s suggest that the actual number of hurricanes per year has not increased.

Oceans

Ocean Heat. Three separate analyses show that the amount of heat stored in the ocean has increased substantially since the 1950s. Ocean heat content not only determines sea surface temperature, but also affects sea level and currents.

Sea Surface Temperature. Ocean surface temperatures increased around the world over the 20th century. Even with some year-to-year variation, the overall increase is clear, and sea surface temperatures have been higher during the past three decades than at any other time since reliable observations began in the late 1800s.

Sea Level. When averaged over all the world's oceans, sea level has increased at a rate of roughly six-tenths of an inch per decade since 1880. The rate of increase has accelerated in recent years to more than an inch per decade. Changes in sea level relative to the land vary by region. Along the U.S. coastline, sea level has risen the most along the Mid-Atlantic coast and parts of the Gulf coast, where some stations registered increases of more than 8 inches between 1960 and 2013. Sea level has decreased relative to the land in parts of Alaska and the Northwest.

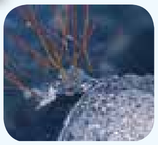
A Closer Look: Land Loss Along the Atlantic Coast. As sea level rises, dry land and wetland can turn into open water. Along many parts of the Atlantic coast, this problem is made worse by low elevations and land that is already sinking. Between 1996 and 2011, the coastline from Florida to New York lost more land than it gained.

Ocean Acidity. The ocean has become more acidic over the past few centuries because of increased levels of atmospheric carbon dioxide, which dissolves in the water. Higher acidity affects the balance of minerals in the water, which can make it more difficult for certain marine animals to build their skeletons and shells.

Snow & Ice

Arctic Sea Ice. Part of the Arctic Ocean is covered by ice year-round. The area covered by ice is typically smallest in September, after the summer melting season. The minimum extent of Arctic sea ice has decreased over time, and in September 2012 it was the smallest on record. Arctic ice has also become thinner, which makes it more vulnerable to additional melting.

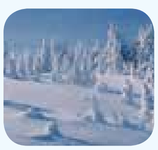
Glaciers. Glaciers in the United States and around the world have generally shrunk since the 1960s, and the rate at which glaciers are melting has accelerated over the last decade. The loss of ice from glaciers has contributed to the observed rise in sea level.



Lake Ice. Most lakes in the northern United States are freezing later and thawing earlier compared with the 1800s and early 1900s. Freeze dates have shifted later at a rate of roughly half a day to one day per decade, while thaw dates for most of the lakes studied have shifted earlier at a rate of half a day to two days per decade.

Community Connection: Ice Breakup in Two Alaskan Rivers. Regions in the far north are warming more quickly than other parts of the world. Two long-running contests on the Tanana and Yukon rivers in Alaska—where people guess the date when the river ice will break up in the spring—provide a century's worth of evidence revealing that the ice on these rivers is generally breaking up earlier in the spring than it used to.

Snowfall. Total snowfall—the amount of snow that falls in a particular location—has decreased in most parts of the country since widespread records began in 1930. One reason for this decline is that more than three-fourths of the locations studied have seen more winter precipitation fall in the form of rain instead of snow.

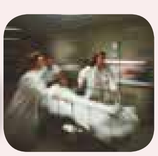


Snow Cover. Snow cover refers to the area of land that is covered by snow at any given time. Between 1972 and 2013, the average portion of North America covered by snow decreased at a rate of about 3,500 square miles per year, based on weekly measurements taken throughout the year. However, there has been much year-to-year variability.

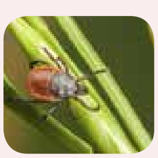
Snowpack. The depth or thickness of snow on the ground (snowpack) in early spring decreased at about three-fourths of measurement sites in the western United States between 1955 and 2013. However, other locations saw an increase in spring snowpack. The average change across all sites for this time period amounts to about a 14 percent decline.

Health & Society

Heating and Cooling Degree Days. Heating and cooling degree days measure the difference between outdoor temperatures and the temperatures that people find comfortable indoors. As the U.S. climate has warmed in recent years, heating degree days have decreased and cooling degree days have increased overall, suggesting that Americans need to use less energy for heating and more energy for air conditioning. This pattern stands out the most in the North and West, while much of the Southeast has experienced the opposite results.



Heat-Related Deaths. Over the past three decades, nearly 8,000 Americans were reported to have died as a direct result of heat-related illnesses such as heat stroke. The annual death rate is higher when accounting for other deaths in which heat was reported as a contributing factor. Considerable year-to-year variability in the data and certain limitations of this indicator make it difficult to determine whether the United States has experienced long-term trends in the number of deaths classified as "heat-related."

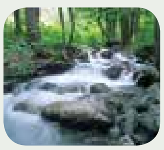


Lyme Disease. Lyme disease is a bacterial illness spread by ticks that bite humans. Tick habitat and populations are influenced by many factors, including climate. Nationwide, the rate of reported cases of Lyme disease has approximately doubled since 1991. Lyme disease is most common in the Northeast and the upper Midwest, where some states now report 50 to 90 more cases of Lyme disease per 100,000 people than they did in 1991.

Length of Growing Season. The average length of the growing season in the contiguous 48 states has increased by nearly two weeks since the beginning of the 20th century. A particularly large and steady increase has occurred over the last 30 years. The observed changes reflect earlier spring warming as well as later arrival of fall frosts. The length of the growing season has increased more rapidly in the West than in the East.

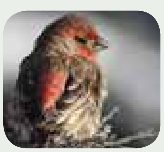
Ragweed Pollen Season. Warmer temperatures and later fall frosts allow ragweed plants to produce pollen later into the year, potentially prolonging the allergy season for millions of people. The length of ragweed pollen season has increased at 10 out of 11 locations studied in the central United States and Canada since 1995. The change becomes more pronounced from south to north.

Wildfires. Since 1983, the United States has had an average of 72,000 recorded wildfires per year. Of the 10 years with the largest acreage burned, nine have occurred since 2000, with many of the largest increases occurring in western states. The proportion of burned land suffering severe damage each year has ranged from 5 to 22 percent.

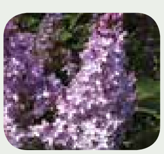


Streamflow. Changes in temperature, precipitation, snowpack, and glaciers can affect the rate of streamflow and the timing of peak flow. Over the last 73 years, minimum, maximum, and average flows have changed in many parts of the country—some higher, some lower. Nearly half of the rivers and streams measured show peak winter-spring runoff happening at least five days earlier than it did in the mid-20th century.

Great Lakes Water Levels and Temperatures. Water levels in most of the Great Lakes have declined in the last few decades. Water levels in lakes are influenced by water temperature, which affects evaporation rates and ice formation. Since 1995, average surface water temperatures have increased by a few degrees for Lakes Superior, Michigan, Huron, and Ontario. Less of a temperature change has been observed in Lake Erie.



Bird Wintering Ranges. Some birds shift their range or alter their migration habits to adapt to changes in temperature or other environmental conditions. Long-term studies have found that bird species in North America have shifted their wintering grounds northward by an average of more than 40 miles since 1966, with several species shifting by hundreds of miles. On average, bird species have also moved their wintering grounds farther from the coast, consistent with inland winter temperatures becoming less severe.



Leaf and Bloom Dates. Leaf growth and flower blooms are examples of natural events whose timing can be influenced by climate change. Observations of lilacs and honeysuckles in the contiguous 48 states suggest that first leaf dates and bloom dates show a great deal of year-to-year variability. Leaf and bloom events are generally happening earlier throughout the North and West but later in much of the South.

Community Connection: Cherry Blossom Bloom Dates in Washington, D.C. "Peak" bloom dates of the iconic cherry trees in Washington, D.C., recorded since the 1920s, indicate that cherry trees are blooming slightly earlier than in the past. Bloom dates are key to planning the Cherry Blossom Festival, one of the region's most popular spring attractions.

GREENHOUSE GASES

Greenhouse gases from human activities are the most significant driver of observed climate change since the mid-20th century.[1] The indicators in this chapter characterize emissions of the major greenhouse gases resulting from human activities, the concentrations of these gases in the atmosphere, and how emissions and concentrations have changed over time. When comparing emissions of different gases, these indicators use a concept called "global warming potential" to convert amounts of other gases into carbon dioxide equivalents.

WHY DOES IT MATTER?

As greenhouse gas emissions from human activities increase, they build up in the atmosphere and warm the climate, leading to many other changes around the world—in the atmosphere, on land, and in the oceans. The indicators in other chapters of this report illustrate many of these changes. These changes have both positive and negative effects on people, society, and the environment—including plants and animals. Because many of the major greenhouse gases stay in the atmosphere for tens to hundreds of years after being released, their warming effects on the climate persist over a long time and can therefore affect both present and future generations.

Summary of Key Points

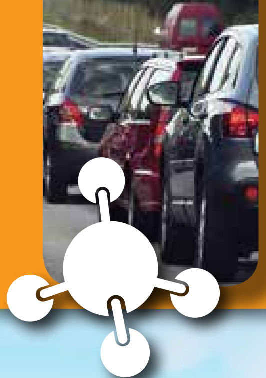
U.S. Greenhouse Gas Emissions. In the United States, greenhouse gas emissions caused by human activities increased by 5 percent from 1990 to 2012. However, since 2005, total U.S. greenhouse gas emissions have decreased by 10 percent. Carbon dioxide accounts for most of the nation's emissions and most of the increase since 1990. Electricity generation is the largest source of greenhouse gas emissions in the United States, followed by transportation. Emissions per person have decreased slightly in the last few years.

Sources of Data on U.S. Greenhouse Gas Emissions. EPA has two key programs that provide data on greenhouse gas emissions in the United States: the Inventory of U.S. Greenhouse Gas Emissions and Sinks and the Greenhouse Gas Reporting Program. The programs are complementary, providing both a higher-level perspective on the nation's total emissions and detailed information about the sources and types of emissions from individual facilities.

Global Greenhouse Gas Emissions. Worldwide, net emissions of greenhouse gases from human activities increased by 35 percent from 1990 to 2010. Emissions of carbon dioxide, which account for about three-fourths of total emissions, increased by 42 percent over this period. As with the United States, the majority of the world's emissions result from electricity generation, transportation, and other forms of energy production and use.

Atmospheric Concentrations of Greenhouse Gases. Concentrations of carbon dioxide and other greenhouse gases in the atmosphere have increased since the beginning of the industrial era. Almost all of this increase is attributable to human activities.[2] Historical measurements show that current levels of many greenhouse gases are higher than any levels recorded for hundreds of thousands of years, even after accounting for natural fluctuations.

Climate Forcing. Climate forcing refers to a change in the Earth's energy balance, leading to either a warming or cooling effect. An increase in the atmospheric concentrations of greenhouse gases produces a positive climate forcing, or warming effect. From 1990 to 2013, the total warming effect from greenhouse gases added by humans to the Earth's atmosphere increased by 34 percent. The warming effect associated with carbon dioxide alone increased by 27 percent.



U.S. Greenhouse Gas Emissions

This indicator describes emissions of greenhouse gases in the United States.

KEY POINTS

- In 2012, U.S. greenhouse gas emissions totaled 6,526 million metric tons (14.4 trillion pounds) of carbon dioxide equivalents. This 2012 total represents a 5 percent increase since 1990 but a 10 percent decrease since 2005 (see Figure 1).
- For the United States, during the period from 1990 to 2012 (see Figure 1):
  - Emissions of carbon dioxide, the primary greenhouse gas emitted by human activities, increased by 5 percent.
  - Methane emissions decreased by 11 percent, as reduced emissions from landfills, coal mines, and natural gas systems were greater than increases in emissions from activities such as livestock production.[3]
  - Nitrous oxide emissions, predominantly from agricultural soil management practices such as the use of nitrogen as a fertilizer, increased by nearly 3 percent.
  - Emissions of fluorinated gases (hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride), released as a result of commercial, industrial, and household uses, increased by 83 percent.
- Electricity generation is the largest U.S. emissions source, accounting for 32 percent of total greenhouse gas emissions since 1990. Transportation is the second-largest source of greenhouse gas emissions, accounting for 27 percent of emissions since 1990 (see Figure 2).
- Emissions sinks, the opposite of emissions sources, absorb carbon dioxide from the atmosphere. In 2012, 15 percent of U.S. greenhouse gas emissions were offset by sinks resulting from land use and forestry practices (see Figure 2). One major sink is the net growth of forests, which remove

(Continued on p. 15)

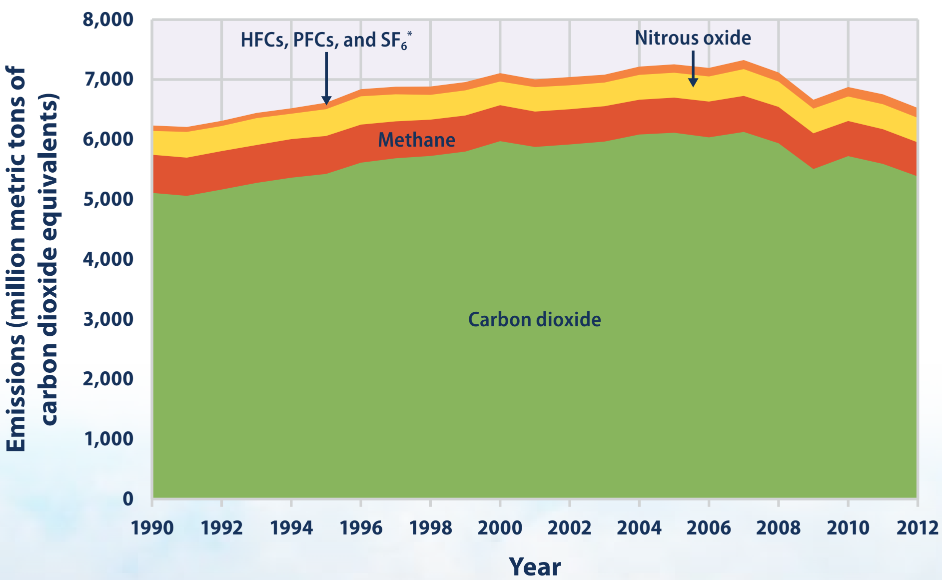
A number of factors influence the quantities of greenhouse gases released into the atmosphere, including economic activity, population, consumption patterns, energy prices, land use, and technology. There are several ways to track these emissions, such as by measuring emissions directly, calculating emissions based on the amount of fuel that people burn, and estimating other activities and their associated emissions. EPA has two key programs that provide data on greenhouse gas emissions in the United States: the Inventory of U.S. Greenhouse Gas Emissions and Sinks and the Greenhouse Gas Reporting Program. See "Sources of Data on U.S. Greenhouse Gas Emissions" (on p. 16) to learn more about these programs.

ABOUT THE INDICATOR

This indicator focuses on emissions of carbon dioxide, methane, nitrous oxide, and several fluorinated gases—all important greenhouse gases that are influenced by human activities. These particular gases are covered under the United Nations Framework Convention on Climate Change, an international agreement that requires participating countries to develop and periodically submit an inventory of greenhouse gas emissions. Data and analysis for this indicator come from EPA's annual inventory submission, the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012.*[4] This indicator is restricted to emissions associated with human activities.

Each greenhouse gas has a different lifetime (how long it stays in the atmosphere) and a different ability to trap heat in our atmosphere. To allow different gases to be compared and added together, emissions are converted into carbon dioxide equivalents. This step uses each gas's 100-year global warming potential, which measures how much a given amount of the gas is estimated to contribute to global warming over a period of 100 years after being emitted. Carbon dioxide is assigned a global warming potential equal to 1. This analysis uses global warming potentials from the Intergovernmental Panel on Climate Change's (IPCC's) Second Assessment Report. In that report, methane has a global warming potential of 21, which means a ton of methane emissions contributes 21 times as much warming as a ton of carbon dioxide emissions over 100 years, and that ton of methane emissions is therefore equal to 21 tons of carbon dioxide equivalents. See the table on p. 7 for comparison with global warming potentials from IPCC's Fifth Assessment Report. For additional perspective, this indicator also shows greenhouse gas emissions in relation to economic output and population.

Figure 1. U.S. Greenhouse Gas Emissions by Gas, 1990–2012

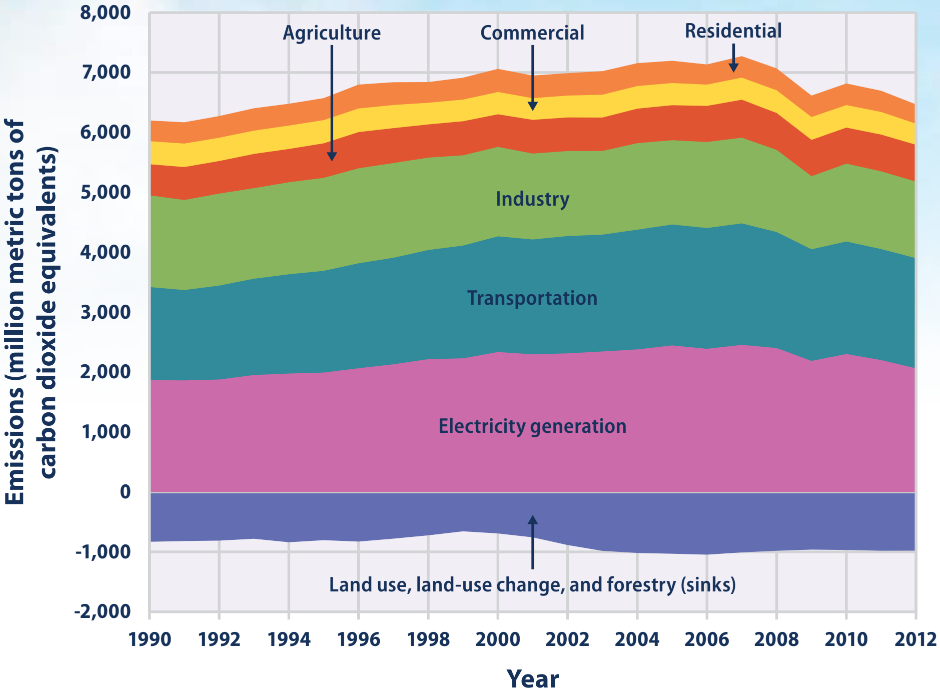


This figure shows emissions of carbon dioxide, methane, nitrous oxide, and several fluorinated gases in the United States from 1990 to 2012. For consistency, emissions are expressed in million metric tons of carbon dioxide equivalents.

** HFCs are hydrofluorocarbons, PFCs are perfluorocarbons, and SF_6 is sulfur hexafluoride.*

Data source: U.S. EPA, 2014[5]

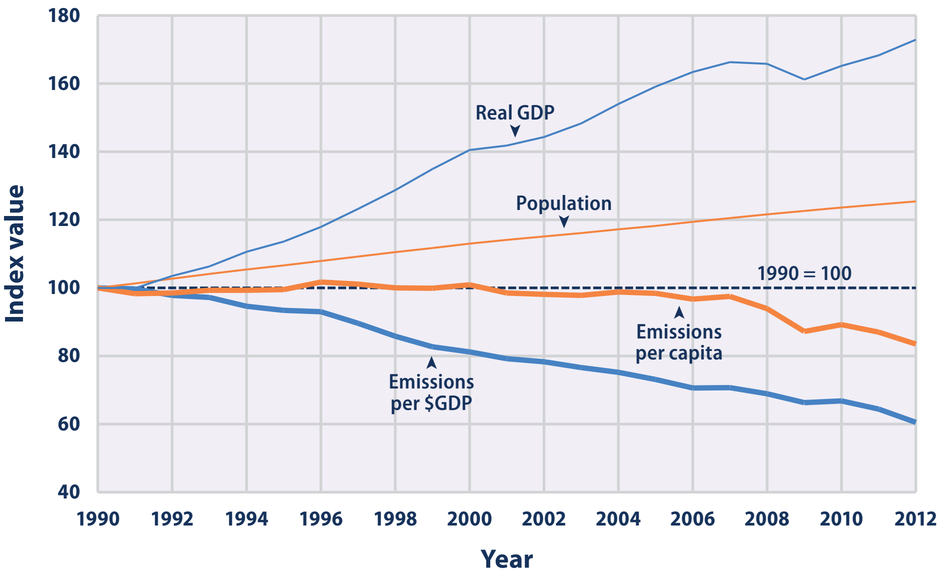
Figure 2. U.S. Greenhouse Gas Emissions and Sinks by Economic Sector, 1990–2012



This figure shows greenhouse gas emissions and sinks (negative values) by source in the United States from 1990 to 2012. For consistency, emissions are expressed in million metric tons of carbon dioxide equivalents. All electric power emissions are grouped together in the "Electricity generation" sector, so other sectors such as "Residential" and "Commercial" are only showing non-electric sources, such as burning oil or gas for heating. Totals do not match Figure 1 exactly because the economic sectors shown here do not include emissions from U.S. territories outside the 50 states.

Data source: U.S. EPA, 2014[6]

Figure 3. U.S. Greenhouse Gas Emissions per Capita and per Dollar of GDP, 1990–2012



This figure shows trends in greenhouse gas emissions from 1990 to 2012 per capita (heavy orange line), based on the total U.S. population (thin orange line). It also shows trends in emissions per dollar of real GDP (heavy blue line). Real GDP (thin blue line) is the value of all goods and services produced in the country during a given year, adjusted for inflation. All data are indexed to 1990 as the base year, which is assigned a value of 100. For instance, a real GDP value of 173 in the year 2012 would represent a 73 percent increase since 1990.

Data source: U.S. EPA, 2014[7]

KEY POINTS

(Continued from p. 14)

carbon from the atmosphere. Other carbon sinks are associated with how people use the land, including the practice of depositing yard trimmings and food scraps in landfills.

- **Emissions increased at about the same rate as the population from 1990 to 2007, which caused emissions per capita to remain fairly level (see Figure 3). Total emissions and emissions per capita declined from 2007 to 2009, due in part to a drop in U.S. economic production during this time. Emissions decreased again from 2010 to 2012, largely due to the growing use of natural gas to generate electricity in place of more carbon-intensive fuels.[8]**
- **From 1990 to 2012, greenhouse gas emissions per dollar of goods and services produced by the U.S. economy (the gross domestic product or GDP) declined by 39 percent (see Figure 3). This change may reflect a combination of increased energy efficiency and structural changes in the economy.**

INDICATOR NOTES

While this indicator includes the major greenhouse gases emitted by human activities, it does not include other greenhouse gases and substances that are not covered under the United Nations Framework Convention on Climate Change but that still affect the Earth's energy balance and climate (see the Climate Forcing indicator on p. 24 for more details). For example, this indicator excludes ozone-depleting substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which have high global warming potentials, as these gases have been or are currently being phased out under an international agreement called the Montreal Protocol. This indicator also excludes black carbon and aerosols, which most greenhouse gas emissions inventories do not cover. There are also many natural greenhouse gas emissions sources; however, this indicator includes only emissions that are associated with human activities—those that are most responsible for the observed buildup of these gases in our atmosphere.

DATA SOURCES

Data for this indicator came from EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012.* This report is available online at: www.epa.gov/climatechange/ghgemissions/usinventoryreport.html. The calculations in Figure 3 are based on GDP and population data provided by the U.S. Bureau of Economic Analysis and the U.S. Census, respectively.

Sources of Data on U.S. Greenhouse Gas Emissions

EPA has two key programs that provide data on greenhouse gas emissions in the United States: the Inventory of U.S. Greenhouse Gas Emissions and Sinks and the Greenhouse Gas Reporting Program.

EPA'S INVENTORY OF GREENHOUSE GAS EMISSIONS AND SINKS

EPA develops an annual report called the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (or the Greenhouse Gas Inventory). This report tracks trends in total annual U.S. emissions by source (or sink), economic sector, and greenhouse gas going back to 1990. EPA uses national energy data, data on national agricultural activities, and other national statistics to provide a comprehensive accounting of total greenhouse gas emissions for all man-made sources in the United States. This inventory fulfills the nation's obligation to provide an annual emissions report under the United Nations Framework Convention on Climate Change.

EPA'S GREENHOUSE GAS REPORTING PROGRAM

EPA's Greenhouse Gas Reporting Program collects annual emissions data from industrial sources that directly emit large amounts of greenhouse gases. Generally, facilities that emit more than 25,000 metric tons of carbon dioxide equivalents per year are required to report. The program also collects data from entities known as "suppliers" that supply certain fossil fuels and industrial gases that will emit greenhouse gases into the atmosphere if burned or released—for example, refineries that supply petroleum products such as gasoline. The Greenhouse Gas Reporting Program only requires reporting; it is not an emissions control program. This program helps EPA and the public understand where greenhouse gas emissions are coming from, and will improve our ability to make informed policy, business, and regulatory decisions. This program:

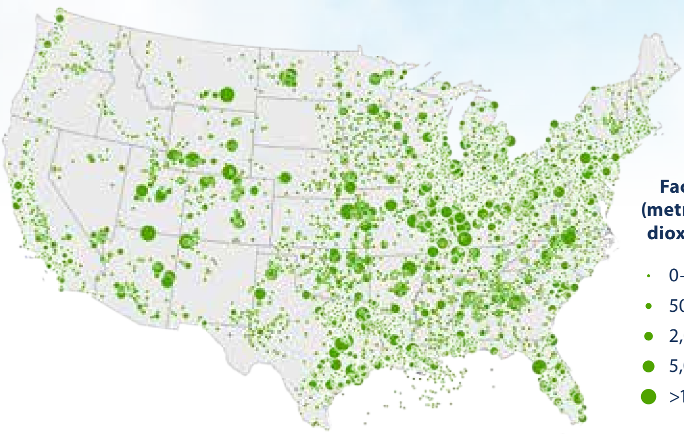
- Covers carbon dioxide, methane, nitrous oxide, and fluorinated gases.
- Represents 85 to 90 percent of U.S. greenhouse gas emissions.
- Covers 41 industrial categories (for example, power plants, oil and gas producers, landfills, and other industrial facilities).
- Collects greenhouse gas data from more than 8,000 entities.

Visit: www.epa.gov/ghgreporting to learn more about the sources that report data.

EPA's Greenhouse Gas Reporting Program provides facility-level information and allows people to track changes in greenhouse gas emissions in various industries, geographic areas, and industrial facilities. EPA has now verified three years of data and made them publicly available.

Data from the Greenhouse Gas Reporting Program are easily accessible from EPA's website at: www.epa.gov/ghgreporting/ghgdata/index.html. Visitors can explore data by facility, industry, location, or gas using a data visualization and mapping tool called FLIGHT.

Facilities That Directly Emit Greenhouse Gases and Report to EPA's Greenhouse Gas Reporting Program (2012)



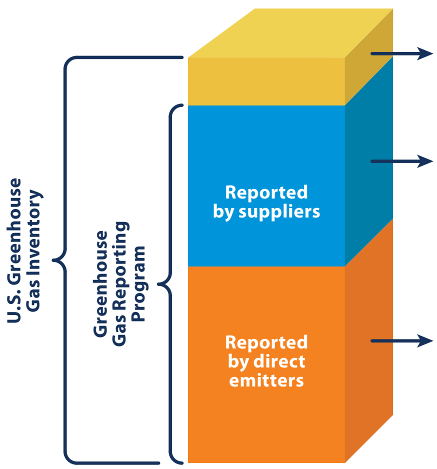
COMPARING THE SOURCES

EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks presents annual national-level greenhouse gas emissions estimates from 1990 to the present. It estimates the total greenhouse gas emissions across all sectors of the economy using national-level data. This inventory and its 20+ years of data serve as the basis for this report's U.S. Greenhouse Gas Emissions indicator (p. 14).

In contrast, the Greenhouse Gas Reporting Program is a relatively new program that began collecting data in 2010. The reporting program collects detailed emissions data from the largest greenhouse gas emitting facilities in the United States.

While the inventory provides high-level perspective needed to understand the United States' total emissions or "carbon footprint," the Greenhouse Gas Reporting Program provides detailed information that helps us better understand the sources and types of greenhouse gas emissions at individual facilities. The inventory provides a more complete estimate of total U.S. emissions because it accounts for some sources that the reporting program does not cover (see diagram at right). Thus, the inventory and the reporting program are complementary tools.

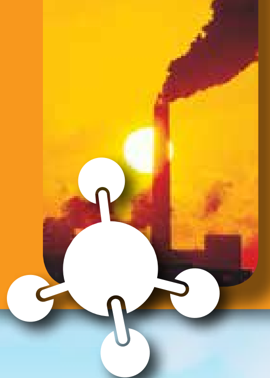
Comparing EPA's Two Sources of Data on Greenhouse Gas Emissions



flight

Facility Level Information on GreenHouse gases Tool

A snapshot of FLIGHT: EPA'S Greenhouse Gas Reporting Program data visualization and mapping tool: http://ghgdata.epa.gov.



Global Greenhouse Gas Emissions

This indicator describes emissions of greenhouse gases worldwide.

KEY POINTS

- In 2010, estimated worldwide emissions from human activities totaled nearly 46 billion metric tons of greenhouse gases, expressed as carbon dioxide equivalents. This represents a 35 percent increase from 1990 (see Figures 1 and 2). These numbers represent net emissions, which include the effects of land use and forestry.
- Between 1990 and 2010, global emissions of all major greenhouse gases increased (see Figure 1). Net emissions of carbon dioxide increased by 42 percent, which is particularly important because carbon dioxide accounts for about three-fourths of total global emissions. Nitrous oxide emissions increased the least—9 percent—while emissions of methane increased by 15 percent. Emissions of fluorinated gases more than doubled.
- Energy production and use (including fuels used by vehicles) represent the largest source of greenhouse gas emissions worldwide (about 71 percent of the total in 2010), followed by agriculture (13 percent in 2010) (see Figure 2). While land-use change and forestry represent a net sink for emissions in the United States, absorbing carbon dioxide and offsetting emissions from other sources (see the U.S. Greenhouse Gas Emissions indicator on p. 14), these activities are a net source of emissions on a global scale, largely because of deforestation.[9]
- Carbon dioxide emissions are increasing faster in some parts of the world (for example, Asia) than in others (see Figure 3). The majority of emissions come from three regions: Asia, Europe, and the United States, which together accounted for 82 percent of total global emissions in 2011.

Increasing emissions of greenhouse gases due to human activities worldwide have led to a substantial increase in atmospheric concentrations of long-lived and other greenhouse gases (see the Atmospheric Concentrations of Greenhouse Gases indicator on p. 20). Every country around the world emits greenhouse gases into the atmosphere, meaning the root cause of climate change is truly global in scope. Some countries produce far more greenhouse gases than others, and several factors—such as economic activity, population, income level, land use, and climatic conditions—can influence a country's emissions levels. Tracking greenhouse gas emissions worldwide provides a global context for understanding the United States' and other nations' roles in climate change.

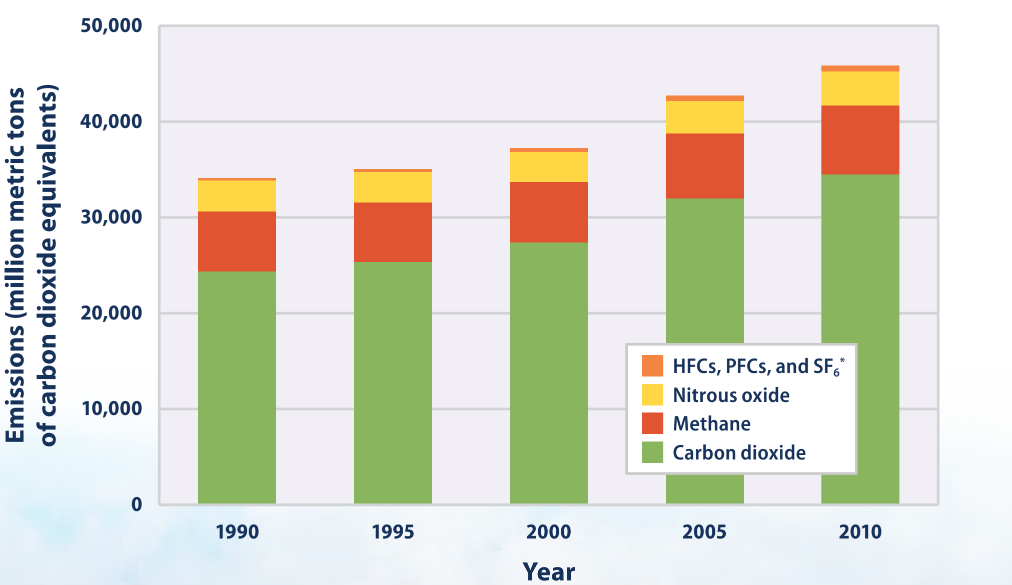
ABOUT THE INDICATOR

Like the U.S. Greenhouse Gas Emissions indicator (on p. 14), this indicator focuses on emissions of gases covered under the United Nations Framework Convention on Climate Change: carbon dioxide, methane, nitrous oxide, and several fluorinated gases. These are all important greenhouse gases that are influenced by human activities, and the Convention requires participating countries to develop and periodically submit an inventory of these emissions.

Data and analysis for this indicator come from the World Resources Institute's Climate Analysis Indicators Tool (CAIT), which compiles data from peer-reviewed and internationally recognized greenhouse gas inventories developed by EPA and other government agencies worldwide. Global estimates for carbon dioxide are published annually, but estimates for other gases, such as methane and nitrous oxide, are available only every fifth year. CAIT includes estimates of emissions and sinks associated with land use and forestry activities, which come from global estimates compiled by the Food and Agriculture Organization of the United Nations.

Each greenhouse gas has a different lifetime (how long it stays in the atmosphere) and a different ability to trap heat in our atmosphere. To allow different gases to be compared and added together, emissions are converted into carbon dioxide equivalents. This step uses each gas's 100-year global warming potential, which measures how much a given amount of the gas is estimated to contribute to global warming over a period of 100 years after being emitted. Carbon dioxide is assigned a global warming potential equal to 1.

Figure 1. Global Greenhouse Gas Emissions by Gas, 1990–2010

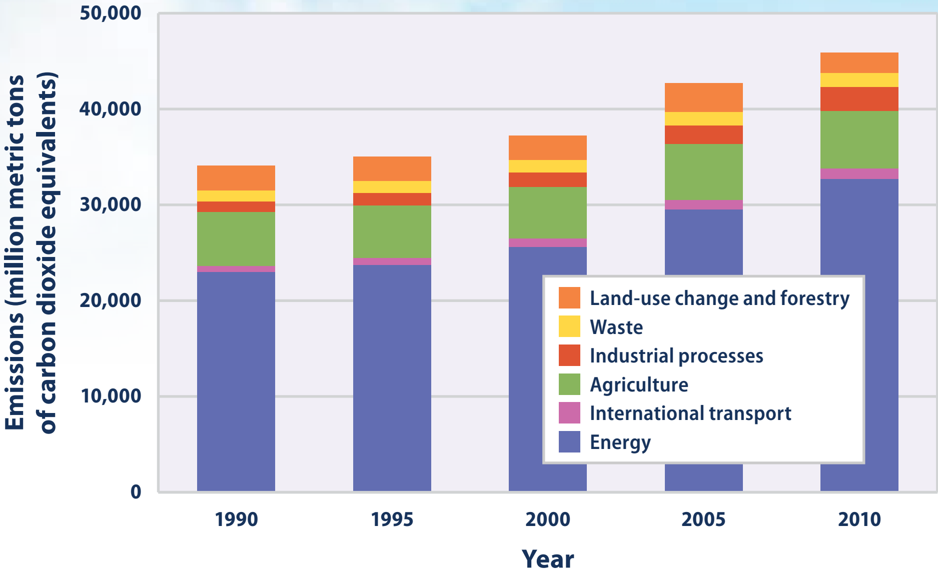


This figure shows worldwide emissions of carbon dioxide, methane, nitrous oxide, and several fluorinated gases from 1990 to 2010. For consistency, emissions are expressed in million metric tons of carbon dioxide equivalents. These totals include emissions and sinks due to land-use change and forestry.

** HFCs are hydrofluorocarbons, PFCs are perfluorocarbons, and SF_6 is sulfur hexafluoride.*

Data source: WRI, 2014;[10] FAO, 2014[11]

Figure 2. Global Greenhouse Gas Emissions by Sector, 1990–2010

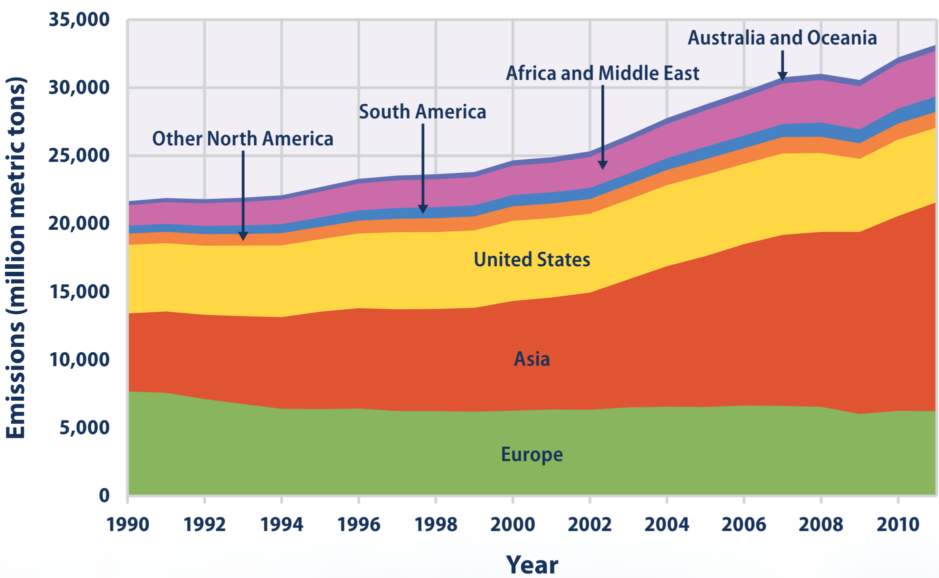


This figure shows worldwide greenhouse gas emissions by sector from 1990 to 2010. For consistency, emissions are expressed in million metric tons of carbon dioxide equivalents. These totals include emissions and sinks due to land-use change and forestry.

Note that the sectors shown here are different from the economic sectors used in U.S. emissions accounting (see the U.S. Greenhouse Gas Emissions indicator on p. 14). Emissions from international transport (aviation and marine) are separate from the energy sector because they are not part of individual countries' emissions inventories. The energy sector includes all other transportation activities.

Data source: WRI, 2014;[12] FAO, 2014[13]

Figure 3. Global Carbon Dioxide Emissions by Region, 1990–2011



This figure shows carbon dioxide emissions from 1990 to 2011 for different regions of the world. These totals do not include emissions or sinks related to land-use change or forestry. Inclusion of land-use change and forestry would increase the apparent emissions from some regions while decreasing the emissions from others.

Data source: WRI, 2014[14]

This analysis uses global warming potentials from the Intergovernmental Panel on Climate Change's (IPCC's) Second Assessment Report. In that report, methane has a global warming potential of 21, which means a ton of methane emissions contributes 21 times as much warming as a ton of carbon dioxide emissions over 100 years, and that ton of methane emissions is therefore equal to 21 tons of carbon dioxide equivalents. See the table on p. 7 for comparison with global warming potentials from IPCC's Fifth Assessment Report.

INDICATOR NOTES

Like the U.S. Greenhouse Gas Emissions indicator (on p. 14), this indicator does not include emissions of gases that affect climate but are not covered under the United Nations Framework Convention on Climate Change. For example, this indicator excludes ozone-depleting substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which have high global warming potentials, because these gases have been or are currently being phased out under an international agreement called the Montreal Protocol. This indicator also excludes black carbon and aerosols, which most emissions inventories do not cover. There are also various emissions of greenhouse gases of natural origin, which this indicator does not cover.

Global emissions inventories for gases other than carbon dioxide are limited to five-year intervals. The United Nations Framework Convention on Climate Change database has more comprehensive data; however, these data are available mainly for a group of mostly developed countries that account for only about half of global greenhouse gas emissions. Thus, to provide a more representative measure of global greenhouse gas emissions, this indicator uses the broader CAIT database.

DATA SOURCES

Data for this indicator came from the World Resources Institute's CAIT database, which is accessible online at: http://cait.wri.org. CAIT compiles data that were originally collected by organizations including the International Energy Agency, EPA, the U.S. Carbon Dioxide Information Analysis Center, and the Food and Agriculture Organization of the United Nations. Other global emissions estimates—such as the estimates published by the Intergovernmental Panel on Climate Change[15]—are based on many of the same sources.

Atmospheric Concentrations of Greenhouse Gases

This indicator describes how the levels of major greenhouse gases in the atmosphere have changed over time.

KEY POINTS

- Global atmospheric concentrations of carbon dioxide, methane, nitrous oxide, and certain manufactured greenhouse gases have all risen significantly over the last few hundred years (see Figures 1, 2, 3, and 4).
- Historical measurements show that the current global atmospheric concentrations of carbon dioxide, methane, and nitrous oxide are unprecedented compared with the past 800,000 years (see Figures 1, 2, and 3).

WATER VAPOR AS A GREENHOUSE GAS

Water vapor is the most abundant greenhouse gas in the atmosphere. Human activities have only a small direct influence on atmospheric concentrations of water vapor, primarily through irrigation and deforestation, so it is not included in this indicator.[16] However, the surface warming caused by human production of other greenhouse gases leads to an increase in atmospheric water vapor, because warmer temperatures make it easier for water to evaporate and stay in the air in vapor form. This creates a positive "feedback loop" in which warming leads to more warming.

Since the Industrial Revolution began in the 1700s, people have added a substantial amount of greenhouse gases into the atmosphere by burning fossil fuels, cutting down forests, and conducting other activities (see the U.S. and Global Greenhouse Gas Emissions indicators on pp. 14 and 18). When greenhouse gases are emitted into the atmosphere, many remain there for long time periods ranging from a decade to many millennia. Over time, these gases are removed from the atmosphere by chemical reactions or by emissions sinks, such as the oceans and vegetation, which absorb greenhouse gases from the atmosphere. However, as a result of human activities, these gases are entering the atmosphere more quickly than they are being removed, and thus their concentrations are increasing.

Carbon dioxide, methane, nitrous oxide, and certain manufactured gases called halogenated gases (gases that contain chlorine, fluorine, or bromine) become well mixed throughout the global atmosphere because of their relatively long lifetimes and because of transport by winds. Concentrations of these greenhouse gases are measured in parts per million (ppm), parts per billion (ppb), or parts per trillion (ppt) by volume. In other words, a concentration of 1 ppb for a given gas means there is one molecule of that gas in every 1 billion molecules of air. Some halogenated gases are considered major greenhouse gases due to their very high global warming potentials and long atmospheric lifetimes even if they only exist at a few ppt (see table on p. 7).

Ozone is also a greenhouse gas, but it differs from other greenhouse gases in several ways. The effects of ozone depend on its altitude, or where the gas is located vertically in the atmosphere. Most ozone naturally exists in the layer of the atmosphere called the stratosphere, which ranges from approximately 6 to 30 miles above the Earth's surface. Ozone in the stratosphere has a slight net warming effect on the planet, but it is good for life on Earth because it absorbs harmful ultraviolet radiation from the sun, preventing it from reaching the Earth's surface. In the troposphere—the layer of the atmosphere near ground level—ozone is an air pollutant that is harmful to breathe, a main ingredient of urban smog, and an important greenhouse gas that contributes to climate change (see the Climate Forcing indicator on p. 24). Unlike the other major greenhouse gases, tropospheric ozone only lasts for days to weeks, so levels often vary by location and by season.

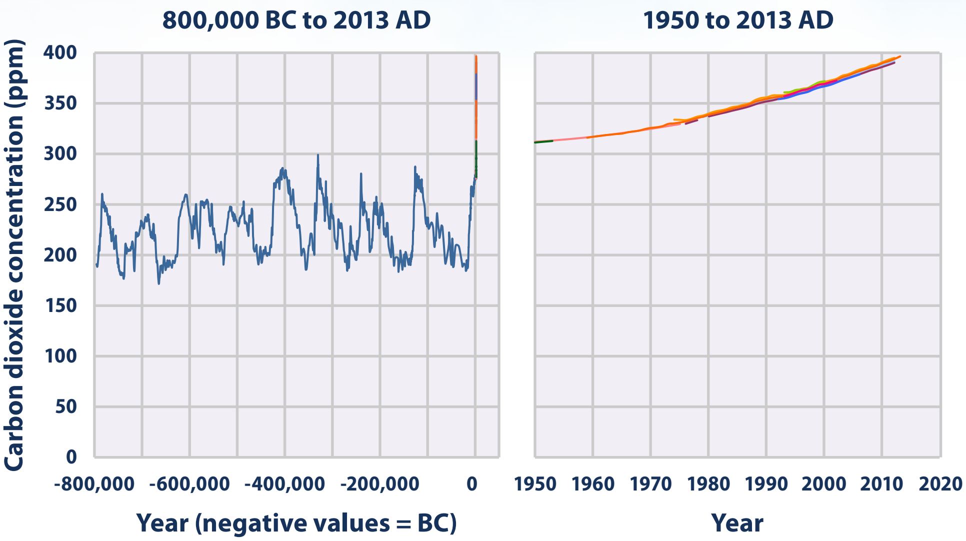
ABOUT THE INDICATOR

This indicator describes concentrations of greenhouse gases in the atmosphere. It focuses on the major greenhouse gases that result from human activities.

For carbon dioxide, methane, nitrous oxide, and halogenated gases, recent measurements come from monitoring stations around the world, while measurements of older air come from air bubbles trapped in layers of ice from Antarctica and Greenland. By determining the age of the ice layers and the concentrations of gases trapped inside, scientists can learn what the atmosphere was like thousands of years ago.

This indicator also shows data from satellite instruments that measure ozone density in the troposphere, the stratosphere, and the "total column," or all layers of the atmosphere. These satellite data are routinely compared with ground-based instruments to confirm their accuracy. Ozone data have been averaged worldwide for each year to smooth out the regional and seasonal variations.

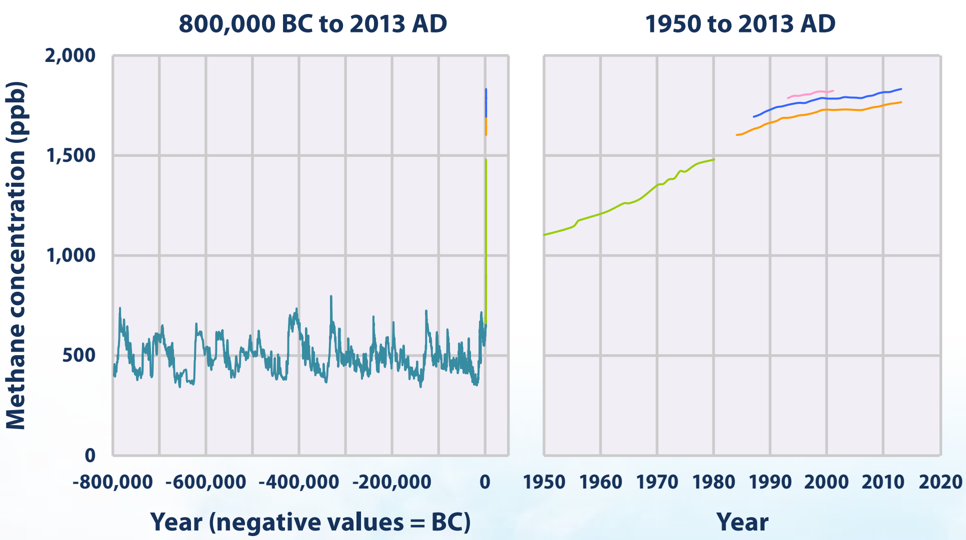
Figure 1. Global Atmospheric Concentrations of Carbon Dioxide Over Time



This figure shows concentrations of carbon dioxide in the atmosphere from hundreds of thousands of years ago through 2013, measured in parts per million (ppm). The data come from a variety of historical ice core studies and recent air monitoring sites around the world. Each line represents a different data source.

Data source: Compilation of 10 underlying datasets[17]

Figure 2. Global Atmospheric Concentrations of Methane Over Time



This figure shows concentrations of methane in the atmosphere from hundreds of thousands of years ago through 2013, measured in parts per billion (ppb). The data come from a variety of historical ice core studies and recent air monitoring sites around the world. Each line represents a different data source.

Data source: Compilation of five underlying datasets[18]

KEY POINTS

- **Carbon dioxide concentrations have increased steadily since the beginning of the industrial era, rising from an annual average of 280 ppm in the late 1700s to 396 ppm at Mauna Loa in 2013—a 41 percent increase (see Figure 1). Almost all of this increase is due to human activities.[19]**
- **The concentration of methane in the atmosphere has more than doubled since preindustrial times, reaching approximately 1,800 ppb in 2013 (see the range of measurements in Figure 2). This increase is predominantly due to agriculture and fossil fuel use.[20]**

(Continued on next page)

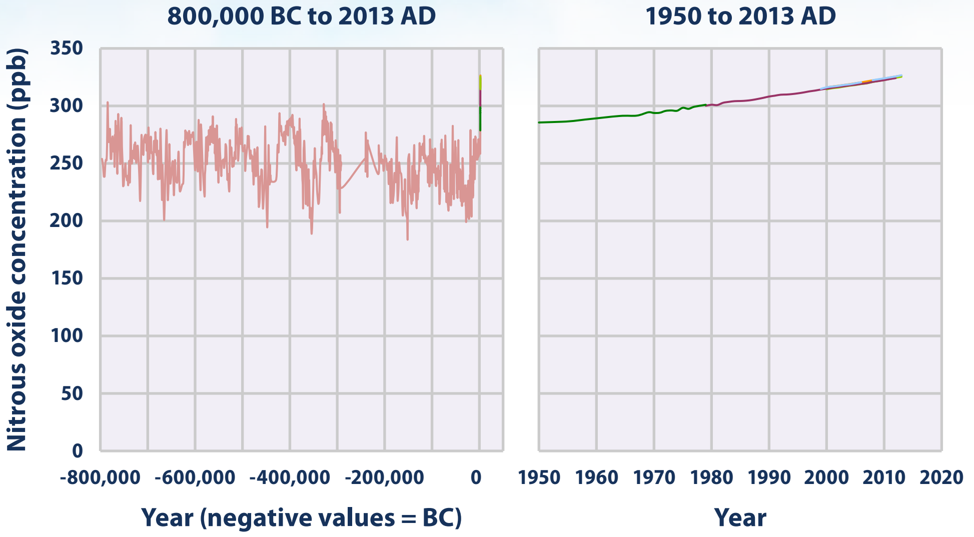
Atmospheric Concentrations of Greenhouse Gases

Continued

KEY POINTS

- Over the past 800,000 years, concentrations of nitrous oxide in the atmosphere rarely exceeded 280 ppb. Levels have risen since the 1920s, however, reaching a new high of 326 ppb in 2013 (average of three sites in Figure 3). This increase is primarily due to agriculture.[21]
- Concentrations of many of the halogenated gases shown in Figure 4 were essentially zero a few decades ago but have increased rapidly as they have been incorporated into industrial products and processes. Some of these chemicals have been or are currently being phased out of use because they are ozone-depleting substances, meaning they also cause harm to the Earth's protective ozone layer. As a result, concentrations of many major ozone-depleting gases have begun to stabilize or decline (see Figure 4, left panel). Concentrations of other halogenated gases have continued to rise, however, especially where the gases have emerged as substitutes for ozone-depleting chemicals (see Figure 4, right panel).

Figure 3. Global Atmospheric Concentrations of Nitrous Oxide Over Time



This figure shows concentrations of nitrous oxide from hundreds of thousands of years ago through 2013, measured in parts per billion (ppb). The data come from a variety of historical ice core studies and recent air monitoring sites around the world. Each line represents a different data source.

Data source: Compilation of six underlying datasets[22]

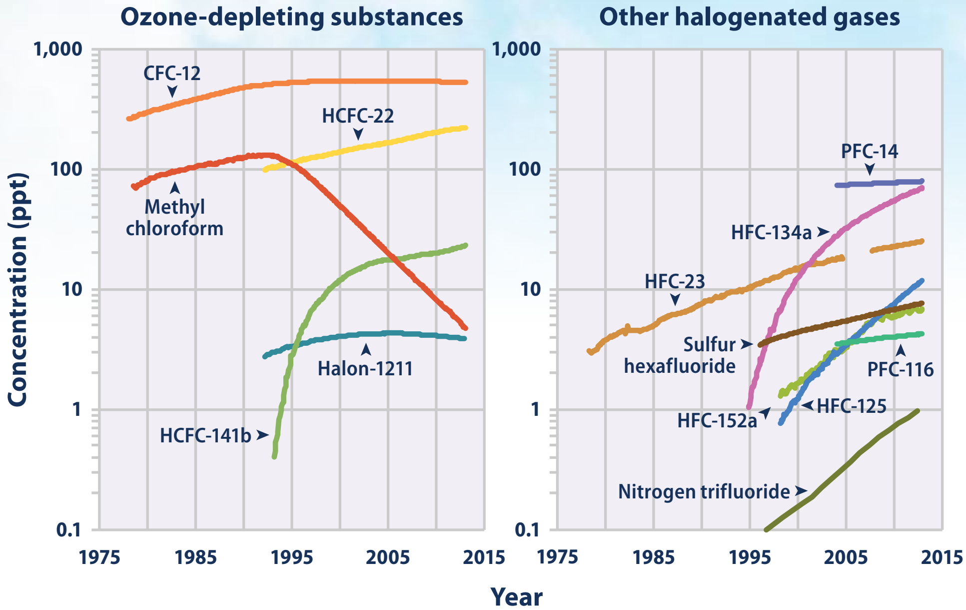
INDICATOR NOTES

This indicator includes several of the most important halogenated gases, but some others are not shown. Many other halogenated gases are also greenhouse gases, but Figure 4 is limited to a set of common examples that represent most of the major types of these gases. The indicator also does not address certain other pollutants that can affect climate by either reflecting or absorbing energy. For example, sulfate particles can reflect sunlight away from the Earth, while black carbon aerosols (soot) absorb energy. Data for nitrogen trifluoride (Figure 4) reflect modeled averages based on measurements made in the Northern Hemisphere and some locations in the Southern Hemisphere, to represent global average concentrations over time. The global averages for ozone only cover the area between 50°N and 50°S latitude (77 percent of the Earth's surface), because at higher latitudes the lack of sunlight in winter creates data gaps and the angle of incoming sunlight during the rest of the year reduces the accuracy of the satellite measuring technique.

DATA SOURCES

Global atmospheric concentration measurements for carbon dioxide (Figure 1), methane (Figure 2), and nitrous oxide (Figure 3) come from a variety of monitoring programs and studies published in peer-reviewed literature. Global atmospheric concentration data for selected halogenated gases (Figure 4) were compiled by the Advanced Global Atmospheric Gases Experiment, the National Oceanic and Atmospheric Administration, and a peer-reviewed study on nitrogen trifluoride. A similar figure with many of these gases appears in the Intergovernmental Panel on Climate Change's Fifth Assessment Report.[23] Satellite measurements of ozone were processed by the National Aeronautics and Space Administration and validated using ground-based measurements collected by the National Oceanic and Atmospheric Administration.

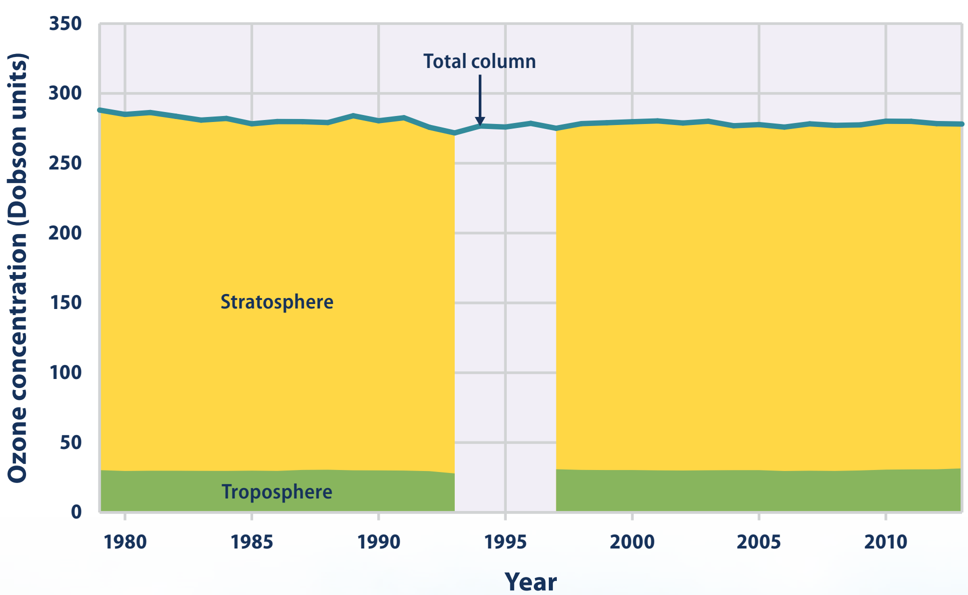
Figure 4. Global Atmospheric Concentrations of Selected Halogenated Gases, 1978–2012



This figure shows concentrations of several halogenated gases (which contain fluorine, chlorine, or bromine) in the atmosphere, measured in parts per trillion (ppt). The data come from monitoring sites around the world. Note that the scale increases by factors of 10. This is because the concentrations of different halogenated gases can vary by a few orders of magnitude. The numbers following the name of each gas (e.g., HCFC-22) are used to denote specific types of those particular gases.

Data sources: AGAGE, 2014;[24] Arnold, 2013;[25] NOAA, 2013[26]

Figure 5. Global Atmospheric Concentrations of Ozone, 1979–2013

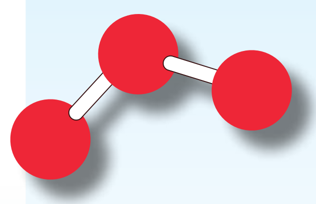


This figure shows the average amount of ozone in the Earth's atmosphere each year, based on satellite measurements. The total represents the "thickness" or density of ozone throughout all layers of the Earth's atmosphere, which is called total column ozone and measured in Dobson units. Higher numbers indicate more ozone. For most years, Figure 5 shows how this ozone is divided between the troposphere (the part of the atmosphere closest to the ground) and the stratosphere. From 1994 to 1996, only the total is available, due to limited satellite coverage.

Data sources: NASA, 2013,[27] 2014[28,29]

KEY POINTS

- Overall, the total amount of ozone in the atmosphere decreased by about 3 percent between 1979 and 2013 (see Figure 5). All of the decrease happened in the stratosphere, with most of the decrease occurring between 1979 and 1994. Changes in stratospheric ozone reflect the effect of ozone-depleting substances. These chemicals have been released into the air for many years, but recently, international efforts have reduced emissions and phased out their use.
- Globally, the amount of ozone in the troposphere increased by about 4 percent between 1979 and 2013 (see Figure 5).



This indicator looks at global average levels of ozone in both the stratosphere and troposphere. For trends in ground-level ozone concentrations within the United States, see EPA's National Air Quality Trends Report at: www.epa.gov/airtrends.

Climate Forcing

This indicator measures the "radiative forcing" or heating effect caused by greenhouse gases in the atmosphere.

KEY POINTS

- In 2013, the Annual Greenhouse Gas Index was 1.34, which represents a 34 percent increase in radiative forcing (a net warming influence) since 1990 (see Figure 1).
- Of the greenhouse gases shown in Figure 1, carbon dioxide accounts for by far the largest share of radiative forcing since 1990, and its contribution continues to grow at a steady rate. Carbon dioxide alone would account for a 27 percent increase in radiative forcing since 1990.
- Although the overall Annual Greenhouse Gas Index continues to rise, the rate of increase has slowed somewhat over time. This change has occurred in large part because methane concentrations have increased at a slower rate in recent years and because chlorofluorocarbon (CFC) concentrations have been declining, as production of CFCs has been phased out globally due to the harm they cause to the ozone layer (see Figure 1).
- Greenhouse gases produced by human activities have caused an overall warming influence on the Earth's climate since 1750. The largest contributor to warming has been carbon dioxide, followed by methane, and black carbon. Although aerosol pollution and certain other activities have caused cooling, the net result is that human activities on the whole have warmed the Earth (see Figure 2).

When energy from the sun reaches the Earth, the planet absorbs some of this energy and radiates the rest back to space as heat. The Earth's surface temperature depends on this balance between incoming and outgoing energy. Average conditions tend to remain stable unless the Earth experiences a force that shifts the energy balance. A shift in the energy balance causes the Earth's average temperature to become warmer or cooler, leading to a variety of other changes in the lower atmosphere, on land, and in the oceans.

A variety of physical and chemical changes can affect the global energy balance and force changes in the Earth's climate. Some of these changes are natural, while others are influenced by humans. These changes are measured by the amount of warming or cooling they can produce, which is called "radiative forcing." Changes that have a warming effect are called "positive" forcing, while changes that have a cooling effect are called "negative" forcing. When positive and negative forces are out of balance, the result is a change in the Earth's average surface temperature.

Changes in greenhouse gas concentrations in the atmosphere affect radiative forcing (see the Atmospheric Concentrations of Greenhouse Gases indicator on p. 20). Greenhouse gases absorb energy that radiates upward from the Earth's surface, re-emitting heat to the lower atmosphere and warming the Earth's surface. Human activities have led to increased concentrations of greenhouse gases that can remain in the atmosphere for decades, centuries, or longer, so the corresponding warming effects will last for a long time.

ABOUT THE INDICATOR

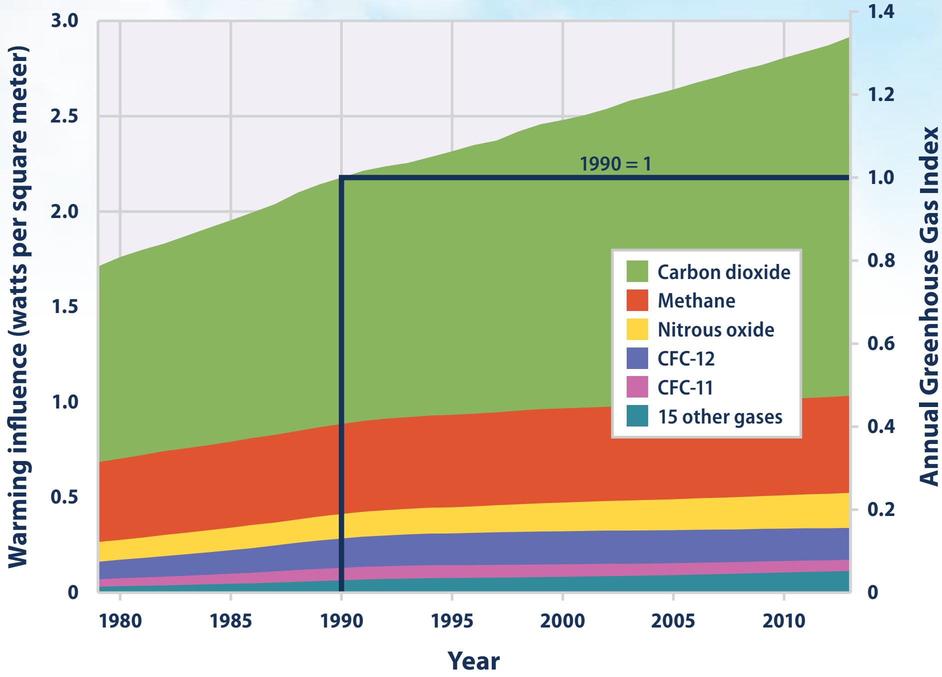
Figure 1 of this indicator measures the average total radiative forcing of 20 long-lived greenhouse gases, including carbon dioxide, methane, and nitrous oxide. The results were calculated by the National Oceanic and Atmospheric Administration based on measured concentrations of the gases in the atmosphere, compared with the concentrations that were present around 1750, before the Industrial Revolution began. Because each gas has a different ability to absorb and emit energy, this indicator converts the changes in greenhouse gas concentrations into a measure of the total radiative forcing (warming effect) caused by each gas. Radiative forcing is calculated in watts per square meter, which represents the size of the energy imbalance in the atmosphere.

The National Oceanic and Atmospheric Administration also translates the total radiative forcing of these measured gases into an index value called the Annual Greenhouse Gas Index (right side of Figure 1). This number compares the radiative forcing for a particular year with the radiative forcing in 1990, which is a common baseline year for global agreements to track and reduce greenhouse gas emissions.

For reference, this indicator also presents an estimate of the total radiative forcing associated with a variety of human activities from 1750 to the present. Figure 2 shows the influence of:

- Tropospheric ozone, a short-lived greenhouse gas.
- Emissions that indirectly lead to greenhouse gases through chemical reactions in the atmosphere. For example, methane emissions also lead to an increase in tropospheric ozone.
- Aerosol pollution, which consists of solid and liquid particles suspended in the air that can reflect incoming sunlight.
- Black carbon (soot), which can make the Earth's surface darker and less reflective when it is deposited on snow and ice.
- Several other factors, like land use change, that affect radiative forcing.

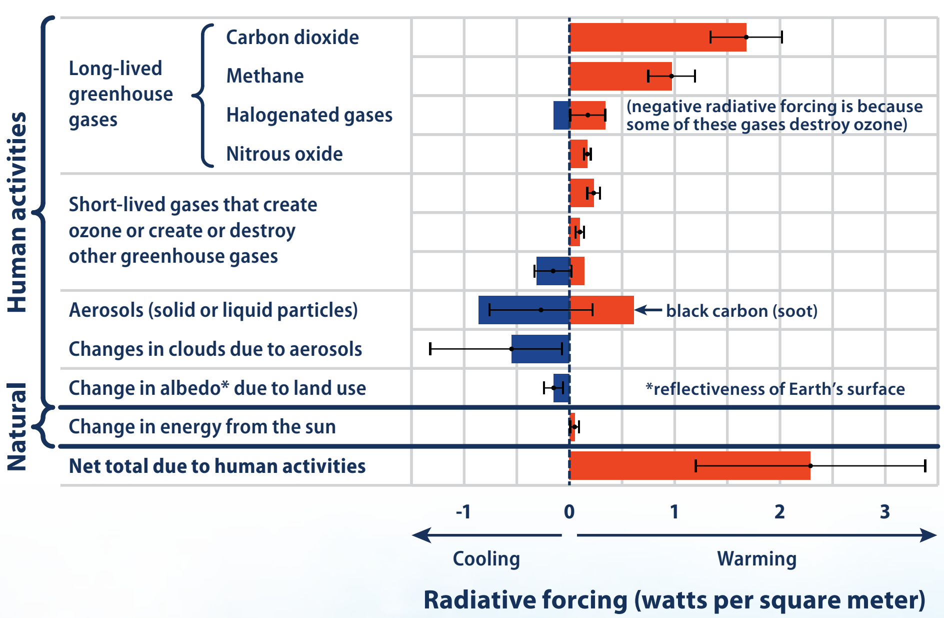
Figure 1. Radiative Forcing Caused by Major Long-Lived Greenhouse Gases, 1979–2013



This figure shows the amount of radiative forcing caused by various greenhouse gases, based on the change in concentration of these gases in the Earth's atmosphere since 1750. Radiative forcing is calculated in watts per square meter, which represents the size of the energy imbalance in the atmosphere. On the right side of the graph, radiative forcing has been converted to the Annual Greenhouse Gas Index, which is set to a value of 1.0 for 1990.

Data source: NOAA, 2014[30]

Figure 2. Radiative Forcing Caused by Human Activities Since 1750



This figure shows the total amount of radiative forcing caused by human activities—including indirect effects—between 1750 and 2011. Radiative forcing is calculated in watts per square meter, which represents the size of the energy imbalance in the atmosphere. Each colored bar represents scientists' best estimate, while the thin black bars indicate the likely range of possibilities. The natural change in the energy received from the sun over this time period is provided for reference.

Data source: IPCC, 2013[31]

INDICATOR NOTES

The index in Figure 1 does not include short-lived greenhouse gases like tropospheric ozone, reflective aerosol particles, black carbon (soot), or the indirect influence of methane through its effects on water vapor and ozone formation. Figure 2 includes these and other indirect influences.

DATA SOURCES

Data for Figure 1 were provided by the National Oceanic and Atmospheric Administration. This figure and other information are available at: www.esrl.noaa.gov/gmd/aggi. Data for Figure 2 came from the Intergovernmental Panel on Climate Change (www.ipcc.ch), which publishes assessment reports based on the best available climate science data.

WEATHER AND CLIMATE

Rising global average temperature is associated with widespread changes in weather patterns. Scientific studies indicate that extreme weather events such as heat waves and large storms are likely to become more frequent or more intense with human-induced climate change. This chapter focuses on observed changes in temperature, precipitation, storms, and droughts.

WHY DOES IT MATTER?

Long-term changes in climate can directly or indirectly affect many aspects of society in potentially disruptive ways. For example, warmer average temperatures could increase air conditioning costs and affect the spread of diseases like Lyme disease, but could also improve conditions for growing some crops. More extreme variations in weather are also a threat to society. More frequent and intense extreme heat events can increase illnesses and deaths, especially among vulnerable populations, and damage some crops. Similarly, increased precipitation can replenish water supplies and support agriculture, but intense storms can damage property, cause loss of life and population displacement, and temporarily disrupt essential services such as transportation, telecommunications, energy, and water supplies.

Summary of Key Points

U.S. and Global Temperature. Average temperatures have risen across the contiguous 48 states since 1901, with an increased rate of warming over the past 30 years. Seven of the top 10 warmest years on record have occurred since 1998. Average global temperatures show a similar trend, and the top 10 warmest years on record worldwide have all occurred since 1998. Within the United States, temperatures in parts of the North, the West, and Alaska have increased the most.

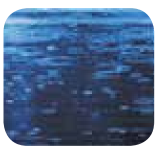
High and Low Temperatures. Many extreme temperature conditions are becoming more common. Since the 1970s, unusually hot summer temperatures have become more common in the United States, and heat waves have become more frequent—although the most severe heat waves in U.S. history remain those that occurred during the "Dust Bowl" in the 1930s. Record-setting daily high temperatures have become more common than record lows. The decade from 2000 to 2009 had twice as many record highs as record lows.

Weather and Climate

Weather is the state of the atmosphere at any given time and place. Most of the weather that affects people, agriculture, and ecosystems takes place in the lower layer of the atmosphere. Familiar aspects of weather include temperature, precipitation, clouds, and wind that people experience throughout the course of a day. Severe weather conditions include hurricanes, tornadoes, blizzards, and droughts.

Climate is the long-term average of the weather in a given place. While the weather can change in minutes or hours, a change in climate is something that develops over longer periods of decades to centuries. Climate is defined not only by average temperature and precipitation but also by the type, frequency, duration, and intensity of weather events such as heat waves, cold spells, storms, floods, and droughts.

While the concepts of climate and weather are often confused, it is important to understand the difference. For example, the eastern United States experienced a cold and snowy winter in 2013/2014, but this short-term regional weather phenomenon does not negate the long-term rise in national and global temperatures, sea level, or other climate indicators. It may be helpful to think about the difference between weather and climate with an analogy: weather influences what clothes you wear on a given day, while the climate where you live influences the entire wardrobe you buy.



U.S. and Global Precipitation. Total annual precipitation has increased in the United States and over land areas worldwide. Since 1901, precipitation has increased at an average rate of 0.5 percent per decade in the contiguous 48 states and 0.2 percent per decade over land areas worldwide. However, shifting weather patterns have caused certain areas, such as Hawaii and parts of the Southwest, to experience less precipitation than usual.

Heavy Precipitation. In recent years, a higher percentage of precipitation in the United States has come in the form of intense single-day events. Nationwide, nine of the top 10 years for extreme one-day precipitation events have occurred since 1990. The occurrence of abnormally high annual precipitation totals (as defined by the National Oceanic and Atmospheric Administration) has also increased.

Drought. Average drought conditions across the nation have varied since records began in 1895. The 1930s and 1950s saw the most widespread droughts, while the last 50 years have generally been wetter than average. However, specific trends vary by region. A more detailed index developed recently shows that between 2000 and 2013, roughly 20 to 70 percent of the United States experienced drought at any given time, but this index has not been in use for long enough to compare with historical drought patterns.

A Closer Look: Temperature and Drought in the Southwest. The southwestern United States is particularly sensitive to changes in temperature and thus vulnerable to drought, as even a small decrease in water availability in this already arid region can threaten natural systems and society.

Tropical Cyclone Activity. Tropical storm activity in the Atlantic Ocean, the Caribbean, and the Gulf of Mexico has increased during the past 20 years. Increased storm intensity is closely related to variations in sea surface temperature in the tropical Atlantic. However, changes in observation methods over time make it difficult to know for sure whether a long-term increase in storm activity has occurred. Records collected since the late 1800s suggest that the actual number of hurricanes per year has not increased.

U.S. and Global Temperatures

This indicator describes trends in average surface temperature for the United States and the world.

KEY POINTS

- Since 1901, the average surface temperature across the contiguous 48 states has risen at an average rate of 0.14°F per decade (see Figure 1). Average temperatures have risen more quickly since the late 1970s (0.31 to 0.48°F per decade). Seven of the top 10 warmest years on record for the contiguous 48 states have occurred since 1998, and 2012 was the warmest year on record.
- Worldwide, 2001–2010 was the warmest decade on record since thermometer-based observations began. Global average surface temperature has risen at an average rate of 0.15°F per decade since 1901 (see Figure 2), similar to the rate of warming within the contiguous 48 states. Since the late 1970s, however, the United States has warmed faster than the global rate.
- Some parts of the United States have experienced more warming than others (see Figure 3). The North, the West, and Alaska have seen temperatures increase the most, while some parts of the Southeast have experienced little change. However, not all of these regional trends are statistically significant.

Temperature is a fundamental measurement for describing the climate, and the temperature in particular places can have wide-ranging effects on human life and ecosystems. For example, increases in air temperature can lead to more intense heat waves, which can cause illness and death, especially in vulnerable populations. Annual and seasonal temperature patterns also determine the types of animals and plants that can survive in particular locations. Changes in temperature can disrupt a wide range of natural processes, particularly if these changes occur more quickly than plant and animal species can adapt.

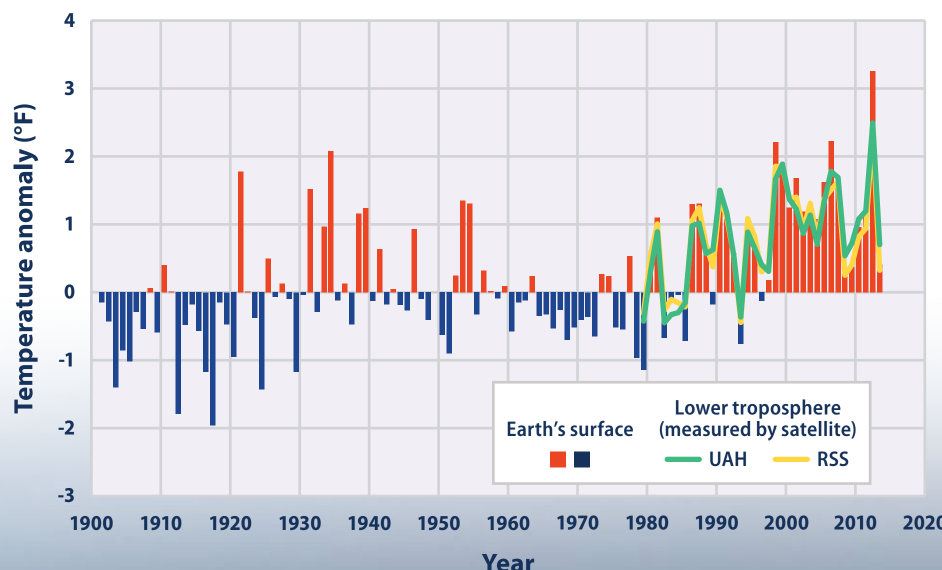
Concentrations of heat-trapping greenhouse gases are increasing in the Earth's atmosphere (see the Atmospheric Concentrations of Greenhouse Gases indicator on p. 20). In response, average temperatures at the Earth's surface are rising and are expected to continue rising. However, because climate change can shift the wind patterns and ocean currents that drive the world's climate system, some areas are warming more than others, and some have experienced cooling.

ABOUT THE INDICATOR

This indicator examines U.S. and global surface temperature patterns from 1901 to the present. U.S. surface measurements come from weather stations on land, while global surface measurements also incorporate observations from buoys and ships on the ocean, thereby providing data from sites spanning much of the surface of the Earth. For comparison, this indicator also displays satellite measurements that can be used to estimate the temperature of the Earth's lower atmosphere since 1979.

This indicator shows anomalies, which compare recorded annual temperature values against a long-term average. For example, an anomaly of +2.0 degrees means the average temperature was 2 degrees higher than the long-term average. This indicator uses the average temperature from 1901 to 2000 as a baseline for comparison. Annual anomalies are calculated for each weather station, starting from daily and monthly average temperatures. Anomalies for broader regions have been determined by dividing the country (or the world) into a grid, averaging the data for all weather stations within the grid, and then averaging the grid cells together (for Figures 1 and 2) or displaying them on a map (Figure 3). This method ensures that the results are not biased toward regions that happen to have many stations close together.

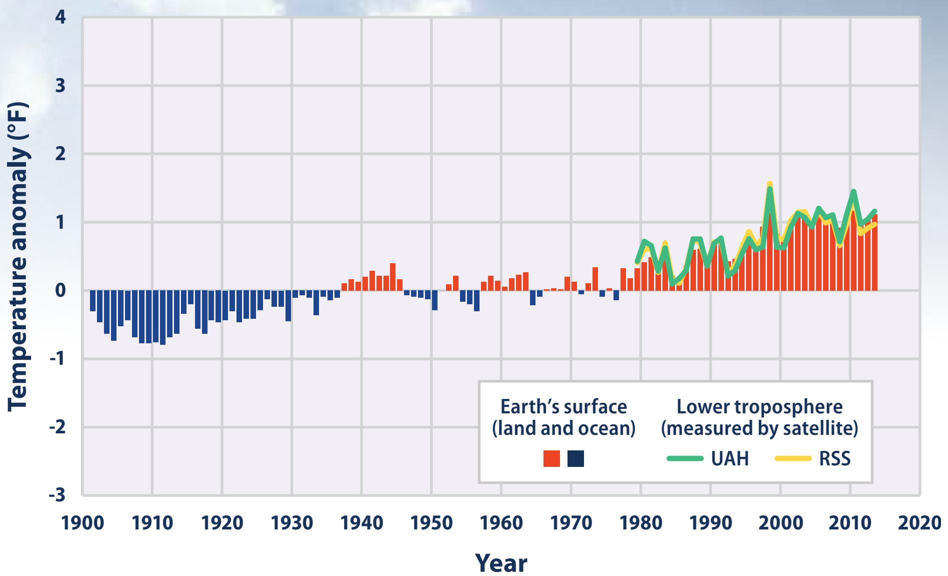
Figure 1. Temperatures in the Contiguous 48 States, 1901–2013



This figure shows how annual average temperatures in the contiguous 48 states have changed since 1901. Surface data come from land-based weather stations. Satellite measurements cover the lower troposphere, which is the lowest level of the Earth's atmosphere. "UAH" and "RSS" represent two different methods of analyzing the original satellite measurements. This graph uses the 1901–2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the data over time.

Data source: NOAA, 2014[1]

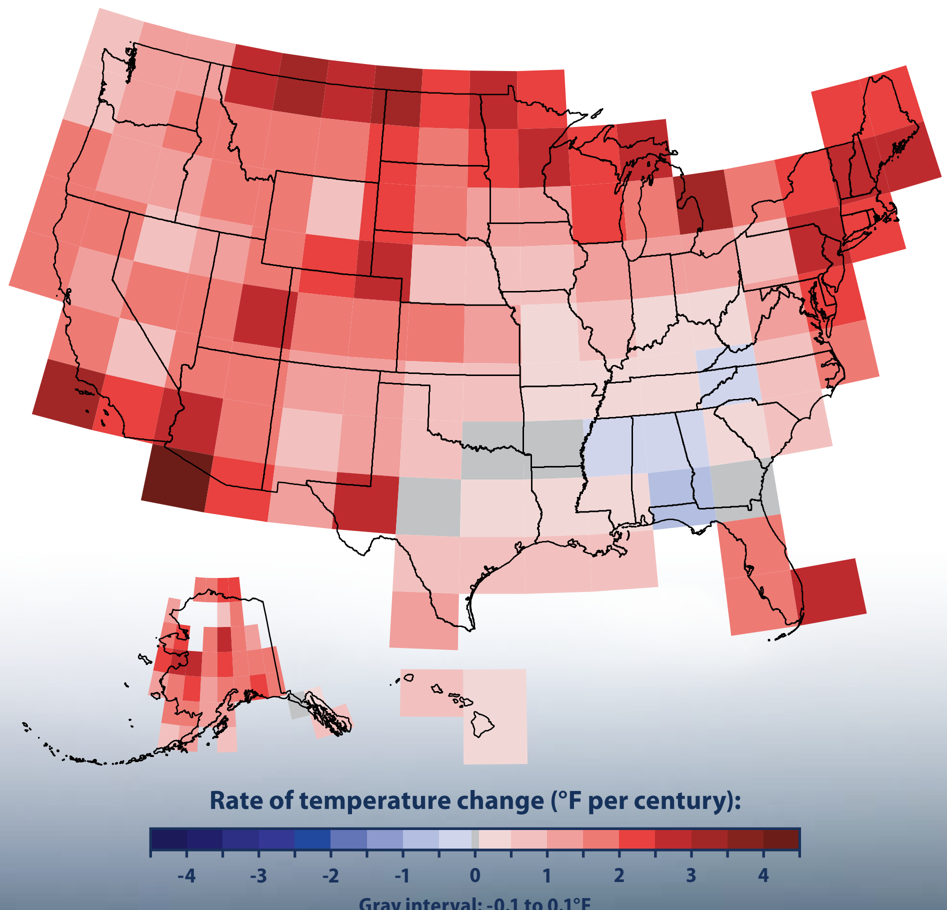
Figure 2. Temperatures Worldwide, 1901–2013



This figure shows how annual average temperatures worldwide have changed since 1901. Surface data come from a combined set of land-based weather stations and sea surface temperature measurements. Satellite measurements cover the lower troposphere, which is the lowest level of the Earth's atmosphere. "UAH" and "RSS" represent two different methods of analyzing the original satellite measurements. This graph uses the 1901–2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the data over time.

Data source: NOAA, 2014[2]

Figure 3. Rate of Temperature Change in the United States, 1901–2012



This figure shows how annual average air temperatures have changed in different parts of the United States since the early 20th century (since 1901 for the contiguous 48 states, 1905 for Hawaii, and 1918 for Alaska).

Data source: NOAA, 2013[3]

INDICATOR NOTES

Data from the early 20th century are somewhat less precise than more recent data because there were fewer stations collecting measurements at the time, especially in the Southern Hemisphere. However, the overall trends are still reliable. Where possible, the data have been adjusted to account for any biases that might be introduced by factors such as station moves, urbanization near the station, changes in measuring instruments, and changes in the exact times at which measurements are taken.

DATA SOURCES

The data for this indicator were provided by the National Oceanic and Atmospheric Administration's National Climatic Data Center, which maintains a large collection of climate data online at: www.ncdc.noaa.gov/oa/ncdc.html. The surface temperature anomalies shown here were calculated based on monthly values from a network of long-term monitoring stations. Satellite data were analyzed by two independent groups—the Global Hydrology and Climate Center at the University of Alabama in Huntsville (UAH) and Remote Sensing Systems (RSS)—resulting in slightly different trend lines.

High and Low Temperatures

This indicator describes trends in unusually hot and cold temperatures across the United States.

KEY POINTS

- Heat waves in the 1930s remain the most severe heat waves in the U.S. historical record (see Figure 1). The spike in Figure 1 reflects extreme, persistent heat waves in the Great Plains region during a period known as the "Dust Bowl." Poor land use practices and many years of intense drought contributed to these heat waves by depleting soil moisture and reducing the moderating effects of evaporation.[4]
- Nationwide, unusually hot summer days (highs) have become more common over the last few decades (see Figure 2). The occurrence of unusually hot summer nights (lows) has increased at an even faster rate. This trend indicates less "cooling off" at night.
- The 20th century had many winters with widespread patterns of unusually low temperatures, including a particularly large spike in the late 1970s (see Figure 3). Since the 1980s, though, unusually cold winter temperatures have become less common—particularly very cold nights (lows).

Unusually hot or cold temperatures can result in prolonged extreme weather events like summer heat waves or winter cold spells. Heat waves can lead to illness and death, particularly among older adults, the very young, and other vulnerable groups (see the Heat-Related Deaths indicator on p. 76). People can also die from exposure to extreme cold (hypothermia). In addition, prolonged exposure to excessive heat and cold can damage crops and injure or kill livestock. Extreme heat can lead to power outages as heavy demands for air conditioning strain the power grid, while extremely cold weather increases the need for heating fuel.

Record-setting daily temperatures, heat waves, and cold spells are a natural part of day-to-day variation in weather. However, as the Earth's climate warms overall, heat waves are expected to become more frequent, longer, and more intense.[5,6] Higher heat index values (which combine temperature and humidity to describe perceived temperature) are expected to increase discomfort and aggravate health issues. Conversely, cold spells are expected to decrease. In most locations, scientists expect daily minimum temperatures—which typically occur at night—to become warmer at a faster rate than daily maximum temperatures.[7] This change will provide less opportunity to cool off and recover from daytime heat.

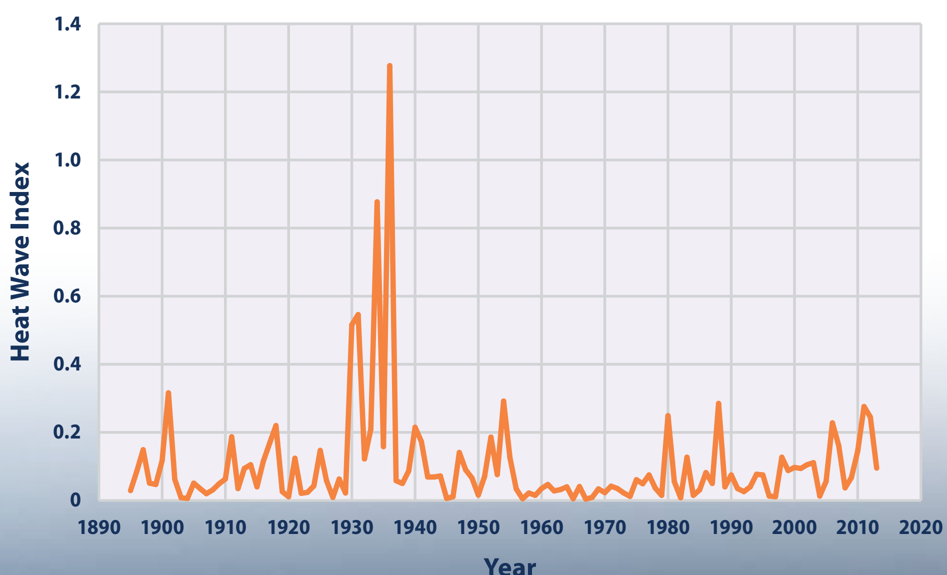
ABOUT THE INDICATOR

This indicator examines trends in unusual temperatures from several perspectives:

- The size and frequency of prolonged heat wave events (Figure 1).
- Unusually hot summer temperatures and cold winter temperatures nationwide (Figures 2 and 3).
- The change in the number of days with unusually hot and cold temperatures at individual weather stations (Figures 4 and 5).
- Changes in record high and low temperatures (Figure 6).

The data come from thousands of weather stations across the United States. National patterns can be determined by dividing the country into a grid and examining the data for one station in each cell of the grid. This method ensures that the results are not biased toward regions that happen to have many stations close together.

Figure 1. U.S. Annual Heat Wave Index, 1895–2013



This figure shows the annual values of the U.S. Heat Wave Index from 1895 to 2013. These data cover the contiguous 48 states. Interpretation: An index value of 0.2 (for example) could mean that 20 percent of the country experienced one heat wave, 10 percent of the country experienced two heat waves, or some other combination of frequency and area resulted in this value.

Data source: Kunkel, 2014[8]

Figure 1 shows the U.S. Annual Heat Wave Index, which tracks the occurrence of heat wave conditions across the contiguous 48 states from 1895 to 2013. While there is no universal definition of a heat wave, this index defines a heat wave as a period lasting at least four days with an average temperature that would only be expected to occur once every 10 years, based on the historical record. The index value for a given year depends on how often heat waves occur and how widespread they are.

Figures 2 and 3 show trends in the percentage of the country's area experiencing unusually hot temperatures in the summer and unusually cold temperatures in the winter. These graphs are based on daily maximum temperatures, which usually occur during the day, and daily minimum temperatures, which usually occur at night. At each station, the recorded highs and lows are compared with the full set of historical records. After averaging over a particular month or season of interest, the coldest 10 percent of years are considered "unusually cold" and the warmest 10 percent are "unusually hot." For example, if last year's summer highs were the 10th warmest on record for a particular location with more than 100 years of data, that year's summer highs would be considered unusually warm. Data are available from 1910 to 2013 for summer (June through August) and from 1911 to 2014 for winter (December of the previous year through February).

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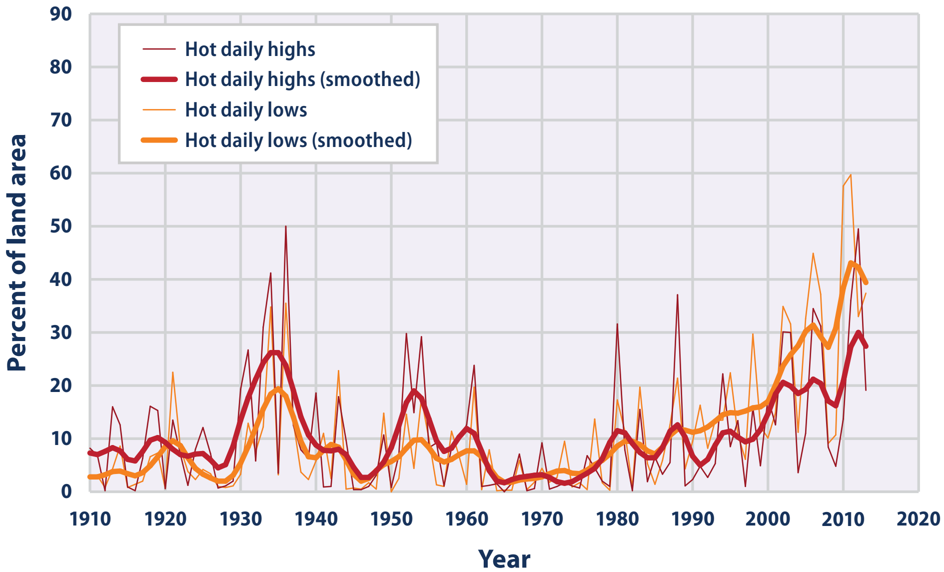
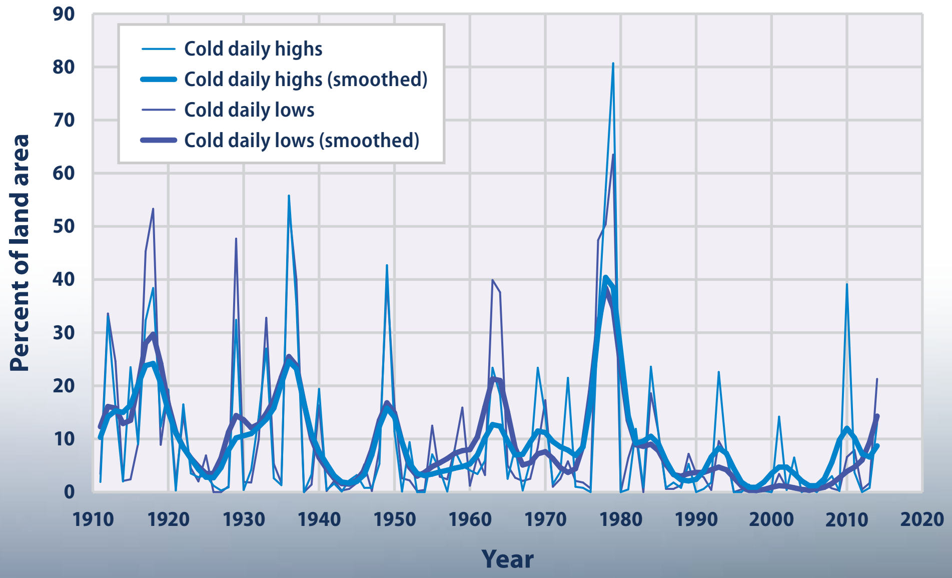
Figure 2. Area of the Contiguous 48 States with Unusually Hot Summer Temperatures, 1910–2013



This graph shows the percentage of the land area of the contiguous 48 states with unusually hot daily high and low temperatures during the months of June, July, and August. The thin lines represent individual years, while the thick lines show a nine-year weighted average. Red lines represent daily highs, while orange lines represent daily lows. The term "unusual" in this case is based on the long-term average conditions at each location.

Data source: NOAA, 2014[9]

Figure 3. Area of the Contiguous 48 States with Unusually Cold Winter Temperatures, 1911–2014



This graph shows the percentage of the land area of the contiguous 48 states with unusually cold daily high and low temperatures during the months of December, January, and February. The thin lines represent individual years, while the thick lines show a nine-year weighted average. Blue lines represent daily highs, while purple lines represent daily lows. The term "unusual" in this case is based on the long-term average conditions at each location.

Data source: NOAA, 2014[10]

High and Low Temperatures
Continued

KEY POINTS

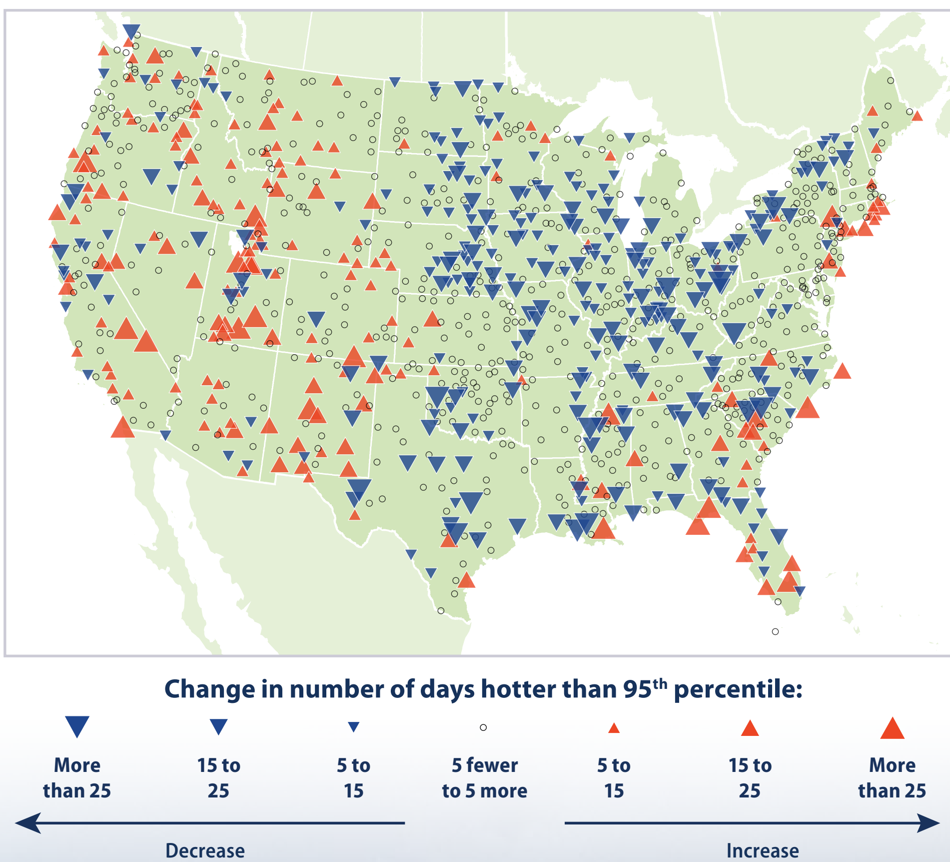
- The two maps show where changes in the number of days with unusually hot (above the 95th percentile) and cold (below the 5th percentile) days have occurred since 1948. Unusually high temperatures have increased in the western United States and in several areas along the Gulf and Atlantic coasts, but decreased in much of the middle of the country (see Figure 4). The number of unusually cold days has generally decreased throughout the country (see Figure 5).
- If the climate were completely stable, one might expect to see highs and lows each accounting for about 50 percent of the records set. However, since the 1970s, record-setting daily high temperatures have become more common than record lows across the United States (see Figure 6). The most recent decade had twice as many record highs as record lows.

(Continued from previous page)

Figures 4 and 5 show how trends in unusually hot and cold daily temperatures throughout the year vary by location. These maps cover 1,119 weather stations that have operated since 1948. Figure 4 was created by reviewing all daily maximum temperatures from 1948 to 2013 and identifying the 95th percentile temperature (a temperature that one would only expect to exceed in five days out of every 100) at each station. Next, for each year, the total number of days with maximum temperatures higher than the 95th percentile (that is, unusually hot days) was determined. The map shows how the total number of unusually hot days per year at each station has changed over time. Figure 5 is similar except that it looks at unusually cold days, based on the 5th percentile of daily minimum temperatures.

Many people are familiar with record daily high and low temperatures, which are frequently mentioned in weather reports. Figure 6 depicts trends in these records by comparing the number of record-setting highs with the number of record-setting lows by decade. These data come from a set of weather stations that have collected data consistently since 1950.

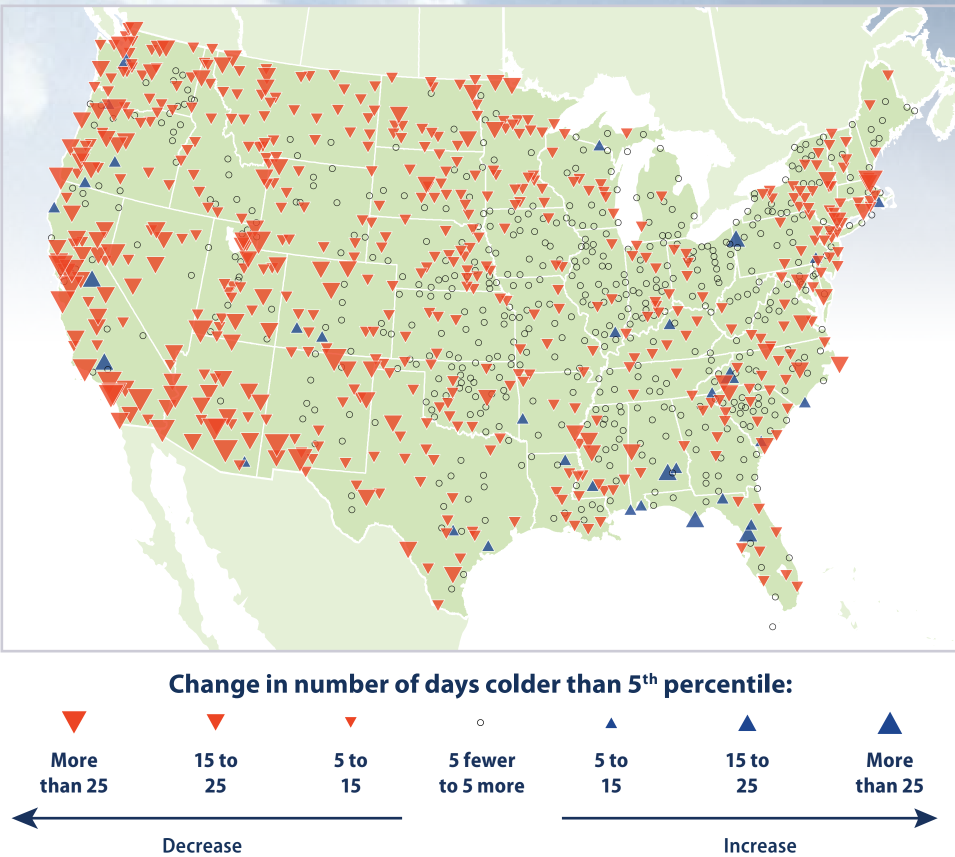
Figure 4. Change in Unusually Hot Temperatures in the Contiguous 48 States, 1948–2013



This map shows trends in unusually hot temperatures at individual weather stations that have operated consistently since 1948. In this case, the term "unusually hot" refers to a daily maximum temperature that is hotter than the 95th percentile temperature during the 1948–2013 period. Thus, the maximum temperature on a particular day at a particular station would be considered "unusually hot" if it falls within the warmest 5 percent of measurements at that station during the 1948–2013 period. The map shows changes in the total number of days per year that were hotter than the 95th percentile. Red upward-pointing symbols show where these unusually hot days are becoming more common. Blue downward-pointing symbols show where unusually hot days are becoming less common.

Data source: NOAA, 2014[11]

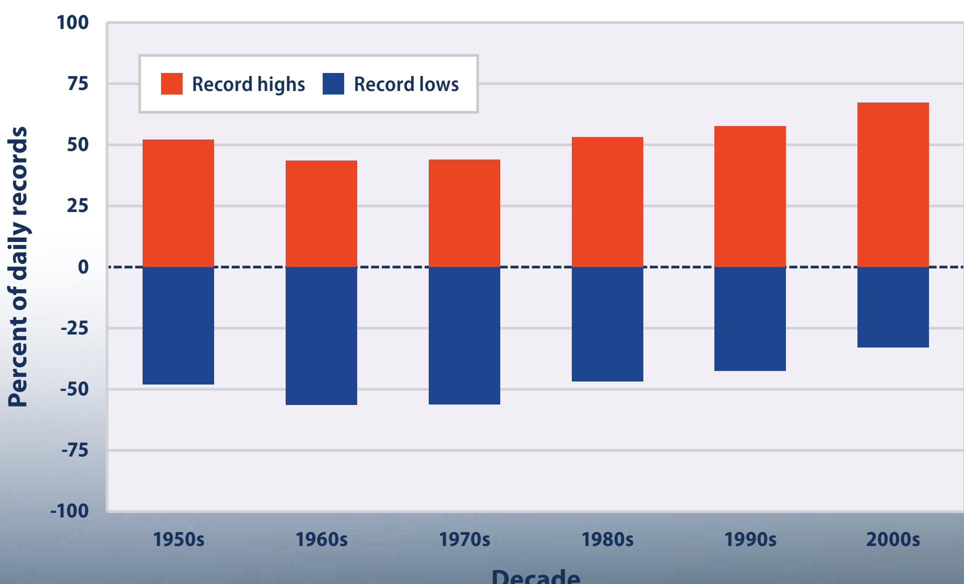
Figure 5. Change in Unusually Cold Temperatures in the Contiguous 48 States, 1948–2013



This map shows trends in unusually cold temperatures at individual weather stations that have operated consistently since 1948. In this case, the term "unusually cold" refers to a daily minimum temperature that is colder than the 5th percentile temperature during the 1948–2013 period. Thus, the minimum temperature on a particular day at a particular station would be considered "unusually cold" if it falls within the coldest 5 percent of measurements at that station during the 1948–2013 period. The map shows changes in the total number of days per year that were colder than the 5th percentile. Blue upward-pointing symbols show where these unusually cold days are becoming more common. Red downward-pointing symbols show where unusually cold days are becoming less common.

Data source: NOAA, 2014[12]

Figure 6. Record Daily High and Low Temperatures in the Contiguous 48 States, 1950–2009



This figure shows the percentage of daily temperature records set at weather stations across the contiguous 48 states by decade. Record highs (red) are compared with record lows (blue).

Data source: Meehl et al., 2009[13]

INDICATOR NOTES

Temperature data are less certain for the early part of the 20th century because fewer stations were operating at that time. In addition, measuring devices and methods have changed over time, and some stations have moved. The data have been adjusted to the extent possible to account for some of these influences and biases, however, and these uncertainties are not sufficient to change the fundamental trends shown in the figures.

DATA SOURCES

The data for this indicator are based on measurements from weather stations managed by the National Oceanic and Atmospheric Administration. Figure 1 uses data from the National Weather Service Cooperative Observer Network. Figures 2 and 3 come from the U.S. Climate Extremes Index, which is based on a smaller group of long-term weather stations that are tracked by the National Climatic Data Center and referred to as the U.S. Historical Climatology Network. Figures 4 and 5 use data from a somewhat larger set of stations tracked by the National Climatic Data Center, known as the Global Historical Climatology Network. Figure 6 uses National Weather Service data processed by Meehl et al. (2009).[14] All of these weather station records are available online at: www.ncdc.noaa.gov, and information about the Climate Extremes Index can be found at: www.ncdc.noaa.gov/extremes/cei.

U.S. and Global Precipitation

This indicator describes trends in average precipitation for the United States and the world.

KEY POINTS

- On average, total annual precipitation has increased over land areas in the United States and worldwide (see Figures 1 and 2). Since 1901, global precipitation has increased at an average rate of 0.2 percent per decade, while precipitation in the contiguous 48 states has increased at a rate of 0.5 percent per decade.
- Some parts of the United States have experienced greater increases in precipitation than others. A few areas such as Hawaii and parts of the Southwest have seen a decrease in precipitation (see Figure 3).

Precipitation can have wide-ranging effects on human well-being and ecosystems. Rainfall, snowfall, and the timing of snowmelt can all affect the amount of water available for drinking, irrigation, and industry, and can also determine what types of animals and plants (including crops) can survive in a particular place. Changes in precipitation can disrupt a wide range of natural processes, particularly if these changes occur more quickly than plant and animal species can adapt.

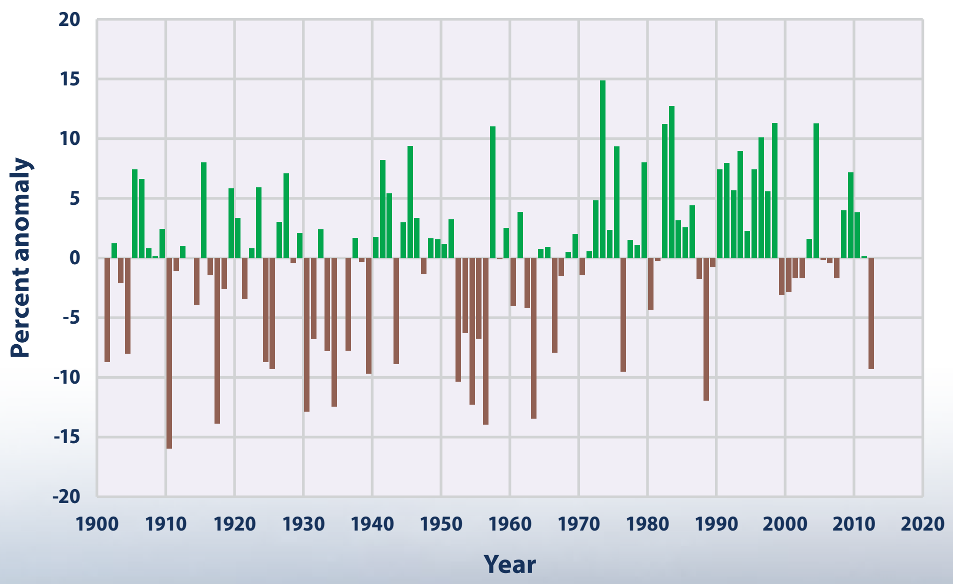
As average temperatures at the Earth's surface rise (see the U.S. and Global Temperature indicator on p. 28), more evaporation occurs, which, in turn, increases overall precipitation. Therefore, a warming climate is expected to increase precipitation in many areas. However, just as precipitation patterns vary across the world, so will the precipitation effects of climate change. By shifting the wind patterns and ocean currents that drive the world's climate system, climate change will also cause some areas to experience decreased precipitation. In addition, higher temperatures lead to more evaporation, so increased precipitation will not necessarily increase the amount of water available for drinking, irrigation, and industry (see the Drought indicator on p. 38).

ABOUT THE INDICATOR

This indicator examines U.S. and global precipitation patterns from 1901 to the present, based on rainfall and snowfall measurements from land-based weather stations worldwide.

This indicator shows annual anomalies, or differences, compared with the average precipitation from 1901 to 2000. These anomalies are presented in terms of percent change compared with the baseline. Annual anomalies are calculated for each weather station. Anomalies for broader regions have been determined by dividing the country (or the world) into a grid, averaging the data for all weather stations within each cell of the grid, and then averaging the grid cells together (for Figures 1 and 2) or displaying them on a map (Figure 3). This method ensures that the results are not biased toward regions that happen to have many stations close together.

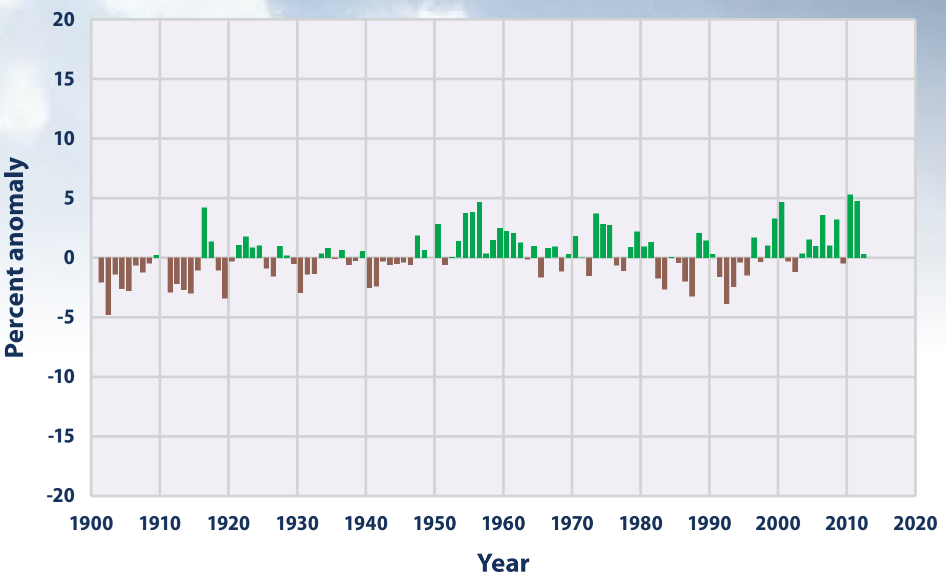
Figure 1. Precipitation in the Contiguous 48 States, 1901–2012



This figure shows how the total annual amount of precipitation in the contiguous 48 states has changed since 1901. This graph uses the 1901–2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the data over time.

Data source: NOAA, 2013[15]

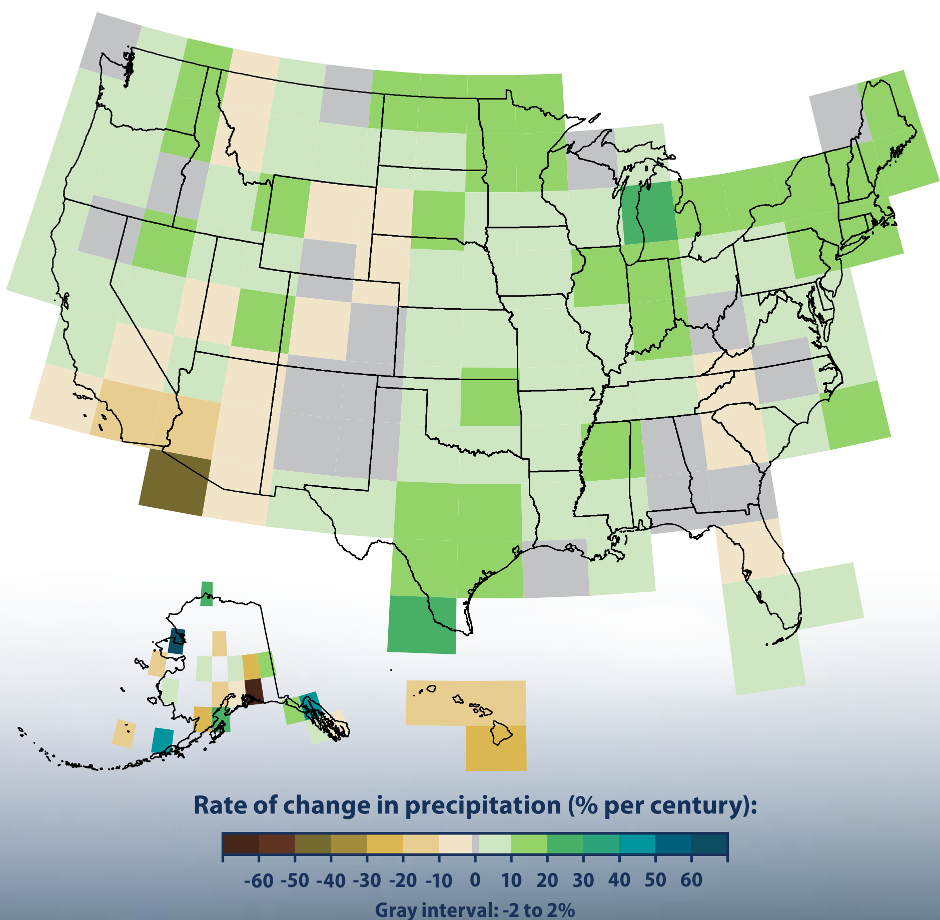
Figure 2. Precipitation Worldwide, 1901–2012



This figure shows how the total annual amount of precipitation over land worldwide has changed since 1901. This graph uses the 1901–2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the data over time.

Data source: NOAA, 2013[16]

Figure 3. Rate of Precipitation Change in the United States, 1901–2012



This figure shows the rate of change in total annual precipitation in different parts of the United States since the early 20th century (since 1901 for the contiguous 48 states, 1905 for Hawaii, and 1918 for Alaska).

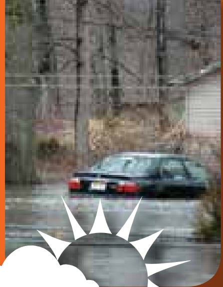
Data source: NOAA, 2013[17]

INDICATOR NOTES

Data from the early 20th century are somewhat less precise because there were fewer stations collecting measurements at the time. To ensure that overall trends are reliable, the data have been adjusted where possible to account for any biases that might be introduced by factors such as station moves or changes in measurement instruments.

DATA SOURCES

The data for this indicator were provided by the National Oceanic and Atmospheric Administration's National Climatic Data Center, which maintains a large collection of climate data online at: www.ncdc.noaa.gov/oa/ncdc.html. The precipitation anomalies shown here were calculated based on monthly values from a network of long-term monitoring stations.



Heavy Precipitation

This indicator tracks the frequency of heavy precipitation events in the United States.

KEY POINTS

- In recent years, a larger percentage of precipitation has come in the form of intense single-day events. Nine of the top 10 years for extreme one-day precipitation events have occurred since 1990 (see Figure 1).
- The prevalence of extreme single-day precipitation events remained fairly steady between 1910 and the 1980s, but has risen substantially since then. Over the entire period from 1910 to 2013, the portion of the country experiencing extreme single-day precipitation events increased at a rate of about half a percentage point per decade (see Figure 1).
- The percentage of land area experiencing much greater than normal yearly precipitation totals increased between 1895 and 2013. However, there has been much year-to-year variability. In some years there were no abnormally wet areas, while a few others had abnormally high precipitation totals over 10 percent or more of the contiguous 48 states' land area (see Figure 2). For example, 1941 was extremely wet in the West, while 1982 was very wet nationwide.[18]
- Figures 1 and 2 are both consistent with other studies that have found an increase in heavy precipitation over timeframes ranging from single days to 90-day periods to whole years.[19] For more information on trends in overall precipitation levels, see the U.S. and Global Precipitation indicator (p. 34).

Heavy precipitation refers to instances during which the amount of precipitation experienced in a location substantially exceeds what is normal. What constitutes a period of heavy precipitation varies according to location and season.

Climate change can affect the intensity and frequency of precipitation. Warmer oceans increase the amount of water that evaporates into the air. When more moisture-laden air moves over land or converges into a storm system, it can produce more intense precipitation—for example, heavier rain and snow storms.[20] The potential impacts of heavy precipitation include crop damage, soil erosion, and an increase in flood risk due to heavy rains. In addition, runoff from precipitation can impair water quality as pollutants deposited on land wash into water bodies.

Heavy precipitation does not necessarily mean the total amount of precipitation at a location has increased—just that precipitation is occurring in more intense events. However, changes in the intensity of precipitation, when combined with changes in the interval between precipitation events, can also lead to changes in overall precipitation totals.

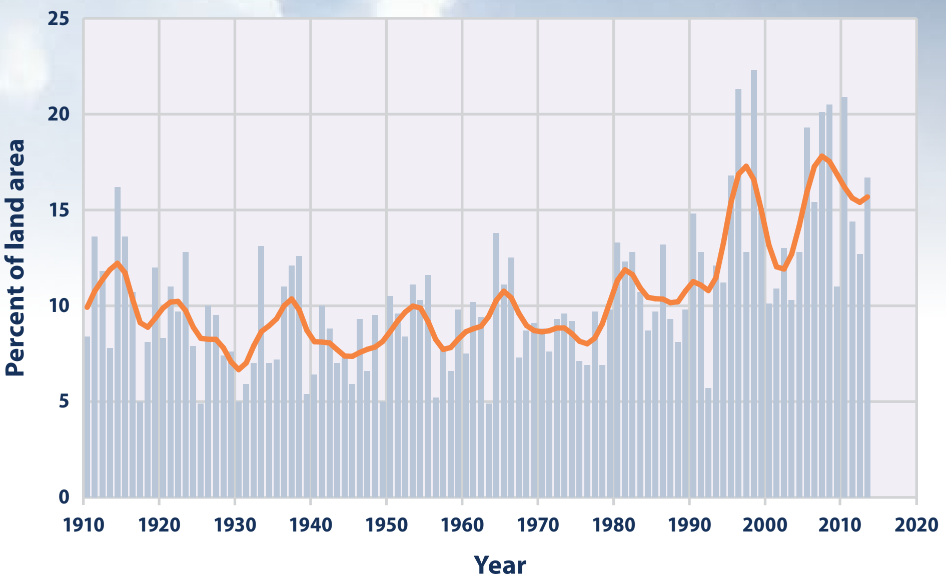
ABOUT THE INDICATOR

Heavy precipitation events can be measured by tracking their frequency, examining their return period (the chance that the event will be equaled or exceeded in a given year), or directly measuring the amount of precipitation in a certain period (for example, inches of rain falling in a 24-hour period).

One way to track heavy precipitation is by calculating what percentage of a particular location's total precipitation in a given year has come in the form of extreme one-day events—or, in other words, what percentage of precipitation is arriving in short, intense bursts. Figure 1 of this indicator looks at the prevalence of extreme single-day precipitation events over time.

For added insight, this indicator also tracks the occurrence of unusually high total yearly precipitation. It does so by looking at the Standardized Precipitation Index (SPI), which compares actual yearly precipitation totals with the range of precipitation totals that one would typically expect at a specific location, based on historical data. If a location experiences less precipitation than normal during a particular period, it will receive a negative SPI score, while a period with more precipitation than normal will receive a positive score. The more precipitation (compared with normal), the higher the SPI score. The SPI is a useful way to look at precipitation totals because it allows comparison of different locations and different seasons on a standard scale. Figure 2 shows what percentage of the total area of the contiguous 48 states had an annual SPI score of 2.0 or above (well above normal) in any given year.

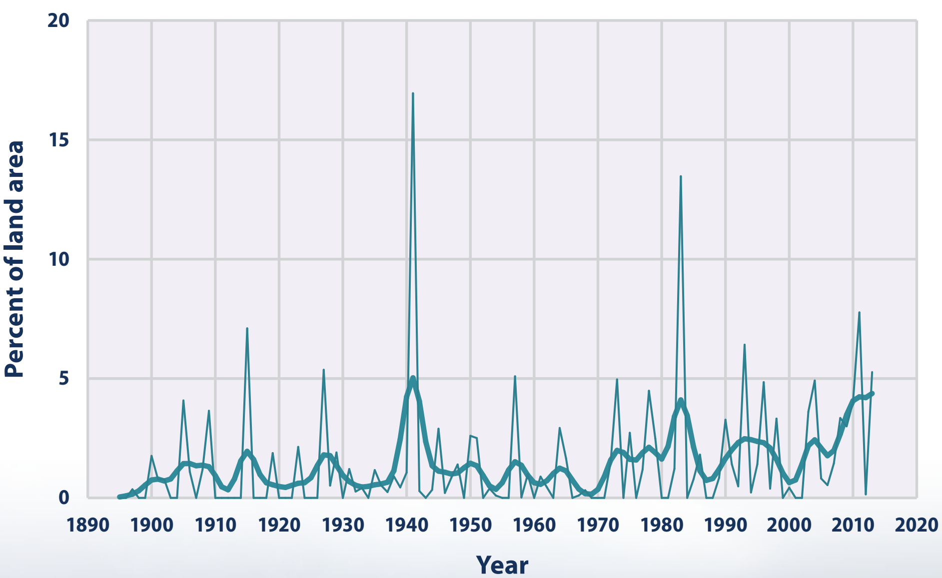
Figure 1. Extreme One-Day Precipitation Events in the Contiguous 48 States, 1910–2013



This figure shows the percentage of the land area of the contiguous 48 states where a much greater than normal portion of total annual precipitation has come from extreme single-day precipitation events. The bars represent individual years, while the line is a nine-year weighted average.

Data source: NOAA, 2014[21]

Figure 2. Unusually High Annual Precipitation in the Contiguous 48 States, 1895–2013



This figure shows the percentage of the land area of the contiguous 48 states that experienced much greater than normal precipitation in any given year, which means it scored 2.0 or above on the annual Standardized Precipitation Index. The thicker line shows a nine-year weighted average that smoothes out some of the year-to-year fluctuations.

Data source: NOAA, 2014[22]

INDICATOR NOTES

Weather monitoring stations tend to be closer together in the eastern and central states than in the western states. In areas with fewer monitoring stations, heavy precipitation indicators are less likely to reflect local conditions accurately.

DATA SOURCES

The data used for this indicator come from a large national network of weather stations and were provided by the National Oceanic and Atmospheric Administration's National Climatic Data Center. Figure 1 is based on Step #4 of the National Oceanic and Atmospheric Administration's U.S. Climate Extremes Index; for data and a description of the index, see: www.ncdc.noaa.gov/extremes/cei. Figure 2 is based on the U.S. SPI, which is shown in a variety of maps available online at: www.ncdc.noaa.gov/oa/climate/research/prelim/drought/spi.html. The data used to construct these maps are available from the National Oceanic and Atmospheric Administration at: ftp://ftp.ncdc.noaa.gov/pub/data/cirs.

Drought

This indicator measures drought conditions of U.S. lands.

KEY POINTS

- Average drought conditions across the nation have varied since records began in 1895. The 1930s and 1950s saw the most widespread droughts, while the last 50 years have generally been wetter than average (see Figure 1).
- Over the period from 2000 through 2013, roughly 20 to 70 percent of the U.S. land area experienced conditions that were at least abnormally dry at any given time (see Figure 2). The years 2002–2003 and 2012–2013 had a relatively large area with at least abnormally dry conditions, while 2001, 2005, and 2009–2011 had substantially less area experiencing drought.
- Both drought figures indicate that in 2012, the United States experienced the driest conditions in more than a decade. During the latter half of 2012, more than half of the U.S. land area was covered by moderate or greater drought (see Figure 2). In several states, 2012 was among the driest years on record.[23] See Temperature and Drought in the Southwest (p. 40) for a closer look at trends in one of the hardest-hit regions.

There are many definitions and types of drought. Meteorologists generally define drought as a prolonged period of dry weather caused by a lack of precipitation that results in a serious water shortage for some activity, population, or ecological system. Drought can also be thought of as an extended imbalance between precipitation and evaporation.

As average temperatures have risen because of climate change, the Earth's water cycle has sped up through an increase in the rate of evaporation. An increase in evaporation makes more water available in the air for precipitation, but contributes to drying over some land areas, leaving less moisture in the soil. Thus, as the climate continues to change, many areas are likely to experience increased precipitation (see the U.S. and Global Precipitation indicator on p. 34) and increased risk of flooding (see the Heavy Precipitation indicator on p. 36), while areas located far from storm tracks are likely to experience less precipitation and increased risk of drought. As a result, since the 1950s, some regions of the world have experienced longer and more intense droughts, particularly in southern Europe and West Africa, while other regions have seen droughts become less frequent, less intense, or shorter (for example, in central North America).[24]

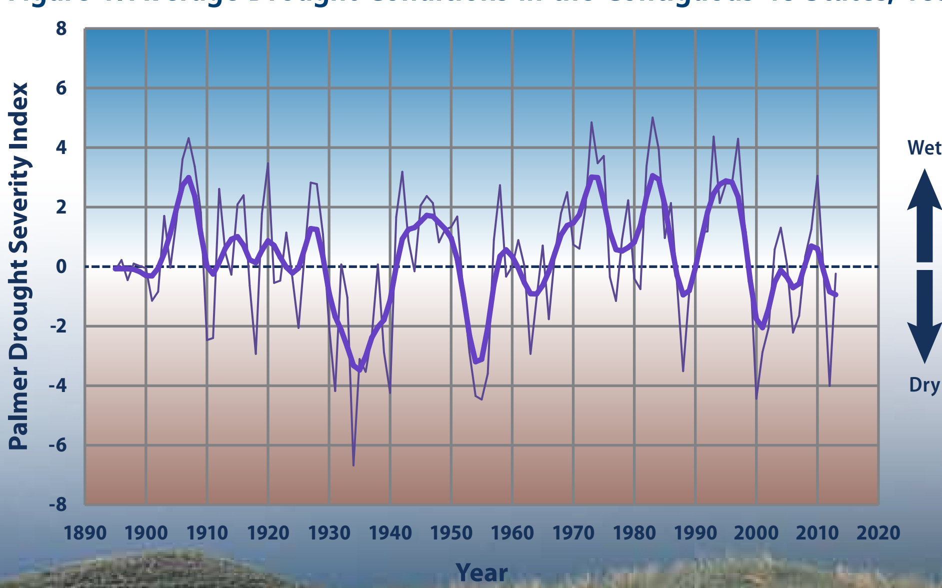
Drought conditions can negatively affect agriculture, water supplies, energy production, and many other aspects of society. The impacts vary depending on the type, location, intensity, and duration of the drought. For example, effects on agriculture can range from slowed plant growth to severe crop losses, while water supply impacts can range from lowered reservoir levels and dried-up streams to major water shortages. Lower streamflow and groundwater levels can also harm plants and animals, and dried-out vegetation increases the risk of wildfires.

ABOUT THE INDICATOR

During the 20th century, many indices were created to measure drought severity by looking at precipitation, soil moisture, stream flow, vegetation health, and other variables.[25] Figure 1 shows annual values of the most widely used index, the Palmer Drought Severity Index, which is calculated from precipitation and temperature measurements at weather stations. An index value of zero represents the average moisture conditions observed between 1931 and 1990 at a given location. A positive value means conditions are wetter than average, while a negative value is drier than average. Index values from locations across the contiguous 48 states have been averaged together to produce the national values shown in Figure 1.

For a more detailed perspective on recent trends, Figure 2 shows a newer index called the Drought Monitor, which is based on several indices (including Palmer), along with additional factors such as snow water content, groundwater levels, reservoir storage, pasture/range conditions, and other impacts. The Drought Monitor uses codes from D0 to D4 (see table below Figure 2) to classify drought severity. This part of the indicator covers all 50 states and Puerto Rico.

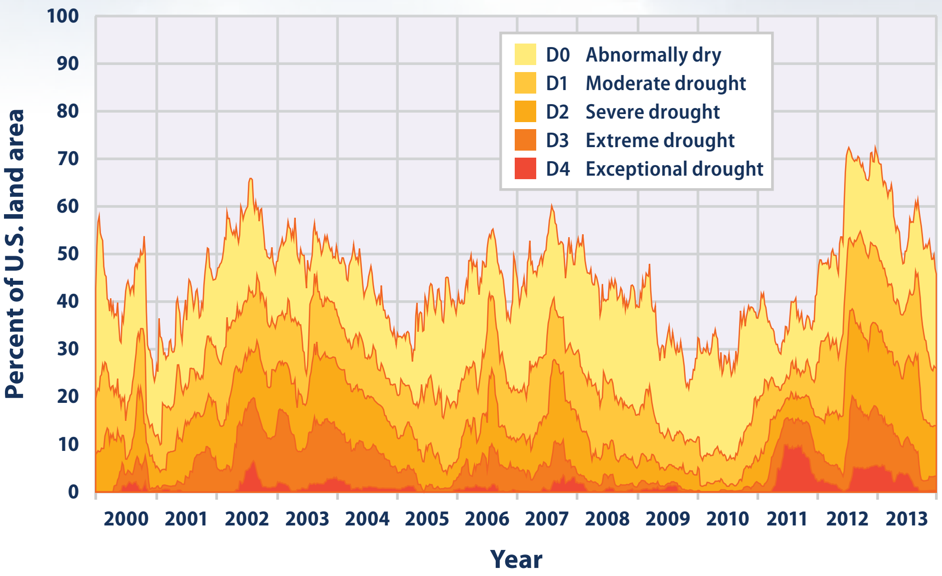
Figure 1. Average Drought Conditions in the Contiguous 48 States, 1895–2013



This chart shows annual values of the Palmer Drought Severity Index, averaged over the entire area of the contiguous 48 states. Positive values represent wetter-than-average conditions, while negative values represent drier-than-average conditions. A value between -2 and -3 indicates moderate drought, -3 to -4 is severe drought, and -4 or below indicates extreme drought. The thicker line is a nine-year weighted average.

Data source: NOAA, 2014[26]

Figure 2. U.S. Lands Under Drought Conditions, 2000–2013



This chart shows the percentage of U.S. lands classified under drought conditions from 2000 through 2013. This figure uses the U.S. Drought Monitor classification system, which is described in the table below. The data cover all 50 states plus Puerto Rico.

Data source: National Drought Mitigation Center, 2014[27]

Categories of Drought Severity

Category	Description	Possible Impacts
D0	Abnormally dry	Going into drought: short-term dryness slowing planting or growth of crops or pastures. Coming out of drought: some lingering water deficits; pastures or crops not fully recovered.
D1	Moderate drought	Some damage to crops or pastures; streams, reservoirs, or wells low; some water shortages developing or imminent; voluntary water use restrictions requested.
D2	Severe drought	Crop or pasture losses likely; water shortages common; water restrictions imposed.
D3	Extreme drought	Major crop/pasture losses; widespread water shortages or restrictions.
D4	Exceptional drought	Exceptional and widespread crop/pasture losses; shortages of water in reservoirs, streams, and wells, creating water emergencies.

Experts update the U.S. Drought Monitor weekly and produce maps that illustrate current conditions as well as short- and long-term trends. Major participants include the National Oceanic and Atmospheric Administration, the U.S. Department of Agriculture, and the National Drought Mitigation Center. For a map of current drought conditions, visit the Drought Monitor website at: http://droughtmonitor.unl.edu.

INDICATOR NOTES

Because this indicator focuses on national trends, it does not show how drought conditions vary by region. For example, even if half of the country suffered from severe drought, Figure 1 could show an average index value close to zero if the rest of the country was wetter than average. Thus, Figure 1 might understate the degree to which droughts are becoming more severe in some areas while other places receive more rain as a result of climate change.

The U.S. Drought Monitor (Figure 2) offers a closer look at the percentage of the country that is affected by drought. However, this index is relatively new and thus too short-lived to be used for assessing long-term climate trends or exploring how recent observations compare with historical patterns. With several decades of data collection, future versions of this indicator should be able to paint a more complete picture of trends over time.

Overall, this indicator gives a broad overview of drought conditions in the United States. It is not intended to replace local or state information that might describe conditions more precisely for a particular region.

DATA SOURCES

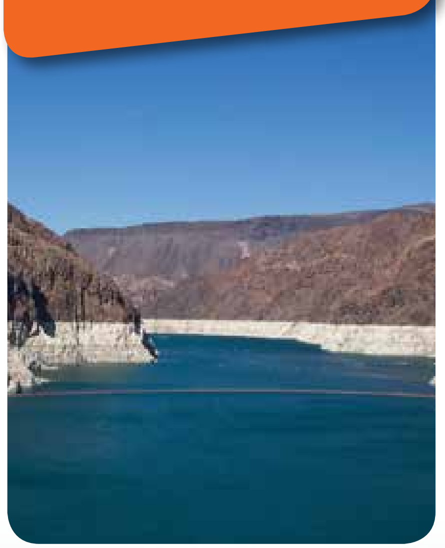
Data for Figure 1 were obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center, which maintains a large collection of climate data online at: www.ncdc.noaa.gov/oa/ncdc.html. Data for Figure 2 were provided by the National Drought Mitigation Center. Historical data in table form are available at: http://droughtmonitor.unl.edu/MapsAndData.aspx.

A Closer Look

Temperature and Drought in the Southwest

KEY POINTS

- Every part of the Southwest experienced higher average temperatures between 2000 and 2013 than the long-term average (1895–2013). Some areas were nearly 2°F warmer than average (see Figure 1).
- Large portions of the Southwest have experienced drought conditions since weekly Drought Monitor records began in 2000. For extended periods from 2002 to 2005 and from 2012 through 2013, nearly the entire region was abnormally dry or even drier (see Figure 2).
- Based on the long-term Palmer Index, drought conditions in the Southwest have varied since 1895. The early 1900s and the 1950s experienced considerable drought, the 1980s were relatively wet, and the last decade has seen the most persistent droughts on record (see Figure 3).



The American Southwest might evoke images of a hot, dry landscape—a land of rock, canyons, and deserts baked by the sun. Indeed, much of this region has low annual rainfall and seasonally high temperatures that contribute to its characteristic desert climate. Yet this landscape actually supports a vast array of plants and animals, along with millions of people who call the Southwest home. All of these plants, animals, and people need water to survive.

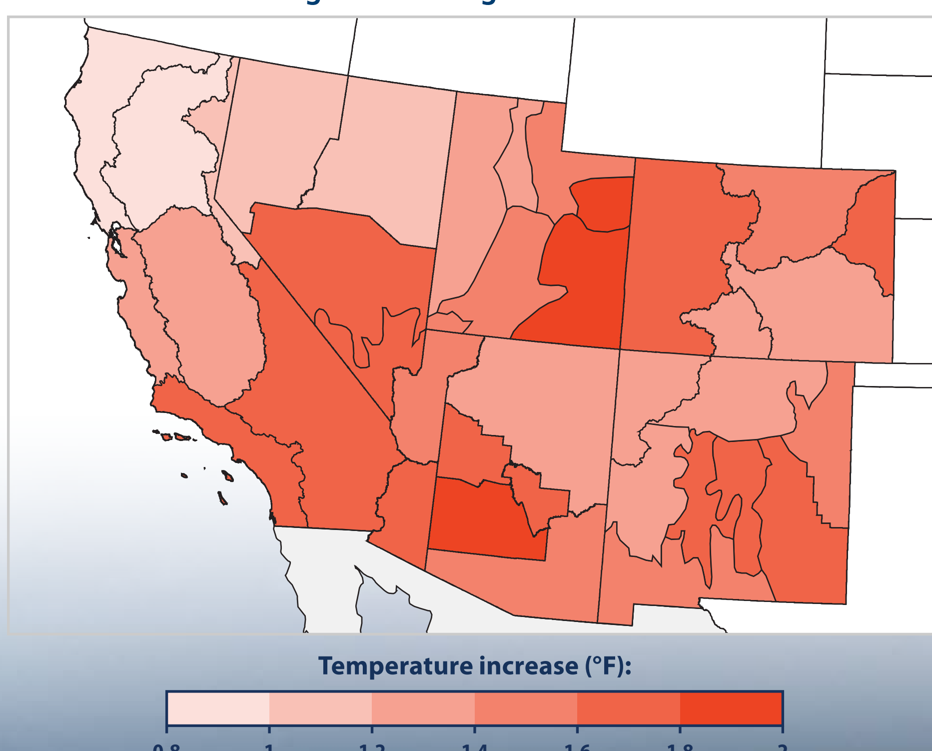
Water is already scarce in the Southwest, so every drop is a precious resource. People in the Southwest are particularly dependent on surface water supplies like Lake Mead, which are vulnerable to evaporation. Thus, even a small increase in temperature (which drives evaporation) or a decrease in precipitation in this already arid region can seriously threaten natural systems and society. Droughts also contribute to increased pest outbreaks and wildfires, both of which damage local economies.[28]

While two indicators in this report present information about unusually high or low temperatures and drought on a national scale (see the High and Low Temperatures indicator on p. 30 and the Drought indicator on p. 38), this feature highlights the Southwest because of its particular sensitivity to temperature and drought. It focuses on six states that are commonly thought of as "southwestern" and characterized at least in part by arid landscapes and scarce water supplies: Arizona, California, Colorado, Nevada, New Mexico, and Utah. Temperature and drought data come from a network of thousands of weather stations overseen by the National Weather Service.

The map in Figure 1 shows how average annual temperatures in the Southwest from 2000 to 2013 differed from the average over the entire period since widespread temperature records became available (1895–2013).

Figures 2 and 3 show two ways of measuring drought in the Southwest: the Drought Monitor and the Palmer Drought Severity Index. The Palmer Index is calculated from precipitation and temperature measurements at weather stations, and has been used widely for many years. The Drought Monitor is a more recent and more detailed index based on several other indices (including Palmer), along with additional factors such as snow water content, groundwater levels, reservoir storage, pasture/range conditions, and other impacts. See the Drought indicator (p. 38) for more information about these indices.

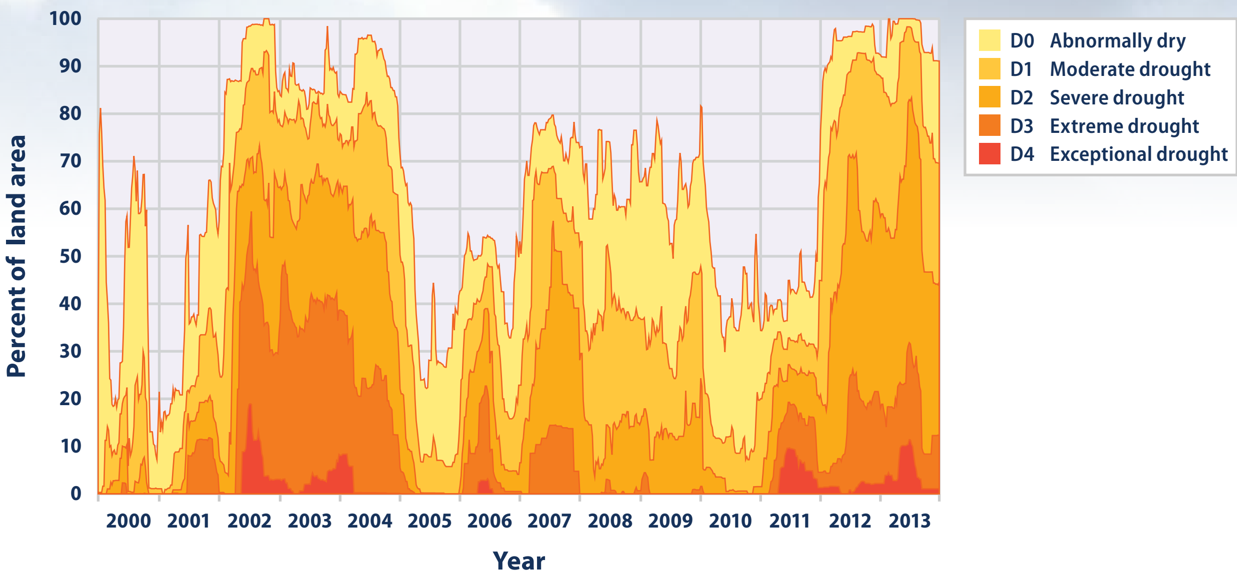
Figure 1. Average Temperatures in the Southwestern United States, 2000–2013 Versus Long-Term Average



This map shows how the average air temperature from 2000 to 2013 has differed from the long-term average (1895–2013). To provide more detailed information, each state has been divided into climate divisions, which are zones that share similar climate features.

Data source: NOAA, 2014[29]

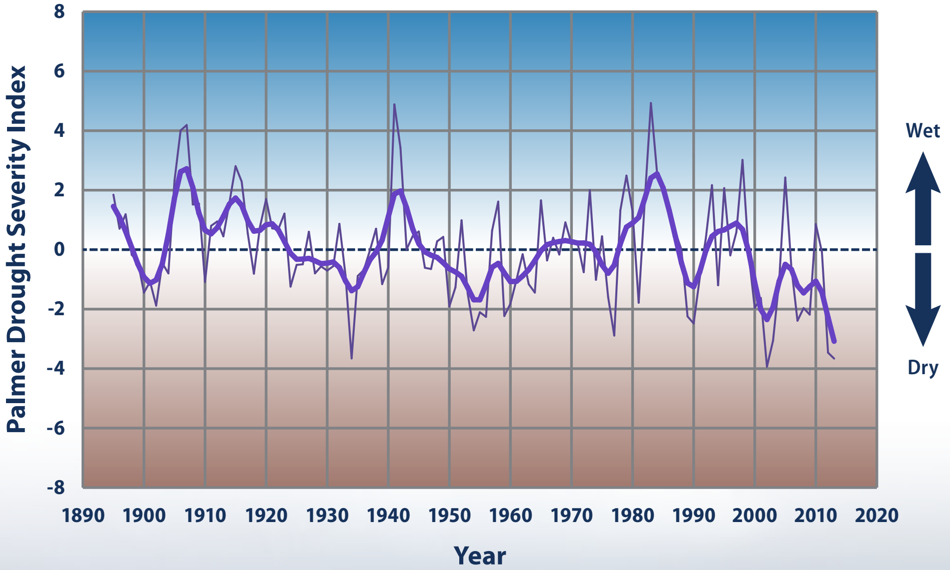
Figure 2. Southwestern U.S. Lands Under Drought Conditions, 2000–2013



This chart shows the percentage of land area in six southwestern states classified under drought conditions from 2000 through 2013. This figure uses the U.S. Drought Monitor classification system, which is described in the table in the Drought indicator on p. 39.

Data source: National Drought Mitigation Center, 2014[30]

Figure 3. Drought Severity in the Southwestern United States, 1895–2013



This chart shows annual values of the Palmer Drought Severity Index, averaged over six states in the Southwest. Positive values represent wetter-than-average conditions, while negative values represent drier-than-average conditions. A value between -2 and -3 indicates moderate drought, -3 to -4 is severe drought, and -4 or below indicates extreme drought. The thicker line is a nine-year weighted average.

Data source: NOAA, 2014[31]

NOTES

Natural variability, changes in irrigation practices, and other diversions of water for human use can influence certain drought-related measurements. Soil moisture, ground water, and streamflow are part of Drought Monitor calculations (Figure 2), and they are all sensitive to human activities.

DATA SOURCES

Data for Figures 1 and 3 were obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center, which maintains a large collection of climate data online at: www.ncdc.noaa.gov/oa/ncdc.html. Data for Figure 2 were provided by the National Drought Mitigation Center. Historical data in table form are available at: http://droughtmonitor.unl.edu/MapsAndData.aspx.

Tropical Cyclone Activity

This indicator examines the frequency, intensity, and duration of hurricanes and other tropical storms in the Atlantic Ocean, Caribbean, and Gulf of Mexico.

KEY POINTS

- Since 1878, about six to seven hurricanes have formed in the North Atlantic every year. Roughly two per year make landfall in the United States. The total number of hurricanes (particularly after being adjusted for improvements in observation methods) and the number reaching the United States do not indicate a clear overall trend since 1878 (see Figure 1).
- According to the total annual ACE Index, cyclone intensity has risen noticeably over the past 20 years, and six of the 10 most active years since 1950 have occurred since the mid-1990s (see Figure 2). Relatively high levels of cyclone activity were also seen during the 1950s and 1960s.
- The PDI (see Figure 3) shows fluctuating cyclone intensity for most of the mid- to late 20th century, followed by a noticeable increase since 1995 (similar to the ACE Index). These trends are associated with variations in sea surface temperature in the tropical Atlantic (see Figure 2).
- Despite the apparent increases in tropical cyclone activity in Figures 2 and 3, changes in observation methods over time make it difficult to know whether tropical storm activity has actually shown a long-term increase.[32]

Hurricanes, tropical storms, and other intense rotating storms fall into a general category called cyclones. There are two main types of cyclones: tropical and extratropical (those that form outside the tropics). Tropical cyclones get their energy from warm tropical oceans. Extratropical cyclones get their energy from the jet stream and from temperature differences between cold, dry air masses from higher latitudes and warm, moist air masses from lower latitudes.

This indicator focuses on tropical cyclones in the Atlantic Ocean, Caribbean, and Gulf of Mexico. Tropical cyclones are most common during the "hurricane season," which runs from June through November. The effects of tropical cyclones are numerous and well known. At sea, storms disrupt and endanger shipping traffic. When cyclones encounter land, their intense rains and high winds can cause severe property damage, loss of life, soil erosion, and flooding. The associated storm surge—the large volume of ocean water pushed toward shore by the cyclone's strong winds—can cause severe flooding and destruction.

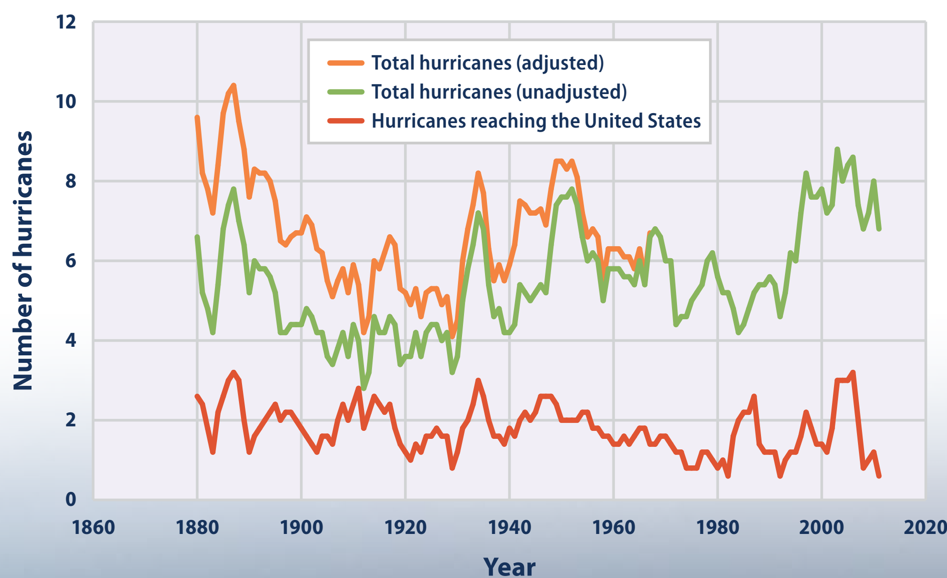
Climate change is expected to affect tropical cyclones by increasing sea surface temperatures, a key factor that influences cyclone formation and behavior. The U.S. Global Change Research Program and the Intergovernmental Panel on Climate Change project that, more likely than not, tropical cyclones will become more intense over the 21st century, with higher wind speeds and heavier rains.[33,34]

ABOUT THE INDICATOR

Records of tropical cyclones in the Atlantic Ocean have been collected since the 1800s. The most reliable long-term records focus on hurricanes, which are the strongest category of tropical cyclones in the Atlantic, with wind speeds of at least 74 miles per hour. This indicator uses historical data from the National Oceanic and Atmospheric Administration to track the number of hurricanes per year in the North Atlantic (north of the equator) and the number reaching the United States since 1878. Some hurricanes over the ocean might have been missed before the start of aircraft and satellite observation, so scientists have used other evidence, such as ship traffic records, to estimate the actual number of hurricanes that might have formed in earlier years.

This indicator also looks at the Accumulated Cyclone Energy (ACE) Index and the Power Dissipation Index (PDI), which are two ways of monitoring the frequency, strength, and duration of tropical cyclones based on wind speed measurements.

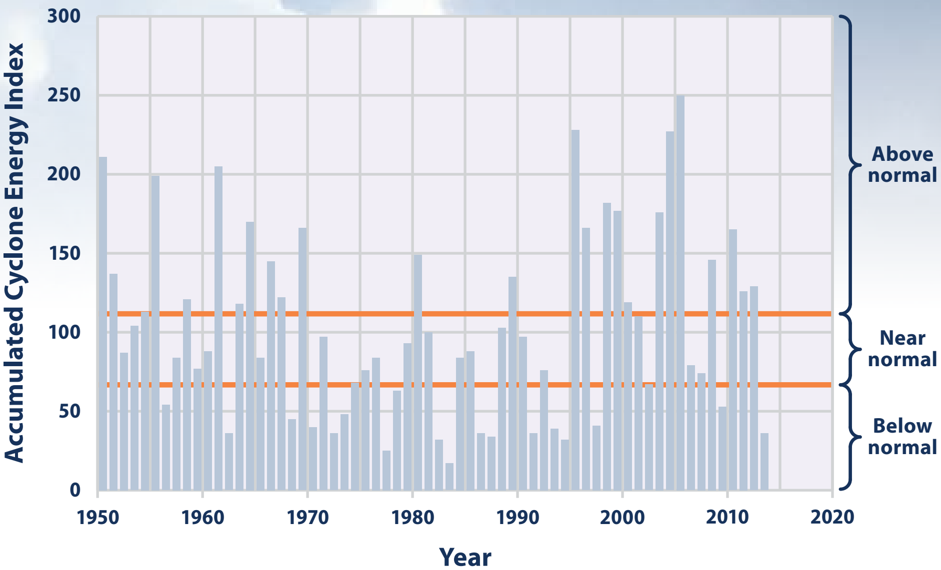
Figure 1. Number of Hurricanes in the North Atlantic, 1878–2013



This graph shows the number of hurricanes that formed in the North Atlantic Ocean each year from 1878 to 2013, along with the number that made landfall in the United States. The orange curve shows how the total count in the green curve can be adjusted to attempt to account for the lack of aircraft and satellite observations in early years. All three curves have been smoothed using a five-year average, plotted at the middle year. The most recent average (2009–2013) is plotted at 2011.

Data source: Knutson, 2014[35]

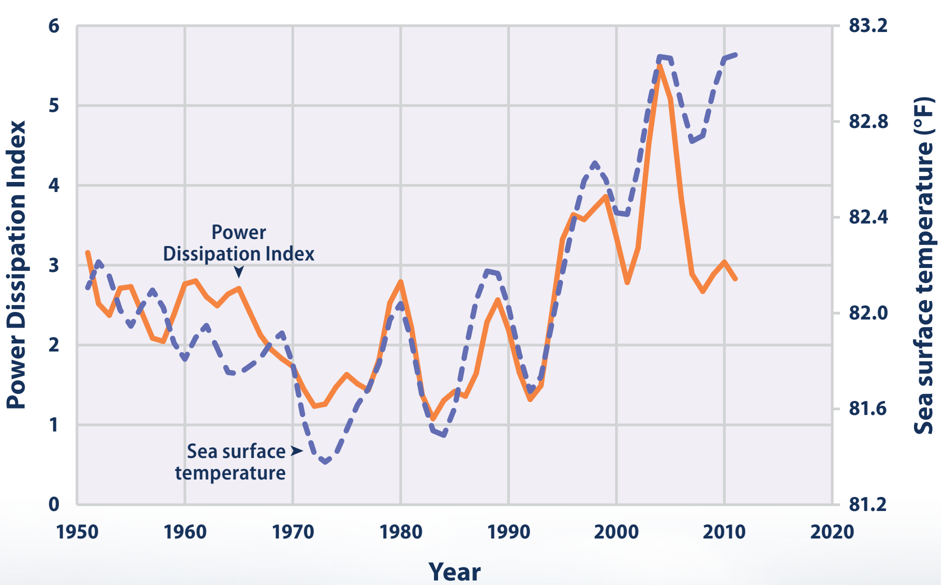
Figure 2. North Atlantic Tropical Cyclone Activity According to the Accumulated Cyclone Energy Index, 1950–2013



This figure shows total annual Accumulated Cyclone Energy (ACE) Index values, which account for cyclone strength, duration, and frequency, from 1950 through 2013. The National Oceanic and Atmospheric Administration has defined "near normal," "above normal," and "below normal" ranges based on the distribution of ACE Index values over the 30 years from 1981 to 2010.

Data source: NOAA, 2014[36]

Figure 3. North Atlantic Tropical Cyclone Activity According to the Power Dissipation Index, 1949–2013



This figure presents annual values of the Power Dissipation Index (PDI), which accounts for cyclone strength, duration, and frequency. Tropical North Atlantic sea surface temperature trends are provided for reference. Note that sea surface temperature is measured in different units, but the values have been plotted alongside the PDI to show how they compare. The lines have been smoothed using a five-year weighted average, plotted at the middle year. The most recent average (2009–2013) is plotted at 2011.

Data source: Emanuel, 2014[37]

Every cyclone has an ACE Index value, which is a number based on the maximum wind speed measured at six-hour intervals over the entire time that the cyclone is classified as at least a tropical storm (wind speed of at least 39 miles per hour). Therefore, a storm's ACE Index value accounts for both strength and duration. The National Oceanic and Atmospheric Administration calculates the total ACE Index value for an entire hurricane season by adding the values for all named storms, including subtropical storms, tropical storms, and hurricanes. The resulting annual total accounts for cyclone strength, duration, and frequency. For this indicator, the index has been converted to a scale where 100 equals the median value (the midpoint) over a base period from 1981 to 2010. The thresholds in Figure 2 define whether the ACE Index for a given year is close to normal, significantly above normal, or significantly below.

Like the ACE Index, the PDI is based on measurements of wind speed, but it uses a different calculation method that places more emphasis on storm intensity. This indicator shows the annual PDI value, which represents the sum of PDI values for all named storms during the year.

INDICATOR NOTES

Over time, data collection methods have changed as technology has improved. For example, wind speed collection methods have evolved substantially over the past 60 years, while aircraft reconnaissance began in 1944 and satellite tracking around 1966. Figure 1 shows how older hurricane counts have been adjusted to attempt to account for the lack of aircraft and satellite observations. Changes in data gathering technologies could substantially influence the overall patterns in Figures 2 and 3. The effects of these changes on data consistency over the life of the indicator would benefit from additional research.

While Figures 2 and 3 cover several different aspects of tropical cyclones, there are other important factors not covered here, including the size of each storm, the amount of rain, and the height of the storm surge.

DATA SOURCES

Hurricane counts are reported on several National Oceanic and Atmospheric Administration websites and were compiled using methods described in Knutson et al. (2010).[38] The ACE Index data (Figure 2) came from the National Oceanic and Atmospheric Administration's Climate Prediction Center, and are available online at: www.cpc.noaa.gov/products/outlooks/background_information.shtml. Values for the PDI have been calculated by Kerry Emanuel at the Massachusetts Institute of Technology. Both indices are based on wind speed measurements compiled by the National Oceanic and Atmospheric Administration.

OCEANS

Covering about 70 percent of the Earth's surface, the world's oceans have a two-way relationship with weather and climate. The oceans influence the weather on local to global scales, while changes in climate can fundamentally alter many properties of the oceans. This chapter examines how some of these important characteristics of the oceans have changed over time.

WHY DOES IT MATTER?

As greenhouse gases trap more energy from the sun, the oceans are absorbing more heat, resulting in an increase in sea surface temperatures and rising sea level. Changes in ocean temperatures and currents brought about by climate change will lead to alterations in climate patterns around the world. For example, warmer waters may promote the development of stronger storms in the tropics, which can cause property damage and loss of life. The impacts associated with sea level rise and stronger storms are especially relevant to coastal communities.

Although the oceans help reduce climate change by storing large amounts of carbon dioxide, increasing levels of dissolved carbon are changing the chemistry of seawater and making it more acidic. Increased ocean acidity makes it more difficult for certain organisms, such as corals and shellfish, to build their skeletons and shells. These effects, in turn, could substantially alter the biodiversity and productivity of ocean ecosystems.

Changes in ocean systems generally occur over much longer time periods than in the atmosphere, where storms can form and dissipate in a single day. Interactions between the oceans and atmosphere occur slowly over many months to years, and so does the movement of water within the oceans, including the mixing of deep and shallow waters. Thus, trends can persist for decades, centuries, or longer. For this reason, even if greenhouse gas emissions were stabilized tomorrow, it would take many more years—decades to centuries—for the oceans to adjust to changes in the atmosphere and the climate that have already occurred.

Summary of Key Points

Ocean Heat. Three separate analyses show that the amount of heat stored in the ocean has increased substantially since the 1950s. Ocean heat content not only determines sea surface temperature, but also affects sea level and currents.

Sea Surface Temperature. Ocean surface temperatures increased around the world over the 20th century. Even with some year-to-year variation, the overall increase is clear, and sea surface temperatures have been higher during the past three decades than at any other time since reliable observations began in the late 1800s.

Sea Level. When averaged over all the world's oceans, sea level has increased at a rate of roughly six-tenths of an inch per decade since 1880. The rate of increase has accelerated in recent years to more than an inch per decade. Changes in sea level relative to the land vary by region. Along the U.S. coastline, sea level has risen the most along the Mid-Atlantic coast and parts of the Gulf coast, where some stations registered increases of more than 8 inches between 1960 and 2013. Sea level has decreased relative to the land in parts of Alaska and the Northwest.

A Closer Look: Land Loss Along the Atlantic Coast. As sea level rises, dry land and wetland can turn into open water. Along many parts of the Atlantic coast, this problem is made worse by low elevations and land that is already sinking. Between 1996 and 2011, the coastline from Florida to New York lost more land than it gained.

Ocean Acidity. The ocean has become more acidic over the past few centuries because of increased levels of atmospheric carbon dioxide, which dissolves in the water. Higher acidity affects the balance of minerals in the water, which can make it more difficult for certain marine animals to build their skeletons and shells.

Ocean Heat

This indicator describes trends in the amount of heat stored in the world's oceans.

KEY POINTS

- In three different data analyses, the long-term trend shows that the oceans have become warmer since 1955 (see Figure 1).
- Although concentrations of greenhouse gases have risen at a relatively steady rate over the past few decades (see the Atmospheric Concentrations of Greenhouse Gases indicator on p. 20), the rate of change in ocean heat content can vary from year to year (see Figure 1). Year-to-year changes are influenced by events such as volcanic eruptions and recurring ocean-atmosphere patterns such as El Niño.

When sunlight reaches the Earth's surface, the world's oceans absorb some of this energy and store it as heat. This heat is initially absorbed at the surface, but some of it eventually spreads to deeper waters. Currents also move this heat around the world. Water has a much higher heat capacity than air, meaning the oceans can absorb larger amounts of heat energy with only a slight increase in temperature.

The total amount of heat stored by the oceans is called "ocean heat content," and measurements of water temperature reflect the amount of heat in the water at a particular time and location. Ocean temperature plays an important role in the Earth's climate system—particularly sea surface temperature (see the Sea Surface Temperature indicator on p. 48)—because heat from ocean surface waters provides energy for storms and thereby influences weather patterns.

Higher greenhouse gas concentrations are trapping more energy from the sun. Because changes in ocean systems occur over centuries, the oceans have not yet warmed as much as the atmosphere, even though they have absorbed more than 90 percent of the Earth's extra heat since 1955.[1,2] If not for the large heat-storage capacity provided by the oceans, the atmosphere would grow warmer more rapidly.[3] Increased heat absorption also changes ocean currents because many currents are driven by differences in temperature, which cause differences in density. These currents influence climate patterns and sustain ecosystems that depend on certain temperature ranges.

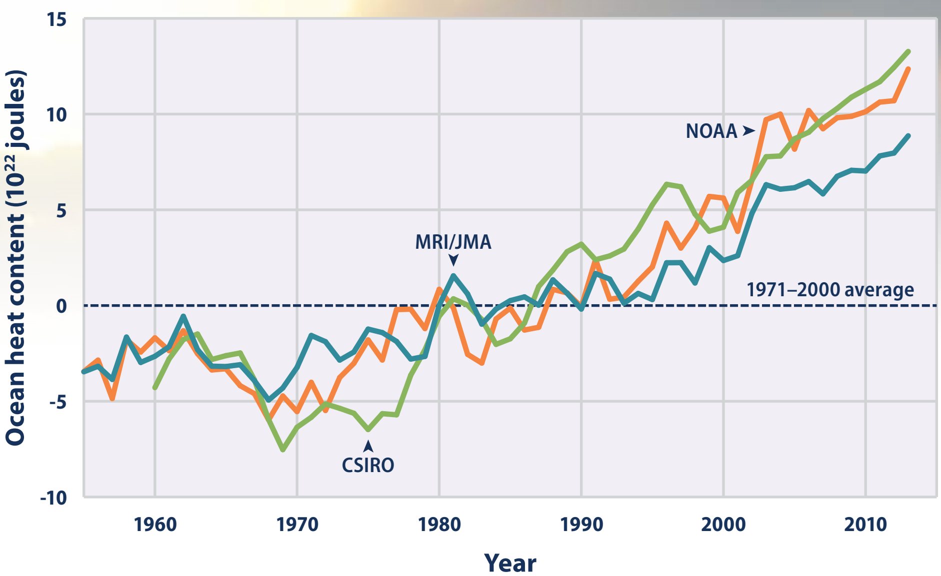
Because water expands slightly as it gets warmer, an increase in ocean heat content will also increase the volume of water in the ocean, which is one cause of the observed increases in sea level (see the Sea Level indicator on p. 50).

ABOUT THE INDICATOR

This indicator shows trends in global ocean heat content from 1955 to 2013. These data are available for the top 700 meters of the ocean (nearly 2,300 feet), which accounts for just under 20 percent of the total volume of water in the world's oceans. The indicator measures ocean heat content in joules, which are units of energy.

The National Oceanic and Atmospheric Administration has calculated changes in ocean heat content based on measurements of ocean temperatures around the world at different depths. These measurements come from a variety of instruments deployed from ships and airplanes and, more recently, underwater robots. Thus, the data must be carefully adjusted to account for differences among measurement techniques and data collection programs. Figure 1 shows three independent interpretations of essentially the same underlying data.

Figure 1. Ocean Heat Content, 1955–2013



This figure shows changes in ocean heat content between 1955 and 2013. Ocean heat content is measured in joules, a unit of energy, and compared against the 1971–2000 average, which is set at zero for reference. Choosing a different baseline period would not change the shape of the data over time. The lines were independently calculated using different methods by three agencies: the National Oceanic and Atmospheric Administration (NOAA), Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), and Japan Meteorological Agency's Meteorological Research Institute (MRI/JMA). For reference, an increase of 5 units on this graph (5 x 10^{22} joules) is equal to approximately 100 times the total amount of energy used by all the people on Earth in a year.[4]

Data sources: CSIRO, 2014;[5] MRI/JMA, 2014;[6] NOAA, 2014[7]

INDICATOR NOTES

Data must be carefully reconstructed and filtered for biases because of different data collection techniques and uneven sampling over time and space. Various methods of correcting the data have led to slightly different versions of the ocean heat trend line. Scientists continue to compare their results and improve their estimates over time. They also test their ocean heat estimates by looking at corresponding changes in other properties of the ocean. For example, they can check to see whether observed changes in sea level match the amount of sea level rise that would be expected based on the estimated change in ocean heat.

DATA SOURCES

Data for this indicator were collected by the National Oceanic and Atmospheric Administration and other organizations around the world. The data were analyzed independently by researchers at the National Oceanic and Atmospheric Administration, Australia's Commonwealth Scientific and Industrial Research Organisation, and the Japan Meteorological Agency's Meteorological Research Institute.

Sea Surface Temperature

This indicator describes global trends in sea surface temperature.

KEY POINTS

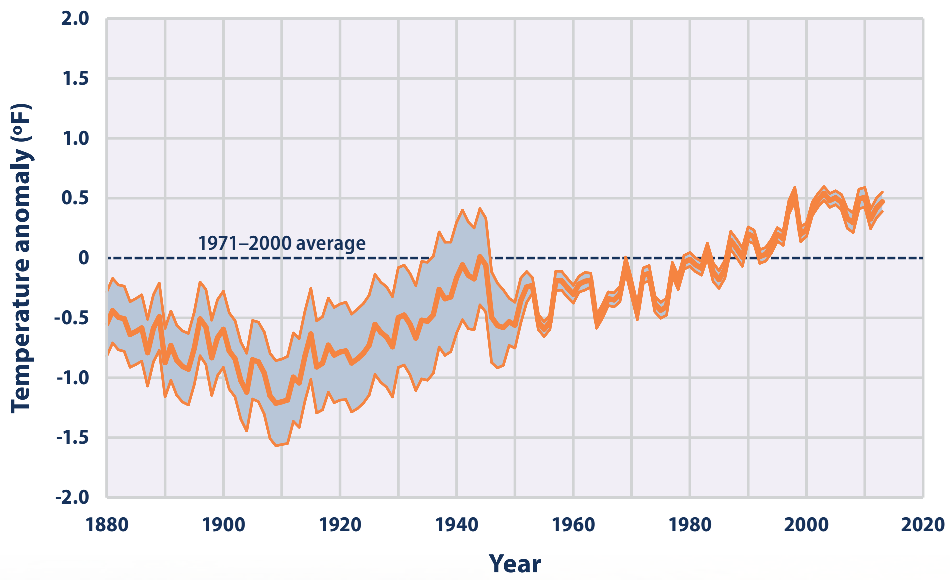
- Sea surface temperature increased over the 20th century and continues to rise. From 1901 through 2013, temperatures rose at an average rate of 0.13°F per decade (see Figure 1).
- Sea surface temperatures have been higher during the past three decades than at any other time since reliable observations began in 1880 (see Figure 1).
- Increases in sea surface temperature have largely occurred over two key periods: between 1910 and 1940, and from about 1970 to the present. Sea surface temperatures appear to have cooled between 1880 and 1910 (see Figure 1).
- Changes in sea surface temperature vary regionally. While most parts of the world's oceans have seen temperatures rise, a few areas have actually experienced cooling—for example, parts of the North Atlantic (see Figure 2).

Sea surface temperature—the temperature of the water at the ocean surface—is an important physical attribute of the world's oceans. The surface temperature of the world's oceans varies mainly with latitude, with the warmest waters generally near the equator and the coldest waters in the Arctic and Antarctic regions. As the oceans absorb more heat, sea surface temperatures will increase and the ocean circulation patterns that transport warm and cold water around the globe will change.

Changes in sea surface temperature can alter marine ecosystems in several ways. For example, variations in ocean temperature can affect what species of plants, animals, and microbes are present in a location, alter migration and breeding patterns, threaten sensitive ocean life such as corals, and change the frequency and intensity of harmful algal blooms such as "red tide."[8] Over the long term, increases in sea surface temperature could also reduce the circulation patterns that bring nutrients from the deep sea to surface waters. Changes in reef habitat and nutrient supply could dramatically alter ocean ecosystems and lead to declines in fish populations, which in turn could affect people who depend on fishing for food or jobs.[9]

Because the oceans continuously interact with the atmosphere, sea surface temperature can also have profound effects on global climate. Increases in sea surface temperature have led to an increase in the amount of atmospheric water vapor over the oceans.[10] This water vapor feeds weather systems that produce precipitation, increasing the risk of heavy rain and snow (see the Heavy Precipitation and Tropical Cyclone Activity indicators on pp. 36 and 42). Changes in sea surface temperature can also shift storm tracks, potentially contributing to droughts in some areas.[11]

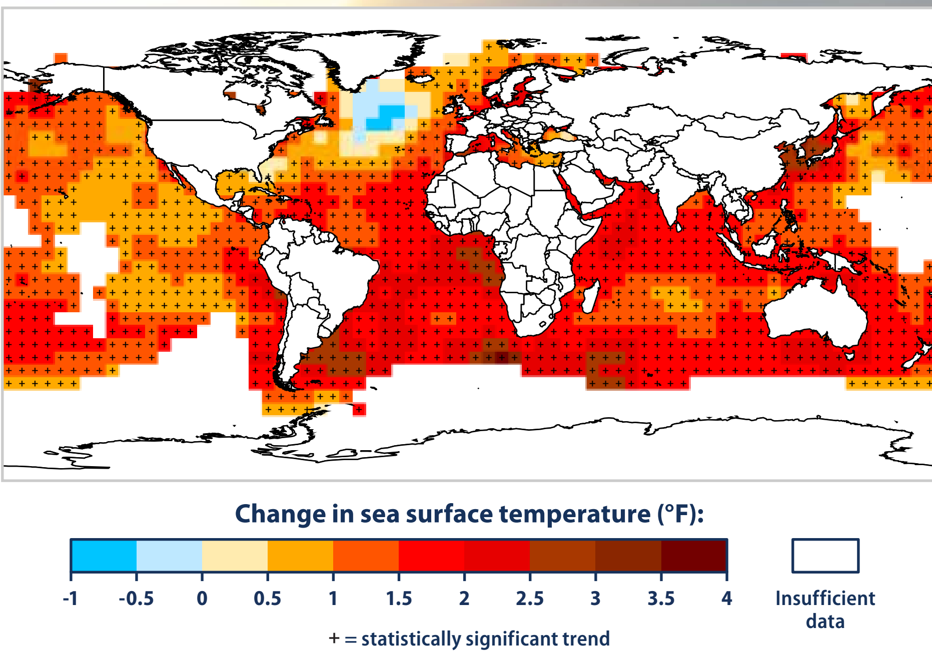
Figure 1. Average Global Sea Surface Temperature, 1880–2013



This graph shows how the average surface temperature of the world's oceans has changed since 1880. This graph uses the 1971 to 2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the data over time. The shaded band shows the range of uncertainty in the data, based on the number of measurements collected and the precision of the methods used.

Data source: NOAA, 2014[12]

Figure 2. Change in Sea Surface Temperature, 1901–2012



This map shows how average sea surface temperatures around the world changed between 1901 and 2012. It is based on a combination of direct measurements and satellite measurements. A black "+" symbol in the middle of a square on the map means the trend shown is statistically significant. White areas did not have enough data to calculate reliable long-term trends.

Data source: IPCC, 2013[13]

ABOUT THE INDICATOR

This indicator tracks average global sea surface temperature from 1880 through 2013. It also includes a map to show how change in sea surface temperature has varied across the world's oceans since 1901.

Techniques for measuring sea surface temperature have evolved since the 1800s. For instance, the earliest data were collected by inserting a thermometer into a water sample collected by lowering a bucket from a ship. Today, temperature measurements are collected more systematically from ships, as well as at stationary and drifting buoys.

The National Oceanic and Atmospheric Administration has carefully reconstructed and filtered the data in Figure 1 to correct for biases in the different collection techniques and to minimize the effects of sampling changes over various locations and times. The data are shown as anomalies, or differences, compared with the average sea surface temperature from 1971 to 2000. The map in Figure 2 was developed by the Intergovernmental Panel on Climate Change, which calculated long-term trends based on a collection of published studies.

INDICATOR NOTES

Both components of this indicator are based on instrumental measurements of surface water temperature. Due to denser sampling and improvements in sampling design and measurement techniques, newer data are more precise than older data. The earlier trends shown by this indicator have less certainty because of lower sampling frequency and less precise sampling methods, as shown by the width of the blue shaded band in Figure 1.

DATA SOURCES

Data for Figure 1 were provided by the National Oceanic and Atmospheric Administration's National Climatic Data Center and are available online at: www.ncdc.noaa.gov/ersst. These data were reconstructed from measurements of water temperature, which are available from the National Oceanic and Atmospheric Administration at: http://icoads.noaa.gov/products.html. Figure 2 comes from the Intergovernmental Panel on Climate Change's Fifth Assessment Report (www.ipcc.ch/report/ar5/wg1), which gathers data from a variety of studies that provide the best available information about climate change.

Sea Level

This indicator describes how sea level has changed over time. The indicator describes two types of sea level changes: absolute and relative.

KEY POINTS

- After a period of approximately 2,000 years of little change (not shown here), global average sea level rose throughout the 20th century, and the rate of change has accelerated in recent years.[14] When averaged over all the world's oceans, absolute sea level increased at an average rate of 0.06 inches per year from 1880 to 2012 (see Figure 1). Since 1993, however, average sea level has risen at a rate of 0.11 to 0.12 inches per year—roughly twice as fast as the long-term trend.
- Relative sea level rose along much of the U.S. coastline between 1960 and 2013, particularly the Mid-Atlantic coast and parts of the Gulf coast, where some stations registered increases of more than 8 inches (see Figure 2). Meanwhile, relative sea level fell at some locations in Alaska and the Pacific Northwest. At those sites, even though absolute sea level has risen, land elevation has risen more rapidly.
- While absolute sea level has increased steadily overall, particularly in recent decades, regional trends vary, and absolute sea level has decreased in some places.[15] Relative sea level also has not risen uniformly because of regional and local changes in land movement and long-term changes in coastal circulation patterns.

As the temperature of the Earth changes, so does sea level. Temperature and sea level are linked for two main reasons:

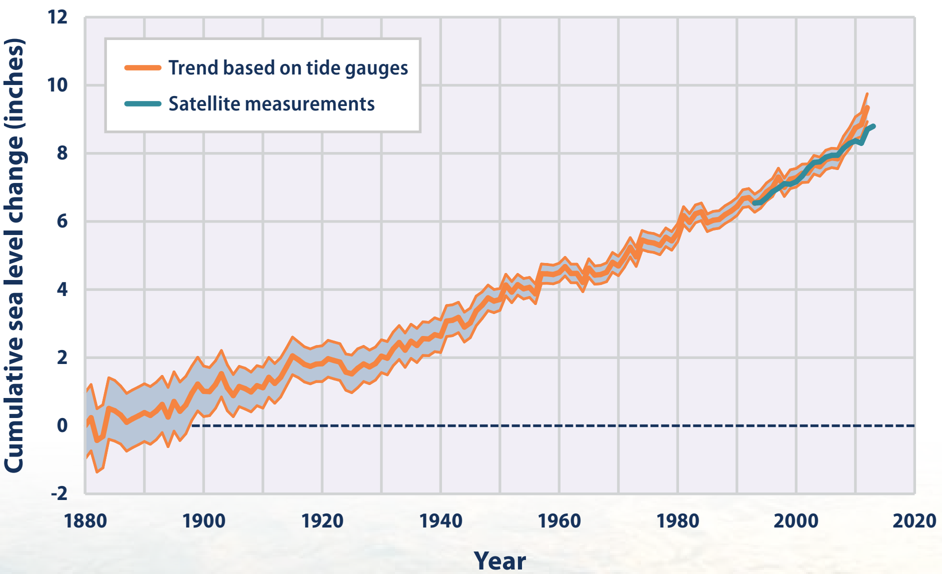
1. Changes in the volume of water and ice on land (namely glaciers and ice sheets) can increase or decrease the volume of water in the ocean (see the Glaciers indicator on p. 60).
2. As water warms, it expands slightly—an effect that is cumulative over the entire depth of the oceans (see the Ocean Heat indicator on p. 46).

Changing sea levels can affect human activities in coastal areas. Rising sea level inundates low-lying wetlands and dry land, erodes shorelines, contributes to coastal flooding, and increases the flow of salt water into estuaries and nearby groundwater aquifers. Higher sea level also makes coastal infrastructure more vulnerable to damage from storms.

The sea level changes that affect coastal systems involve more than just expanding oceans, however, because the Earth's continents can also rise and fall relative to the oceans. Land can rise through processes such as sediment accumulation (the process that built the Mississippi River delta) and geological uplift (for example, as glaciers melt and the land below is no longer weighed down by heavy ice). In other areas, land can sink because of erosion, sediment compaction, natural subsidence (sinking due to geologic changes), or engineering projects that prevent rivers from naturally depositing sediments along their banks. Changes in ocean currents such as the Gulf Stream can also affect sea levels by pushing more water against some coastlines and pulling it away from others, raising or lowering sea levels accordingly.

Scientists account for these types of changes by measuring sea level change in two different ways. *Relative* sea level change is how the height of the ocean rises or falls relative to the land at a particular location. In contrast, *absolute* sea level change refers to the height of the ocean surface above the center of the earth, without regard to whether nearby land is rising or falling.

Figure 1. Global Average Absolute Sea Level Change, 1880–2013



This graph shows cumulative changes in sea level for the world's oceans since 1880, based on a combination of long-term tide gauge measurements and recent satellite measurements. This figure shows average absolute sea level change, which refers to the height of the ocean surface, regardless of whether nearby land is rising or falling. Satellite data are based solely on measured sea level, while the long-term tide gauge data include a small correction factor because the size and shape of the oceans are changing slowly over time. (On average, the ocean floor has been gradually sinking since the last Ice Age peak, 20,000 years ago.) The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used.

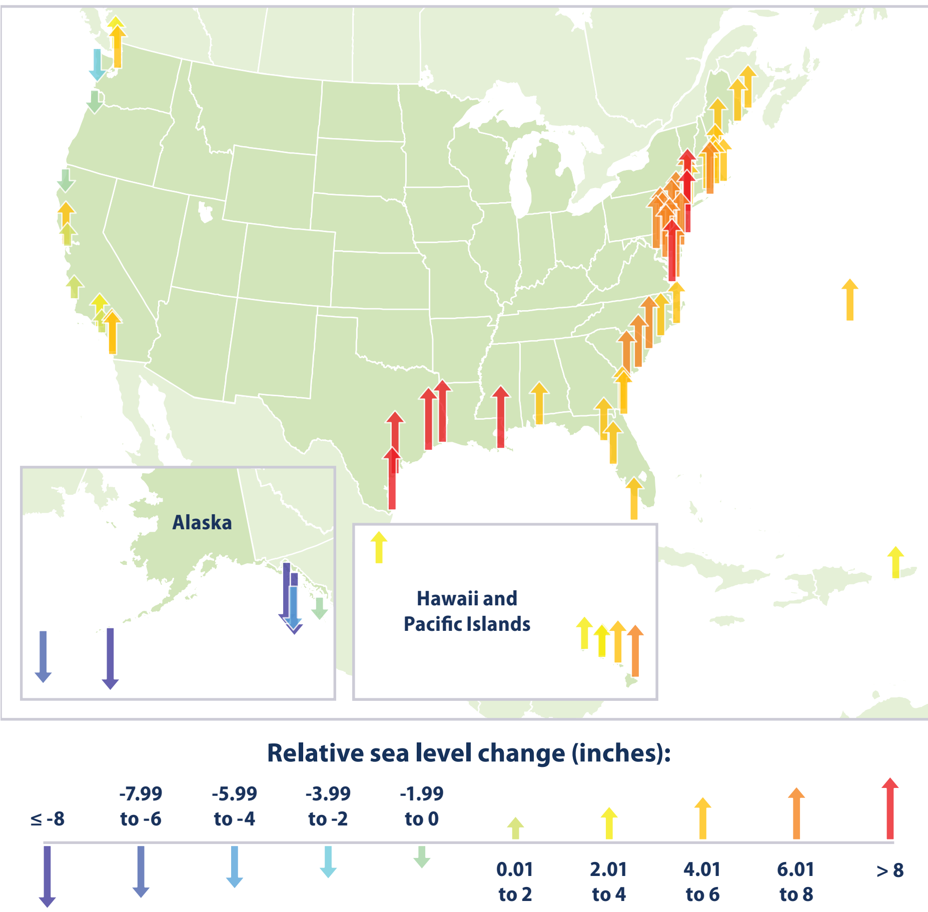
Data sources: CSIRO, 2013;[16] NOAA, 2014[17]

ABOUT THE INDICATOR

This indicator presents trends in sea level based on measurements from tide gauges and from satellites that orbit the Earth. Tide gauges measure relative sea level change at points along the coast, while satellite instruments measure absolute sea level change over nearly the entire ocean surface. Many tide gauges have collected data for more than 100 years, while satellites have collected data since the early 1990s.

Figure 1 shows annual absolute sea level change averaged over the entire Earth's ocean surface. The long-term trend is based on tide gauge data that have been adjusted to show absolute global trends through calibration with recent satellite data. This long-term data set has been calculated through 2012, while satellite data are now available through the end of 2013. Figure 2 shows trends at a more local scale, highlighting the 1960 to 2013 change in relative sea level at 67 tide gauges along the Atlantic, Pacific, and Gulf coasts of the United States.

Figure 2. Relative Sea Level Change Along U.S. Coasts, 1960–2013



This map shows cumulative changes in relative sea level from 1960 to 2013 at tide gauge stations along U.S. coasts. Relative sea level reflects changes in sea level as well as land elevation.

Data source: NOAA, 2014[18]

INDICATOR NOTES

Relative sea level trends represent a combination of absolute sea level change and any local land movement. Tide gauge measurements such as those in Figure 2 generally cannot distinguish between these two different influences without an accurate measurement of vertical land motion nearby.

Some changes in relative and absolute sea level can be due to multi-year cycles such as El Niño and La Niña, which affect coastal ocean temperatures, salt content, wind patterns, atmospheric pressure (and thus storm tracks), and currents. Obtaining a reliable trend can require many years of data, which is why the satellite record in Figure 1 has been supplemented with a longer-term reconstruction based on tide gauge measurements.

DATA SOURCES

Absolute sea level trends were provided by Australia's Commonwealth Scientific and Industrial Research Organisation and the National Oceanic and Atmospheric Administration. These data are based on measurements collected by satellites and tide gauges. Relative sea level data are available from the National Oceanic and Atmospheric Administration, which publishes an interactive online map (http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml) with links to detailed data for each tide gauge.

Land Loss Along the Atlantic Coast

KEY POINTS

- Roughly 20 square miles of dry land and wetland were converted to open water along the Atlantic coast between 1996 and 2011. (For reference, Manhattan is 33 square miles.) More of this loss occurred in the Southeast than in the Mid-Atlantic (see Figure 1).
- The data suggest that at least half of the land lost since 1996 has been tidal wetland. The loss of dry land appears to be larger than the loss of non-tidal wetland (see Figure 2).

Why is the Atlantic coast particularly vulnerable to sea level rise?

Much of the land along the Atlantic coast is flat and close to sea level—including thousands of square miles of marshes and other productive wetlands, plus many low-lying cities. In addition, much of the land along the Atlantic coast is sinking, which magnifies the local effect of sea level rise. The land in North America is actually still adjusting to the loss of ice after the last ice age, which peaked about 20,000 years ago. Back then, thick sheets of ice covered areas of what is now Canada and the northern United States. The weight of all that ice depressed the land beneath it, but caused the land farther south (particularly the Mid-Atlantic region from North Carolina to New York) to bulge upward. After the ice melted and the extra weight was lifted, northern areas began to rise, and the Mid-Atlantic region started to sink. This very slow process continues today.

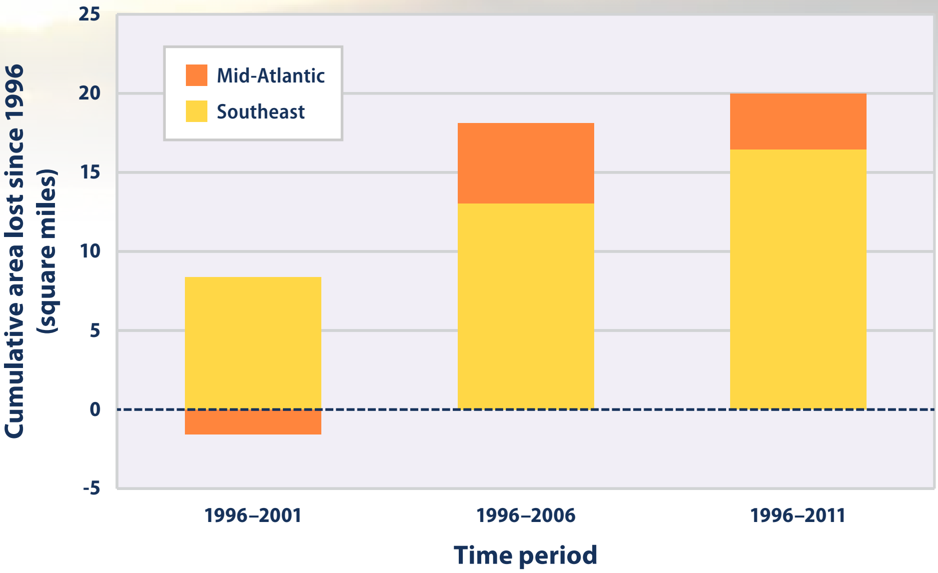
Rising sea level tends to make headlines during extreme events, like the storm surge that caused billions of dollars in damage during Hurricane Sandy in 2012. Yet rising sea level can also cause permanent changes in the landscape when it inundates (submerges) low-lying land. The Atlantic coast is particularly vulnerable because of low elevations and sinking shorelines.

The loss of coastal land can affect a large number of people, as nearly 10 million Americans live in a coastal floodplain.[19] Coastal ecosystems are also at risk. These environments provide habitat for many kinds of plants and animals, as well as services that ensure people's well-being, ranging from food production to recreation. Coastal wetlands provide valuable nursery, feeding, breeding, staging, and resting areas for many fish, shellfish, mammals, and birds, and they can buffer coastal areas against storm and wave damage.

As sea level rises, dry land can turn into wetland or open water. Existing wetlands can be threatened, too, as salt marshes, mangrove forests, and other coastal wetlands are at risk of being converted to open water.

The Sea Level indicator (p. 50) shows that sea level is rising overall in connection with climate change, but the rate of change varies by region, as do the effects. To provide a useful regional perspective, this feature examines the amount of land lost to sea level rise along the Atlantic coast from Florida to New York. It is based on satellite data that have been collected and analyzed at five-year intervals since 1996. Figure 1 divides the Atlantic coast into two regions for comparison, while Figure 2 shows the different types of land that have been lost.

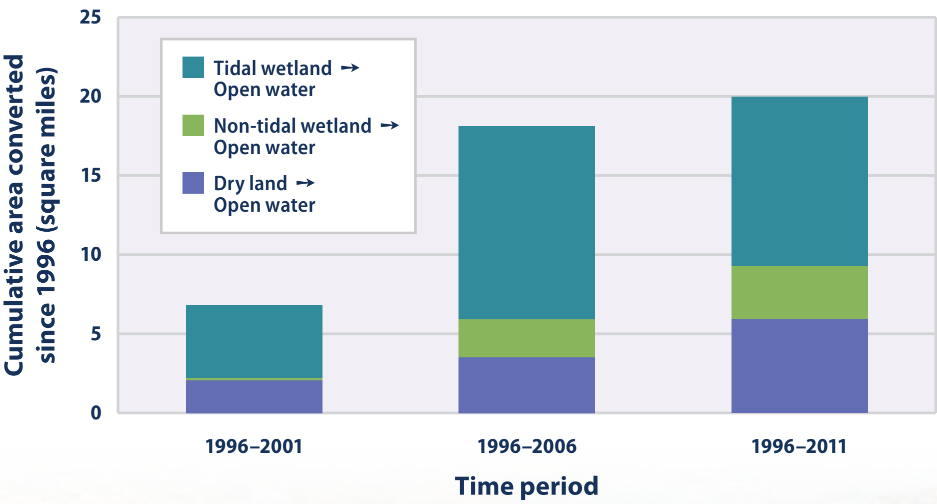
Figure 1. Land Loss Along the Atlantic Coast, 1996–2011



This graph shows the net amount of land converted to open water along the Atlantic coast during three time periods: 1996–2001, 1996–2006, and 1996–2011. The results are divided into two regions: the Southeast and the Mid-Atlantic (see locator map). Negative numbers show where land loss is outpaced by the accumulation of new land.

Data source: NOAA, 2013[20]

Figure 2. Land Submergence Along the Atlantic Coast, 1996–2011



This graph shows the net amount of land converted to open water along the Atlantic coast during three time periods: 1996–2001, 1996–2006, and 1996–2011. The results are divided into categories to show the type of land that has been converted to open water.

Data source: NOAA, 2013[21]

NOTES

Measurements of the change in coastal land depend on land cover and elevation data, which have significant limits in terms of accuracy and precision. Some results are field-checked for accuracy. The coastal land cover data are routinely compiled by the National Oceanic and Atmospheric Administration's Coastal Change Analysis Program, and they represent the federal government's most comprehensive set of data on land use and land cover in the coastal zone.

Sea level rise is not the only factor that contributes to the loss of coastal land. In addition to the natural sinking of the shoreline in some areas, such as the Mid-Atlantic, coastal land loss has been made worse by human activities such as navigation and flood control structures that block wetland migration or the movement of sediment; withdrawal of ground water, oil, or natural gas in some regions; and boat traffic that accelerates wetland erosion.[22] Natural processes unrelated to current sea level rise can also cause shores to erode.

DATA SOURCES

This feature is based on land cover data from the Coastal Change Analysis Program, which is coordinated by the National Oceanic and Atmospheric Administration. For more information about this program, visit: http://csc.noaa.gov/digitalcoast.

Ocean Acidity

This indicator describes changes in the chemistry of the ocean, which relate to the amount of carbon dioxide dissolved in the water.

KEY POINTS

- Measurements made over the last few decades have demonstrated that ocean carbon dioxide levels have risen in response to increased carbon dioxide in the atmosphere, leading to an increase in acidity (that is, a decrease in pH) (see Figure 1).
- Historical modeling suggests that since the 1880s, increased carbon dioxide has led to lower aragonite saturation levels in the oceans around the world, which makes it more difficult for certain organisms to build and maintain their skeletons and shells (see Figure 2).
- The largest decreases in aragonite saturation have occurred in tropical waters (see Figure 2). However, decreases in cold areas may be of greater concern because colder waters typically have lower aragonite saturation levels to begin with.[23]

The ocean plays an important role in regulating the amount of carbon dioxide in the atmosphere. As atmospheric concentrations of carbon dioxide rise (see the Atmospheric Concentrations of Greenhouse Gases indicator on p. 20), the ocean absorbs more carbon dioxide. Because of the slow mixing time between surface waters and deeper waters, it can take hundreds to thousands of years to establish this balance. Over the past 250 years, oceans have absorbed about 28 percent of the carbon dioxide produced by human activities that burn fossil fuels.[24]

Although the ocean's ability to take up carbon dioxide prevents atmospheric levels from climbing even higher, rising levels of carbon dioxide dissolved in the ocean can have a negative effect on some marine life. Carbon dioxide reacts with sea water to produce carbonic acid. The resulting increase in acidity (measured by lower pH values) changes the balance of minerals in the water. This makes it more difficult for corals, some types of plankton, and other creatures to produce a mineral called calcium carbonate, which is the main ingredient in their hard skeletons and shells. Thus, declining pH can make it more difficult for these animals to thrive. This can lead to broader changes in the overall structure of ocean and coastal ecosystems, and can ultimately affect fish populations and the people who depend on them.[25] Signs of damage are already starting to appear in certain areas.[26]

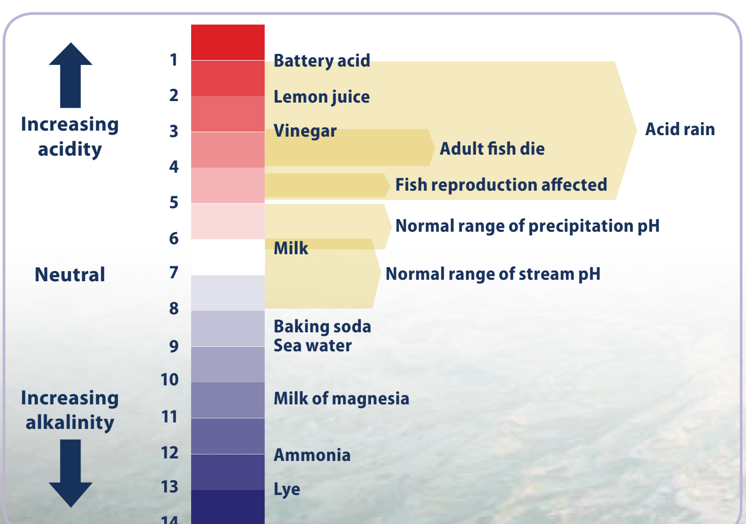
While changes in ocean pH and mineral saturation caused by the uptake of atmospheric carbon dioxide generally occur over many decades, these properties can fluctuate over shorter periods, especially in coastal and surface waters. For example, increased photosynthesis during the day and during the summer leads to natural fluctuations in pH. Acidity also varies with water temperature.

ABOUT THE INDICATOR

This indicator describes trends in pH and related properties of ocean water, based on a combination of direct observations, calculations, and modeling.

Figure 1 shows pH values and levels of dissolved carbon dioxide at three locations that have collected measurements consistently over the last few decades. These data have been either measured directly or calculated from related measurements, such as dissolved inorganic carbon and alkalinity. Data come from two stations in the Atlantic Ocean (Bermuda and the Canary Islands) and one in the Pacific (Hawaii).

The global map in Figure 2 shows changes over time in aragonite saturation level. Aragonite is a specific form of calcium carbonate that many organisms produce and use to build their skeletons and shells, and the saturation state is a measure of how easily aragonite can dissolve in the water. The lower the saturation level, the more difficult it is for organisms to build and maintain their skeletons and shells. This map was created by comparing average conditions during the 1880s with average conditions during the most recent 10 years (2004–2013). Aragonite saturation has only been measured at selected locations during the last few decades, but it can be calculated reliably for different times and locations based on the relationships scientists have observed among aragonite saturation, pH, dissolved carbon, water temperature, concentrations of carbon dioxide in the atmosphere, and other factors that can be measured. Thus, while Figure 2 was created using a computer model, it is based on measurements.

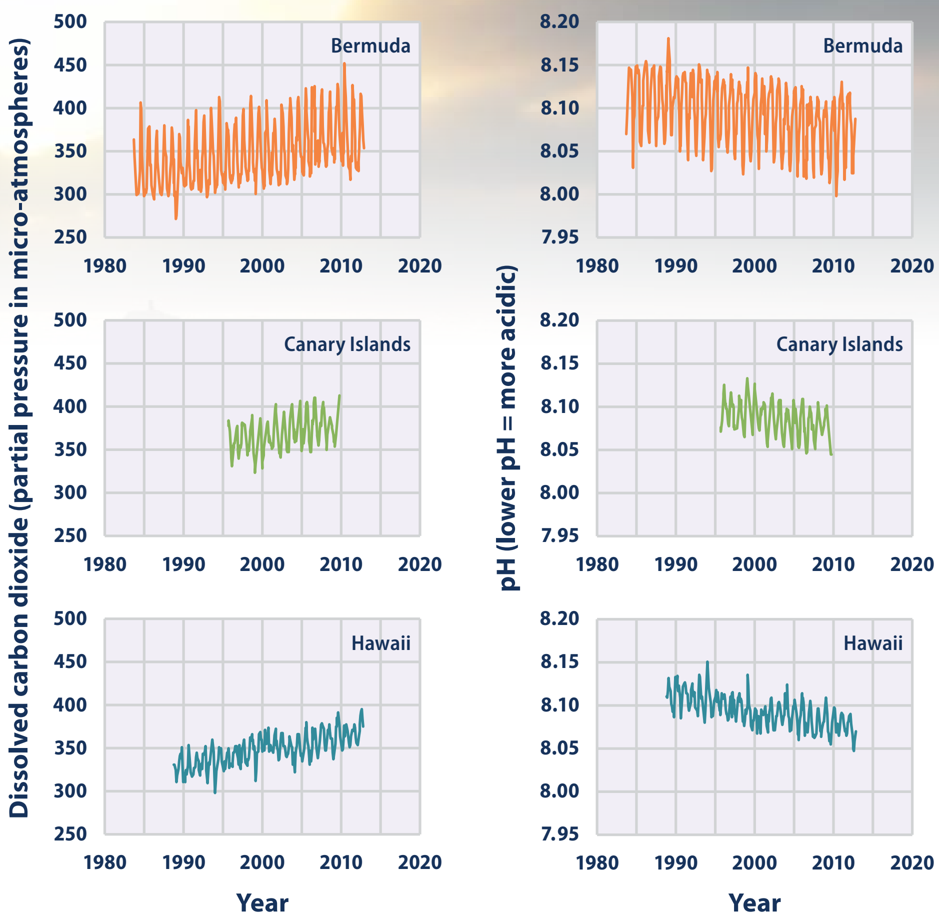


pH Scale

Acidity is commonly measured using the pH scale. Pure water has a pH of about 7, which is considered neutral. A substance with a pH less than 7 is considered to be acidic, while a substance with a pH greater than 7 is considered to be basic or alkaline. The lower the pH, the more acidic the substance. Like the well-known Richter scale for measuring earthquakes, the pH scale is based on powers of 10, which means a substance with a pH of 3 is 10 times more acidic than a substance with a pH of 4. For more information about pH, visit: www.epa.gov/acidrain/measure/ph.html.

Source: Environment Canada, 2008[27]

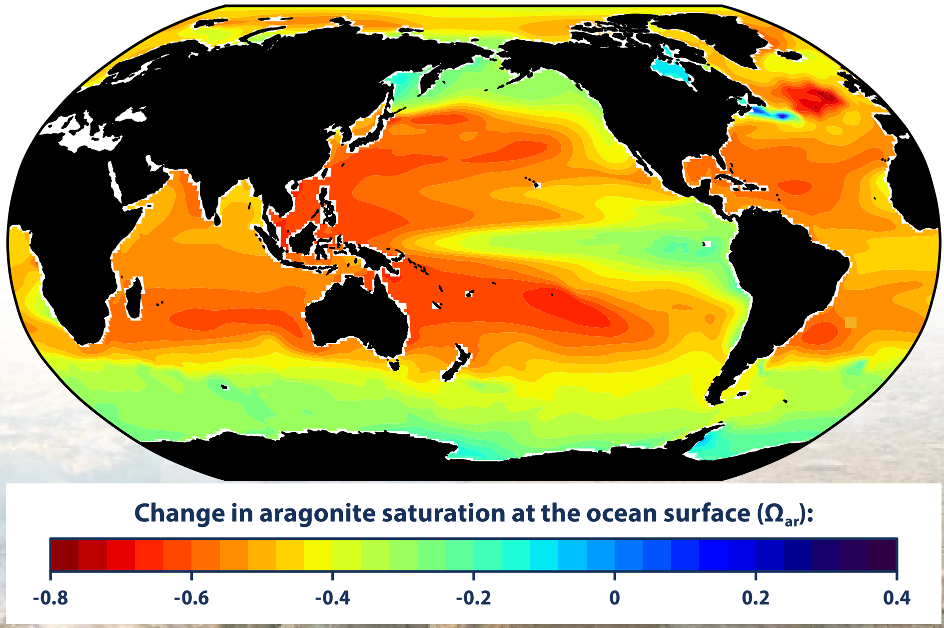
Figure 1. Ocean Carbon Dioxide Levels and Acidity, 1983–2012



This figure shows the relationship between changes in ocean carbon dioxide levels (measured in the left column as a partial pressure—a common way of measuring the amount of a gas) and acidity (measured as pH in the right column). The data come from two observation stations in the North Atlantic Ocean (Canary Islands and Bermuda) and one in the Pacific (Hawaii). The up-and-down pattern shows the influence of seasonal variations.

Data sources: Bermuda Institute of Ocean Sciences, 2014;[28] González-Dávila, 2012;[29] University of Hawaii, 2014[30]

Figure 2. Changes in Aragonite Saturation of the World's Oceans, 1880–2013



This map shows changes in the aragonite saturation level of ocean surface waters between the 1880s and the most recent decade (2004–2013). Aragonite is a form of calcium carbonate that many marine animals use to build their skeletons and shells. The lower the saturation level, the more difficult it is for organisms to build and maintain their skeletons and shells. A negative change represents a decrease in saturation.

Data source: Woods Hole Oceanographic Institution, 2014[33]

INDICATOR NOTES

This indicator focuses on surface waters, which can absorb carbon dioxide from the atmosphere within a few months.[31] It can take much longer for changes in pH and mineral saturation to spread to deeper waters, so the full effect of increased atmospheric carbon dioxide concentrations on ocean acidity may not be seen for many decades, if not centuries. Studies suggest that the impacts of ocean acidification may be greater at depth, because the aragonite saturation level is naturally lower in deeper waters.[32]

Ocean chemistry is not uniform around the world, so local conditions can cause pH or aragonite saturation measurements to differ from the global average. For example, carbon dioxide dissolves more readily in cold water than in warm water, so colder regions could experience greater impacts from acidity than warmer regions. Air and water pollution also lead to increased acidity in some areas.

DATA SOURCES

Data for Figure 1 came from three studies: the Bermuda Atlantic Time-Series Study, the European Station for Time-Series in the Ocean (Canary Islands), and the Hawaii Ocean Time-Series. Bermuda data are available at: http://bats.bios.edu. Canary Islands data are available at: www.eurosites.info/estoc/data.php. Hawaii data are available at: http://hahana.soest.hawaii.edu/hot/products/products.html.

The map in Figure 2 was created by the National Oceanic and Atmospheric Administration and the Woods Hole Oceanographic Institution using Community Earth System Model data. Related information can be found at: http://sos.noaa.gov/Datasets/list.php?category=Ocean.

SNOW AND ICE

The Earth's surface contains many forms of snow and ice, including sea, lake, and river ice; snow cover; glaciers, ice caps, and ice sheets; and frozen ground. Climate change can dramatically alter the Earth's snow- and ice-covered areas because snow and ice can easily change between solid and liquid states in response to relatively minor changes in temperature. This chapter focuses on trends in snow, glaciers, and the freezing and thawing of oceans and lakes.

WHY DOES IT MATTER?

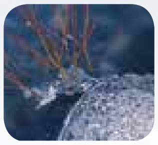
Reduced snowfall and less snow cover on the ground could diminish the beneficial insulating effects of snow for vegetation and wildlife, while also affecting water supplies, transportation, cultural practices, travel, and recreation for millions of people. For communities in Arctic regions, reduced sea ice could increase coastal erosion and exposure to storms, threatening homes and property, while thawing ground could damage roads and buildings and accelerate erosion. Conversely, reduced snow and ice could present commercial opportunities for others, including ice-free shipping lanes and increased access to natural resources.

Such changing climate conditions can have worldwide implications because snow and ice influence air temperatures, sea level, ocean currents, and storm patterns. For example, melting ice sheets on Greenland and Antarctica add fresh water to the ocean, increasing sea level and possibly changing ocean circulation that is driven by differences in temperature and salinity. Because of their light color, snow and ice also reflect more sunlight than open water or bare ground, so a reduction in snow cover and ice causes the Earth's surface to absorb more energy from the sun and become warmer.

Summary of Key Points

Arctic Sea Ice. Part of the Arctic Ocean is covered by ice year-round. The area covered by ice is typically smallest in September, after the summer melting season. The minimum extent of Arctic sea ice has decreased over time, and in September 2012 it was the smallest on record. Arctic ice has also become thinner, which makes it more vulnerable to additional melting.

Glaciers. Glaciers in the United States and around the world have generally shrunk since the 1960s, and the rate at which glaciers are melting has accelerated over the last decade. The loss of ice from glaciers has contributed to the observed rise in sea level.



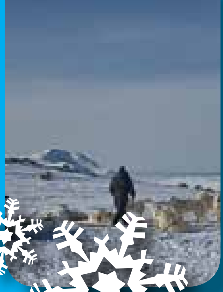
Lake Ice. Most lakes in the northern United States are freezing later and thawing earlier compared with the 1800s and early 1900s. Freeze dates have shifted later at a rate of roughly half a day to one day per decade, while thaw dates for most of the lakes studied have shifted earlier at a rate of half a day to two days per decade.

Community Connection: Ice Breakup in Two Alaskan Rivers. Regions in the far north are warming more quickly than other parts of the world. Two long-running contests on the Tanana and Yukon rivers in Alaska—where people guess the date when the river ice will break up in the spring—provide a century's worth of evidence revealing that the ice on these rivers is generally breaking up earlier in the spring than it used to.

Snowfall. Total snowfall—the amount of snow that falls in a particular location—has decreased in most parts of the country since widespread records began in 1930. One reason for this decline is that more than three-fourths of the locations studied have seen more winter precipitation fall in the form of rain instead of snow.

Snow Cover. Snow cover refers to the area of land that is covered by snow at any given time. Between 1972 and 2013, the average portion of North America covered by snow decreased at a rate of about 3,500 square miles per year, based on weekly measurements taken throughout the year. However, there has been much year-to-year variability.

Snowpack. The depth or thickness of snow on the ground (snowpack) in early spring decreased at about three-fourths of measurement sites in the western United States between 1955 and 2013. However, other locations saw an increase in spring snowpack. The average change across all sites for this time period amounts to about a 14 percent decline.



Arctic Sea Ice

This indicator tracks the extent and age of sea ice in the Arctic Ocean.

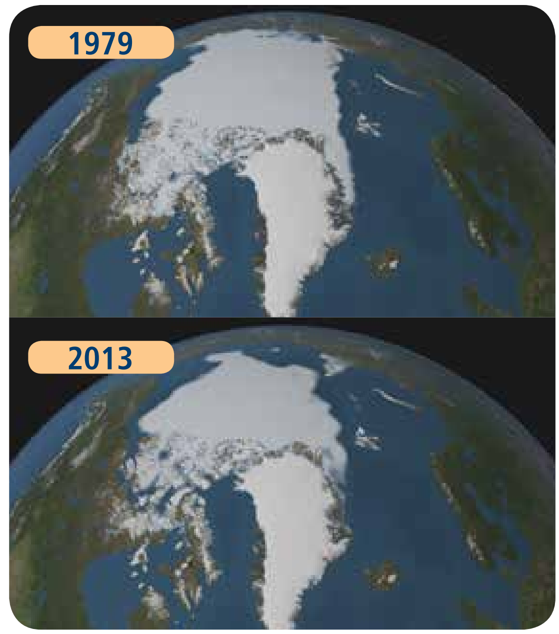
KEY POINTS

- September 2012 had the lowest sea ice extent on record, 49 percent below the 1979–2000 average for that month.
- The September 2013 sea ice extent was nearly 700,000 square miles less than the historical 1979–2000 average—a difference more than twice the size of Texas (see Figure 1).
- Although the annual minimum of sea ice extent typically occurs in September, all months have shown a decreasing trend in sea ice extent over the past several decades. The largest decreases have occurred in the summer and fall.[1, 2]
- Evidence of the age of Arctic sea ice suggests an overall loss of multi-year ice. The proportion of sea ice five years or older has declined dramatically over the recorded time period, from more than 30 percent of September ice in the 1980s to 7 percent in 2013. A growing percentage of Arctic sea ice is only one or two years old. This thinning of Arctic ice makes it more vulnerable to further melting.

Sea ice is an integral part of the Arctic Ocean. During the dark winter months, sea ice essentially covers the entire Arctic Ocean. In summer, some of this ice melts because of warmer temperatures and long hours of sunlight. Sea ice typically reaches its minimum thickness and extent in mid-September, when the area covered by ice is roughly half the size of the winter maximum. The ice then begins expanding again.

The extent of area covered by Arctic sea ice is an important indicator of changes in global climate because warmer air and water temperatures are reducing the amount of sea ice present. Because sea ice is more reflective than liquid water, it plays a significant role in the Earth's energy balance and keeping polar regions cool. (For more information on the effects of surface color on reflecting sunlight, see the Snow Cover indicator on p. 68.) Sea ice also keeps the air cool by forming a barrier between the cold air above and the warmer water below. As the amount of sea ice decreases, the Arctic region's ability to stabilize the Earth's climate is reduced, potentially leading to a "feedback loop" of more absorption of solar energy, higher air temperatures, and even greater loss of sea ice.

Dwindling Arctic Sea Ice



Source: NASA, 2014[3]

The age of sea ice is also an important indicator of Arctic conditions, because older ice is generally thicker and stronger than younger ice. A loss of older ice suggests that the Arctic is losing ice faster than it is accumulating it.

Changes in sea ice can directly affect the health of Arctic ecosystems. Mammals such as polar bears and walruses rely on the presence of sea ice for hunting, breeding, and migrating. These animals face the threat of declining birth rates and restricted access to food sources because of reduced sea ice coverage and thickness. Impacts on Arctic wildlife, as well as the loss of ice itself, are already restricting the traditional subsistence hunting lifestyle of indigenous Arctic populations such as the Yup'ik, Iñupiat, and Inuit.

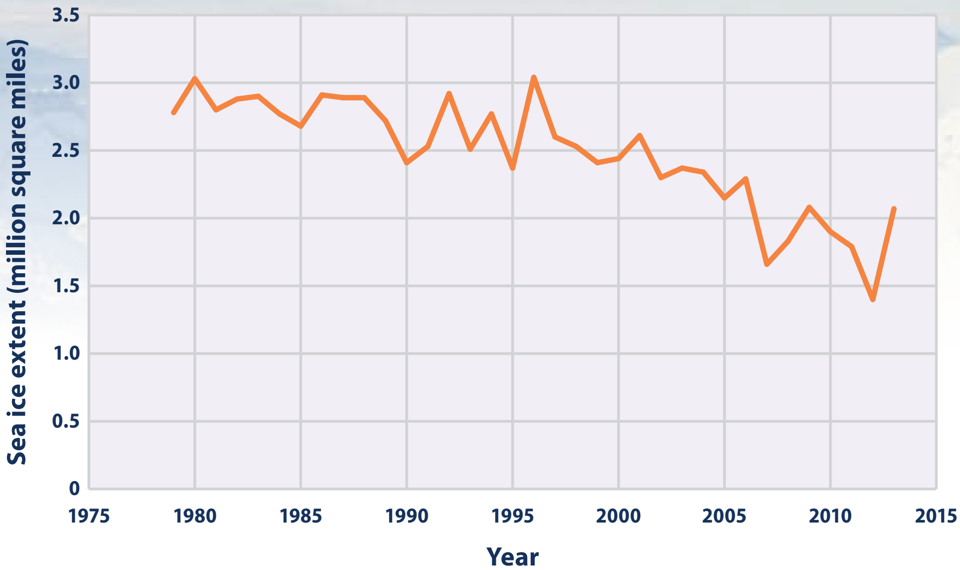
While diminished sea ice can have negative ecological effects, it can also present commercial opportunities. For instance, reduced sea ice opens shipping lanes and increases access to natural resources in the Arctic region.

ABOUT THE INDICATOR

Figure 1 presents trends in Arctic sea ice extent from 1979, when extensive measurements started, to 2013. Sea ice extent is defined as the area of ocean where at least 15 percent of the surface is frozen. This threshold was chosen because scientists have found that it gives the best approximation of the edge of the ice. Data are collected throughout the year, but for comparison, this indicator focuses on the average sea ice extent in September of each year. This is because September is typically when the sea ice extent reaches its annual minimum after melting during the spring and summer. Data for this indicator were gathered by the National Snow and Ice Data Center using satellite imaging technology.

Figure 2 examines the age of the ice that is present in the Arctic during the week in September with the smallest extent of ice. By combining daily satellite images, wind measurements, and data from surface buoys that move with the ice, scientists can track specific parcels of ice as they move over time. This tracking enables them to calculate the age of the ice in different parts of the Arctic. Although satellites started collecting data in 1979, Figure 2 only shows trends back to 1983 because it is not possible to know the full age distribution until the ice has been tracked for at least five years.

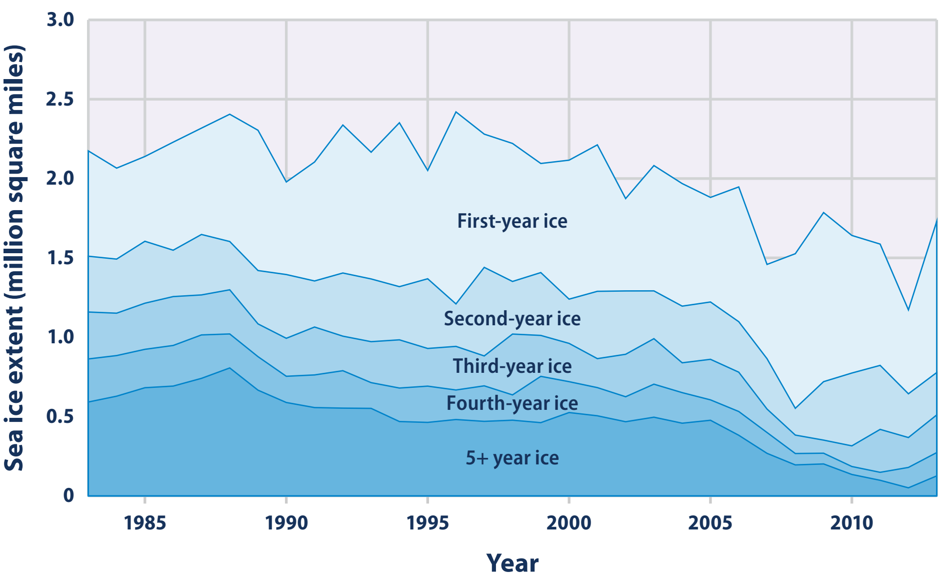
Figure 1. September Monthly Average Arctic Sea Ice Extent, 1979–2013



This figure shows Arctic sea ice extent from 1979 through 2013 using data from September of each year, which is when the minimum extent typically occurs.

Data source: NSIDC, 2013[4]

Figure 2. Age of Arctic Sea Ice at Minimum September Week, 1983–2013



This figure shows the distribution of Arctic sea ice extent by age group during the week in September with the smallest extent of ice for each year. The total extent in Figure 2 differs from the extent in Figure 1 because Figure 1 shows a monthly average, while Figure 2 shows conditions during a single week.

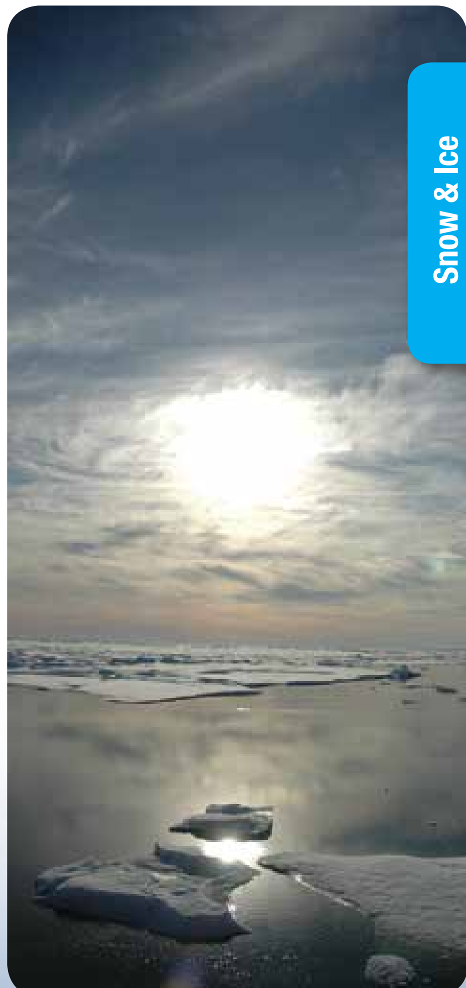
Data source: NSIDC, 2013[5]

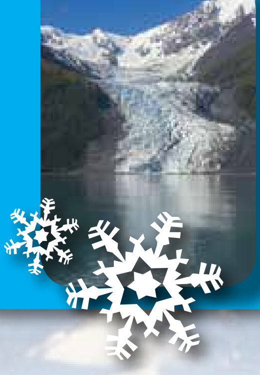
INDICATOR NOTES

Increasing temperatures associated with climate change are not the only factor contributing to reductions in sea ice. Other conditions that may be affected by climate change, such as fluctuations in oceanic and atmospheric circulation and typical annual and decadal variability, also affect the extent of sea ice. Determining the age of ice is an imperfect science, as there are cases where a small amount of older ice might exist within an area classified as younger, or vice-versa.

DATA SOURCES

The data for this indicator were provided by the National Snow and Ice Data Center. Data for Figure 1 are also available online at: http://nsidc.org/data/seaice_index/archives.html, while Figure 2 is based on an analysis by the University of Colorado and a map published at: http://nsidc.org/arcticseaicenews/2013/10. The National Snow and Ice Data Center produces a variety of reports and a seasonal newsletter analyzing Arctic sea ice data.





Glaciers

This indicator examines the balance between snow accumulation and melting in glaciers, and it describes how glaciers in the United States and around the world have changed over time.

KEY POINTS

- On average, glaciers worldwide have been losing mass since at least the 1970s (see Figure 1), which in turn has contributed to observed changes in sea level (see the Sea Level indicator on p. 50). A longer measurement record from a smaller number of glaciers suggests that they have been shrinking since the 1940s. The rate at which glaciers are losing mass appears to have accelerated over roughly the last decade.
- All three U.S. benchmark glaciers have shown an overall decline in mass balance since the 1950s and 1960s and an accelerated rate of decline in recent years (see Figure 2). Year-to-year trends vary, with some glaciers gaining mass in certain years (for example, Wolverine Glacier during the 1980s). However, most of the measurements indicate a loss of glacier mass over time.
- Trends for the three benchmark glaciers are consistent with the retreat of glaciers observed throughout the western United States, Alaska, and other parts of the world.[6] Observations of glaciers losing mass are also consistent with warming trends in U.S. and global temperatures during this time period (see the U.S. and Global Temperature indicator on p. 28).

A glacier is a large mass of snow and ice that has accumulated over many years and is present year-round. In the United States, glaciers can be found in the Rocky Mountains, the Sierra Nevada, the Cascades, and throughout Alaska. A glacier flows naturally like a river, only much more slowly. At higher elevations, glaciers accumulate snow, which eventually becomes compressed into ice. At lower elevations, the "river" of ice naturally loses mass because of melting and ice breaking off and floating away (iceberg calving) if the glacier ends in a lake or the ocean. When melting and calving are exactly balanced by new snow accumulation, a glacier is in equilibrium and its mass will neither increase nor decrease.

In many areas, glaciers provide communities and ecosystems with a reliable source of streamflow and drinking water, particularly in times of extended drought and late in the summer, when seasonal snowpack has melted away. Freshwater runoff from glaciers also influences ocean ecosystems. Glaciers are important as an indicator of climate change because physical changes in glaciers—whether they are growing or shrinking, advancing or receding—provide visible evidence of changes in temperature and precipitation. If glaciers lose more ice than they can accumulate through new snowfall, they ultimately add more water to the oceans, leading to a rise in sea level (see the Sea Level indicator on p. 50). The same kinds of changes occur on a much larger scale within the giant ice sheets that cover Greenland and Antarctica, potentially leading to even bigger implications for sea level. Small glaciers tend to respond more quickly to climate change than the giant ice sheets. Altogether, the world's small glaciers are adding roughly the same amount of water to the oceans per year as the ice sheets of Greenland and Antarctica. During the last two decades, they added more water overall to the oceans than the ice sheets did.[7]

ABOUT THE INDICATOR

This indicator is based on long-term monitoring data collected at selected glaciers around the world. Scientists collect detailed measurements to determine glacier mass balance, which is the net gain or loss of snow and ice over the course of the year. A negative mass balance indicates that a glacier has lost ice or snow. If cumulative mass balance becomes more negative over time, it means glaciers are losing mass more quickly than they can accumulate new snow.

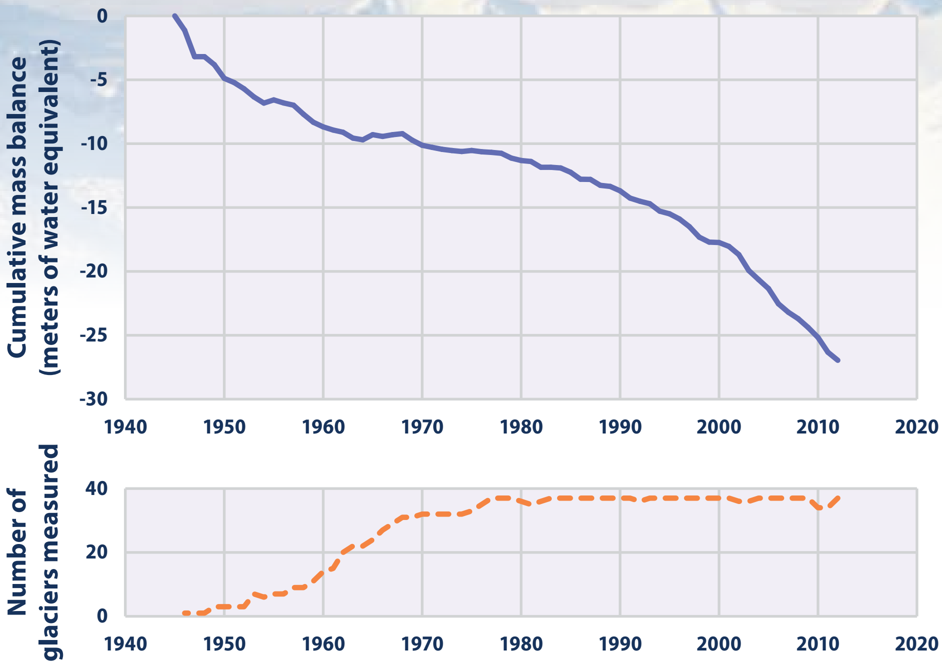
Figure 1 shows trends in mass balance for a set of 37 reference glaciers around the world that have been measured consistently since the 1970s, including a few that have been measured since the 1940s. Data from these reference glaciers have been averaged together to depict changes over time. Figure 2 shows trends for three "benchmark" glaciers: South Cascade Glacier in Washington state, Wolverine Glacier near Alaska's southern coast, and Gulkana Glacier in Alaska's interior. These three glaciers were chosen because they have been studied extensively by the U.S. Geological Survey for many years and because they are thought to be representative of other glaciers nearby.

This indicator describes the change in glacier mass balance, which is measured as the average change in thickness across the surface of a glacier. The change in ice or snow has been converted to the equivalent amount of liquid water.

Photographs of McCall Glacier, Alaska, 1958 and 2003

Sources: Post, 1958;[8] Nolan, 2003[9]

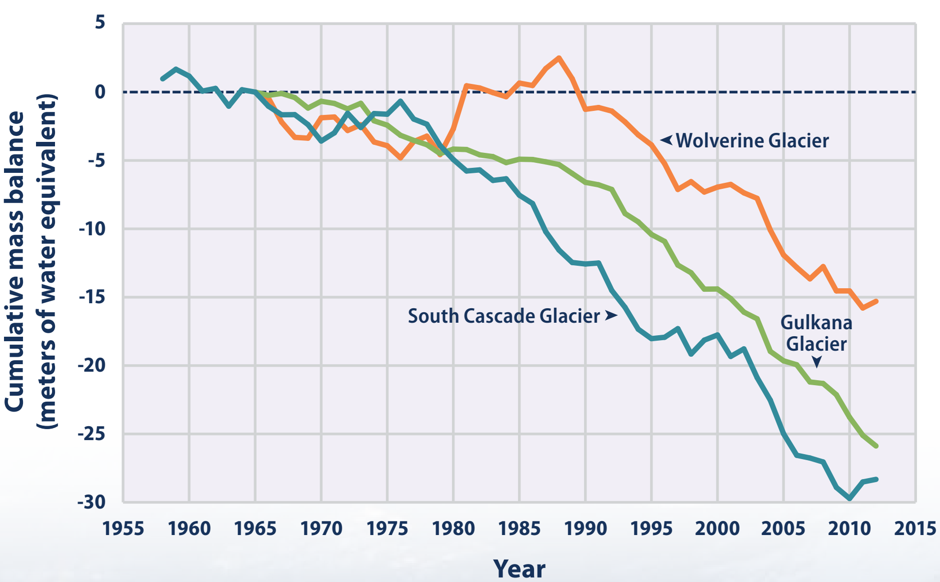
Figure 1. Average Cumulative Mass Balance of "Reference" Glaciers Worldwide, 1945–2012



This figure shows the cumulative change in mass balance of a set of "reference" glaciers worldwide beginning in 1945. The line on the graph represents the average of all the glaciers that were measured. Negative values indicate a net loss of ice and snow compared with the base year of 1945. For consistency, measurements are in meters of water equivalent, which represent changes in the average thickness of a glacier. The small chart below shows how many glaciers were measured in each year. Some glacier measurements have not yet been finalized for the last few years, hence the smaller number of sites.

Data sources: WGMS, 2013,[10] 2014[11]

Figure 2. Cumulative Mass Balance of Three U.S. Glaciers, 1958–2012



This figure shows the cumulative mass balance of the three U.S. Geological Survey "benchmark" glaciers since measurements began in the 1950s or 1960s. For each glacier, the mass balance is set at zero for the base year of 1965. Negative values indicate a net loss of ice and snow compared with the base year. For consistency, measurements are in meters of water equivalent, which represent changes in the average thickness of a glacier.

Data sources: O'Neel and Sass, 2013;[12] USGS, 2014[13]

INDICATOR NOTES

The relationship between climate change and glacier mass balance is complex, and the observed changes at specific reference or benchmark glaciers might reflect a combination of global and local variations in temperature and precipitation. Individual glaciers also vary in their structure, flow, and response to climate. Slightly different measurement and analysis methods have been used at different glaciers, but overall trends appear to be similar.

Long-term measurements are available for only a relatively small percentage of the world's glaciers. This indicator does not include the Greenland and Antarctic ice sheets, although two decades of satellite data suggest that these ice sheets are also experiencing a net loss of ice.[14] Continued satellite data collection will allow scientists to evaluate long-term trends in the future.

DATA SOURCES

The World Glacier Monitoring Service compiled data for Figure 1, based on measurements collected by a variety of organizations around the world. The U.S. Geological Survey Benchmark Glacier Program provided the data for Figure 2. These data, as well as periodic reports and measurements of the benchmark glaciers, are available on the program's website at: http://ak.water.usgs.gov/glaciology.

Glaciers Shown in Figure 2

Lake Ice

This indicator measures the amount of time that ice is present on lakes in the United States.

KEY POINTS

- The lakes covered by this indicator are generally freezing later than they did in the past. Freeze dates have shifted later at a rate of roughly half a day to one day per decade (see Figure 1).
- Thaw dates for most of these lakes show a general trend toward earlier ice breakup in the spring (see Figure 2). Thaw dates have grown earlier by up to 23 days in the past 107 years, except for two lakes that remained unchanged (see Figure 3). None of these lakes were found to be thawing later in the year.
- The changes in lake freeze and thaw dates shown here are consistent with other studies. For example, a broad study of lakes and rivers throughout the Northern Hemisphere found that since the mid-1800s, freeze dates have occurred later and thaw dates have occurred earlier, both shifting at an average rate of 0.8 days to one day per decade.[15]

The formation of ice cover on lakes in the winter and its disappearance the following spring depends on climate factors such as air temperature, cloud cover, and wind. Conditions such as heavy rains or snowmelt in locations upstream or elsewhere in the watershed also affect the length of time a lake is frozen. Thus, ice formation and breakup dates are key indicators of climate change. If lakes remain frozen for longer periods, it can signify that the climate is cooling. Conversely, shorter periods of ice cover suggest a warming climate.

Changes in ice cover can affect the physical, chemical, and biological characteristics of a body of water. For example, ice influences heat and moisture transfers between a lake and the atmosphere. Reduced ice cover leads to increased evaporation and lower water levels, as well as an increase in water temperature and sunlight penetration. These changes, in turn, can affect plant and animal life cycles and the availability of suitable habitat. Additionally, ice cover affects the amount of heat that is reflected from the Earth's surface. Exposed water will absorb and retain heat, making the Earth's surface warmer, whereas an ice- and snow-covered lake will reflect more of the sun's energy and absorb less. (For more information on ice and snow reflecting sunlight, see the Snow Cover indicator on p. 68.)

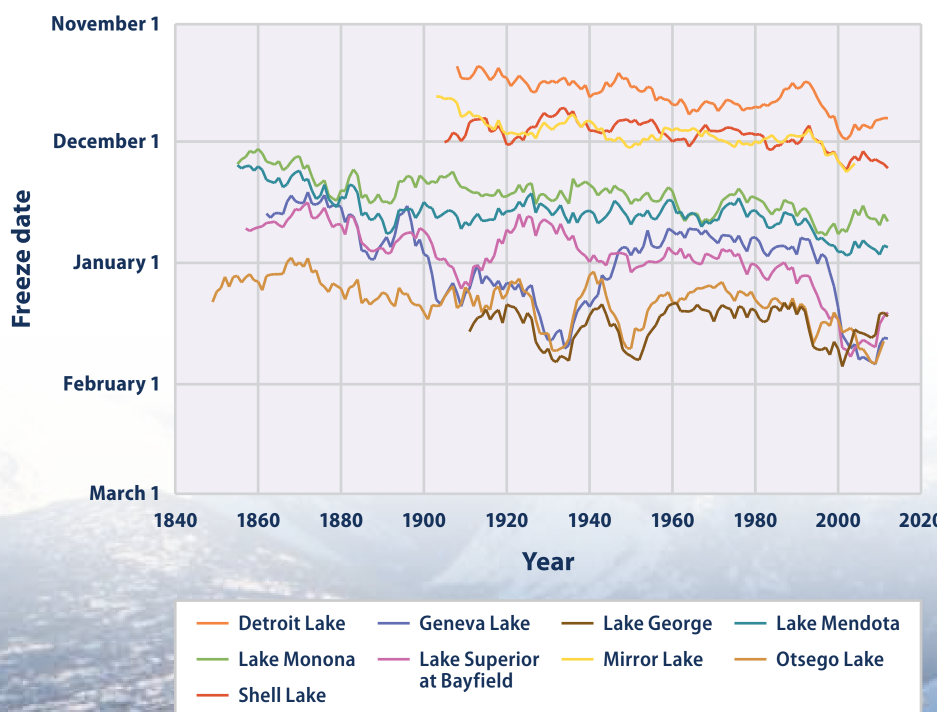
The timing and duration of ice cover on lakes and other bodies of water can also affect society—particularly in relation to shipping and transportation, hydroelectric power generation, and fishing. The impacts can be positive or negative. For example, reduced ice cover on a large lake could extend the open-water shipping season but require vessels to reduce their cargo capacity, as increased evaporation leads to lower water levels.

ABOUT THE INDICATOR

This indicator analyzes the dates at which lakes freeze and thaw. Freeze dates occur when a continuous and immobile ice cover forms over a body of water. Thaw dates occur when the ice cover breaks up and open water becomes extensive.

Freeze and thaw dates have been recorded through human visual observations for more than 150 years. The National Snow and Ice Data Center maintains a database with freeze and thaw observations from more than 700 lakes and rivers throughout the Northern Hemisphere. This indicator focuses on 14 lakes within the United States that have the longest and most complete historical records. The lakes of interest are located in Minnesota, Wisconsin, New York, and Maine.

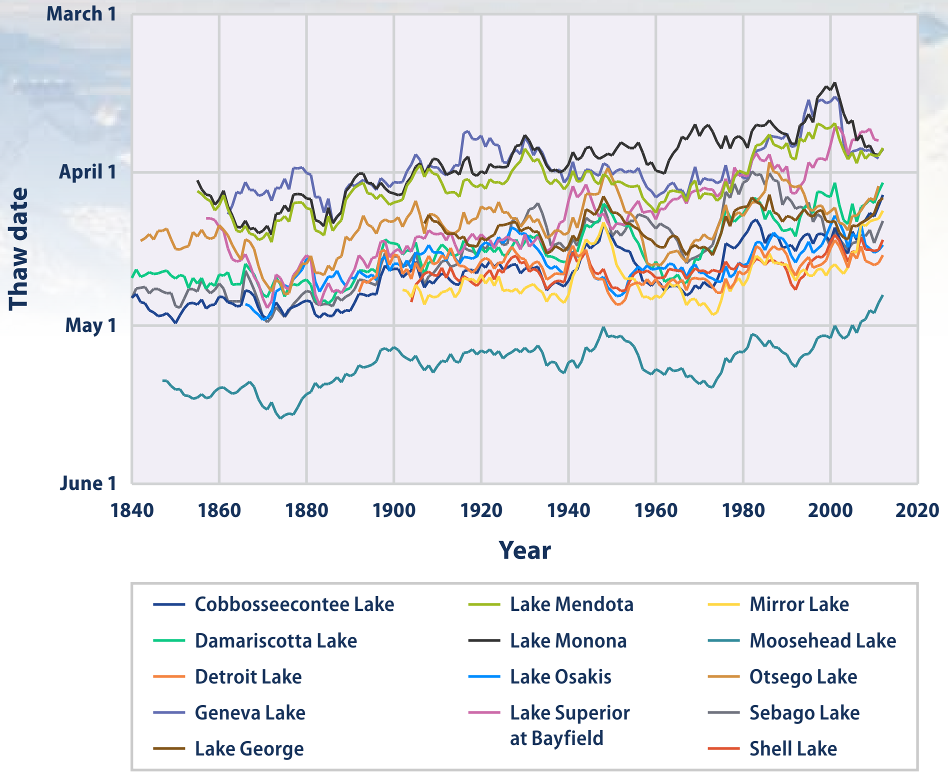
Figure 1. Date of First Freeze for Selected U.S. Lakes, 1850–2012



This figure shows the "ice-on" date, or date of first freeze, for nine U.S. lakes. The data are available from as early as 1850 to 2012, depending on the lake, and have been smoothed using a nine-year moving average.

Data source: Various organizations[16]

Figure 2. Date of Ice Thaw for Selected U.S. Lakes, 1850–2012



This figure shows the "ice-off" date, or date of ice thawing and breakup, for 14 U.S. lakes. The data are available from as early as 1850 to 2012, depending on the lake, and have been smoothed using a nine-year moving average.

Data source: Various organizations[17]

Figure 3. Change in Ice Thaw Dates for Selected U.S. Lakes, 1905–2012

This figure shows the change in the "ice-off" date, or date of ice thawing and breakup, for 14 U.S. lakes during the period from 1905 to 2012. All but two of the lakes have red circles with negative numbers, which represent earlier thaw dates. The other two lakes have not experienced a significant change in thaw dates. Larger circles indicate larger changes.

Data source: Various organizations[18]

INDICATOR NOTES

Although there is a lengthy historical record of freeze and thaw dates for a much larger set of lakes and rivers, some records are incomplete, with breaks ranging from brief lapses to large gaps in data. This indicator is limited to 14 lakes with sufficiently complete historical records. The four Maine lakes and Lake Osakis only have data for ice thaw, so they do not appear in Figure 1 (first freeze date).

Data used in this indicator are all based on visual observations. While the procedures for making observations of lake ice are consistent over time, visual observations by individuals are open to some interpretation and can differ from one individual to the next. In addition, historical observations for lakes have typically been made from a particular spot on the shore, which might not be representative of lakes as a whole or comparable to satellite-based observations. Considerations for defining the thaw date are specific to each lake.

DATA SOURCES

Data through 2004 for most lakes were obtained from the Global Lake and River Ice Phenology Database, which is maintained by the National Snow and Ice Data Center. These data are available at: http://nsidc.org/data/lake_river_ice. More recent data were obtained from state, local, and other organizations that collected or compiled the observations.

Community Connection

Ice Breakup in Two Alaskan Rivers

KEY POINTS

- The Tanana and Yukon rivers both demonstrate long-term trends toward earlier ice breakup in the spring. The ice breakup dates for both the Tanana and Yukon rivers have shifted earlier by six to seven days over their respective periods of record.
- Despite the overall trend toward earlier breakup, the most recent breakup dates for both rivers are within the range of historical variation.

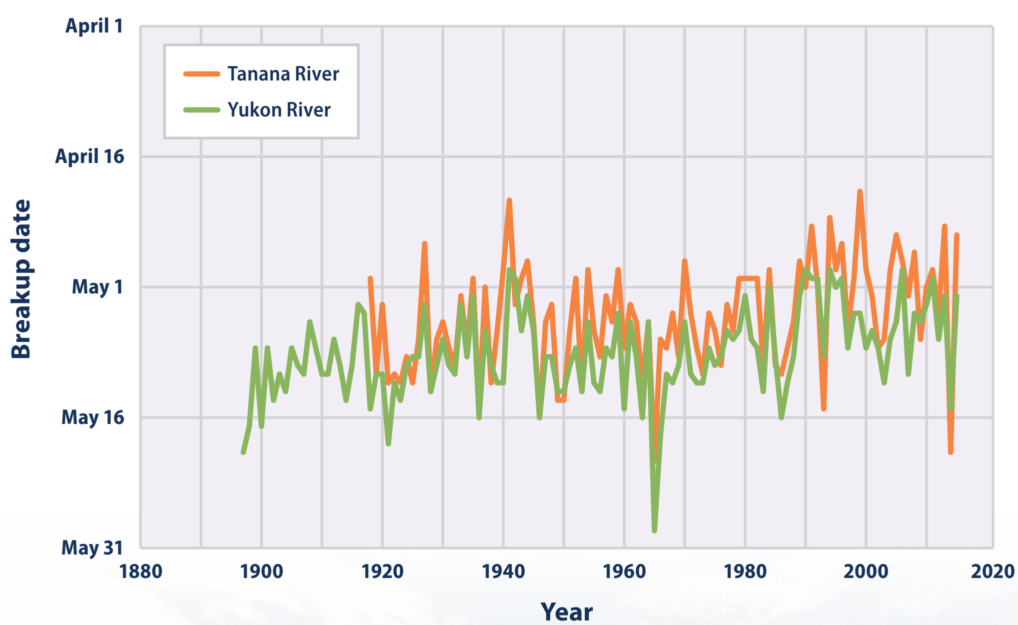
Regions in the far north are warming more quickly than other parts of the world, and this pattern is expected to continue[19,20] (see the Arctic Sea Ice indicator on p. 58; for more information about regional temperature changes, see the U.S. and Global Temperature indicator on p. 28). The Tanana and Yukon rivers in Alaska provide a particularly noteworthy record of northern climate because, for a century or more, local citizens have recorded the date when the ice on these rivers starts to move or break up each spring. In fact, some towns have annual competitions to guess when ice breakup will occur.

Since 1917, the Nenana Ice Classic competition on the Tanana River in central Alaska has paid several million dollars in winnings to the people who come closest to guessing the exact date and time of day when the river ice will break up. A similar tradition exists in Dawson City on the Yukon River, just across the border in Canada, where breakup dates have been recorded since 1896.

River ice breakup is more than just a friendly competition, though. Ice breakup is an important time of transition for communities that rely on these relatively remote and unmodified (wild) rivers for transportation, subsistence hunting and fishing, and other needs. In addition, early thawing can lead to severe ice movement, jamming, damage to infrastructure, and destructive floods.[21]

The data collected by these communities highlights how the river ice breakup dates in Nenana and Dawson City have changed over time. Both towns use the same method to measure the exact time of river ice breakup. Residents place a tripod on the ice in the center of the river. This tripod is attached by a cable to a clock on the shore. When the ice under the tripod breaks or starts to move, the tripod moves, pulling the cable and stopping the clock.

Figure 1. Ice Breakup Dates for Two Alaskan Rivers, 1896–2014



This figure shows the date each year when ice breaks up at two locations: the town of Nenana on the Tanana River and Dawson City on the Yukon River.

Data sources: Nenana Ice Classic, 2014;[22] Yukon River Breakup, 2014[23]

Town Locations on the Tanana and Yukon Rivers

NOTES

Besides climate change, natural year-to-year variations and other factors such as local development and land use patterns can influence ice breakup dates. The two locations featured here are relatively remote and undeveloped, so the ice breakup dates are more likely to reflect natural changes in weather and climate conditions. However, corresponding measurements of water conditions and air temperature would be useful to help understand the connection between changes in river ice breakup and changes in climate.

DATA SOURCES

Ice breakup dates for the Tanana River at Nenana and the Yukon River at Dawson City have been recorded and made publicly available as part of two long-running, community competitions: the Nenana Ice Classic and the Yukon River Breakup. The data shown here and other information can be found online at: www.nenanaakiceclassic.com and http://yukon-riverbreakup.com. Data records of ice breakup dates for these two rivers are also archived by the National Snow and Ice Data Center at: http://nsidc.org/data/lake_river_ice.

Snowfall

This indicator uses two different measures to show how snowfall has changed in the contiguous 48 states.

KEY POINTS

- Total snowfall has decreased in many parts of the country since widespread observations became available in 1930, with 57 percent of stations showing a decline (see Figure 1). Among all of the stations shown, the average change is a decrease of 0.19 percent per year.
- In addition to changing the overall rate of precipitation, climate change can lead to changes in the type of precipitation. One reason for the decline in total snowfall is because more winter precipitation is falling in the form of rain instead of snow. More than three-fourths of the stations across the contiguous 48 states have experienced a decrease in the proportion of precipitation falling as snow (see Figure 2).
- Snowfall trends vary by region. The Pacific Northwest has seen a decline in both total snowfall and the proportion of precipitation falling as snow. Parts of the Midwest have also experienced a decrease, particularly in terms of the snow-to-precipitation ratio. A few regions have seen modest increases, including some areas near the Great Lakes that now receive more snow than they used to (see Figures 1 and 2).

Snowfall is an important aspect of winter in much of the United States. Many people depend on snow to provide water when it melts in the spring—including 60 million people in the western United States[24]—and many communities rely on snow for winter recreation. Some plants and animals also depend on snow and snowmelt for survival. The amount of snow that falls in a particular area directly influences both snow cover and snowpack, which refer to snow that accumulates on the ground (see the Snow Cover indicator on p. 68 and the Snowpack indicator on p. 70).

Warmer temperatures cause more water to evaporate from the land and oceans, which leads to more precipitation, larger storms, and more variation in precipitation in some areas. In general, a warmer climate will cause more of this precipitation to fall in the form of rain instead of snow. However, some places could see more snowfall if temperatures rise but still remain below the freezing point, or if storm tracks change. Areas near large lakes might also experience more snowfall as lakes remain unfrozen for longer periods, allowing more water to evaporate. In contrast, other areas might experience less snowfall as a result of wintertime droughts.

Changes in the amount and timing of snowfall could affect the spawning of fish in the spring and the amount of water available for people to use in the spring and summer. Changes in snowfall could also affect winter recreation activities, like skiing, and the communities that rely on these activities.

ABOUT THE INDICATOR

This indicator tracks total snowfall as well as the percentage of precipitation that falls in the form of snow versus rain. These data were collected from hundreds of weather stations across the contiguous 48 states.

Total snowfall is determined by the height of snow that accumulates each day. These measured values commonly appear in weather reports (for example, a storm that deposits 10 inches of snow). Figure 1 shows how snowfall accumulation totals changed between 1930 and 2007 at more than 400 weather stations. These stations were selected because they had high-quality data for this entire time period.

Figure 2 shows trends in the proportion of total precipitation that falls in the form of snow during each winter season. This is called the "snow-to-precipitation" ratio, and it is based on comparing the amount of snowfall with the total amount of precipitation (snow plus rain) in each year. For this comparison, snow has been converted to the equivalent amount of liquid water. These data are available from 1949 to 2014.

INDICATOR NOTES

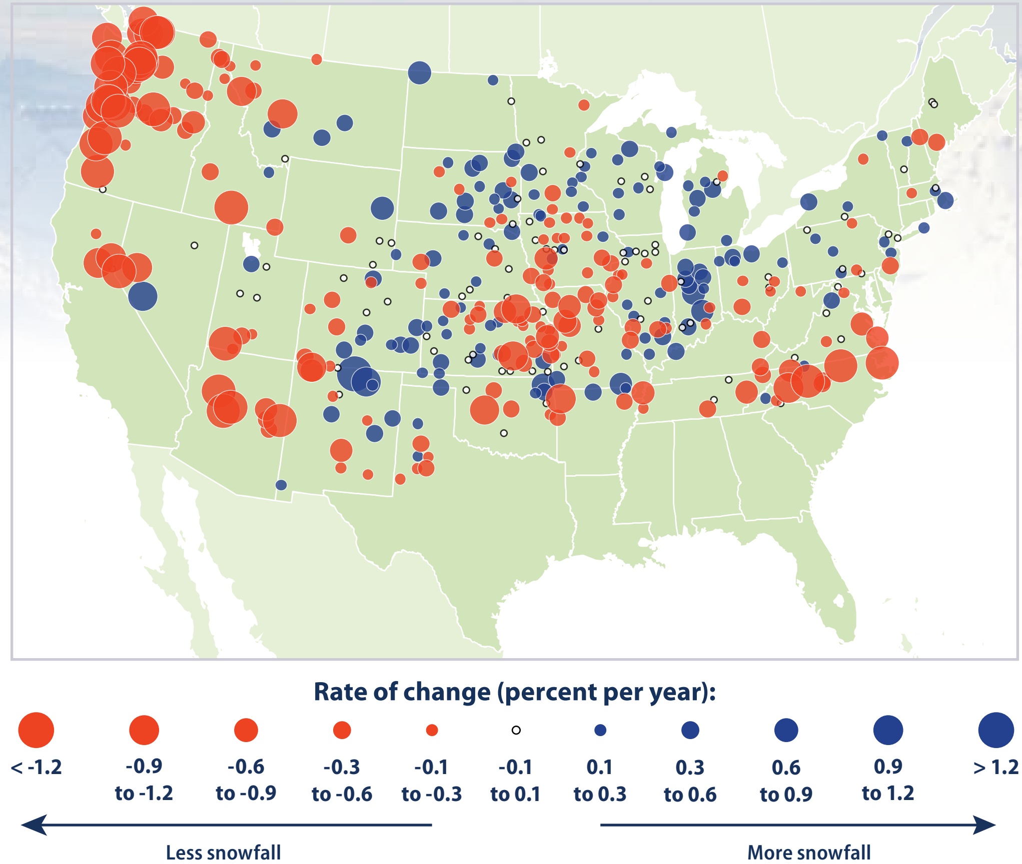
Several factors make it difficult to measure snowfall precisely. The snow accumulations shown in Figure 1 are based on the use of measuring rods. This measurement method is subject to human error, as well as the effects of wind (drifting snow) and the surrounding environment (such as tall trees). Similarly, snow gauges for Figure 2 may catch less snow than rain because of the effects of wind. However, steps have been taken to limit this indicator to weather stations with the most consistent methods and the highest-quality data.[25] As a result, some parts of the country have a higher station density than others.

Both figures are limited to the winter season. Figure 1 comes from an analysis of October-to-May snowfall, while Figure 2 covers November through March. Although these months account for the vast majority of snowfall in most locations, this indicator might not represent the entire snow season in some areas. Most of the data shown for mountainous regions come from lower elevations (towns in valleys) because that is where weather stations tend to be located.

DATA SOURCES

This indicator shows trends based on two sets of weather records collected and maintained by the National Oceanic and Atmospheric Administration. Figure 1 was adapted from an analysis by Kunkel et al. (2009)[26] based on records from Cooperative Observer Program weather stations. Figure 2 is an updated version of an analysis by Feng and Hu (2007)[27] using data from the U.S. Historical Climatology Network. Additional information about the Cooperative Observer Program is available online at: www.nws.noaa.gov/om/coop. Information about the U.S. Historical Climate Network can be found at: www.ncdc.noaa.gov/oa/climate/research/ushcn.

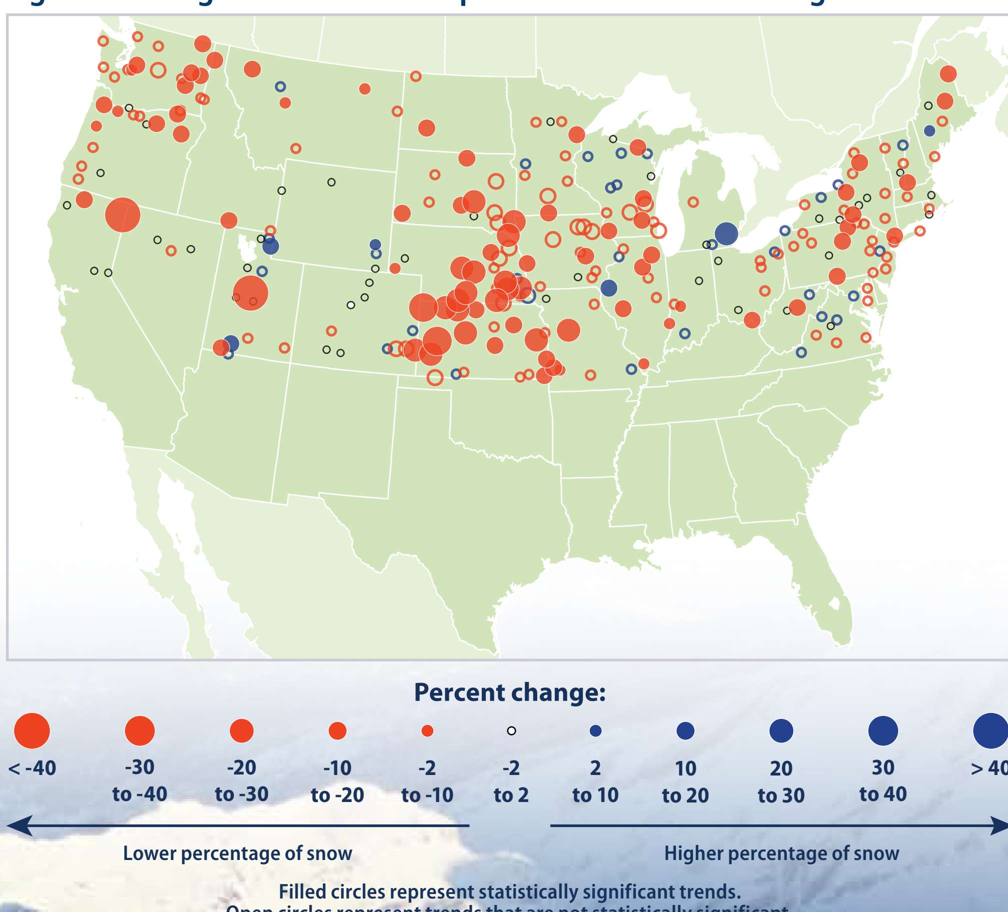
Figure 1. Change in Total Snowfall in the Contiguous 48 States, 1930–2007



This figure shows the average rate of change in total snowfall from 1930 to 2007 at 419 weather stations in the contiguous 48 states. Blue circles represent increased snowfall; red circles represent a decrease.

Data source: Kunkel et al., 2009[28]

Figure 2. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2014



This figure shows the percentage change in winter snow-to-precipitation ratio from 1949 to 2014 at 261 weather stations in the contiguous 48 states. This ratio measures what percentage of total winter precipitation falls in the form of snow. A decrease (red circle) indicates that more precipitation is falling in the form of rain instead of snow. Filled circles represent stations where the trend was statistically significant.

Data source: NOAA, 2014[29]

Snow Cover

This indicator measures the amount of land in North America that is covered by snow.

KEY POINTS

- When averaged over the entire year, snow covered an average of 3.25 million square miles of North America during the period from 1972 to 2013 (see Figure 1).
- The extent of snow cover has varied from year to year. The average area covered by snow has ranged from 3.0 million to 3.6 million square miles, with the minimum value occurring in 1998 and the maximum in 1978 (see Figure 1).
- Between 1972 and 2013, the average extent of North American snow cover decreased at a rate of about 3,500 square miles per year. The average area covered by snow during the most recent decade (2004–2013) was 3.21 million square miles, which is about 4 percent smaller than the average extent during the first 10 years of measurement (1972–1981)—a difference of 120,000 square miles, or approximately an area the size of New Mexico (see Figure 1).
- Decreases in snow cover have largely occurred in spring and summer, whereas fall and winter snow cover have remained fairly steady over the time period studied (see Figure 2). Spring and summer snow cover can have a particularly important influence on water supplies.

Snow cover refers to the amount of land covered by snow at any given time. Naturally, it is influenced by the amount of precipitation that falls as snow. Air temperature also plays a role because it determines whether precipitation falls as snow or rain, and it affects the rate at which snow on the ground will melt. As temperature and precipitation patterns change, so can the overall area covered by snow.

Snow cover is not just something that is affected by climate change; it also exerts an influence on climate. Because snow is white, it only absorbs a small portion of the sunlight that hits it (10 to 20 percent in the case of fresh snow), and it reflects the rest back to space. In contrast, darker surfaces such as bare ground and open water absorb the majority of the energy they receive and heat up more quickly. In this way, the overall amount of snow cover affects patterns of heating and cooling over the Earth's surface. More snow means more energy reflects back to space, resulting in cooling, while less snow cover means more energy is absorbed at the Earth's surface, resulting in warming.

On a more local scale, snow cover is important for many plants and animals. For example, some plants rely on a protective blanket of snow to insulate them from sub-freezing winter temperatures. Humans and ecosystems also rely on snowmelt to replenish streams and ground water.

ABOUT THE INDICATOR

This indicator tracks the total area covered by snow across all of North America (not including Greenland) since 1972. It is based on maps generated by analyzing satellite images collected by the National Oceanic and Atmospheric Administration. The indicator was created by analyzing each weekly map to determine the extent of snow cover, then averaging the weekly observations together to get a value for each year. Average snow cover was also calculated for each season: spring (defined as March–May), summer (June–August), fall (September–November), and winter (December–February).

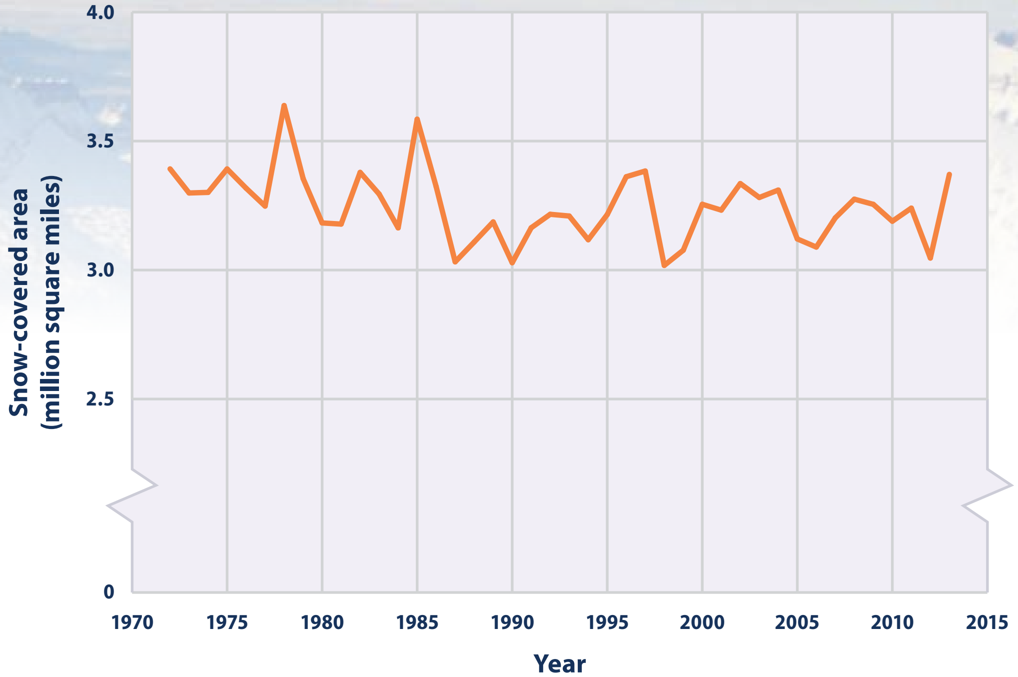
INDICATOR NOTES

Although satellite-based snow cover maps are available starting in the mid-1960s, some of the early years are missing data from several weeks during the summer, which would lead to an inaccurate annual average. Thus, the indicator is restricted to 1972 and later, with all years having a full set of data.

DATA SOURCES

The data for this indicator were provided by the Rutgers University Global Snow Lab, which posts data online at: http://climate.rutgers.edu/snowcover. The data are based on measurements collected by the National Oceanic and Atmospheric Administration's National Environmental Satellite, Data, and Information Service at: www.nesdis.noaa.gov.

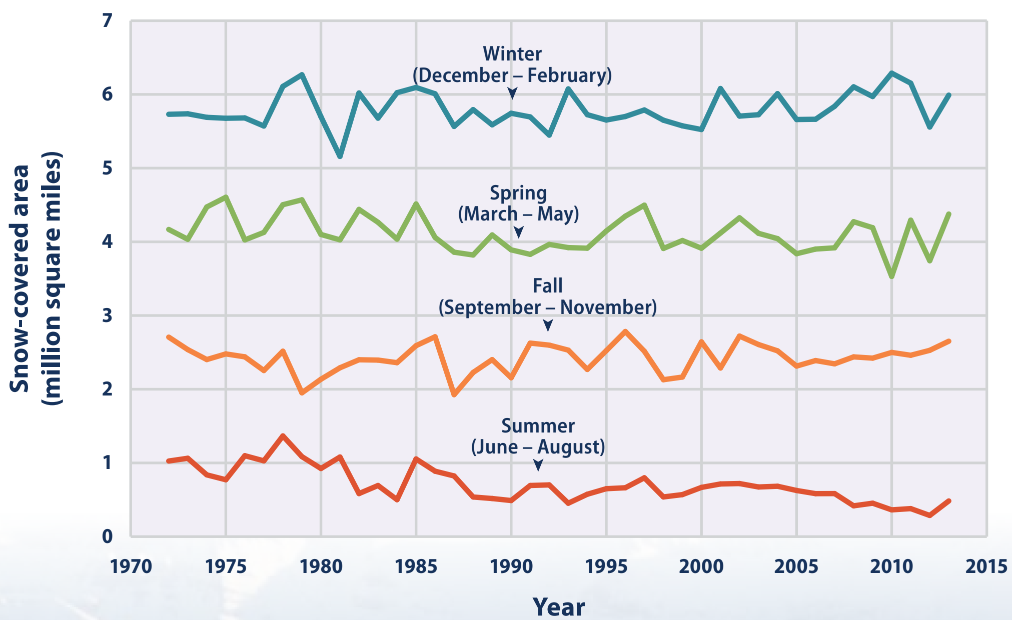
Figure 1. Snow-Covered Area in North America, 1972–2013



This graph shows the average area covered by snow in a given calendar year, based on an analysis of weekly maps. The area is measured in square miles. These data cover all of North America (not including Greenland).

Data source: Rutgers University Global Snow Lab, 2014[30]

Figure 2. Snow-Covered Area in North America by Season, 1972–2013



This graph shows the average area covered by snow during spring (March–May), summer (June–August), fall (September–November), and winter (December–February), based on an analysis of weekly maps. The area is measured in square miles. These data cover all of North America (not including Greenland).

Data source: Rutgers University Global Snow Lab, 2014[31]

Snowpack

This indicator measures trends in mountain snowpack in the western United States.

KEY POINTS

- From 1955 to 2013, April snowpack declined at about three-fourths of the sites measured (see Figure 1). The average change across all sites amounts to about a 14 percent decline.
- In general, the largest and most consistent decreases were observed in Washington, Oregon, and the northern Rockies.
- Some areas have seen increases in snowpack, primarily in the southern Sierra Nevada of California.

Temperature and precipitation are key factors affecting snowpack, which is the amount or thickness of snow that accumulates on the ground. In a warming climate, more precipitation will be expected to fall as rain rather than snow in most areas—reducing the extent and depth of snowpack. Higher temperatures in the spring can cause snow to melt earlier.

Mountain snowpack plays a key role in the water cycle in western North America, storing water in the winter when the snow falls and releasing it as runoff in spring and summer when the snow melts. Millions of people in the West depend on the melting of mountain snowpack for power, irrigation, and drinking water. In most western river basins, snowpack is a larger component of water storage than human-constructed reservoirs.[32]

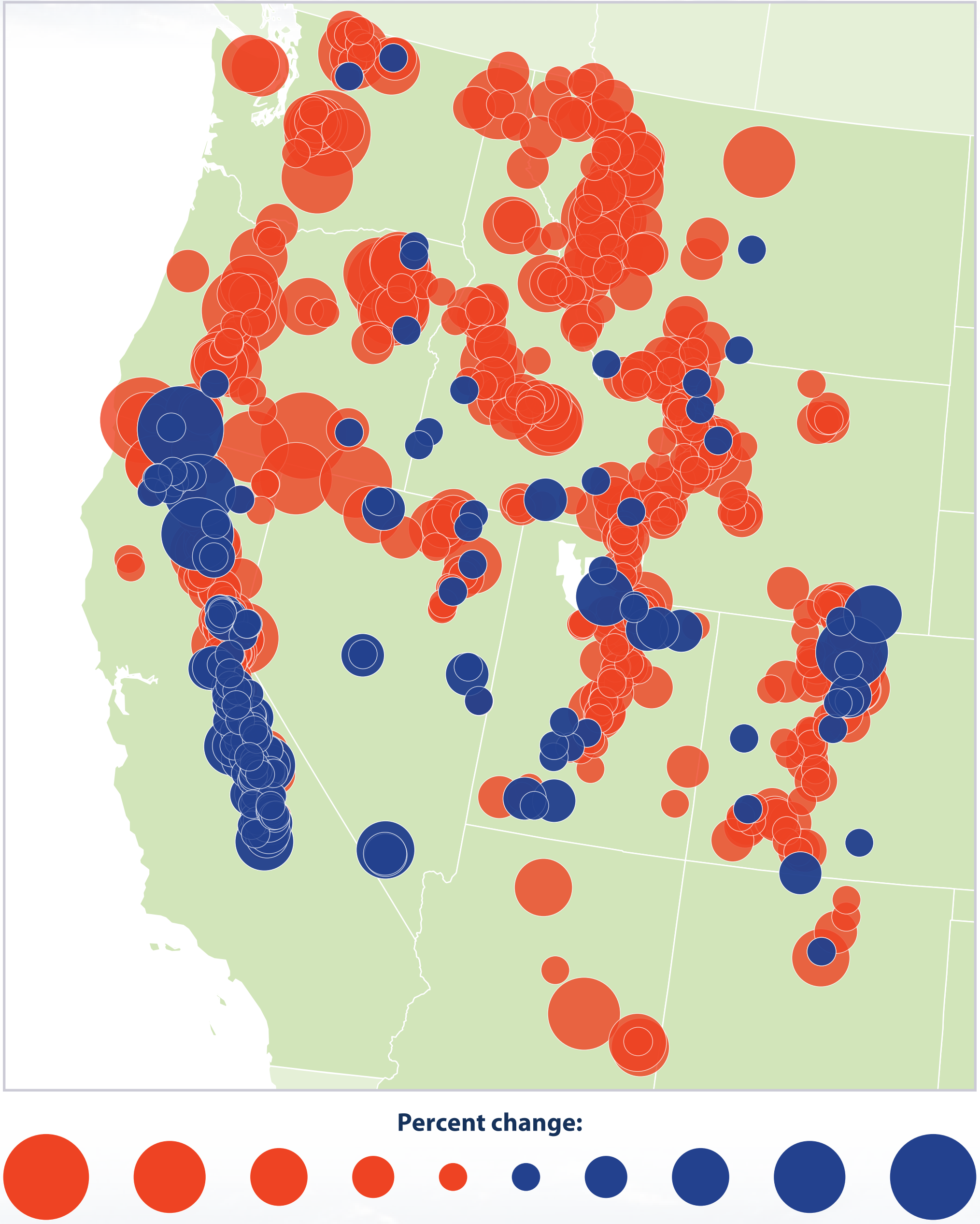
Changes in mountain snowpack can affect agriculture, winter recreation, and tourism in some areas, as well as plants and wildlife. For example, certain types of trees rely on snow for insulation from freezing temperatures, as do some animal species. In addition, fish spawning could be disrupted if changes in snowpack or snowmelt alter the timing and abundance of streamflows.

ABOUT THE INDICATOR

This indicator uses a measurement called snow water equivalent to determine trends in snowpack. Snow water equivalent is the amount of water contained within the snowpack at a particular location. It can be thought of as the depth of water that would result if the entire snowpack were to melt.

The U.S. Department of Agriculture and other collaborators have measured snowpack since the early 1900s. In the early years of data collection, researchers measured snow water equivalent manually, but since 1980, measurements at some locations have been collected with automated instruments. This indicator is based on data from approximately 700 permanent measurement sites in the western United States. The indicator shows long-term rates of change for the month of April, which could reflect changes in winter snowfall as well as the timing of spring snowmelt.

Figure 1. Trends in April Snowpack in the Western United States, 1955–2013



This map shows trends in April snowpack in the western United States, measured in terms of snow water equivalent. Blue circles represent increased snowpack; red circles represent a decrease.

Data source: Mote and Sharp, 2014[33]

INDICATOR NOTES

EPA selected 1955 as a starting point for this analysis because many measurement sites in the Southwest were established in the early 1950s. Natural variability in the Earth's climate means that snowpack trends may vary slightly when measured over different time periods. For example, the period from 1945 to 1955 was unusually snowy in the Northwest, so if this indicator were to start in 1945 or 1950, the Northwest would appear to show larger decreases over time. However, the general direction of the trend is the same regardless of the start date.

Although most parts of the West have seen reductions in snowpack—consistent with overall warming trends shown in the U.S. and Global Temperature indicator (p. 28)—snowfall trends may be partially influenced by non-climatic factors such as observation methods, land-use changes, and forest canopy changes.

DATA SOURCES

Data for this indicator came from the U.S. Department of Agriculture's Natural Resources Conservation Service Water and Climate Center and the California Department of Water Resources. The map was constructed using methods described by Mote et al. (2005).[34] The U.S. Department of Agriculture data are available at: www.wcc.nrcs.usda.gov. The California Department of Water Resources data are available at: http://cdec.water.ca.gov/snow/current/snow/index.html.

HEALTH AND SOCIETY

Changes in the Earth's climate can affect public health, agriculture, water supplies, energy production and use, land use and development, and recreation. The nature and extent of climate change effects, and whether these effects will be harmful or beneficial, will vary regionally and over time. This chapter looks at some of the ways that climate change is affecting human health and society, including changes in Lyme disease, ragweed pollen season, heat-related deaths, heating and cooling needs, and the agricultural growing season across the United States.

Because impacts on human health are complex, often indirect, and dependent on multiple societal and environmental factors, the development of appropriate health-related climate indicators is challenging and still emerging. It is important for health-related climate indicators to be clear, measurable, and timely to better understand the link between climate change and health effects.

WHY DOES IT MATTER?

Changes in climate affect the average weather conditions to which we are accustomed. These changes may result in multiple threats to human health and welfare. Warmer average temperatures will likely lead to hotter days and more frequent and longer heat waves, which could increase the number of heat-related illnesses and deaths. Increases in the frequency or severity of extreme weather events, such as storms, could increase the risk of dangerous flooding, high winds, and other direct threats to people and property. Warmer temperatures could also reduce air quality by increasing the chemical reactions that produce smog, and, along with changes in precipitation patterns and extreme events, could enhance the spread of some diseases.

In addition, climate change could require adaptation on larger and faster scales than in the past, presenting challenges to human well-being and the economy. The more extensively and more rapidly the climate changes, the larger the potential effects on society. The extent to which climate change will affect different regions and sectors of society will depend not only on the sensitivity of those systems to climate change, but also on their ability to adapt to or cope with climate change. Vulnerable populations, including the poor, the elderly, those already in poor health, the disabled, and indigenous populations, are most at risk.

Summary of Key Points

Heating and Cooling Degree Days. Heating and cooling degree days measure the difference between outdoor temperatures and the temperatures that people find comfortable indoors. As the U.S. climate has warmed in recent years, heating degree days have decreased and cooling degree days have increased overall, suggesting that Americans need to use less energy for heating and more energy for air conditioning. This pattern stands out the most in the North and West, while much of the Southeast has experienced the opposite results.

Heat-Related Deaths. Over the past three decades, nearly 8,000 Americans were reported to have died as a direct result of heat-related illnesses such as heat stroke. The annual death rate is higher when accounting for other deaths in which heat was reported as a contributing factor. Considerable year-to-year variability in the data and certain limitations of this indicator make it difficult to determine whether the United States has experienced long-term trends in the number of deaths classified as "heat-related."

Lyme Disease. Lyme disease is a bacterial illness spread by ticks that bite humans. Tick habitat and populations are influenced by many factors, including climate. Nationwide, the rate of reported cases of Lyme disease has approximately doubled since 1991. Lyme disease is most common in the Northeast and the upper Midwest, where some states now report 50 to 90 more cases of Lyme disease per 100,000 people than they did in 1991.

Length of Growing Season. The average length of the growing season in the contiguous 48 states has increased by nearly two weeks since the beginning of the 20th century. A particularly large and steady increase has occurred over the last 30 years. The observed changes reflect earlier spring warming as well as later arrival of fall frosts. The length of the growing season has increased more rapidly in the West than in the East.

Ragweed Pollen Season. Warmer temperatures and later fall frosts allow ragweed plants to produce pollen later into the year, potentially prolonging the allergy season for millions of people. The length of ragweed pollen season has increased at 10 out of 11 locations studied in the central United States and Canada since 1995. The change becomes more pronounced from south to north.

Heating and Cooling Degree Days

This indicator examines changing temperatures from the perspective of heating and cooling needs for buildings.

KEY POINTS

- Heating degree days have declined in recent years as the U.S. climate has warmed (see Figure 1). This change suggests that heating needs have decreased overall.
- Overall, cooling degree days have not increased significantly over the past 100 years. However, a slight increase is evident over the past few decades, suggesting that air conditioning energy demand has also been increasing recently (see Figure 1).
- Heating degree days have generally decreased in the North and West, and cooling degree days have generally increased in the West. The Southeast has seen the opposite: more heating degree days and fewer cooling degree days (see Figures 2 and 3).

Outdoor temperatures can affect daily life in many ways. In particular, temperature affects our comfort level and our demand for heating and air conditioning. Collectively, heating and cooling the spaces in which we live accounts for 48 percent of the energy that American households use every year.[1] As climate change contributes to an increase in average temperatures, an increase in unusually hot days, and a decrease in unusually cold days (see the U.S. and Global Temperature and High and Low Temperatures indicators on pp. 28 and 30), the overall demand for heating is expected to decline and the demand for cooling is expected to increase.

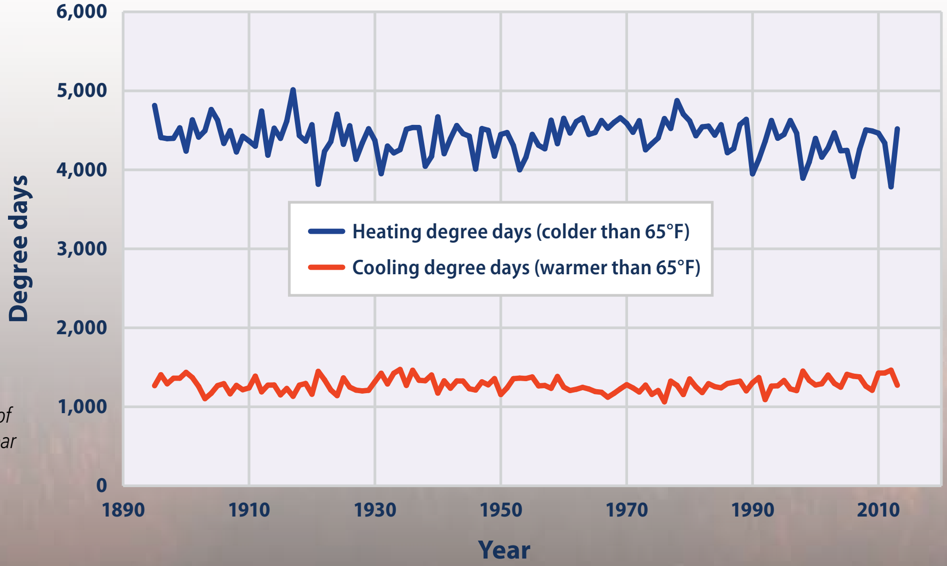
One way to measure the influence of temperature change on energy demand is using heating and cooling degree days, which measure the difference between outdoor temperatures and a temperature that people generally find comfortable indoors. These measurements suggest how much energy people might need to use to heat and cool their homes and workplaces, thus providing a sense of how climate change could affect people's daily lives and finances.

ABOUT THE INDICATOR

This indicator uses daily temperature data from thousands of weather stations across the United States to calculate heating and cooling degree days. A "degree day" is determined by comparing the daily average outdoor temperature with a defined baseline temperature for indoor comfort (in this case, 65°F). For example, if the average temperature on a particular day is 78°F, then that day counts as 13 cooling degree days, as a building's interior would need to be cooled by 13°F to reach 65°F. Conversely, if the average outdoor temperature is 34°F, then that day counts as 31 heating degree days, as a building's interior would need to be warmed by 31°F to reach 65°F. For reference, New York City experiences far more heating degree days than cooling degree days per year—a reflection of the relatively cool climate in the Northeast—while Houston, Texas, has far more cooling degree days than heating degree days—a reflection of the much warmer climate in the South.[2]

Figure 1 shows each year's average heating and cooling degree days across the contiguous 48 states. Figures 2 and 3 show how heating and cooling degree days have changed by state, based on a comparison of the first 59 years of available data (1895–1953) with the most recent 60 years (1954–2013). State and national averages were calculated by finding the total number of heating and cooling degree days per year at each weather station, averaging the results from all stations within regions called climate divisions (each state has up to 10 climate divisions), then calculating state and national averages weighted by the population of each climate division. With this population-weighting approach, average state and national heating and cooling degree days more closely reflect the conditions that the average resident would experience.

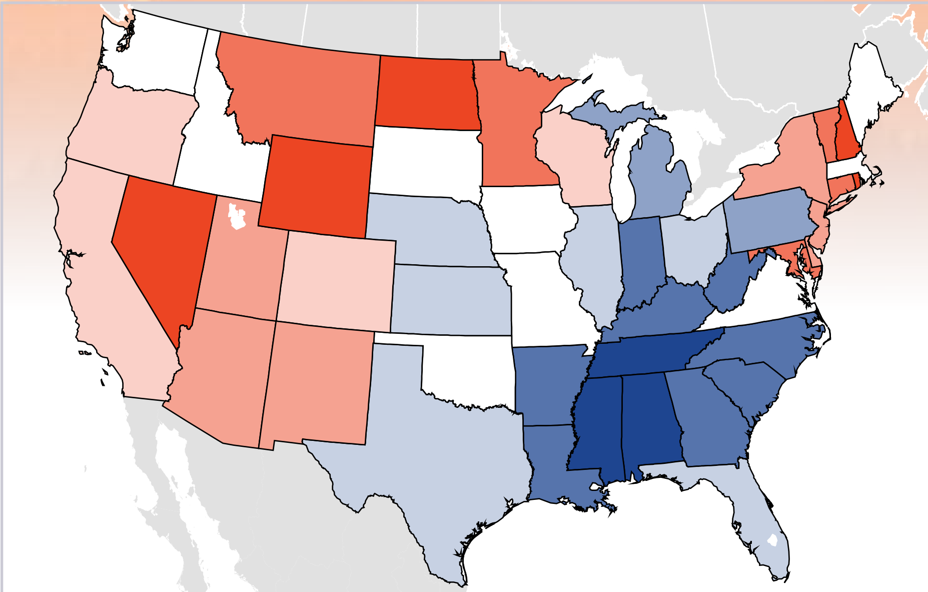
Figure 1. Heating and Cooling Degree Days in the Contiguous 48 States, 1895–2013



This figure shows the average number of heating and cooling degree days per year across the contiguous 48 states.

Data source: NOAA, 2014[3]

Figure 2. Change in Annual Heating Degree Days by State, 1954–2013 Versus 1895–1953



Difference in annual heating degree days

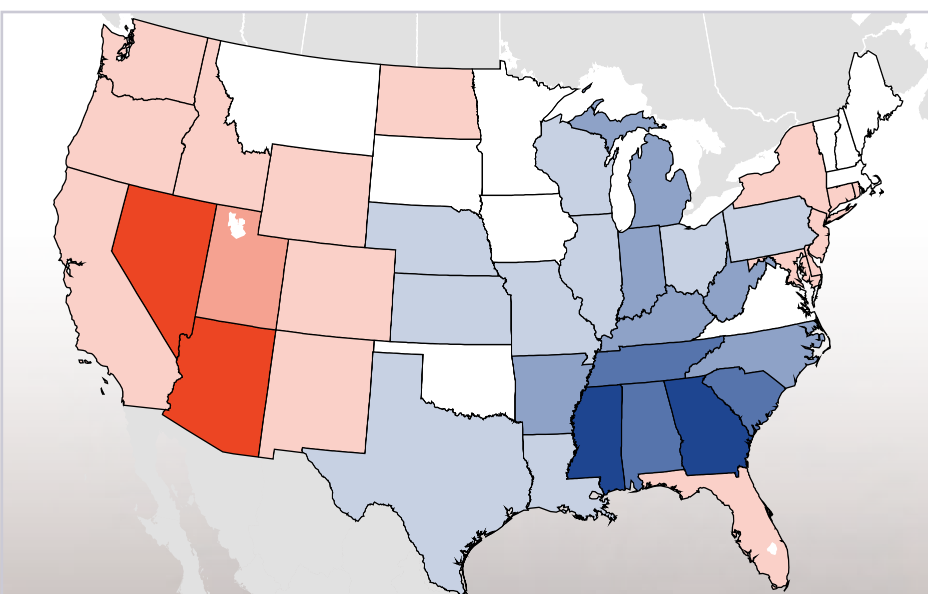
< -175 | -175 to -125 | -125 to -75 | -75 to -25 | -25 to 25 | 25 to 75 | 75 to 125 | 125 to 175 | > 175

Warmer (less heating needed) | Colder (more heating needed)

This map shows how the average number of heating degree days per year has changed in each state over time. The map was created by comparing the first 59 years of available data (1895–1953) with the most recent 60 years (1954–2013). "Warmer" colors indicate an increase in temperatures between the two periods, leading to less of a need to turn on the heat—that is, fewer heating degree days. "Cooler" colors indicate a decrease in temperatures, leading to more of a need to turn on the heat—that is, more heating degree days.

Data source: NOAA, 2014[4]

Figure 3. Change in Annual Cooling Degree Days by State, 1954–2013 Versus 1895–1953



Difference in annual cooling degree days

< -175 | -175 to -125 | -125 to -75 | -75 to -25 | -25 to 25 | 25 to 75 | 75 to 125 | 125 to 175 | > 175

Colder (less air conditioning needed) | Warmer (more air conditioning needed)

This map shows how the average number of cooling degree days per year has changed in each state over time. The map was created by comparing the first 59 years of available data (1895–1953) with the most recent 60 years (1954–2013). "Warmer" colors indicate an increase in temperatures between the two periods, leading to more demand for air conditioning—that is, more cooling degree days. "Cooler" colors indicate a decrease in temperatures, leading to less demand for air conditioning—that is, fewer cooling degree days.

Data source: NOAA, 2014[5]

INDICATOR NOTES

Heating and cooling degree days suggest how temperature changes affect energy demand, but they do not necessarily reflect actual energy use. Many other factors have influenced energy demand over time, such as more energy-efficient heating systems, the introduction and increasingly widespread use of cooling technologies, larger but better-insulated homes, behavior change, and population shifts (such as more people moving to warmer regions). All of the population-weighting in this indicator is based on the population distribution according to the 1990 U.S. Census, so any changes in heating and cooling degree days over time in this indicator reflect actual changes in the climate, not the influence of shifting populations. A nationally applied baseline—in this case, 65°F—has certain limitations considering the various climate regimes across the United States.

DATA SOURCES

The data for this indicator were provided by the National Oceanic and Atmospheric Administration's National Climatic Data Center, which maintains a large collection of climate data online at: www.ncdc.noaa.gov/oa/ncdc.html.

Heat-Related Deaths

This indicator presents data on deaths classified as "heat-related" in the United States.

KEY POINTS

- Between 1979 and 2010, the death rate as a direct result of exposure to heat (underlying cause of death) generally hovered around 0.5 deaths per million population, with spikes in certain years (see Figure 1). Overall, a total of nearly 8,000 Americans suffered heat-related deaths since 1979. This number does not capture the full extent of heat-related deaths for several reasons (see example on p. 77).
- For years in which the two records overlap (1999–2010), accounting for those additional deaths in which heat was listed as a *contributing* factor results in a higher death rate—nearly double for some years—compared with the estimate that only includes deaths where heat was listed as the *underlying* cause. However, even this expanded metric does not necessarily capture the full extent of heat-related deaths.
- The indicator shows a peak in heat-related deaths in 2006, a year that was associated with widespread heat waves and was the second-hottest year on record in the contiguous 48 states (see the U.S. and Global Temperature indicator on p. 28).
- Considerable year-to-year variability in the data and certain limitations of this indicator make it difficult to determine whether the United States has experienced a meaningful increase or decrease in deaths classified as "heat-related" over time. Dramatic increases in heat-related deaths are closely associated with both the occurrence of hot temperatures and heat waves, though these deaths may not be reported as "heat-related" on death certificates. For example, studies of the 1995 heat wave event in Chicago (see example on p. 77) suggest that there may have been hundreds more deaths than were actually reported as "heat-related" on death certificates.

When people are exposed to extreme heat, they can suffer from potentially deadly heat-related illnesses, such as heat exhaustion and heat stroke. Heat is the leading weather-related killer in the United States, even though most heat-related deaths are preventable through outreach and intervention (see EPA's *Excessive Heat Events Guidebook* at: www.epa.gov/heatisland/about/pdf/EHEguide_final.pdf).

Unusually hot summer temperatures have become more frequent across the contiguous 48 states in recent decades[6] (see the High and Low Temperatures indicator on p. 30), and extreme heat events (heat waves) are expected to become longer, more frequent, and more intense in the future.[7] As a result, the risk of heat-related deaths and illness is also expected to increase.[8]

Increases in summertime temperature variability may increase the risk of heat-related death for the elderly and other vulnerable populations.[9] Older adults have the highest risk of heat-related death, although young children are also sensitive to the effects of heat. Across North America, the population over the age of 65 is growing dramatically. People with certain diseases, such as cardiovascular and respiratory illnesses, are especially vulnerable to excessive heat exposure, as are the economically disadvantaged.

Some studies suggest that the number of deaths caused by extremely cold temperatures might drop in certain areas as the climate gets warmer, while others do not expect the number to change at all.[10,11] Any decrease in cold-related deaths will most likely be substantially less than the increase in summertime heat-related deaths.[12,13,14]

ABOUT THE INDICATOR

This indicator shows the annual rate for deaths classified by medical professionals as "heat-related" each year in the United States, based on death certificate records. Every death is recorded on a death certificate, where a medical professional identifies the main cause of death (also known as the underlying cause), along with other conditions that contributed to the death. These causes are classified using a set of standard codes. Dividing the annual number of deaths by the U.S. population in that year, then multiplying by one million, will result in the death rates (per million people) shown in Figure 1.

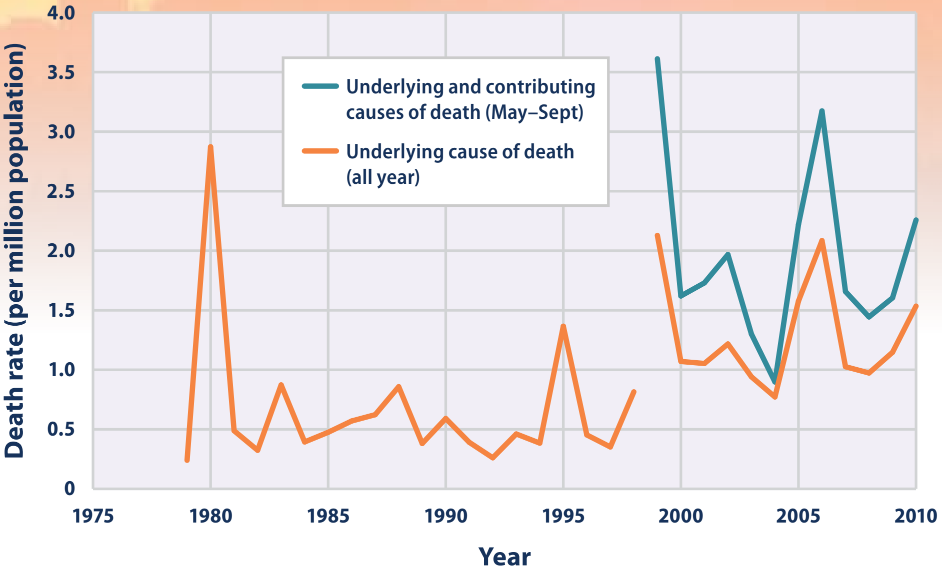
This indicator shows heat-related deaths using two methodologies. One method shows deaths for which excessive natural heat was stated as the underlying cause of death from 1979 to 2010. The other data series shows deaths for which heat was listed as either the underlying cause or a contributing cause, based on a broader set of data that at present can only be evaluated back to 1999. For example, in a case where cardiovascular disease was determined to be the underlying cause of death, heat could be listed as a contributing factor because it can make the individual more susceptible to the effects of this disease. Because excessive heat events are associated with summer months, the 1999–2010 analysis was limited to May through September.

INDICATOR NOTES

Several factors influence the sensitivity of this indicator and its ability to estimate the true number of deaths associated with extreme heat events. It has been well-documented that many deaths associated with extreme heat are not identified as such by the medical examiner and might not be correctly coded on the death certificate. In many cases, the medical examiner might classify the cause of death as a cardiovascular or respiratory disease, not knowing for certain whether heat was a contributing factor, particularly if the death did not occur during a well-publicized heat wave. By studying how daily death rates vary with temperature in selected cities, scientists have found that extreme heat contributes to far more deaths than the official death certificates might suggest.[15] This is because the stress of a hot day can increase the chance of dying from a heart attack, other heart conditions, or respiratory diseases such as pneumonia.[16] These causes of death are much more common than heat-related illnesses such as heat stroke. Thus, this indicator very likely underestimates the number of deaths caused by exposure to heat.

Just because a death is classified as "heat-related" does not mean that high temperatures were the only factor that caused or contributed to the death. Pre-existing medical conditions can significantly increase an individual's vulnerability to heat. Other important factors, such as the overall vulnerability of the population, the extent to which people have adapted and acclimated to higher temperatures, and the local climate and topography, can affect trends in "heat-related" deaths. Heat response measures, such as early warning and surveillance systems, air conditioning, health care, public education, cooling centers, infrastructure standards, and air quality management, can also make a big difference in death rates. For example, after a 1995 heat wave, the city

Figure 1. Deaths Classified as "Heat-Related" in the United States, 1979–2010

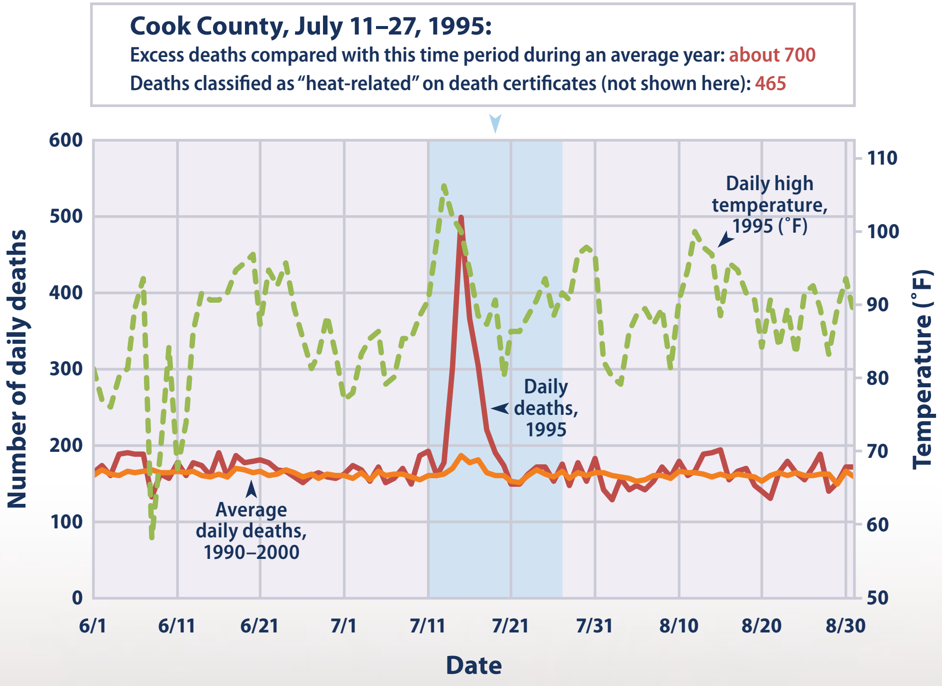


This figure shows the annual rates for deaths classified as "heat-related" by medical professionals in the 50 states and the District of Columbia. The orange line shows deaths for which heat was listed as the main (underlying) cause. The blue line shows deaths for which heat was listed as either the underlying or contributing cause of death during the months from May to September, based on a broader set of data that became available in 1999.*

** Between 1998 and 1999, the World Health Organization revised the international codes used to classify causes of death. As a result, data from earlier than 1999 cannot easily be compared with data from 1999 and later.*

Data source: CDC, 2014[18,19]

Example: Examining Heat-Related Deaths During the 1995 Chicago Heat Wave



Many factors can influence the nature, extent, and timing of health consequences associated with extreme heat events.[20] Studies of heat waves are one way to better understand health impacts, but different methods can lead to very different estimates of heat-related deaths. For example, during a severe heat wave that hit Chicago between July 11 and July 27, 1995, 465 heat-related deaths were recorded on death certificates in Cook County.[21] However, studies that compared the total number of deaths during this heat wave (regardless of the recorded cause of death) with the long-term average of daily deaths found that the heat wave likely led to about 700 more deaths than would otherwise have been expected.[22] Differences in estimated heat-related deaths that result from different methods may be even larger when considering the entire nation and longer time periods.*

** This graph shows data for the Chicago Standard Metropolitan Statistical Area.*

Data sources: CDC, 2012;[23] NOAA, 2012[24]

of Milwaukee developed a plan for responding to extreme heat conditions; during the 1999 heat wave, heat-related deaths were roughly half of what would have been expected.[17]

Future development related to this indicator should focus on capturing *all* heat-related deaths, not just those with a reported link to heat stress, as well as examining heat-related illnesses more systematically.

DATA SOURCES

Data for this indicator were provided by the U.S. Centers for Disease Control and Prevention (CDC). The 1979–2010 underlying cause data are publicly available through the CDC WONDER database at: http://wonder.cdc.gov/mortSQL.html. The 1999–2010 analysis was developed by CDC's Environmental Public Health Tracking Program, which provides a summary at: www.cdc.gov/nceh/tracking.

Lyme Disease

This indicator tracks the rate of reported Lyme disease cases across the United States.

KEY POINTS

- The incidence of Lyme disease in the United States has approximately doubled since 1991, from 3.74 reported cases per 100,000 people to 7.01 reported cases per 100,000 people in 2012 (see Figure 1).
- Among the states where Lyme disease is most common, New Hampshire and Delaware have experienced the largest increases in reported case rates since 1991, followed by Maine, Vermont, and Massachusetts. On average, these five states now report 50 to 90 more cases per 100,000 people than they did in 1991 (see Figure 2).
- Driven by multiple factors, the number and distribution of reported cases of Lyme disease appear to be increasing over time (see example maps).

Lyme disease is a bacterial illness that can cause fever, fatigue, joint pain, and skin rash, as well as more serious joint and nervous system complications. Lyme disease is the most common vector-borne disease (that is, a disease transmitted by mosquitoes, ticks, or fleas) in the United States. In recent years, approximately 20,000–30,000 confirmed cases of Lyme disease per year have been reported to the Centers for Disease Control and Prevention.[25] However, the actual number of illnesses is likely greater than what is reported to health officials.[26] Lyme disease is transmitted through the bite of certain species of infected ticks (referred to commonly as deer ticks) that carry the bacteria that cause Lyme disease. These ticks live not only on deer, but also on rodents, birds, and other host animals. Deer do not harbor the bacteria that cause Lyme disease, but certain other hosts such as white-footed mice do, and ticks pick up the bacteria by feeding on these infected hosts.

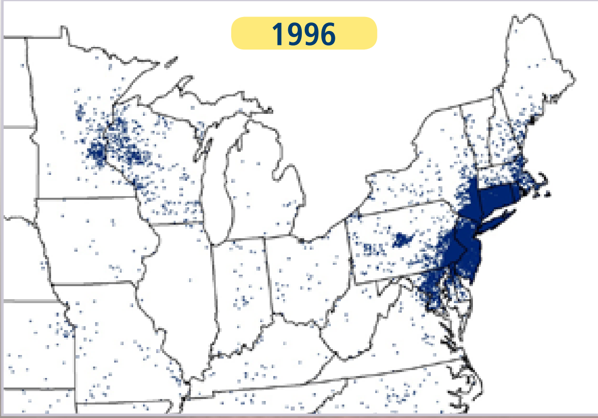
Climate is just one of many important factors that influence the transmission, distribution, and incidence of Lyme disease. However, studies provide evidence that climate change has contributed to the expanded range of ticks,[27] increasing the potential risk of Lyme disease, such as in areas of Canada where the ticks were previously unable to survive. The life cycle and prevalence of deer ticks are strongly influenced by temperature.[28] For example, deer ticks are mostly active when temperatures are above 45°F, and they thrive in areas with at least 85 percent humidity. Thus, warming temperatures associated with climate change could increase the range of suitable tick habitat, and are therefore one of multiple factors driving the observed spread of Lyme disease.[29] Because tick activity depends on temperatures being above a certain minimum, shorter winters could also extend the period when ticks are active each year, increasing the time that humans could be exposed to Lyme disease. Unlike some other vector-borne diseases, tick-borne disease patterns are generally less influenced by short-term changes in weather (weeks to months) than by longer-term climate change.

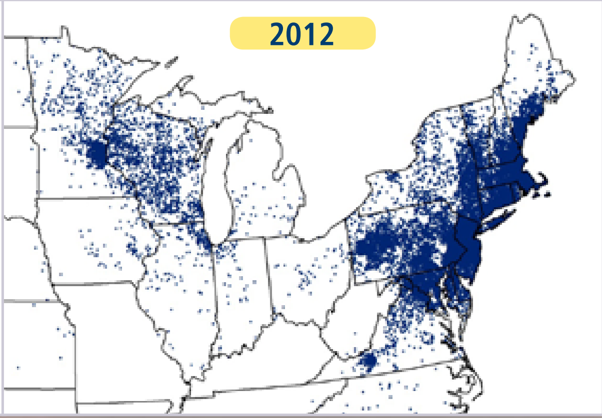
Other factors that affect the number of Lyme disease cases include changes in the populations of host species (particularly deer), which affect tick population size. The percentage of ticks that are infected depends on the prevalence and infection rates of white-footed mice and certain other hosts. Host species populations and habitats can be affected by climate change and other ecosystem disturbances. Human exposure to infected ticks is also influenced by multiple factors, including changes in the proximity of human populations to ticks and other hosts, increased awareness of Lyme disease, and modified behaviors, such as spending less time outdoors, taking precautions against being bitten, and checking more carefully for ticks.

ABOUT THE INDICATOR

This indicator looks at the incidence of Lyme disease, which reflects the rate of new cases contracted in a given geographic area and time period. Incidence is typically calculated as the number of cases per 100,000 people per year. Annual Lyme disease totals and rates for each state were provided by the Centers for Disease Control and Prevention. The original data were collected by state and local health departments, which track confirmed cases of Lyme disease that are diagnosed by health care providers and report these cases to the National Notifiable Diseases Surveillance System. Nationwide reporting of Lyme disease began in 1991.

Example: Reported Lyme Disease Cases in 1996 and 2012

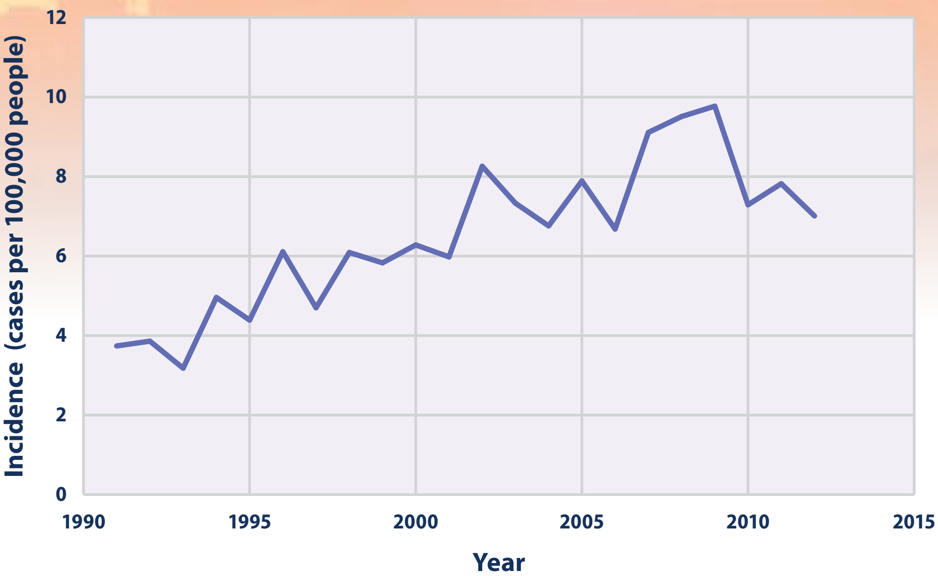




These maps show the distribution of reported cases of Lyme disease in 1996 and 2012. Each dot represents an individual case placed according to the patient's county of residence, which may be different than the county of exposure. The year 1996 was chosen as a reasonable starting point for comparison with recent years. These maps focus on the parts of the United States where Lyme disease is most common.

Data source: CDC, 2014[30]

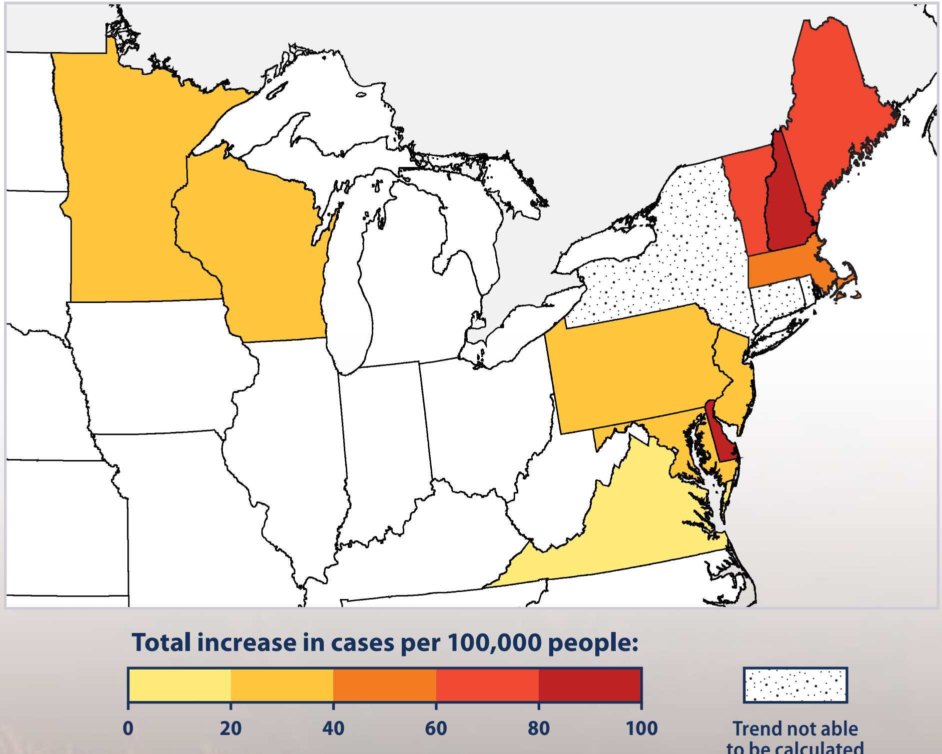
Figure 1. Reported Cases of Lyme Disease in the United States, 1991–2012



This figure shows the annual incidence of Lyme disease, which is calculated as the number of new cases per 100,000 people. The graph is based on cases that local and state health departments report to CDC's national disease tracking system.

Data source: CDC, 2014[31]

Figure 2. Change in Reported Lyme Disease Incidence in the Northeast and Upper Midwest, 1991–2012



This map shows how reported Lyme disease incidence has changed by state since 1991, based on the number of new cases per 100,000 people. The total change has been estimated from the average annual rate of change in each state. This map is limited to the 14 states where Lyme disease is most common, where annual rates are consistently above 10 cases per 100,000. Connecticut, New York, and Rhode Island had too much year-to-year variation in reporting practices to allow trend calculation.

Data source: CDC, 2014[32]

Figure 1 shows the national incidence of Lyme disease since 1991, and Figure 2 shows trends in incidence over time in 14 states that collectively account for about 95 percent of the nation's reported cases. To provide a simple illustration of changes over time, example maps show the distribution of reported cases in the years 1996 and 2012.

INDICATOR NOTES

For consistency, this indicator only includes data for confirmed cases of Lyme disease that are reported to CDC, not cases that are considered "probable." Changes in diagnosing practices and awareness of the disease over time can affect trends. Cases are reported based on the patient's county of residence, which is not necessarily the place where they were infected. Risk of infection is focused in certain regions of the country, and confirmed reports from low-incidence states are often the result of travel to an area of higher incidence. Evidence suggests that expanding ranges of ticks in certain northern states may be more related to a warming climate than expanding ranges in southern states.[33,34] However, because of the many factors affecting tick populations and reporting of Lyme disease, this indicator does not provide sufficient information to determine what proportion of the observed changes in Lyme disease incidence is directly driven by climate change. Further study is critical to improving the usefulness of this indicator and informing decisions affecting public health. For information on prevention, symptoms, and treatment of Lyme disease, see: www.cdc.gov/lyme.

DATA SOURCES

All three figures are based on publicly available Lyme disease data compiled by the Centers for Disease Control and Prevention at: www.cdc.gov/lyme/stats/index.html. Incidence was calculated using mid-year population estimates from the U.S. Census Bureau.[35]

Length of Growing Season

This indicator measures the length of the growing season in the contiguous 48 states.

KEY POINTS

- The average length of the growing season in the contiguous 48 states has increased by nearly two weeks since the beginning of the 20th century. A particularly large and steady increase occurred over the last 30 years (see Figure 1).
- The length of the growing season has increased more rapidly in the West than in the East. In the West, the length of the growing season has increased at an average rate of about 22 days per century since 1895, compared with a rate of about eight days per century in the East (see Figure 2).
- In recent years, the final spring frost has been occurring earlier than at any point since 1895, and the first fall frosts have been arriving later. Since 1980, the last spring frost has occurred an average of three days earlier than the long-term average, and the first fall frost has occurred about two days later (see Figure 3).

The length of the growing season in any given region refers to the number of days when plant growth takes place. The growing season often determines which crops can be grown in an area, as some crops require long growing seasons, while others mature rapidly. Growing season length is limited by many different factors. Depending on the region and the climate, the growing season is influenced by air temperatures, frost days, rainfall, or daylight hours.

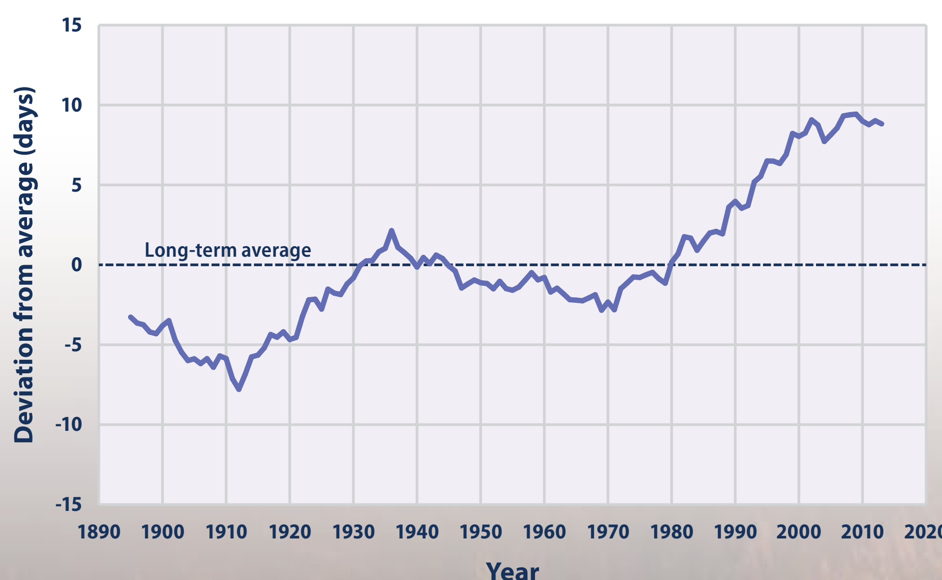
Changes in the length of the growing season can have both positive and negative effects on the yield and prices of particular crops. Overall, warming is expected to have negative effects on yields of major crops, but some individual locations may benefit.[36] A longer growing season could allow farmers to diversify crops or have multiple harvests from the same plot. However, it could also limit the types of crops grown, encourage invasive species or weed growth, or increase demand for irrigation. A longer growing season could also disrupt the function and structure of a region's ecosystems and could, for example, alter the range and types of animal species in the area.

ABOUT THE INDICATOR

This indicator looks at the impact of temperature on the length of the growing season in the contiguous 48 states, as well as trends in the timing of spring and fall frosts. For this indicator, the length of the growing season is defined as the period of time between the last frost of spring and the first frost of fall, when the air temperature drops below the freezing point of 32°F. This is referred to as the frost-free season.

Trends in the growing season were calculated using temperature data from 750 weather stations throughout the contiguous 48 states. These data were obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center. Growing season length and the timing of spring and fall frosts were averaged across the nation, then compared with long-term average numbers (1895–2013) to determine how each year differed from the long-term average.

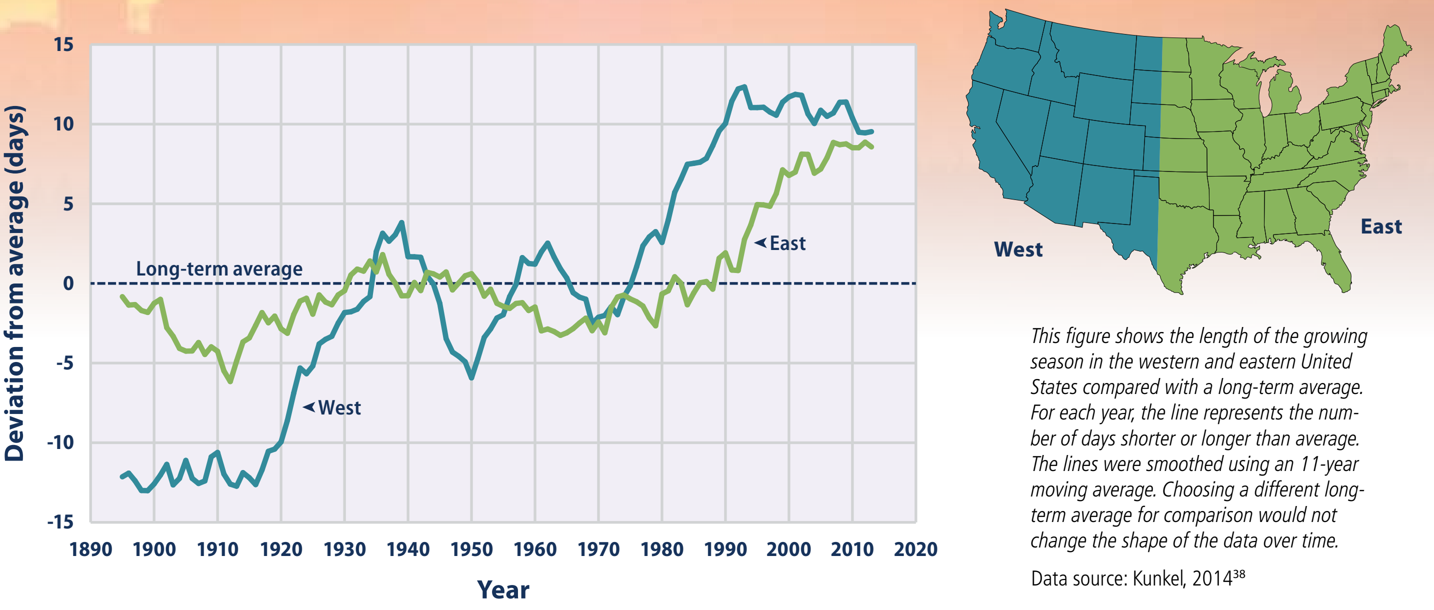
Figure 1. Length of Growing Season in the Contiguous 48 States, 1895–2013



This figure shows the length of the growing season in the contiguous 48 states compared with a long-term average. For each year, the line represents the number of days shorter or longer than average. The line was smoothed using an 11-year moving average. Choosing a different long-term average for comparison would not change the shape of the data over time.

Data source: Kunkel, 2014[37]

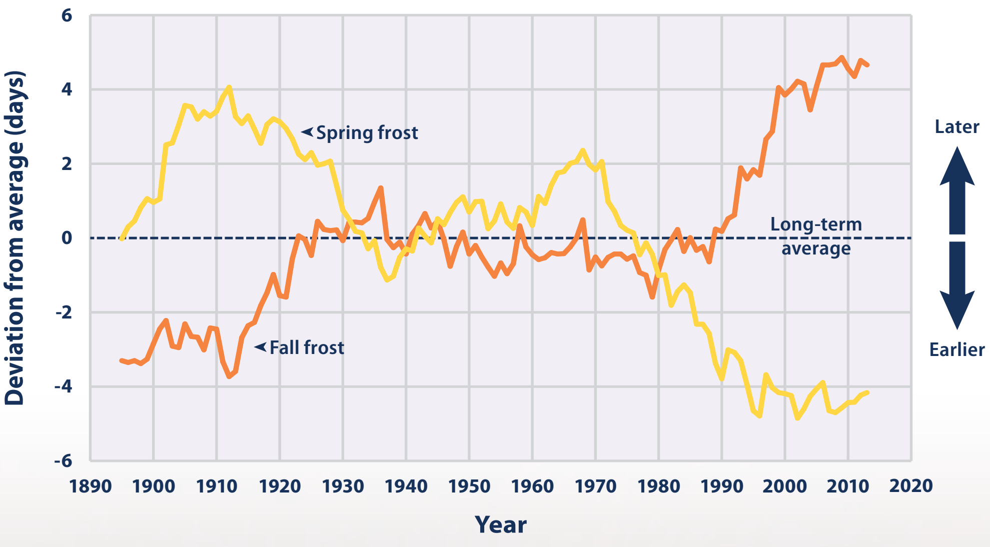
Figure 2. Length of Growing Season in the Contiguous 48 States, 1895–2013: West Versus East



This figure shows the length of the growing season in the western and eastern United States compared with a long-term average. For each year, the line represents the number of days shorter or longer than average. The lines were smoothed using an 11-year moving average. Choosing a different long-term average for comparison would not change the shape of the data over time.

Data source: Kunkel, 2014[38]

Figure 3. Timing of Last Spring Frost and First Fall Frost in the Contiguous 48 States, 1895–2013



This figure shows the timing of the last spring frost and the first fall frost in the contiguous 48 states compared with a long-term average. Positive values indicate that the frost occurred later in the year, and negative values indicate that the frost occurred earlier in the year. The lines were smoothed using an 11-year moving average. Choosing a different long-term average for comparison would not change the shape of the data over time.

Data source: Kunkel, 2014[39]

INDICATOR NOTES

Changes in measurement techniques and instruments over time can affect trends. This indicator only includes data from weather stations with a consistent record of data points for the time period.

DATA SOURCES

All three figures are based on temperature data compiled by the National Oceanic and Atmospheric Administration's National Climatic Data Center, and these data are available online at: www.ncdc.noaa.gov/oa/ncdc.html. Frost timing and growing season length were analyzed by Kunkel (2014).[40]

Ragweed Pollen Season

This indicator depicts changes in the length of ragweed pollen season in the United States and Canada.

KEY POINTS

- Since 1995, ragweed pollen season has grown longer at 10 of the 11 locations studied (see Figure 1).
- The increase in ragweed season length generally becomes more pronounced from south to north. Ragweed season increased by 27 days in Saskatoon, Saskatchewan; 22 days in Winnipeg, Manitoba; 21 days in Minneapolis, Minnesota; and 19 days in Fargo, North Dakota (see Figure 1). This trend is consistent with many other observations showing that climate is changing more rapidly at higher latitudes.[41]
- The trends in Figure 1 are strongly related to changes in the length of the frost-free season and the timing of the first fall frost. Northern areas have seen fall frosts happening later than they used to, with the delay in first frost closely matching the increase in pollen season. Meanwhile, some southern stations have experienced only a modest change in frost-free season length since 1995.[42]

Allergies are a major public health concern, with hay fever (congestion, runny nose, itchy eyes) accounting for more than 13 million visits to physicians' offices and other medical facilities every year.[43] One of the most common environmental allergens is ragweed, which can cause hay fever and trigger asthma attacks, especially in children and the elderly. An estimated 26 percent of all Americans are sensitive to ragweed.[44]

Ragweed plants mature in mid-summer and produce small flowers that generate pollen. Ragweed pollen season usually peaks in late summer and early fall, but these plants often continue to produce pollen until the first frost. A single ragweed plant can produce up to a billion pollen grains in one season, and these grains can be carried long distances by the wind.[45]

Climate change can affect pollen allergies in several ways. Warmer spring temperatures cause some plants to start producing pollen earlier (see the Leaf and Bloom Dates indicator on p. 94), while warmer fall temperatures extend the growing season for other plants, such as ragweed (see the Length of Growing Season indicator on p. 80). Warmer temperatures and increased carbon dioxide concentrations also enable ragweed and other plants to produce more pollen.[46] This means that many locations could experience longer allergy seasons and higher pollen counts as a result of climate change.

ABOUT THE INDICATOR

This indicator shows changes in the length of the ragweed pollen season in 11 cities in the central United States and Canada. These locations were selected as part of a study that looked at trends in pollen season at sites similar in elevation, but across a range of latitudes from south to north. At each location, air samples have been collected and examined since at least the 1990s as part of a national allergy monitoring network. Pollen spores are counted and identified using microscopes.

Pollen counts from each station have been analyzed to determine the start and end dates of each year's ragweed pollen season. Because the length of ragweed season naturally varies from year to year, statistical techniques have been used to determine the average rate of change over time. This indicator shows the total change in season length from 1995 to 2013, which was determined by multiplying the average annual rate of change by the number of years in the period.

INDICATOR NOTES

This indicator is based on data from a limited number of cities in the central states and provinces. These cities cover a broad range from north to south, however, which allows researchers to establish a clear connection between pollen season changes and latitude.

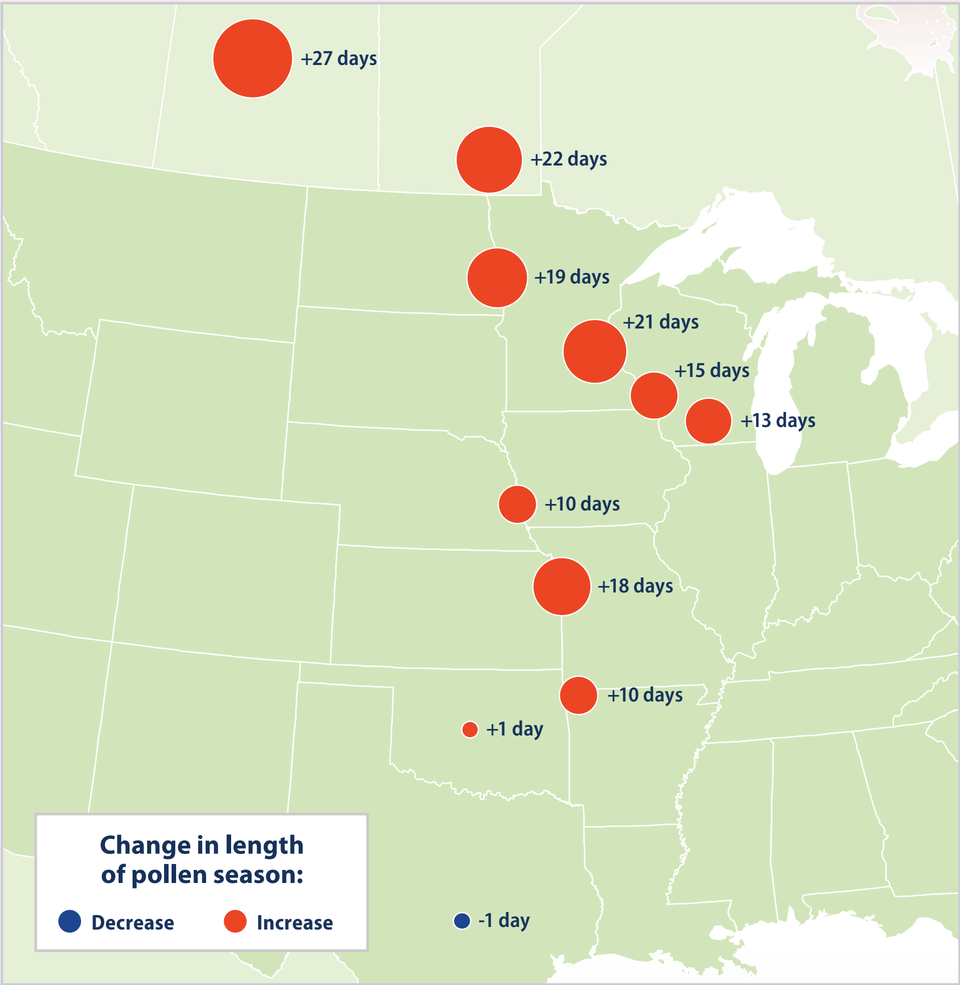
Many factors can influence year-to-year changes in pollen season, including typical local and regional variations in temperature and precipitation, extreme events such as floods and droughts, and changes in plant diversity. Adding more years of data would provide a better picture of long-term trends, but widespread data were not available prior to 1995.

This indicator does not show how the intensity of ragweed pollen season (pollen counts) might also be changing.

DATA SOURCES

Data for this indicator come from the National Allergy Bureau, which is part of the American Academy of Allergy, Asthma, and Immunology's Aeroallergen Network. Data were compiled and analyzed by a team of researchers who published a more detailed version of this analysis in a scientific journal with data through 2009.[47]

Figure 1. Change in Ragweed Pollen Season, 1995–2013



This figure shows how the length of ragweed pollen season changed at 11 locations in the central United States and Canada between 1995 and 2013. Red circles represent a longer pollen season; the blue circle represents a shorter season. Larger circles indicate larger changes.

Data source: Ziska et al., 2014[48]

ECOSYSTEMS

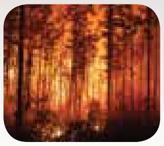
Ecosystems provide humans with food, clean water, and a variety of other services that can be affected by climate change. This chapter looks at some of the ways that climate change affects ecosystems, including changes in wildfires, streams and lakes, bird migration patterns, and plant growth.

WHY DOES IT MATTER?

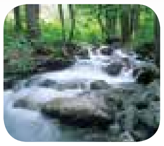
Changes in the Earth's climate can affect ecosystems by altering the water cycle, habitats, animal behavior—such as nesting and migration patterns—and the timing of natural processes such as flower blooms. Changes that disrupt the functioning of ecosystems may increase the risk of harm or even extinction for some species. While wildfires occur naturally, more frequent and more intense fires can significantly disrupt ecosystems, damage property, put people and communities at risk, and create air pollution problems even far away from the source.

While plants and animals have adapted to environmental change for millions of years, the climate changes being experienced now could require adaptation on larger and faster scales than current species have successfully achieved in the past, thus increasing the risk of extinction or severe disruption for many species.

Summary of Key Points

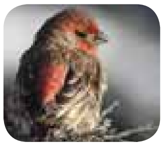


Wildfires. Since 1983, the United States has had an average of 72,000 recorded wildfires per year. Of the 10 years with the largest acreage burned, nine have occurred since 2000, with many of the largest increases occurring in western states. The proportion of burned land suffering severe damage each year has ranged from 5 to 22 percent.

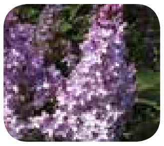


Streamflow. Changes in temperature, precipitation, snowpack, and glaciers can affect the rate of streamflow and the timing of peak flow. Over the last 73 years, minimum, maximum, and average flows have changed in many parts of the country—some higher, some lower. Nearly half of the rivers and streams measured show peak winter-spring runoff happening at least five days earlier than it did in the mid-20th century.

Great Lakes Water Levels and Temperatures. Water levels in most of the Great Lakes have declined in the last few decades. Water levels in lakes are influenced by water temperature, which affects evaporation rates and ice formation. Since 1995, average surface water temperatures have increased by a few degrees for Lakes Superior, Michigan, Huron, and Ontario. Less of a temperature change has been observed in Lake Erie.

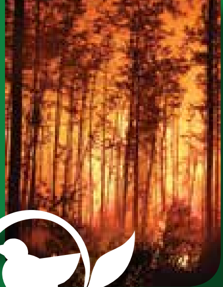


Bird Wintering Ranges. Some birds shift their range or alter their migration habits to adapt to changes in temperature or other environmental conditions. Long-term studies have found that bird species in North America have shifted their wintering grounds northward by an average of more than 40 miles since 1966, with several species shifting by hundreds of miles. On average, bird species have also moved their wintering grounds farther from the coast, consistent with inland winter temperatures becoming less severe.



Leaf and Bloom Dates. Leaf growth and flower blooms are examples of natural events whose timing can be influenced by climate change. Observations of lilacs and honeysuckles in the contiguous 48 states suggest that first leaf dates and bloom dates show a great deal of year-to-year variability. Leaf and bloom events are generally happening earlier throughout the North and West but later in much of the South.

Community Connection: Cherry Blossom Bloom Dates in Washington, D.C. "Peak" bloom dates of the iconic cherry trees in Washington, D.C., recorded since the 1920s, indicate that cherry trees are blooming slightly earlier than in the past. Bloom dates are key to planning the Cherry Blossom Festival, one of the region's most popular spring attractions.



Wildfires

This indicator tracks the frequency, extent, and severity of wildfires in the United States.

KEY POINTS

- Since 1983, the National Interagency Fire Center has documented an average of 72,000 wildfires per year (see Figure 1). Compiled data from the Forest Service suggest that the actual total may be even higher for the first few years of nationwide data collection that can be compared. The data do not show an obvious trend during this time.
- The extent of area burned by wildfires each year appears to have increased since the 1980s. According to National Interagency Fire Center data, of the 10 years with the largest acreage burned, nine have occurred since 2000 (see Figure 2). This period coincides with many of the warmest years on record nationwide (see the U.S. and Global Temperature indicator on p. 28).
- The late 1990s were a period of transition in certain climate cycles that tend to shift every few decades.[1] This shift—combined with other ongoing changes in temperature, drought, and snowmelt—may have contributed to warmer, drier conditions that have fueled wildfires in parts of the western United States.[2,3]
- Of the total area burned each year from 1984 to 2012, the proportion of burned land suffering severe damage has ranged from 5 to 22 percent (see Figure 3).
- Land area burned by wildfires varies by state. Fires burn more land in the western United States than in the East, and parts of the West and Southwest show the largest increase in burned acreage between the first half of the record (1984–1998) and the second half (1999–2012) (see Figure 4).

Together, forests, shrubland, and grassland cover more than half of the land area in the United States.[4] These ecosystems are important resources, both environmentally and economically. Although wildfires occur naturally and play a long-term role in the health of these ecosystems, climate change threatens to increase the frequency, extent, and severity of fires through increased temperatures and drought (see the U.S. and Global Temperature and Drought indicators on pp. 28 and 38). Earlier spring melting and reduced snowpack (see the Snowpack indicator on p. 70) result in decreased water availability during hot summer conditions, which in turn contributes to an increased wildfire risk, allowing fires to start more easily and burn hotter. In addition to climate change, other factors—like the spread of insects, land use, and management practices, including fire suppression—play an important role in wildfire frequency and intensity. All of these factors influencing wildfires vary greatly by region, as do variations in precipitation, wind, temperature, vegetation types, and landscape conditions. Therefore, understanding changes in fire characteristics requires a regional perspective and consideration of many factors.[5]

Wildfires have the potential to harm property, livelihoods, and human health. The recreation and timber industries depend on healthy forests, and wildfire smoke has been directly linked to poor air quality and illness, even in communities far downwind.[6] Fire-related threats are increasing, especially as more people live in and around forests, grasslands, and other natural areas.[7] The United States spends more than $1 billion every year to fight wildfires,[8] and these efforts have resulted in the deaths of hundreds of firefighters since 1910.[9]

Beyond the human impact, wildfires also affect the Earth's climate. Forests in particular store large amounts of carbon. When they burn, they release carbon dioxide into the atmosphere, which in turn contributes to additional climate change.

ABOUT THE INDICATOR

This indicator defines wildfires as "unplanned, unwanted wildland fire[s]" in forests, shrubland, and grassland, where "the objective is to put the fire out."[10] This indicator tracks three aspects of wildfires over time: the total number of fires (frequency), the total land area burned (extent), and the degree of damage that fires cause to the landscape (severity). The total area and total number of fires are tracked by the National Interagency Fire Center, which compiles reports from local, state, and federal agencies that are involved in fighting wildfires. The U.S. Forest Service tracked similar data using a different reporting system until 1997. Those data have been added to this indicator for comparison. Wildfire severity is measured by comparing the "greenness" of satellite images taken before and after a fire to classify how severely the land has been burned. Burn severity provides an indication of the ecological damage and how long the effects of wildfires are likely to last.

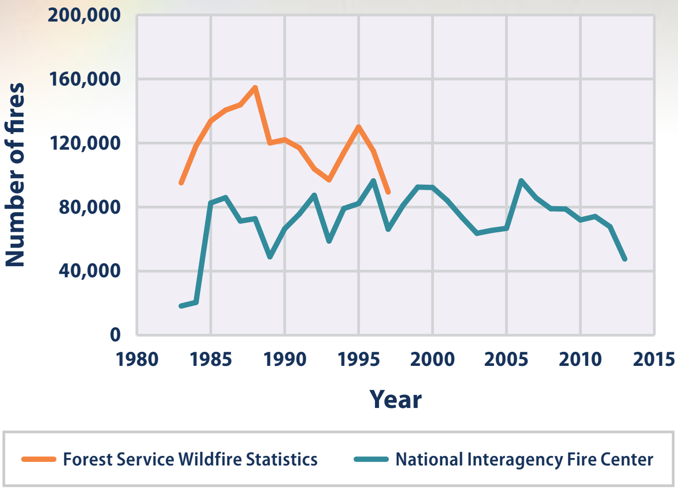
Although some nationwide fire data have been collected since the early 1900s, this indicator starts in 1983 (Figures 1 and 2) and 1984 (Figures 3 and 4), when nationwide data collection became more complete and standardized.

INDICATOR NOTES

Many environmental impacts associated with climate change can affect wildfire frequency, extent, or severity, including changes in temperature, precipitation, and drought. Human activities and land management practices also affect wildfire activity, and preferred practices in wildfire management have evolved over time, from older policies that favored complete wildfire prevention to more recent policies of wildfire suppression and controlled burns. While this indicator is limited to "wildland" fires, it includes fires that encroach on—or perhaps started in—developed areas. Increased development in previous wild lands could influence trends in wildfire frequency and extent. The total number of fires may also vary due to reporting irregularities, as fires that split or merge together across jurisdictional lines may be counted differently.

Along with the influence of ongoing climate change, wildfire patterns can be influenced by natural climate cycles that tend to shift every few decades. Thus, the approximately 30 years of data shown here may not be enough to draw conclusions about long-term trends. While a longer record would be ideal, data from before 1983 are not consistent enough nationally to be included in this indicator.

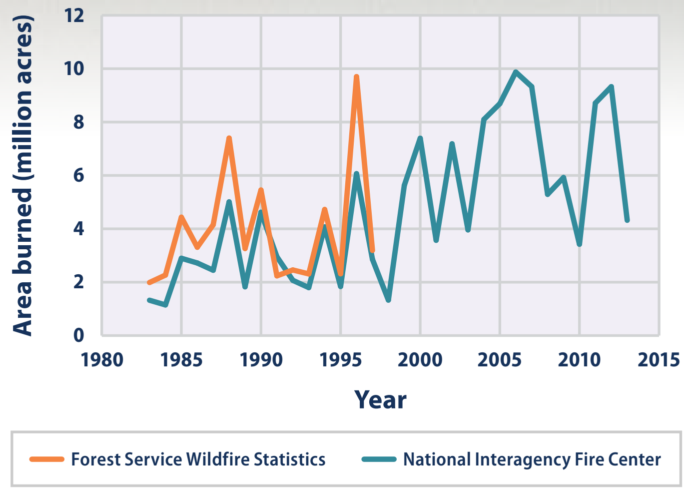
Figure 1. Wildfire Frequency in the United States, 1983–2013



This figure shows the total number of wildfires per year from 1983 to 2013. These totals include all reported wildfires, which can be as small as just a few acres. The two lines represent two different reporting systems; though Forest Service statistics (orange line) stopped being compiled in 1997 and will not be updated, they are shown here for comparison.

Data source: NIFC, 2014;[11] USDA Forest Service, 2014[12]

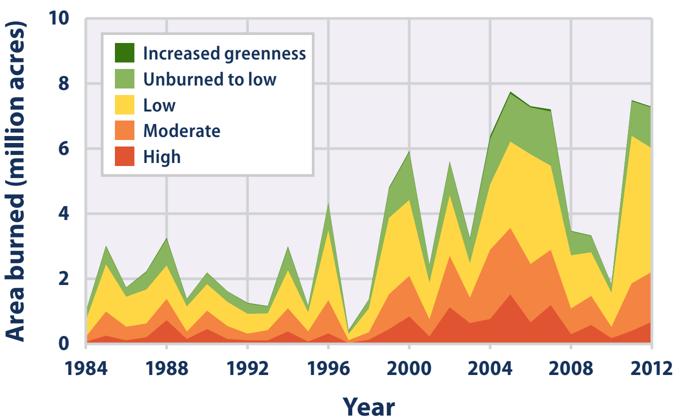
Figure 2. Wildfire Extent in the United States, 1983–2013



This figure shows annual wildfire-burned area (in millions of acres) from 1983 to 2013. The two lines represent two different reporting systems; though Forest Service statistics (orange line) stopped being compiled in 1997 and will not be updated, they are shown here for comparison.

Data source: NIFC, 2014;[13] USDA Forest Service, 2014[14]

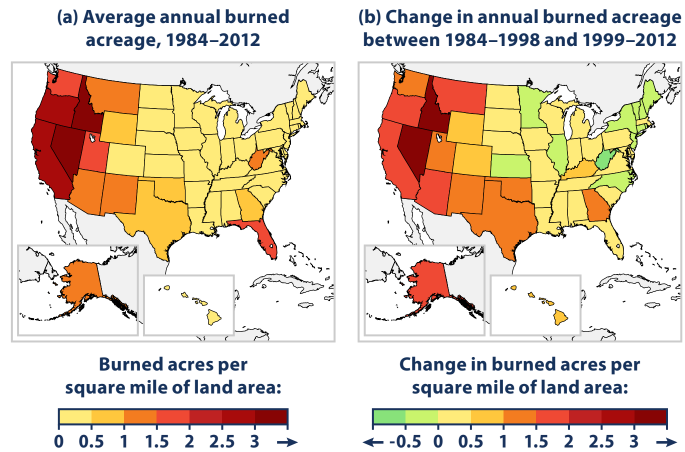
Figure 3. Damage Caused by Wildfires in the United States, 1984–2012



This figure shows the distribution of acreage burned by large wildfires, based on the level of damage caused to the landscape—a measure of wildfire severity. Large wildfires are defined as fires with an area larger than 1,000 acres in the western United States and 500 acres in the eastern United States. The total acreage shown in Figure 3 is slightly less than the total in Figure 2 because Figure 3 is limited to large fires and because a few areas did not have sufficient satellite imagery to allow damage to be assessed.

Data source: MTBS, 2014[15]

Figure 4. Land Area Burned by Wildfires by State, 1984–2012

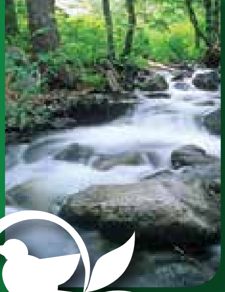


These maps show the number of acres burned in each state as a proportion of that state's total land area. For reference, there are 640 acres in a square mile; therefore, an average burned area of 6.4 acres per square mile would mean that fires burned 1 percent of a state's total land area. (a) The map on the left shows the average extent of fires per year from 1984 to 2012. Darker-shaded states have the largest proportion of acreage burned. (b) The map on the right shows how burned acreage has changed over time, based on a simple comparison between the first half of the available years (1984–1998) and the second half (1999–2012).

Data source: MTBS, 2014[16]

DATA SOURCES

The full set of wildfire frequency and burned acreage data in Figures 1 and 2 comes from the National Interagency Fire Center, which compiles wildfire reports sent from local, state, and federal entities that are involved in fighting fires. These data are available online at: www.nifc.gov/fireInfo/fireInfo_statistics.html. Additional data were provided by the U.S. Forest Service based on a different set of records, referred to as Smokey Bear Reports. Burn severity data and state-by-state acreage totals in Figures 3 and 4 come from a multi-agency project called Monitoring Trends in Burn Severity, which maintains a database of wildfire events across the United States. These data are publicly available at: http://mtbs.gov/data/search.html.



Streamflow

This indicator describes trends in the amount of water carried by streams across the United States, as well as the timing of runoff associated with snowmelt.

KEY POINTS

- Over the past 73 years, seven-day low flows have generally increased in the Northeast and Midwest (in other words, on the days of lowest flows, streams in these areas are carrying more water than before). In parts of the Southeast and the Pacific Northwest, low flows have generally decreased (that is, streams are carrying less water than before). Overall, sites show more increases than decreases (see Figure 1).
- Three-day high-flow trends vary from region to region across the country. For example, streams in the Northeast have generally seen an increase or little change in high flows since 1940, while some West Coast streams have seen a decrease and others have seen an increase. Overall, sites show more increases than decreases (see Figure 2).
- The largest changes in annual average streamflow have taken place in the Northeast and Midwest. Other regions saw few substantial changes. Overall, sites show more increases than decreases (see Figure 3).
- Nearly half of the streams studied show winter-spring runoff happening more than five days earlier than in the mid-20th century. The largest changes occurred in the Pacific Northwest and Northeast (see Figure 4).

Streamflow is a measure of the rate at which water is carried by rivers and streams, and it represents a critical resource for people and the environment. Changes in streamflow can directly influence the supply of drinking water and the amount of water available for irrigating crops, generating electricity, and other needs. In addition, many plants and animals depend on streamflow for habitat and survival.

Streamflow naturally varies over the course of a year. For example, rivers and streams in many parts of the country have their highest flows when snow melts in the spring and their lowest flows in late summer. The amount of streamflow is important because very high flows can cause erosion, flooding, and ecosystem disruption, while very low flows can diminish water quality, harm fish, and reduce the amount of water available for people. The timing of high flow is important because it affects the ability of reservoir managers to store water to meet needs later in the year. In addition, some plants and animals (such as fish that migrate) depend on a particular pattern of streamflow as part of their life cycles.

Climate change can affect streamflow in several ways. Changes in the amount of snowpack and earlier spring melting (see the Snowpack indicator on p. 70) can alter the size and timing of high streamflows. Because of the relationship between precipitation and runoff, more precipitation will potentially cause higher average streamflow in some places, while heavier storms (see the Heavy Precipitation indicator on p. 36) could lead to larger peak flows. However, more frequent or severe droughts could reduce streamflow in certain areas.

ABOUT THE INDICATOR

The U.S. Geological Survey measures streamflow in rivers and streams across the United States using continuous monitoring devices called stream gauges. This indicator is based on 193 stream gauges located in areas where trends will not be substantially influenced by dams, reservoir management, wastewater treatment facilities, or land-use change. The indicator also excludes stream gauges with substantially overlapping watershed areas.

This indicator examines four important measures of streamflow conditions that occur during the course of a year. Figure 1 shows trends in low flow conditions, which are commonly calculated by averaging the lowest seven consecutive days of streamflow in a year. In many locations, this method captures the year's driest conditions. Figure 2 shows trends in high flow conditions, which are commonly calculated by averaging the highest three consecutive days of streamflow in a year. Three days is an optimal length of time to characterize runoff associated with large storms and peak snowmelt. Figure 3 shows changes in the annual average streamflow, which is calculated by averaging daily flows over the entire year.

Figure 4 shows trends in the timing of winter and spring runoff. This measure is limited to 56 stream gauges in areas where at least 30 percent of annual precipitation falls as snow. Scientists look at the total volume of water that passes by a gauge between January 1 and June 30, then determine the date when exactly half of that water has gone by. This date is called the winter-spring center of volume date. A long-term trend toward an earlier date could be caused by earlier spring snowmelt, more precipitation falling as rain instead of snow, or other changes in precipitation patterns.

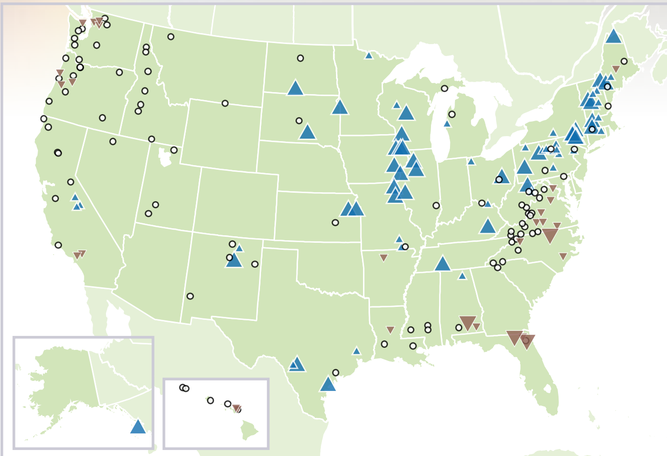
INDICATOR NOTES

Streamflow measurements were used from gauges in areas where streamflow is not highly affected by human influences such as dams, land development, or changes in land cover. However, changes in land cover and land use over time could still influence streamflow trends at some streams. The gauges used for this indicator are not evenly distributed across the country.

DATA SOURCES

Streamflow data were collected by the U.S. Geological Survey. These data came from a set of gauges in watersheds with minimal human impacts, which have been classified as reference gauges.[17] Daily average streamflow data are stored in the National Water Information System and are publicly available at: http://waterdata.usgs.gov/nwis.

Figure 1. Seven-Day Low Streamflows in the United States, 1940–2012

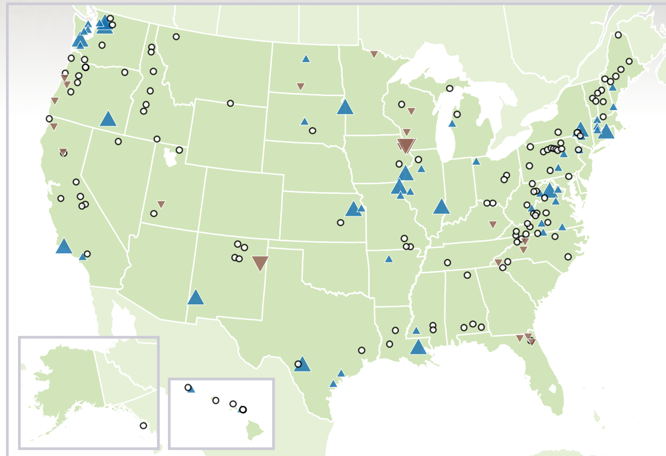


More than 50% decrease | 20% to 50% decrease | 20% decrease to 20% increase | 20% to 50% increase | More than 50% increase

This map shows percentage changes in the minimum annual rate of water carried by rivers and streams across the country, based on the long-term rate of change from 1940 to 2012. Minimum streamflow is based on the consecutive seven-day period with the lowest average flow during a given year.

Data source: USGS, 2014[18]

Figure 2. Three-Day High Streamflows in the United States, 1940–2012

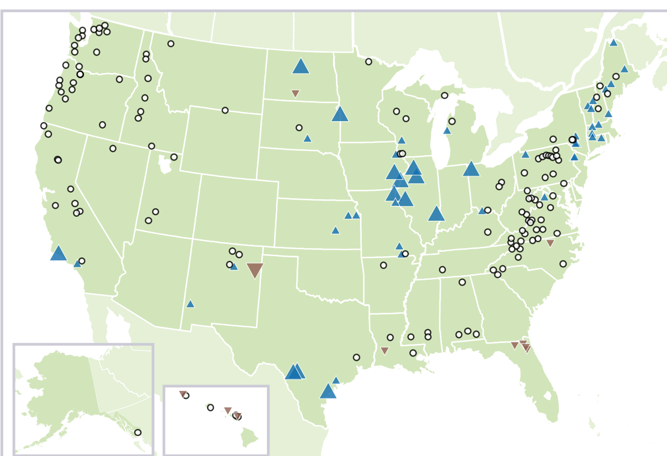


More than 50% decrease | 20% to 50% decrease | 20% decrease to 20% increase | 20% to 50% increase | More than 50% increase

This map shows percentage changes in the maximum annual rate of water carried by rivers and streams across the country, based on the long-term rate of change from 1940 to 2012. Maximum streamflow is based on the consecutive three-day period with the highest average flow during a given year.

Data source: USGS, 2014[19]

Figure 3. Annual Average Streamflow in the United States, 1940–2012

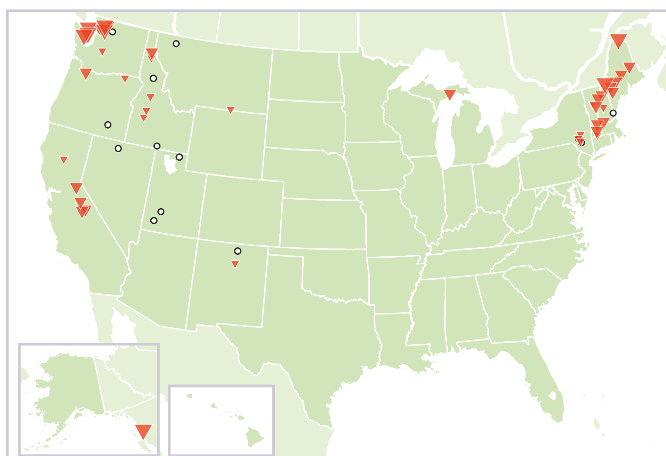


More than 50% decrease | 20% to 50% decrease | 20% decrease to 20% increase | 20% to 50% increase | More than 50% increase

This map shows percentage changes in the annual average rate of water carried by rivers and streams across the country, based on the long-term rate of change from 1940 to 2012. This map is based on daily streamflow measurements, averaged over the entire year.

Data source: USGS, 2014[20]

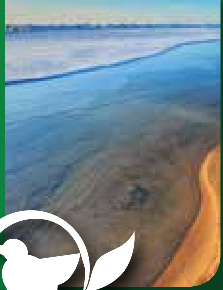
Figure 4. Timing of Winter-Spring Runoff in the United States, 1940–2012



More than 10 days earlier | 5 to 10 days earlier | 2 to 5 days earlier | 2 days earlier to 2 days later | 2 to 5 days later | 5 to 10 days later | More than 10 days later

This map shows changes in the timing of annual high spring flow carried by rivers and streams from 1940 to 2012. This analysis focuses on parts of the country where streamflow is strongly influenced by snowmelt. Trends are based on the winter-spring center of volume, which is the date when half of the streamflow between January 1 and June 30 of each year has passed a streamflow gauge.

Data source: USGS, 2014[21]



Great Lakes Water Levels and Temperatures

This indicator measures water levels and surface water temperatures in the Great Lakes.

KEY POINTS

- Water levels in the Great Lakes have fluctuated since 1860. Over the last few decades, they appear to have declined for most of the Great Lakes (see Figure 1). However, the most recent levels are all within the range of historical variation.
- Since 1995, average surface water temperatures have increased by a few degrees for Lakes Superior, Michigan, Huron, and Ontario (see Figure 2). Less change has been observed in water temperature in Lake Erie.
- Recent increases in water temperature have mostly been driven by warming during the spring and summer months (see Figure 2). These trends could relate in part to an earlier thawing of winter ice (see the Lake Ice indicator on p. 62).

The Great Lakes, consisting of Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario, form the largest group of freshwater lakes on Earth. These lakes support a variety of ecosystems and play a vital role in the economy of the eight neighboring states and the Canadian province of Ontario, providing drinking water, shipping lanes, fisheries, recreational opportunities, and more.

Water level and water temperature are two important and interrelated indicators of weather and climate change in the Great Lakes. Water level (the height of the lake surface above sea level) is influenced by many factors, including precipitation, snowmelt runoff, drought, evaporation rates, and people withdrawing water for multiple uses. Water temperature is influenced by many factors, too, but most directly by air temperature.

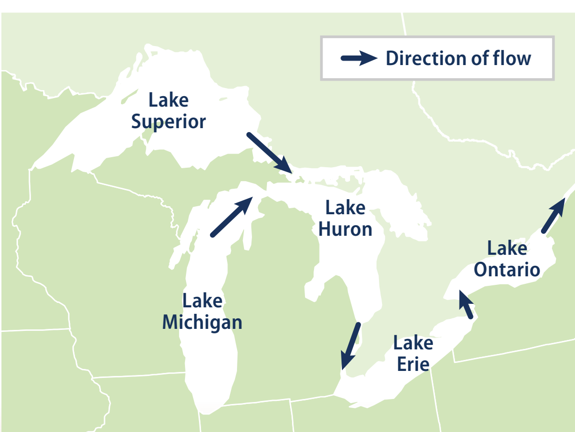
In recent years, warmer surface water temperatures in the Great Lakes have contributed to lower water levels by increasing rates of evaporation and causing lake ice to form later than usual (see the Lake Ice indicator on p. 62), which extends the season for evaporation.[22] Lower water levels in the Great Lakes forced ships to reduce their cargo tonnage by 5 to 8 percent between 1997 and 2000, which increased shipping costs. Lower water levels can also affect water supplies, the usability of infrastructure such as docks and piers, and shoreline ecosystems. These types of disruptions from low water levels are expected to continue as the climate changes.[23]

Another possible effect of warmer water, reduced ice cover, and increased evaporation is a corresponding increase in precipitation over nearby land, especially "lake effect" snow (see the Snowfall indicator on p. 66).[24] Rising water temperatures are also expected to expand the ranges of and give new advantages to some invasive species such as the zebra mussel, and to encourage the growth of certain waterborne bacteria that can make people ill.[25,26]

ABOUT THE INDICATOR

This indicator analyzes water levels and surface water temperatures in the Great Lakes. Water levels are recorded by gauges along the shore of each lake, some of which have been operated since the 1800s. Pre-1918 data came from one water level gauge per lake. Data since 1918 have come from a designated set of gauges in each lake. Figure 1 shows annual water level anomalies, or differences, in feet compared with the average water levels in each lake from 1860 to 2013. Lakes Michigan and Huron are combined because they are connected at the same water level.

Surface water temperatures are measured by satellites. Figure 2 shows annual average temperatures over the entire surface of each lake, along with the pattern of daily temperatures over the course of the year. This figure's data begin in 1995, which was the first year with complete satellite data for all five lakes.



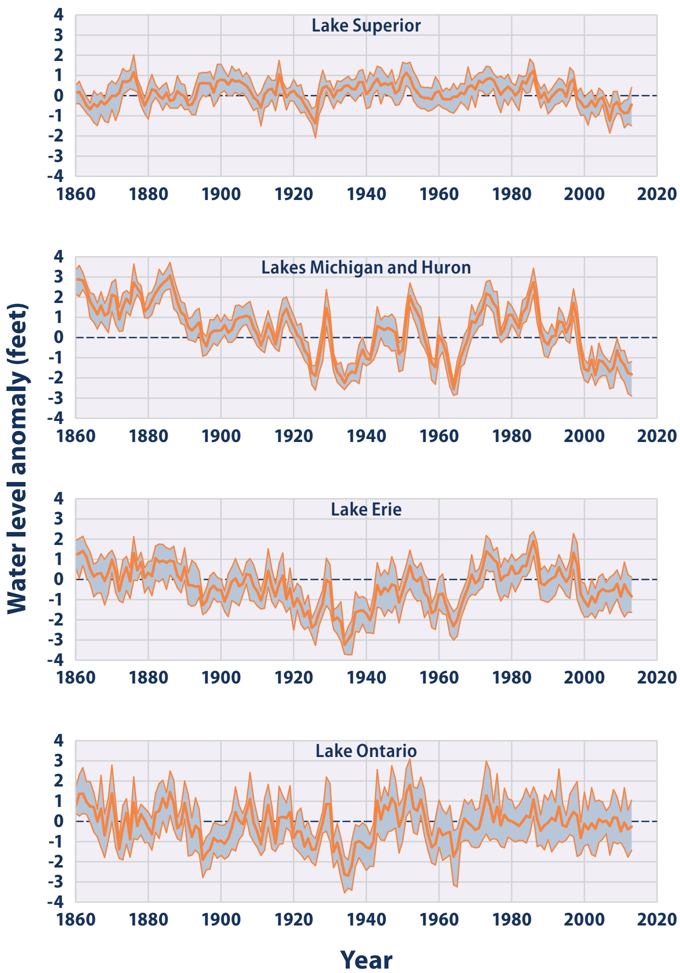
INDICATOR NOTES

While climate change influences water levels, human activities such as dredging can also play a role. For example, the St. Clair river opening was enlarged in the 1910s, 1930s, and 1960s, contributing to greater outflows from Lakes Michigan and Huron.[27] Similarly, natural year-to-year variability and other factors such as human use and wastewater discharges can influence water temperatures.

DATA SOURCES

Water level data were provided by the Canadian Hydrographic Service and the National Oceanic and Atmospheric Administration's Center for Operational Oceanographic Products and Services, and can be downloaded from: www.glerl.noaa.gov/data/now/wlevels/levels.html. Surface water temperature data were provided by the National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory (satellite data at: http://coastwatch.glerl.noaa.gov).

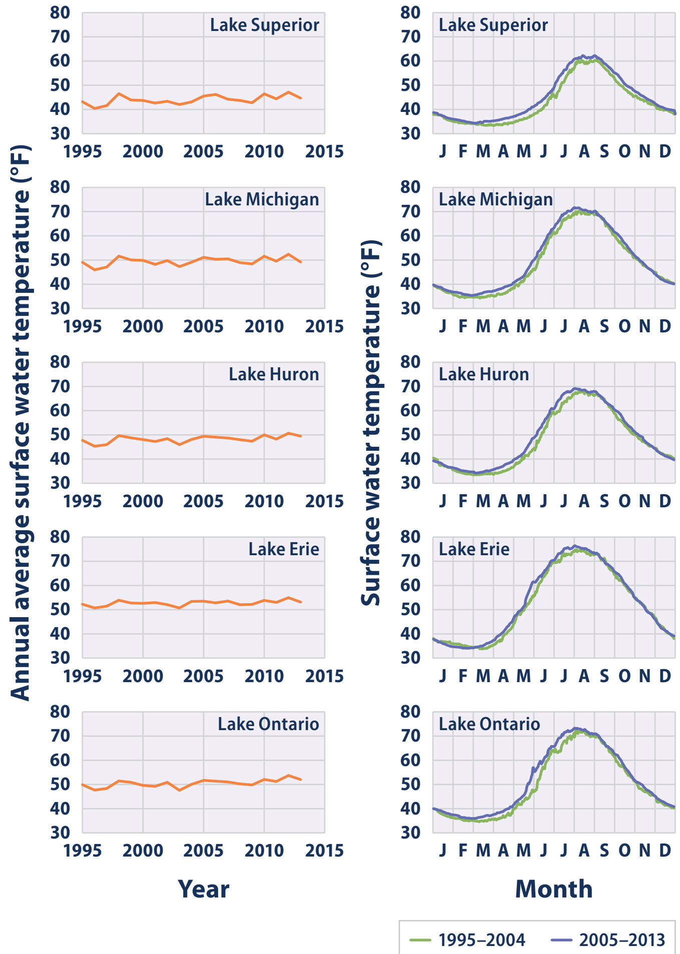
Figure 1. Water Levels of the Great Lakes, 1860–2013



This figure displays how water levels in each of the Great Lakes have changed since 1860. For each year, the shaded band shows the range of monthly average water levels, and the line in the middle shows the annual average. The graph uses the 1981 to 2010 average as a baseline for depicting the change. Choosing a different baseline period would not change the shape of the data over time. Lakes Michigan and Huron are shown together because they are connected at the same water level.

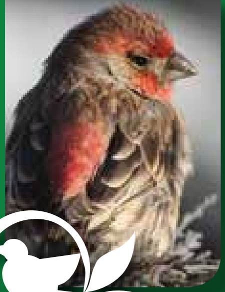
Data source: NOAA, 2014[28]

Figure 2. Surface Water Temperatures of the Great Lakes, 1995–2013



This figure shows the average surface water temperatures in each of the Great Lakes, as measured by satellites. The graphs on the left show annual averages, while the graphs on the right show how average daily temperatures have changed between two time periods. The full time period has been divided approximately in half for comparison: 2005–2013 (nine years) versus 1995–2004 (10 years).

Data source: NOAA, 2014[29]



Bird Wintering Ranges

This indicator examines changes in the winter ranges of North American birds.

KEY POINTS

- Among 305 widespread North American bird species, the average mid-December to early January center of abundance moved northward by more than 40 miles between 1966 and 2013 (see Figure 1). Trends in center of abundance moving northward can be closely related to increasing winter temperatures.[30]
- On average, bird species have also moved their wintering grounds farther from the coast since the 1960s (see Figure 2). A shift away from the coasts can also relate to changes in winter temperatures. Inland areas tend to experience more extreme cold than coastal areas, but those extremes are becoming less severe as the climate warms overall.[31]
- Some species have moved farther than others. A total of 48 species have moved northward by more than 200 miles. Of the 305 species studied, 186 (61 percent) have shifted their wintering grounds northward since the 1960s, while 82 (27 percent) have shifted southward. Some others have not moved at all.

Changes in climate can affect ecosystems by influencing animal behavior and ranges. Birds are a particularly good indicator of environmental change for several reasons:

- Each species of bird has adapted to or evolved to favor certain habitat types, food sources, and temperature ranges. In addition, the timing of certain events in their life cycles—such as migration and reproduction—is driven by cues from the environment. For example, many North American birds follow a regular seasonal migration pattern, moving north to feed and breed in the summer, then moving south to spend the winter in warmer areas. Changing conditions can influence the distribution of both migratory and non-migratory birds as well as the timing of important life cycle events.
- Birds are easy to identify and count, and thus there is a wealth of scientific knowledge about their distribution and abundance. People have kept detailed records of bird observations for more than a century.
- There are many different species of birds living in a variety of habitats, including water birds, coastal birds, and land birds. If a change in behavior or range occurs across a range of bird types, it suggests that a common external factor might be the cause.

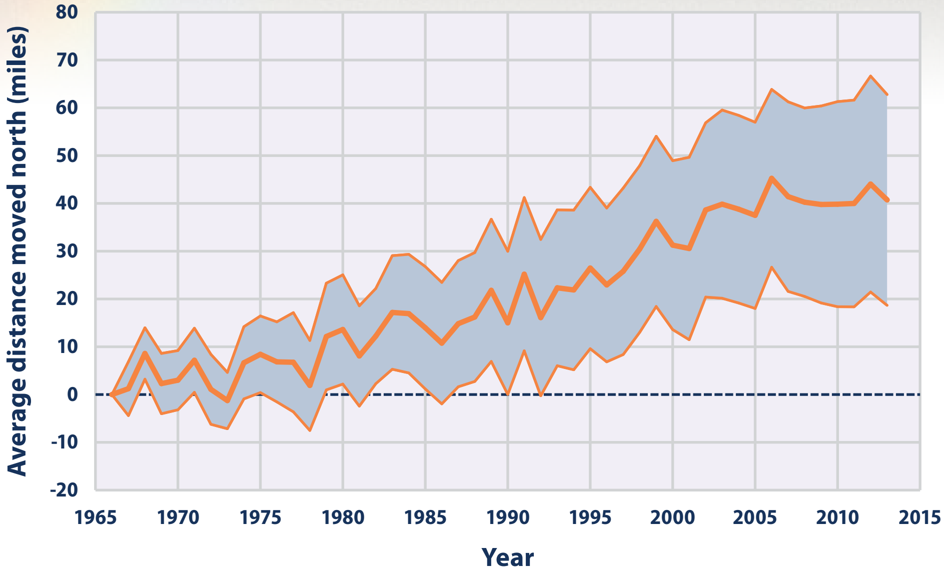
Temperature and precipitation patterns are changing across the United States (see the U.S. and Global Temperature indicator on p. 28 and the U.S. and Global Precipitation indicator on p. 34). Some bird species can adapt to generally warmer temperatures by changing where they live—for example, by migrating farther north in the summer but not as far south in the winter, or by shifting inland as winter temperature extremes grow less severe. Non-migratory species might shift as well, expanding into newly suitable habitats while moving out of areas that become less suitable. Other types of birds might not adapt to changing conditions and could experience a population decline as a result. Climate change can also alter the timing of events that are based on temperature cues, such as migration and breeding (especially egg-laying).

ABOUT THE INDICATOR

This indicator looks collectively at the "center of abundance" of hundreds of widespread North American bird species over a 48-year period. The center of abundance is a point on the map that represents the middle of each species' distribution. If a whole population of birds were to shift generally northward, one would see the center of abundance shift northward as well.

For year-to-year consistency, this indicator uses observations from the National Audubon Society's Christmas Bird Count, which takes place every year in early winter. The Christmas Bird Count is a long-running citizen science program in which individuals are organized by the National Audubon Society, Bird Studies Canada, local Audubon chapters, and other bird clubs to identify and count bird species. The data presented in this indicator were collected from more than 2,000 locations throughout the United States and parts of Canada. At each location, skilled observers follow a standard counting procedure to estimate the number of birds within a 15-mile diameter "count circle" over a 24-hour period. Study methods remain generally consistent from year to year. Data produced by the Christmas Bird Count go through several levels of review before Audubon scientists analyze the final data, which have been used to support a wide variety of peer-reviewed studies.

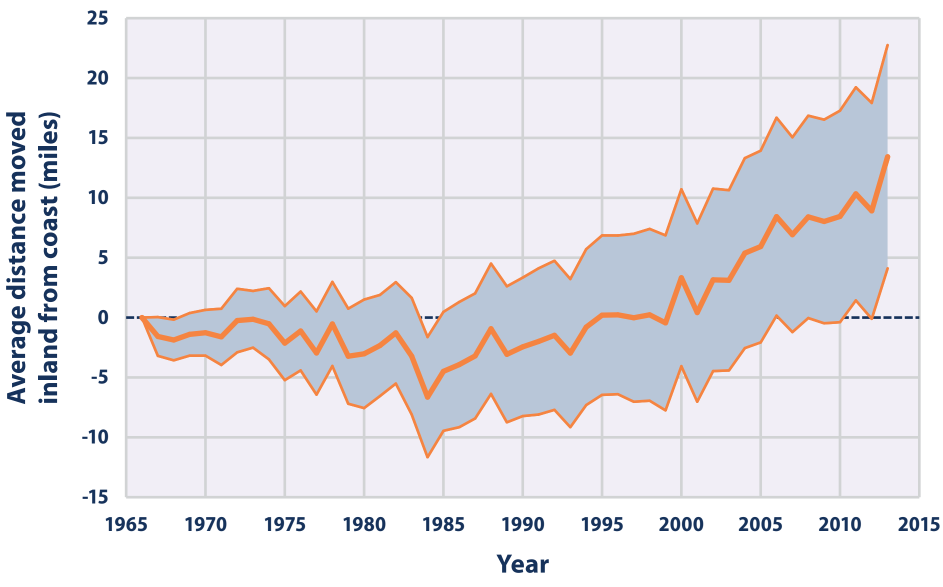
Figure 1. Change in Latitude of Bird Center of Abundance, 1966–2013



This figure shows annual change in latitude of bird center of abundance for 305 widespread bird species in North America from 1966 to 2013. Each winter is represented by the year in which it began (for example, winter 2013–2014 is shown as 2013). The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used.

Data source: National Audubon Society, 2014[32]

Figure 2. Change in Distance to Coast of Bird Center of Abundance, 1966–2013



This figure shows annual change in distance to the coast of bird center of abundance for 272 widespread bird species in North America from 1966 to 2013. This figure covers 272 species instead of the 305 species shown in Figure 1 because 33 of the species in Figure 1 need access to salt water, which means they cannot move inland. Each winter is represented by the year in which it began (for example, winter 2013–2014 is shown as 2013). The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used.

Data source: National Audubon Society, 2014[33]

INDICATOR NOTES

Many factors can influence bird ranges, including food availability, habitat alteration, and interactions with other species. As a result, some of the birds included in this indicator might have moved north for reasons other than changing temperatures. This indicator does not show how responses to climate change vary among different types of birds. For example, a more detailed National Audubon Society analysis found large differences among coastal birds, grassland birds, and birds adapted to feeders, which all have different abilities to adapt to temperature changes.[34]

Some data variations can be caused by differences among count circles, such as inconsistent level of effort by volunteer observers, but these differences are carefully corrected in Audubon's statistical analysis.

DATA SOURCES

Bird center of abundance data were collected by the annual Christmas Bird Count organized by the National Audubon Society and Bird Studies Canada. Recent and historical Christmas Bird Count data are available at: http://birds.audubon.org/christmas-bird-count. The National Audubon Society published a previous version of this analysis in 2009;[35] it is available at: www.audubon.org/bird/bacc/index.html.

Leaf and Bloom Dates

This indicator examines the timing of leaf growth and flower blooms for two widely distributed plants in the United States.

KEY POINTS

- First leaf and bloom dates in lilacs and honeysuckles in the contiguous 48 states show a great deal of year-to-year variability, which makes it difficult to determine whether a statistically meaningful change has taken place. However, earlier dates appear more prevalent in the last few decades (see Figure 1).
- Leaf and bloom events are generally happening earlier throughout the North and West but later in much of the South (see Figures 2 and 3). This observation is generally consistent with regional differences in temperature change (see the U.S. and Global Temperature indicator on p. 28).
- Other studies have looked at trends in leaf and bloom dates across all of North America and the entire Northern Hemisphere. These studies have also found a trend toward earlier spring events—some more pronounced than the trends seen in just the contiguous 48 states.[36]

The timing of natural events, such as flower blooms and animal migration, can be influenced by changes in climate. Phenology is the study of such important seasonal events. Phenological events are influenced by a combination of environmental factors, including temperature, light, rainfall, and humidity. Different plant and animal species respond to different cues.

Scientists have high confidence that the earlier arrival of spring events is linked to recent warming trends in global climate.[37] Disruptions in the timing of these events can have a variety of impacts on ecosystems and human society. For example, an earlier spring might lead to longer growing seasons (see the Length of Growing Season indicator on p. 80), more abundant invasive species and pests, and earlier and longer allergy seasons. Unusually warm weather in late winter can create a "false spring" that triggers the new growth of plants to begin too early, leaving them vulnerable to any subsequent frosts.

Because of their close connection with climate, the timing of phenological events can be used as an indicator of the sensitivity of ecological processes to climate change. Two particularly useful indicators of the timing of spring events are the first leaf dates and the first bloom dates of lilacs and honeysuckles, which have an easily monitored flowering season, a relatively high survival rate, and a large geographic distribution. The first leaf date in these plants relates to the timing of events that occur in early spring, while the first bloom date is consistent with the timing of later spring events, such as the start of growth in forest vegetation.[38]

ABOUT THE INDICATOR

This indicator shows trends in the timing of first leaf dates and first bloom dates in lilacs and honeysuckles across the contiguous 48 states. Because many of the phenological observation records in the United States are less than 40 years long, and because these records may have gaps in time or space, computer models have been used to provide a more complete understanding of long-term trends nationwide.

The models for this indicator were developed using data from the USA National Phenology Network, which collects ground observations from a network of federal agencies, field stations, educational institutions, and citizens who have been trained to log observations of leaf and bloom dates. For consistency, observations were limited to a few specific types of lilacs and honeysuckles. Next, models were created to relate actual leaf and bloom observations with records from nearby weather stations. Once scientists were able to determine the relationship between climate factors (particularly temperatures) and leaf and bloom dates, they used this knowledge to estimate leaf and bloom dates for earlier years based on historical weather records. They also used the models to estimate how leaf and bloom dates would have changed in a few areas (mostly in the far South) where lilacs and honeysuckles are not widespread.

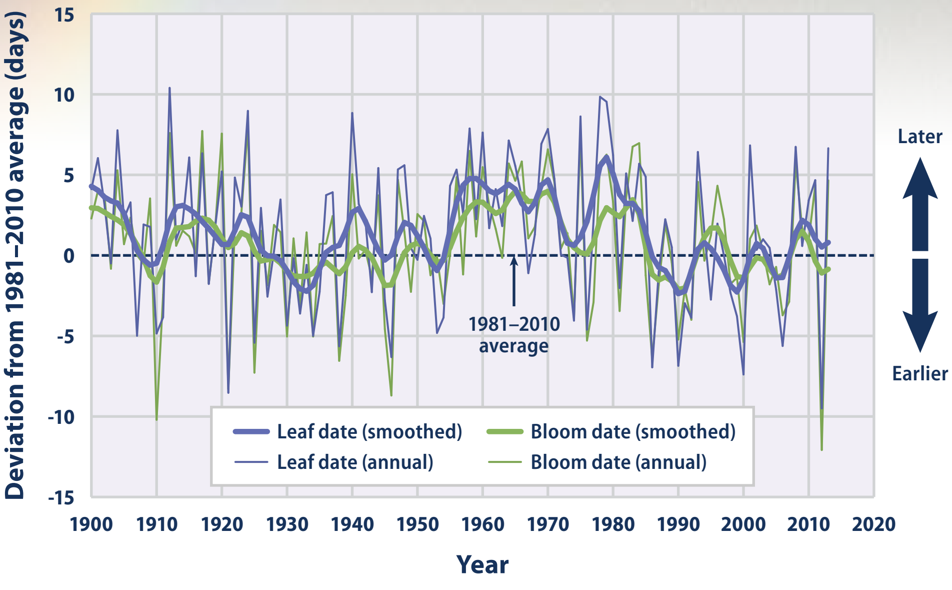
This indicator uses data from several hundred weather stations throughout the contiguous 48 states. The exact number of stations varies from year to year. For each year, the timing of first leaf and first bloom at each station was compared with the 1981 to 2010 average to determine the number of days' "deviation from normal." This indicator presents the average deviation across all stations, along with maps that compare the most recent 10-year period (2004–2013) with a mid-20th-century baseline (1951–1960) at individual stations. These time periods were chosen to match published studies.[39]

INDICATOR NOTES

Plant phenological events are studied using several data collection methods, including satellite images, models, and direct observations. Locational differences, the use of varying data collection methods, and different phenological indicators (such as leaf or bloom dates for different types of plants) can lead to a range of estimates of the arrival of spring.

Climate is not the only factor that can affect phenology. Observed variations can also reflect plant genetics, changes in the surrounding ecosystem, and other factors. This indicator minimizes the influence of genetic variations by relying on cloned plants (that is, plants with no genetic differences).

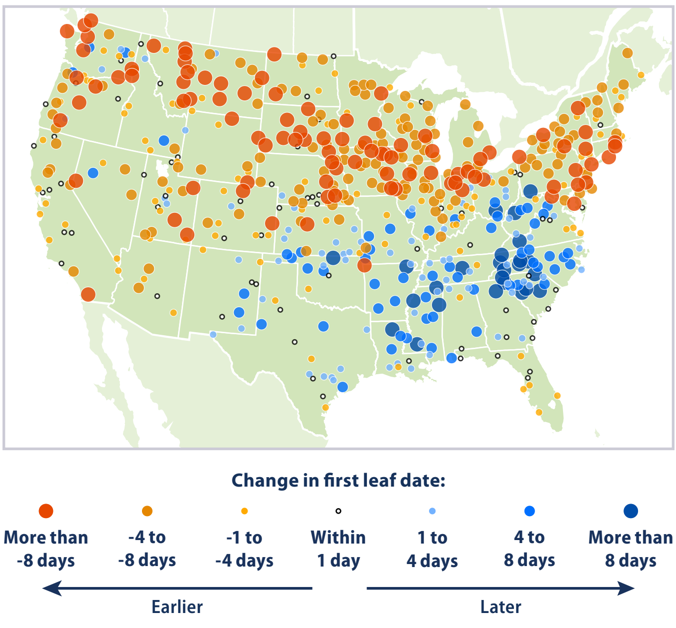
Figure 1. First Leaf and Bloom Dates in the Contiguous 48 States, 1900–2013



This figure shows modeled trends in lilac and honeysuckle first leaf dates and first bloom dates across the contiguous 48 states, using the 1981 to 2010 average as a baseline. Positive values indicate that leaf growth and blooming began later in the year, and negative values indicate that leafing and blooming occurred earlier. The thicker lines were smoothed using a nine-year weighted average. Choosing a different long-term average for comparison would not change the shape of the data over time.

Data source: Schwartz, 2013[40]

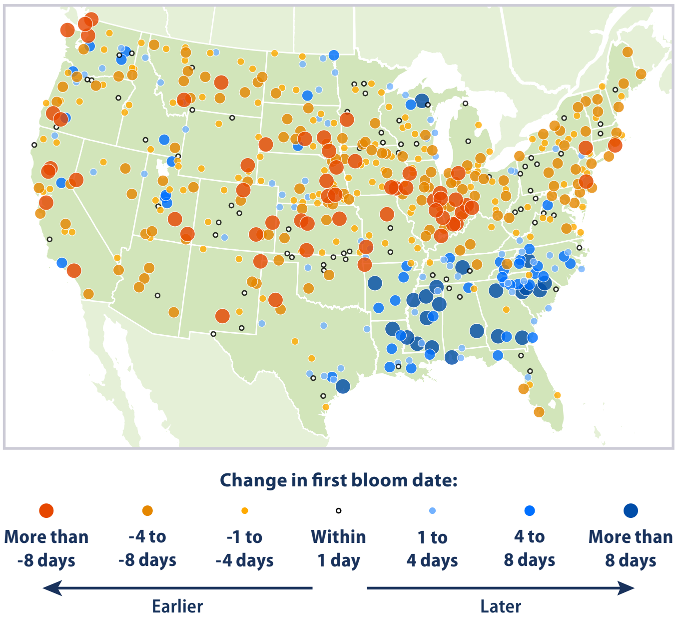
Figure 2. Change in First Leaf Date Between 1951–1960 and 2004–2013



This figure shows modeled trends in lilac and honeysuckle first leaf dates at weather stations across the contiguous 48 states. This map compares the average first leaf date during two 10-year periods.

Data source: Schwartz, 2013[41]

Figure 3. Change in First Bloom Date Between 1951–1960 and 2004–2013



This figure shows modeled trends in lilac and honeysuckle first bloom dates at weather stations across the contiguous 48 states. This map compares the average first bloom date during two 10-year periods.

Data source: Schwartz, 2013[42]

DATA SOURCES

Leaf and bloom observations were compiled by the USA National Phenology Network and are available at: www.usanpn.org. This indicator is also based on climate data that were provided by the U.S. Historical Climatology Network and are available at: www.ncdc.noaa.gov/oa/climate/research/ushcn. Data for this indicator were analyzed using methods described by Schwartz et al. (2013).[43]

Cherry Blossom Bloom Dates in Washington, D.C.

KEY POINTS

- Based on the entire 94 years of data in Figure 1, Washington's blossoms reach their peak on April 4 in an average year. By comparison, the peak bloom date in 2014 was April 10.
- Peak bloom date for the cherry trees is occurring earlier than it did in the past. Since 1921, peak bloom dates have shifted earlier by approximately five days.
- While the length of the National Cherry Blossom Festival has continued to expand, the Yoshino cherry trees have bloomed near the beginning of the festival in recent years. During some years, the festival missed the peak bloom date entirely.

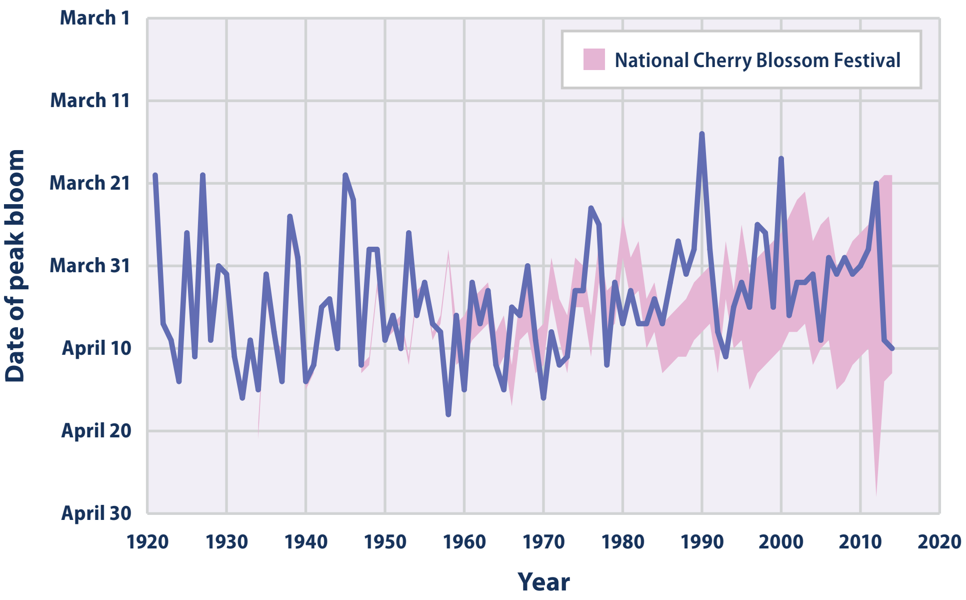
In Washington, D.C., the arrival of spring brings a splash of color as the city's iconic cherry trees burst into bloom. The city has enjoyed cherry blossoms each year dating back to 1912, when Japan gave 3,020 cherry trees to the United States as a gift of friendship. There are currently almost 3,800 of these trees around Washington's Tidal Basin, and the beautiful blooms set against the backdrop of the national monuments bring more than 1.5 million visitors to the area every year during the National Cherry Blossom Festival. Not surprisingly, the Festival is planned to coincide with the peak bloom of the cherry trees every year.

The exact timing of peak bloom varies from year to year, and it is largely driven by local temperatures during the winter and early spring. As the Leaf and Bloom Dates indicator (p. 94) explains, scientists have very high confidence that recent warming trends in global climate are causing spring events such as leaf growth and flower blooms to happen earlier.[44] In the case of Washington's cherry blossoms, earlier bloom dates could affect tourism and the local economy.

The peak bloom date for the most common type of cherry tree around Washington's Tidal Basin—the Yoshino variety—has been carefully estimated and recorded since 1921 by the National Park Service. The peak bloom date is defined as the day when 70 percent of the blossoms are in full bloom.

Figure 1 shows how the peak bloom date of the Yoshino cherry trees has changed since 1921. It also shows the dates of the National Cherry Blossom Festival, which has grown to several weeks as its popularity has expanded. As Figure 1 shows, there is considerable variability in the peak bloom date, which makes predicting the exact timing difficult. Each year, meteorologists, city planners, the National Park Service, and more than one million tourists speculate about the timing of peak bloom.

Figure 1. Peak Bloom Date for Cherry Trees Around Washington, D.C.'s Tidal Basin, 1921–2014



This figure shows the peak bloom date each year for the main type of cherry tree around the Tidal Basin in Washington, D.C. The peak bloom date occurs when 70 percent of the blossoms are in full bloom. The shaded band shows the timing of the annual National Cherry Blossom Festival. The festival began in 1934 but was not held during World War II.

Data source: National Park Service, 2014[45]

NOTES

In addition to winter and early spring temperatures, the timing of the peak bloom for cherry trees can be affected by other weather, climate, and location factors. For example, extended growing periods and warmer autumns could affect bloom dates by altering other stages of cherry tree growth.[46]

DATA SOURCES

Peak bloom dates and festival dates were provided by the National Park Service. The data shown here and other information about Washington's cherry trees can be found online at: www.nps.gov/cherry.

Climate Change Resources

EPA's Climate Change website (www.epa.gov/climatechange) provides a good starting point for further exploration of this topic. From this site, you can:

- View the latest information about EPA's climate change indicators (www.epa.gov/climatechange/indicators) and download figures as well as accompanying technical documentation.
- Learn more about greenhouse gases and the science of climate change, discover the potential impacts of climate change on human health and ecosystems, read about how people can adapt to changes, and get up-to-date news.
- Read about greenhouse gas emissions, look through EPA's greenhouse gas inventories, and explore EPA's Greenhouse Gas Data Publication Tool.
- Learn about EPA's regulatory initiatives and partnership programs.
- Search EPA's database of frequently asked questions about climate change and ask your own questions. Explore a glossary of terms related to climate change, including many terms that appear in this report.
- Find out what you can do at home, on the road, at work, and at school to help reduce greenhouse gas emissions.
- Explore U.S. climate policy and climate economics.
- Find resources for educators and students.

Many other government and nongovernment websites also provide information about climate change. Here are some examples:

- The Intergovernmental Panel on Climate Change (IPCC) is the international authority on climate change science. The IPCC website (www.ipcc.ch/index.htm) summarizes the current state of scientific knowledge about climate change.
- The U.S. Global Change Research Program (www.globalchange.gov) is a multi-agency effort focused on improving our understanding of the science of climate change and its potential impacts on the United States through reports such as the National Climate Assessment.
- The National Academy of Sciences (http://nas-sites.org/americasclimatechoices) has developed many independent scientific reports on the causes of climate change, its impacts, and potential solutions. The National Academy's Koshland Science Museum (https://koshland-science-museum.org) provides an interactive online Earth Lab where people can learn more about these issues.

- The National Oceanic and Atmospheric Administration (NOAA) is charged with helping society understand, plan for, and respond to climate variability and change. Find out more about NOAA's climate indicators and other activities at: www.climate.gov.
- NOAA's National Climatic Data Center website (www.ncdc.noaa.gov) provides access to data that demonstrate the effects of climate change on weather, climate, and the oceans.
- The Centers for Disease Control and Prevention (CDC) provides extensive information about the relationship between climate change and public health at: www.cdc.gov/climateandhealth/default.htm.
- The U.S. Geological Survey's Climate and Land Use Change website (www.usgs.gov/climate_landuse) looks at the relationships between natural processes on the surface of the earth, ecological systems, and human activities.
- The National Aeronautics and Space Administration (NASA) maintains its own set of climate change indicators (http://climate.nasa.gov). Another NASA site (http://earthobservatory.nasa.gov/Features/EnergyBalance/page1.php) discusses the Earth's energy budget and how it relates to greenhouse gas emissions and climate change.
- The National Snow and Ice Data Center's website (http://nsidc.org/cryosphere) provides more information about ice and snow and how they influence and are influenced by climate change.
- The Woods Hole Oceanographic Institution's website (www.whoi.edu/main/climate-ocean) explains how climate change affects the oceans and how scientists measure these effects.

For more indicators of environmental condition, visit EPA's Report on the Environment (www.epa.gov/roe). This resource presents a wide range of indicators of national conditions and trends in air, water, land, human health, and ecological systems.

Endnotes

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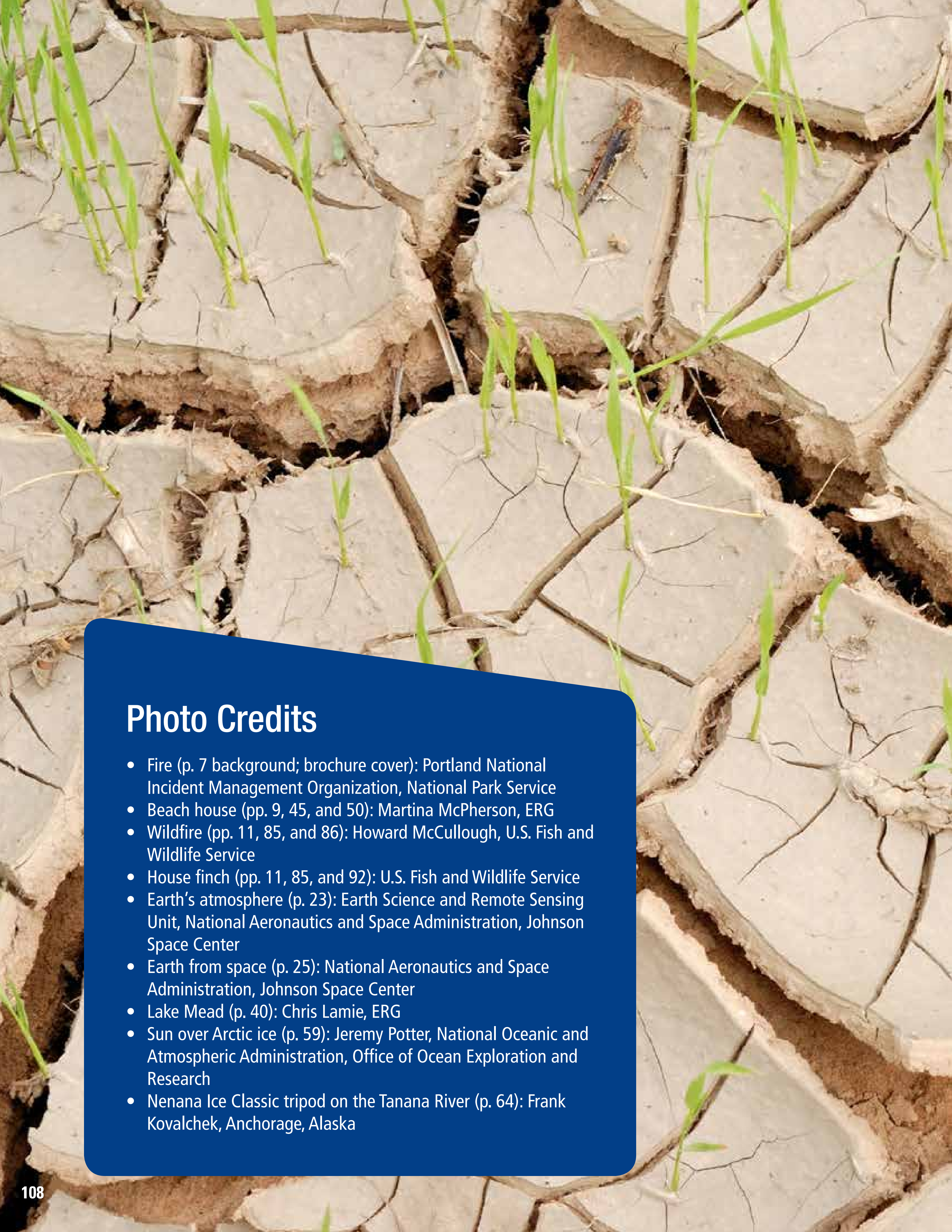

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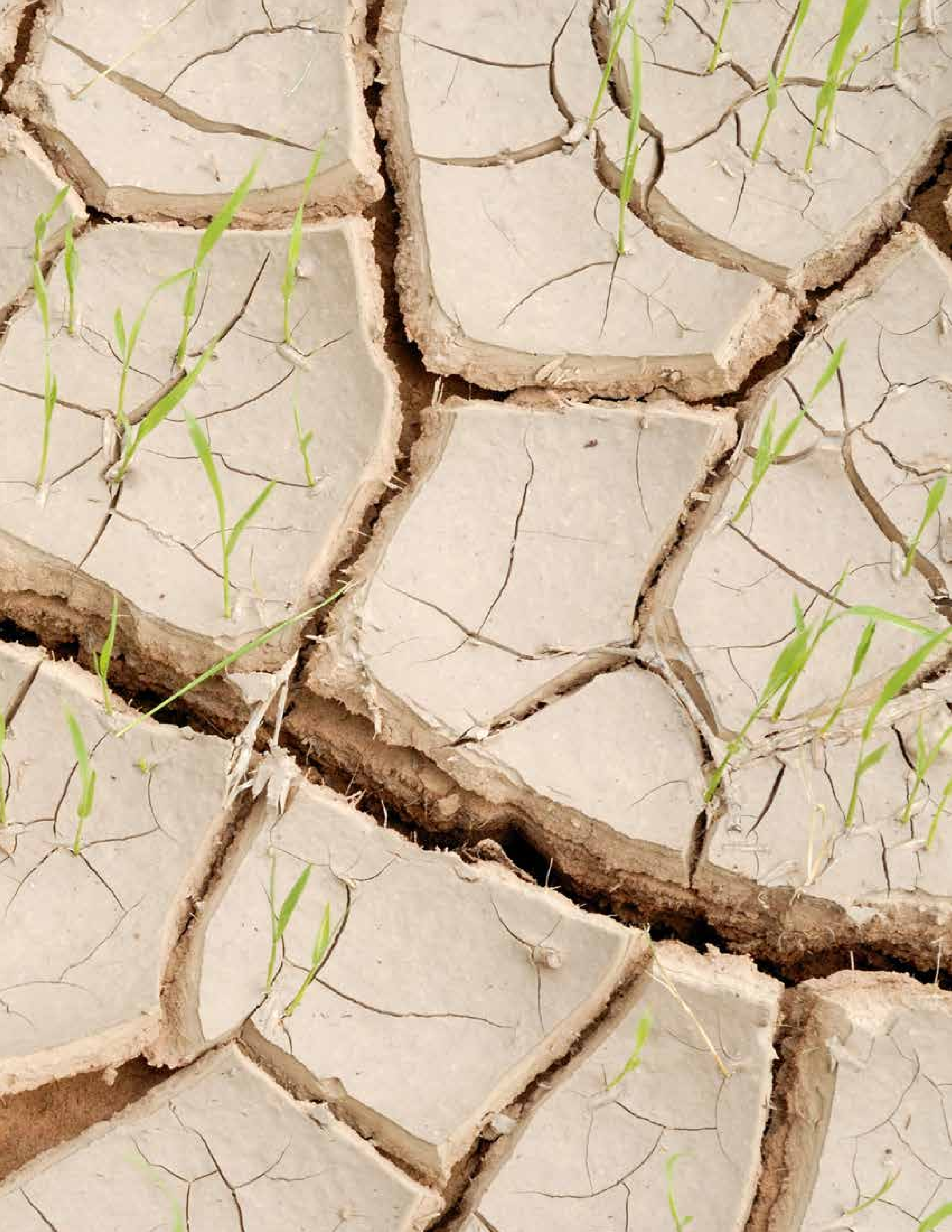

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