

Climate Change Indicators in the United States





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Introduction

Over the last several decades, evidence of human influences on climate change has become increasingly clear and compelling. There is indisputable evidence that human activities such as electricity production and transportation are adding to the concentrations of greenhouse gases that are already naturally present in the atmosphere. These heat-trapping gases are now at record-high levels in the atmosphere compared with the recent and distant past.

Warming of the climate system is well documented, evident from increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. The buildup of greenhouse gases in the atmosphere is very likely the cause of most of the recent observed increase in average temperatures, and contributes to other climate changes.¹

Collecting and interpreting environmental indicators has played a critical role in our increased understanding of climate change and its causes. An indicator represents the state of certain environmental conditions over a given area and a specified period of time. Scientists, analysts, decision-makers, and others use environmental indicators, including those related to climate, to help track trends over time in the state of the environment, key factors that influence the environment, and effects on ecosystems and society.

About This Report

The U.S. Environmental Protection Agency (EPA) has published this report, *Climate Change Indicators in the United States*, to help readers interpret a set of important indicators to better understand climate change. The report presents 24 indicators, each describing trends in some way related to the causes and effects of climate change. The indicators focus primarily on the United States, but in some cases global trends are presented in order to provide context or a basis for comparison. The indicators span a range of time periods, depending on

What Is Climate Change?

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

The term “climate change” is often used interchangeably with the term **global warming**. Global warming refers to an average increase in the temperature of the atmosphere near the Earth’s surface, which can contribute to changes in global climate patterns. However, rising temperatures are just one aspect of climate change.

The phrase “climate change” is growing in preferred use to “global warming” because it helps convey that there are changes in addition to rising temperatures.

—The National Academies²

Ground-Level Ozone, Particles, and Aerosols

This report does not document trends in various short-lived greenhouse gases (such as ground-level ozone) or particles and aerosols (such as black carbon and sulfate aerosols).

Ground-level ozone is a greenhouse gas: it traps some of the Earth's outgoing energy, thus having a warming effect on the atmosphere and contributing to increases in global temperature. Depending on their composition, particles and aerosols can have net heating or cooling effects at the Earth's surface. For example, airborne sulfate aerosols have a cooling effect on the atmosphere, while airborne black carbon aerosols have a warming effect.

Readers can learn more about ozone, particles, and other air pollutants from EPA's *Our Nation's Air—Status and Trends* report (www.epa.gov/airtrends/2010/index.html). The report presents information on the status and trends of air pollutant emissions and atmospheric concentrations in the United States, but does not interpret those data in the context of climate change.

For more information on the linkages between climate change and air quality, see EPA's April 2009 *Assessment of the Impacts of Global Change on Regional U.S. Air Quality* (<http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=203459>).

data availability. For each indicator, this report presents one or more graphics showing trends over time; a list of key points; and text that describes how the indicator relates to climate change, how the indicator was developed, and any factors that might contribute to uncertainty in the trend or the supporting data (referred to in this report as “indicator limitations”).

The report also includes a summary of major findings associated with each indicator (see Summary of Key Findings on p. 4). Additional resources that can provide readers with more information appear at the end of the report (see Climate Change Resources on p. 69).

Although some of the indicators show that fundamental environmental changes are now occurring likely as a result of climate change, others are not as clear. As new or more complete data become available, EPA plans to update the indicators presented in this report and provide additional indicators that can broaden our understanding of climate change.

EPA selected the 24 indicators presented in this report from a broader set of 110 indicators, many of which were identified at an expert workshop (November 30 to December 1, 2004) on climate change indicators convened by the National Academy of Sciences and funded by EPA. The indicators in this report were chosen using a set of screening criteria that considered usefulness, objectivity, data quality, transparency, ability to show a meaningful trend, and relevance to climate change.

All of the indicators selected for this report are based on data that have been collected and compiled by following rigorous protocols that are widely accepted by the scientific community. Various government agencies, academic institutions, and other organizations collected the data.

The indicators are divided into five chapters:



Greenhouse Gases: The indicators in this chapter characterize the amount of greenhouse gases emitted into the atmosphere through human activities, the concentrations of these gases in the atmosphere, and how emissions and concentrations have changed over time.



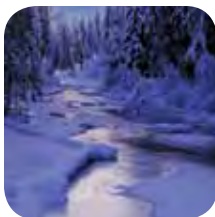
Weather and Climate: This chapter focuses on indicators related to weather and climate patterns, including temperature, precipitation, storms, droughts, and heat waves. These indicators can reveal long-term changes in the Earth's climate system.

Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.

—Intergovernmental Panel on Climate Change³



Oceans: The world's oceans have a two-way relationship with climate. The oceans influence climate on regional and global scales, while changes in climate can fundamentally alter certain properties of the ocean. This chapter examines trends in ocean characteristics that relate to climate change, such as acidity, temperature, heat storage, and sea level.



Snow and Ice: Climate change can dramatically alter the Earth's snow- and ice-covered areas. These changes, in turn, can affect air temperatures, sea levels, ocean currents, and storm patterns. This chapter focuses on trends in glaciers; the extent and depth of snow cover; and the freezing and thawing of oceans and lakes.



Society and Ecosystems: Changes in the Earth's climate can affect public health, agriculture, energy production and use, land use and development, and recreation. Climate change can also disrupt the functioning of ecosystems and increase the risk of harm or even extinction for some species. This chapter looks at just a few of the impacts that may be linked to climate change, including heat-related illnesses and changes in plant growth. EPA looks forward to expanding this chapter in future reports as the science evolves and the capacity to report on these types of indicators is broadened.

Looking Ahead

Environmental indicators are a key tool for evaluating existing and future programs and supporting new decisions with sound science. In the years to come, the indicators in this report will provide data to help the Agency decide how best to use its policy-making and program management resources to respond to climate change. Ultimately, these indicators will help EPA and its constituents evaluate the success of their climate change efforts.

Indicator Updates

Suggestions for new indicators are welcome. To provide input or to get more information on climate change indicators, visit: www.epa.gov/climatechange/indicators.html.

Summary of Key Findings

The indicators in this report present clear evidence that the composition of the atmosphere is being altered as a result of human activities and that the climate is changing. They also illustrate a number of effects on society and ecosystems related to these changes.

Greenhouse Gases



U.S. Greenhouse Gas Emissions. In the United States, greenhouse gas emissions caused by human activities increased by 14 percent from 1990 to 2008. Carbon dioxide accounts for most of the nation's emissions and most of this increase. Electricity generation is the largest source of greenhouse gas emissions in the United States, followed by transportation. Emissions per person have remained about the same since 1990.



Global Greenhouse Gas Emissions. Worldwide, emissions of greenhouse gases from human activities increased by 26 percent from 1990 to 2005. Emissions of carbon dioxide, which account for nearly three-fourths of the total, increased by 31 percent over this period. Like in the United States, the majority of the world's emissions are associated with energy use.



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



Climate Forcing. Climate or “radiative” forcing is a way to measure how substances such as greenhouse gases affect the amount of energy that is absorbed by the atmosphere. An increase in radiative forcing leads to warming while a decrease in forcing produces cooling. From 1990 to 2008, the radiative forcing of all the greenhouse gases in the Earth's atmosphere increased by about 26 percent. The rise in carbon dioxide concentrations accounts for approximately 80 percent of this increase.

Weather and Climate



U.S. and Global Temperature. Average temperatures have risen across the lower 48 states since 1901, with an increased rate of warming over the past 30 years. Seven of the top 10 warmest years on record for the lower 48 states have occurred since 1990, and the last 10 five-year periods have been the warmest five-year periods on record. Average global temperatures show a similar trend, and 2000–2009 was the warmest decade on record worldwide. Within the United States, parts of the North, the West, and Alaska have seen temperatures increase the most.



Heat Waves. The frequency of heat waves in the United States decreased in the 1960s and 1970s, but has risen steadily since then. The percentage of the United States experiencing heat waves has also increased. The most severe heat waves in U.S. history remain those that occurred during the “Dust Bowl” in the 1930s, although average temperatures have increased since then.



Drought. Over the period from 2001 through 2009, roughly 30 to 60 percent of the U.S. land area experienced drought conditions at any given time. However, the data for this indicator have not been collected for long enough to determine whether droughts are increasing or decreasing over time.



U.S. and Global Precipitation. Average precipitation has increased in the United States and worldwide. Since 1901, precipitation has increased at an average rate of more than 6 percent per century in the lower 48 states and nearly 2 percent per century worldwide. However, shifting weather patterns have caused certain areas, such as Hawaii and parts of the Southwest, to experience less precipitation than they used to.



Heavy Precipitation. In recent years, a higher percentage of precipitation in the United States has come in the form of intense single-day events. Eight of the top 10 years for extreme one-day precipitation events have occurred since 1990. The occurrence of abnormally high annual precipitation totals has also increased.



Tropical Cyclone Intensity. The intensity of tropical storms in the Atlantic Ocean, Caribbean, and Gulf of Mexico did not exhibit a strong long-term trend for much of the 20th century, but has risen noticeably over the past 20 years. Six of the 10 most active hurricane seasons have occurred since the mid-1990s. This increase is closely related to variations in sea surface temperature in the tropical Atlantic.

Oceans



Ocean Heat. Several studies have shown 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 it also affects sea level and currents.



Sea Surface Temperature. The surface temperature of the world's oceans increased over the 20th century. Even with some year-to-year variation, the overall increase is statistically significant, and sea surface temperatures have been higher during the past three decades than at any other time since large-scale measurement 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 1870. The rate of increase has accelerated in recent years to more than an inch per decade. Changes in sea level relative to the height of the land vary widely because the land itself moves. Along the U.S. coastline, sea level has risen the most relative to the land along the Mid-Atlantic coast and parts of the Gulf Coast. Sea level has decreased relative to the land in parts of Alaska and the Northwest.



Ocean Acidity. The ocean has become more acidic over the past 20 years, and studies suggest that the ocean is substantially more acidic now than it was a few centuries ago. Rising acidity is associated with increased levels of carbon dioxide dissolved in the water. Changes in acidity can affect sensitive organisms such as corals.

Snow and Ice



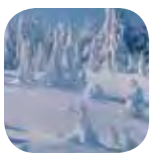
Arctic Sea Ice. Part of the Arctic Ocean stays frozen year-round. The area covered by ice is typically smallest in September, after the summer melting season. September 2007 had the least ice of any year on record, followed by 2008 and 2009. The extent of Arctic sea ice in 2009 was 24 percent below the 1979 to 2000 historical average.



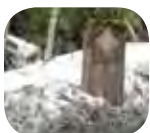
Glaciers. Glaciers in the United States and around the world have generally shrunk since the 1960s, and the rate at which glaciers are melting appears to have accelerated over the last decade. Overall, glaciers worldwide have lost more than 2,000 cubic miles of water since 1960, which has contributed to the observed rise in sea level.



Lake Ice. Lakes in the northern United States generally appear to be freezing later and thawing earlier than they did in the 1800s and early 1900s. The length of time that lakes stay frozen has decreased at an average rate of one to two days per decade.



Snow Cover. The portion of North America covered by snow has generally decreased since 1972, although there has been much year-to-year variability. Snow covered an average of 3.18 million square miles of North America during the years 2000 to 2008, compared with 3.43 million square miles during the 1970s.



Snowpack. Between 1950 and 2000, the depth of snow on the ground in early spring decreased at most measurement sites in the western United States and Canada. Spring snowpack declined by more than 75 percent in some areas, but increased in a few others.

Society and Ecosystems



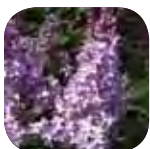
Heat-Related Deaths. Over the past three decades, more than 6,000 deaths across the United States were caused by heat-related illness such as heat stroke. However, considerable year-to-year variability makes it difficult to determine long-term trends.



Length of Growing Season. The average length of the growing season in the lower 48 states has increased by about 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.



Plant Hardiness Zones. Winter low temperatures are a major factor in determining which plants can survive in a particular area. Plant hardiness zones have shifted noticeably northward since 1990, reflecting higher winter temperatures in most parts of the country. Large portions of several states have warmed by at least one hardiness zone.

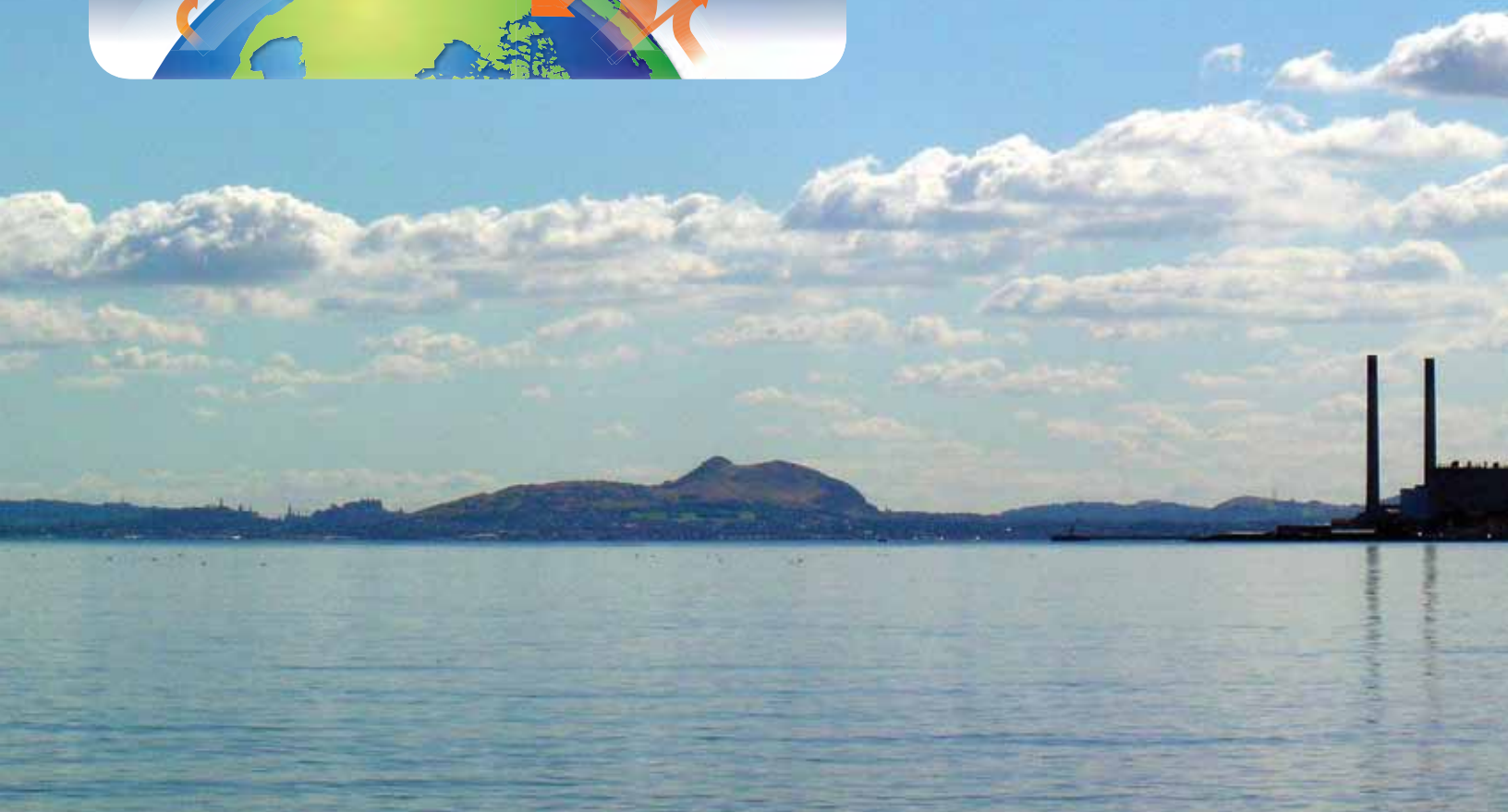
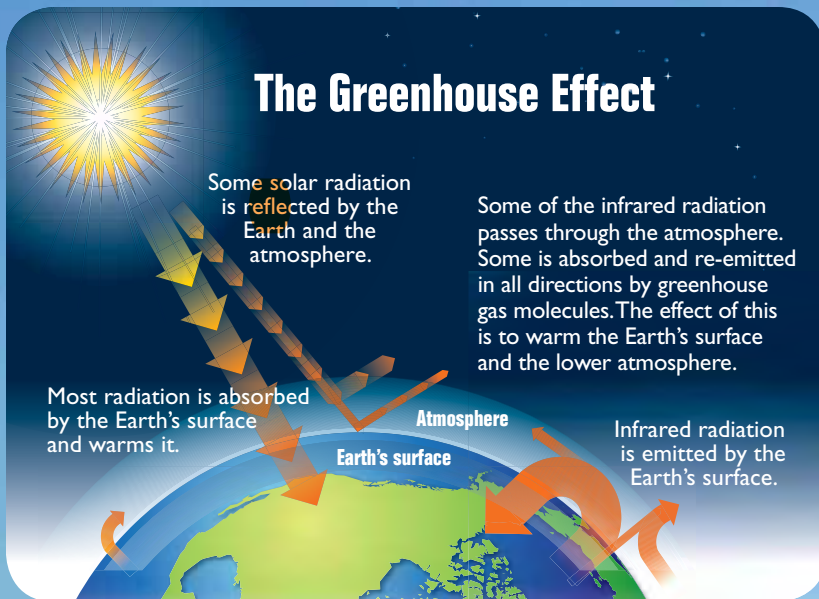


Leaf and Bloom Dates. Leaf growth and flower blooms are examples of natural events whose timing can be influenced by climate change. Observations of lilacs and honeysuckles in the lower 48 states suggest that leaf growth is now occurring a few days earlier than it did in the early 1900s. Lilacs and honeysuckles are also blooming slightly earlier than in the past, but it is difficult to determine whether this change is statistically meaningful.



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 35 miles since 1966, with a few species shifting by several hundred miles. On average, bird species have also moved their wintering grounds farther from the coast, consistent with rising inland temperatures.

Greenhouse



**U.S.
Greenhouse
Gas Emissions**



**Global
Greenhouse
Gas Emissions**



**Atmospheric
Concentrations
of Greenhouse
Gases**

Gases

Energy from the sun drives the Earth's weather and climate. The Earth absorbs some of the energy it receives from the sun and radiates the rest back toward space. However, certain gases in the atmosphere, called greenhouse gases, absorb some of the energy radiated from the Earth and trap it in the atmosphere. These gases essentially act as a blanket, making the Earth's surface warmer than it would be otherwise.

The "greenhouse effect" occurs naturally, making life as we know it possible. During the past century, however, human activities have substantially increased the amount of greenhouse gases in the atmosphere, changing the composition of the atmosphere and influencing climate. Some greenhouse gases are almost entirely man-made. Other greenhouse gases come from a combination of natural sources and human activities. For example, carbon dioxide is a greenhouse gas that occurs naturally because of volcanoes, forest fires, and biological processes (such as breathing), but is also produced by burning fossil fuels in power plants and automobiles. Other major sources of greenhouse gases include industrial and agricultural processes, waste management, and land use changes.

The major greenhouse gases emitted into the atmosphere through human activities are carbon dioxide, methane, nitrous oxide, and fluorinated gases (see Greenhouse Gases Associated With Human Activities at right). Many of these gases can remain in the atmosphere for tens to hundreds of years after being released. Thus, to get a more complete picture of the amount of greenhouse gases in the atmosphere, both emissions (how much of a given greenhouse gas is produced and emitted into the air) and concentrations (the amount of a greenhouse gas present in a certain volume of air) are measured. Long-lived greenhouse gases become globally mixed in the atmosphere, reflecting both past and recent contributions from emission sources worldwide.

Greenhouse Gases Associated With Human Activities

The principal greenhouse gases that enter the atmosphere because of human activities are:

- **Carbon dioxide** is emitted primarily through the burning of fossil fuels (oil, natural gas, and coal), solid waste, and trees and wood products. Changes in land use, such as growing new forests or disturbing soils, can lead to the addition or removal of carbon dioxide to/from the atmosphere.
- **Methane** is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and agricultural practices and from the decay of organic waste in municipal solid waste landfills.
- **Nitrous oxide** is emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste.
- **Fluorinated gases**, such as hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride, are emitted from a variety of industrial processes and commercial and household uses. Fluorinated gases are sometimes used as substitutes for ozone-depleting substances such as chlorofluorocarbons (CFCs).

Some short-lived greenhouse gases, such as tropospheric ozone, and aerosols (or particles in the atmosphere), such as black carbon and sulfates, are relevant to climate change. While this report focuses only on major, long-lived greenhouse gases, these shorter-lived substances might be included in future editions of this report. For the latest trends and information on these gases, visit EPA's Air Trends Report at: www.epa.gov/airtrends/2010/index.html.



U.S. Greenhouse

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

Background

A number of factors influence the quantities of greenhouse gases released into the atmosphere, including economic activity, population, income level, energy prices, land use, technology, and weather conditions. There are several ways to track these emissions. In addition to tracking overall emissions and emissions from specific industrial sectors in absolute terms, many countries also track emissions per capita.

Methods to reduce greenhouse gas emissions include fuel switching (such as switching from fossil fuels to wind power); conservation and energy efficiency; and methane recovery from emission sources such as landfills and coal mines.

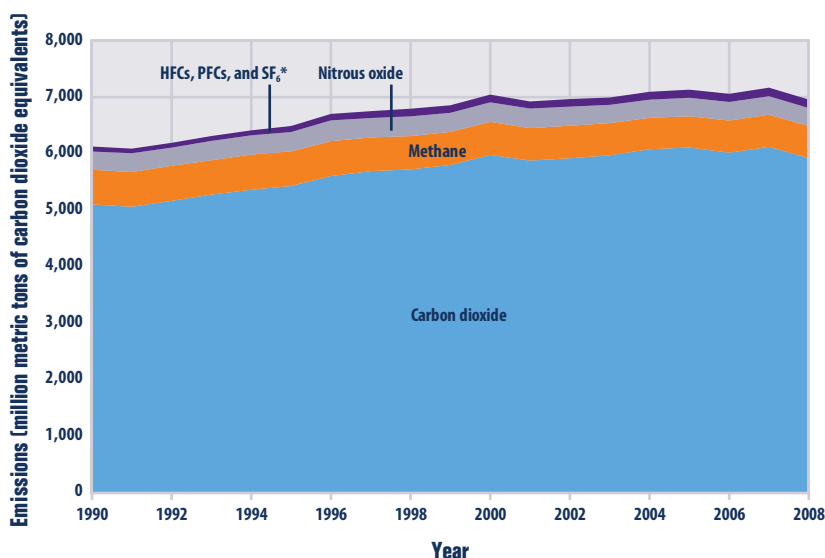
About the Indicator

This indicator focuses on emissions of carbon dioxide, methane, nitrous oxide, and several fluorinated compounds—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 *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008*.¹

This indicator reports emissions of greenhouse gases according to their global warming potential, a measure of how much a given amount of the greenhouse gas is estimated to contribute to global warming over a selected period of time. For the purposes of comparison, global warming potential values are given in relation to carbon dioxide and are expressed in terms of carbon dioxide equivalents. For additional perspective, this indicator also shows greenhouse gas emissions in relation to economic activity and population.

Figure 1. U.S. Greenhouse Gas Emissions by Gas, 1990–2008

This figure shows emissions of carbon dioxide, methane, nitrous oxide, and several fluorinated compounds in the United States from 1990 to 2008. For consistency, emissions are expressed in million metric tons of carbon dioxide equivalents.

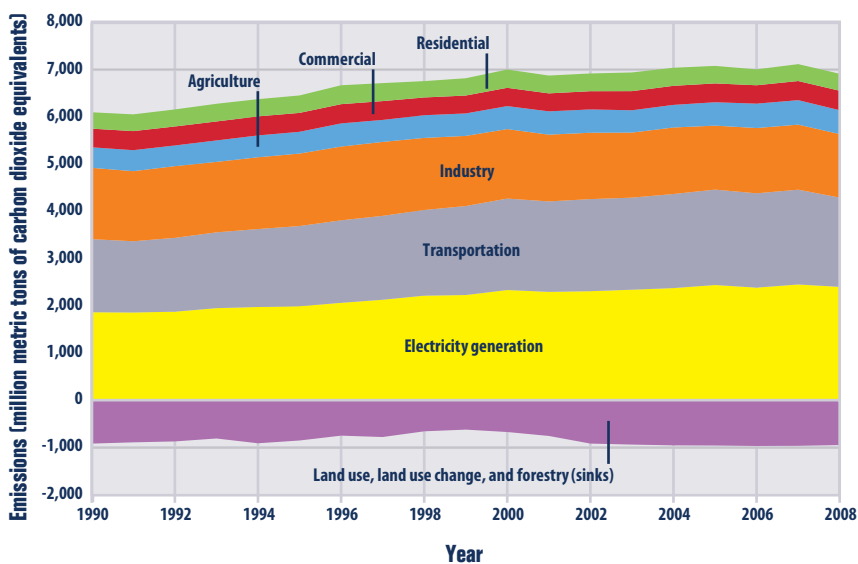


* HFCs are hydrofluorocarbons, PFCs are perfluorocarbons, and SF₆ is sulfur hexafluoride.

Data source: U.S. EPA, 2010²

Figure 2. U.S. Greenhouse Gas Emissions and Sinks by Economic Sector, 1990–2008

This figure shows greenhouse gas sinks and emissions by source in the United States from 1990 to 2008. For consistency, emissions are expressed in million metric tons of carbon dioxide equivalents. Totals do not match Figure 1 exactly because the economic sectors shown here do not include emissions from U.S. territories.

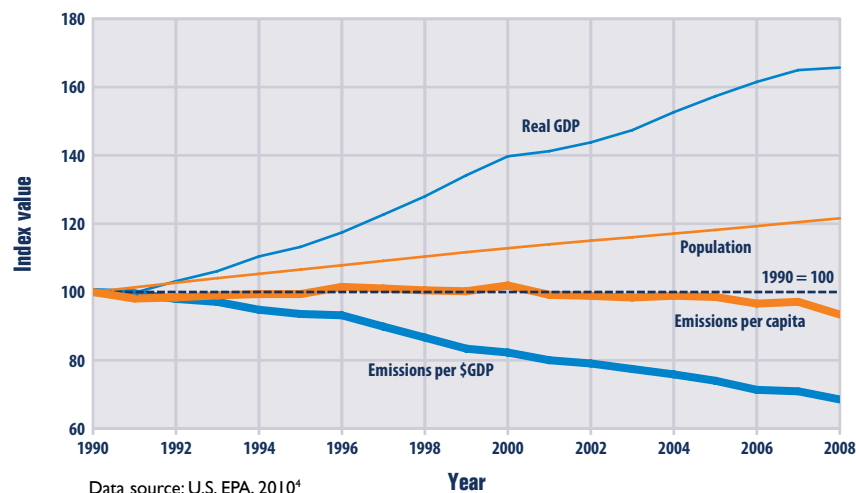


Data source: U.S. EPA, 2010³

Gas Emissions

Figure 3. U.S. Greenhouse Gas Emissions per Capita and per Dollar of GDP, 1990–2008

This figure shows trends in greenhouse gas emissions from 1990 to 2008 per capita, based on the total U.S. population (heavy orange line). It also shows trends in emissions compared with the real GDP, which is the value of all goods and services produced in the country during a given year, adjusted for inflation (heavy blue line). All data are indexed to 1990 as the base year, which is assigned a value of 100; thus a value of 140 in 2000 would represent a 40 percent increase since 1990.



Key Points

- In 2008, U.S. greenhouse gas emissions totaled 6,957 million metric tons of carbon dioxide equivalents, a 14 percent increase from 1990 (see Figure 1).
- During the period from 1990 to 2008 (see Figure 1):
 - Emissions of carbon dioxide, the primary greenhouse gas emitted by human activities, increased by 16 percent.
 - Emissions of fluorinated compounds, released as a result of commercial, industrial, and household uses, rose by 66 percent. Although fluorinated gases accounted for only 2 percent of all greenhouse gas emissions in 2008, they are important because they have extremely high global warming potential values and long atmospheric lifetimes.
 - Methane emissions decreased by 7 percent, largely because of reduced emissions from landfills and coal mines.⁵
 - Nitrous oxide emissions, largely derived from agricultural soil management, nitrogen application, and vehicle emissions, declined by 1 percent.
- Electricity generation has accounted for about 32 percent of total U.S. 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).
- In 2008, 14 percent of U.S. greenhouse gas emissions were offset by uptake of carbon and “sequestration” in forests, trees, agricultural soils, and landfilled yard trimmings and food scraps (these are referred to as sinks, as shown in Figure 2 beneath the axis).
- Emissions per capita have remained nearly level since 1990 (see Figure 3), as emissions have increased at about the same rate as the population.
- From 1990 to 2008, greenhouse gas emissions per unit of U.S. GDP declined by 31 percent (see Figure 3).

Indicator Limitations

While this indicator addresses many of the most important greenhouse gases, it does not include other gases that are not covered under the United Nations Framework Convention on Climate Change but could still affect the Earth’s energy balance and climate (see the Climate Forcing indicator on p. 18 for more details). For example, this indicator excludes ozone-depleting substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons, which have high global warming potentials, as these gases are being phased out under an international agreement called the Montreal Protocol. There also are a variety of natural greenhouse gas emission sources; however, this indicator includes only man-made and human-influenced greenhouse gas emissions.

Data Sources

Data for this indicator came from EPA’s *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008*. This report is available online at: www.epa.gov/climatechange/emissions/usinventoryreport.html. The calculations in Figure 3 are based on gross domestic product (GDP) and population data provided by the U.S. Bureau of Economic Analysis and the U.S. Census, respectively.



Global Greenhouse

This indicator describes emissions of greenhouse gases worldwide.

Background

Every country around the world emits greenhouse gases, meaning the root causes of climate change are truly global. Some countries produce more greenhouse gases than others, however, depending on factors such as economic activity, population, income level, land use, and weather conditions. Tracking greenhouse gas emissions worldwide provides a global context for understanding the United States' role in addressing climate change.

About the Indicator

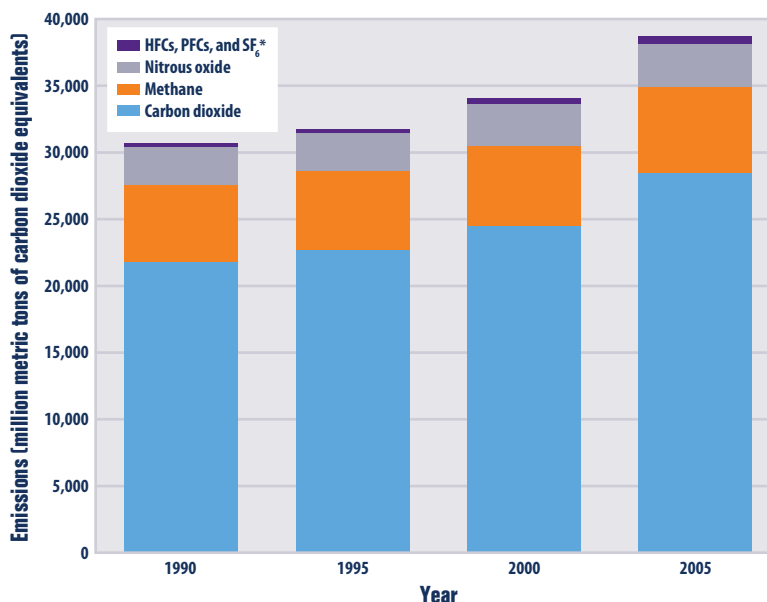
Like the U.S. Greenhouse Gas Emissions indicator (p. 10), this indicator focuses on emissions of gases covered under the United Nations Framework Convention on Climate Change: carbon dioxide, methane, nitrous oxide, and several fluorinated compounds. These are all important greenhouse gases that are influenced by human activities, and the Convention requires participating countries to develop and periodically submit an inventory of emissions.

Data and analysis for this indicator come from the World Resources Institute's Climate Analysis Indicators Tool (CAIT), which compiles data from greenhouse gas inventories developed by EPA and other 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.

This indicator tracks emissions of greenhouse gases according to their global warming potential, a measure of how much a given amount of the greenhouse gas is estimated to contribute to global warming over a selected period of time. For the purposes of comparison, global warming potential values are given in relation to carbon dioxide and are expressed in terms of carbon dioxide equivalents.

Figure 1. Global Greenhouse Gas Emissions by Gas, 1990–2005

This figure shows worldwide emissions of carbon dioxide, methane, nitrous oxide, and several fluorinated compounds from 1990 to 2005. For consistency, emissions are expressed in million metric tons of carbon dioxide equivalents. These totals do not include emissions due to land use change or forestry because estimates are not available for the most recent years.

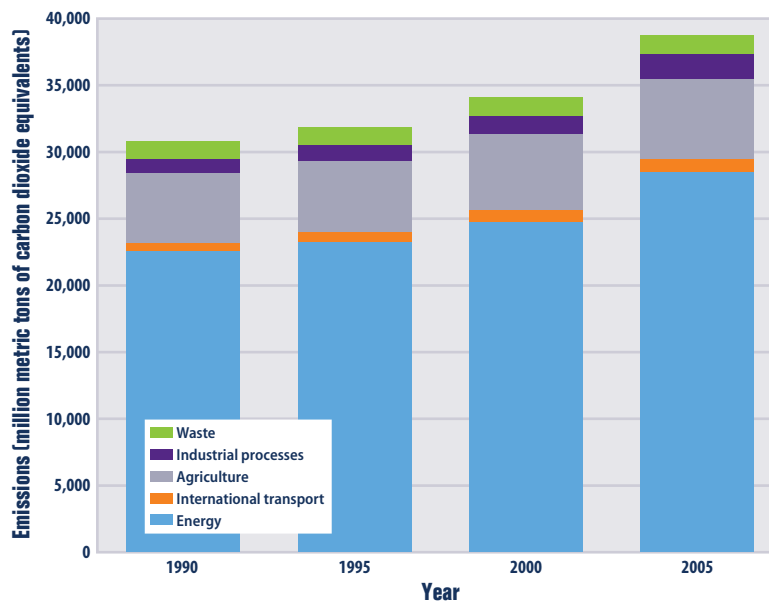


* HFCs are hydrofluorocarbons, PFCs are perfluorocarbons, and SF₆ is sulfur hexafluoride.

Data source: World Resources Institute, 2009⁶

Figure 2. Global Greenhouse Gas Emissions by Sector, 1990–2005

This figure shows worldwide greenhouse gas emissions by sector from 1990 to 2005.* For consistency, emissions are expressed in million metric tons of carbon dioxide equivalents. These totals do not include emissions due to land use change or forestry because estimates are not available for the most recent years.



* 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). Emissions from international transport (aviation and marine) are separate from the energy sector because they are not part of individual countries' emission inventories.

Data source: World Resources Institute, 2009⁷

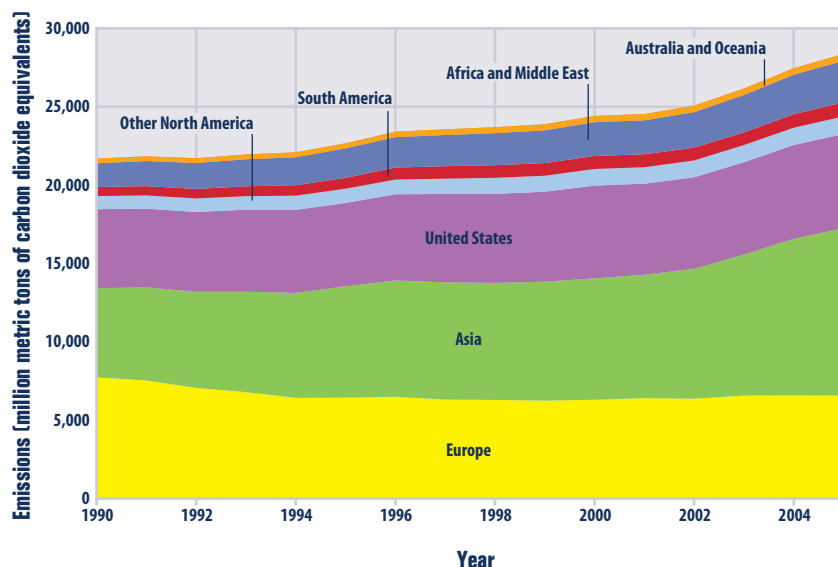
Gas Emissions

Key Points

- In 2005, the world is estimated to have emitted over 38,000 million metric tons of greenhouse gases, expressed as carbon dioxide equivalents. This represents a 26 percent increase from 1990 (see Figures 1 and 2).
- During the period from 1990 to 2005, global emissions of all major greenhouse gases increased (see Figure 1). Methane emissions rose the least—10 percent—while emissions of fluorinated compounds more than doubled. Emissions of carbon dioxide increased by 31 percent, which is particularly important because carbon dioxide accounts for nearly three-fourths of total global emissions.
- Energy use is the largest source of greenhouse gas emissions worldwide (about 73 percent of the total), followed by agriculture (16 to 17 percent) (see Figure 2).
- In the United States, changes in land use and forestry represent a net “sink” for greenhouse gases, meaning they absorb more greenhouse gases (for example, through the net growth of forests) than they emit. On a global scale, however, these activities represent an additional source of greenhouse gases due to factors such as human-caused destruction of forests.⁸
- Greenhouse gas emissions are increasing faster in some parts of the world than in others (see Figure 3).

Figure 3. Global Carbon Dioxide Emissions by Region, 1990–2005

This figure shows carbon dioxide emissions from 1990 to 2005 for different regions of the world. These data do not include emissions attributable to land use, land use change, or forestry.



Data source: World Resources Institute, 2009⁹

Indicator Limitations

Like the U.S. Greenhouse Gas Emissions indicator (p. 10), this indicator does not include emissions of a number of gases that might 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, which have high global warming potentials, as these gases are being phased out under an international agreement called the Montreal Protocol. There also are a variety of natural greenhouse gas emission sources; however, this indicator includes only man-made and human-influenced greenhouse gas emissions.

Global emission inventories for gases other than carbon dioxide are limited. Data are only available at five-year intervals, and the most recent year—2005—represents a set of projections. The United Nations Framework Convention on Climate Change database has more comprehensive data; however, these data are available only for developed countries that are parties to the Convention—a group that accounts 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 such as the United Nations, International Energy Agency, EPA, and U.S. Carbon Dioxide Information Analysis Center.

Atmospheric Concentrations of Greenhouse Gases

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

Background

Since the Industrial Revolution, humans have added a significant amount of greenhouse gases into the atmosphere by burning fossil fuels, cutting down forests, and other activities (see the U.S. and Global Greenhouse Gas Emissions Indicators on pp. 10–13). When greenhouse gases are emitted into the atmosphere, most remain in the atmosphere for long time periods, ranging from a decade to many millennia. If emissions exceed their uptake by “sinks,” such as oceans and vegetation, these gases accumulate and their concentrations rise. Long-lived greenhouse gases become well mixed in the atmosphere because of transport by winds, and concentrations are similar throughout the world. Concentrations of short-lived greenhouse gases such as tropospheric ozone often vary regionally and are not described in this indicator.

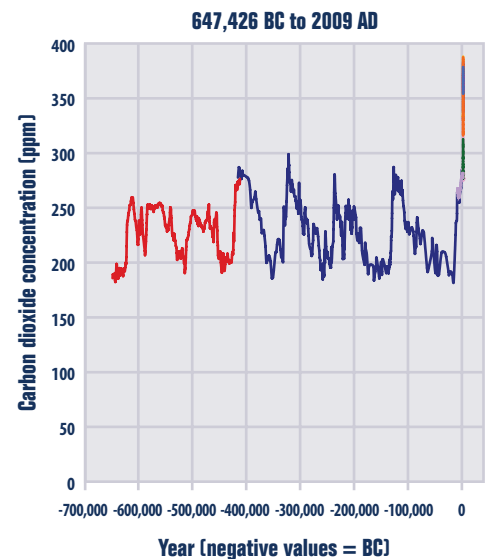
Concentrations of greenhouse gases are measured in parts per million (ppm), parts per billion (ppb), or parts per trillion (ppt) by volume. In other words, if a parcel of air were divided into a million parts (or a billion or trillion), this indicator measures how many of those parts would be made up of greenhouse gases.

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: carbon dioxide, methane, nitrous oxide, and certain manufactured gases—known as halocarbons—that contain fluorine, chlorine, bromine, or iodine. This indicator shows concentrations of greenhouse gases over thousands of years. Measurements in recent years have come from monitoring stations around the world, while older measurements 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.

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 2009. The data come from a variety of historical studies and monitoring sites around the world.



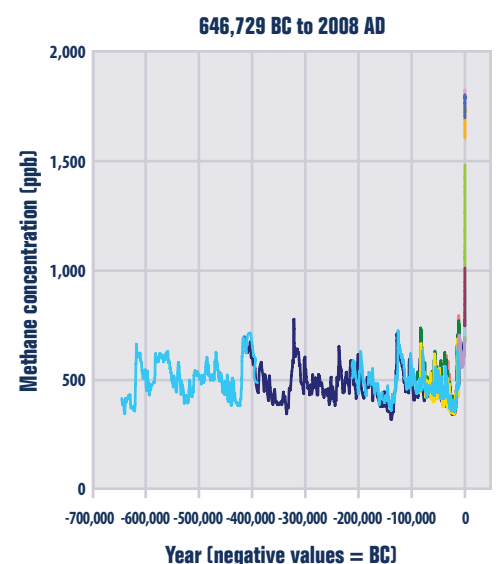
Measurement locations:

(Please see Endnotes for complete list of data sources)¹⁰

- EPICA Dome C, Antarctica: 647,426 BC to 411,548 BC
- Vostok Station, Antarctica: 415,157 BC to 339 BC
- EPICA Dome C, Antarctica: 9002 BC to 1515 AD

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 2008. The data come from a variety of historical studies and monitoring sites around the world.



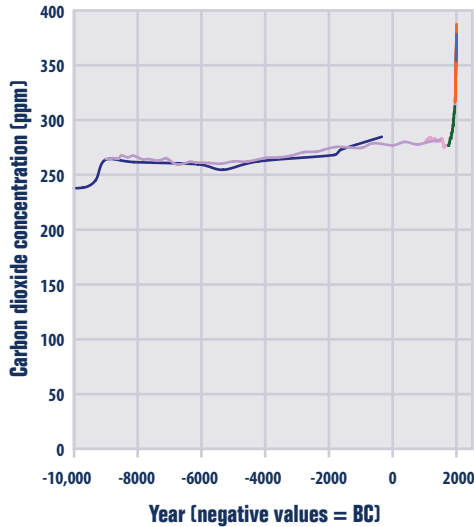
Measurement locations:

(Please see Endnotes for complete list of data sources)¹¹

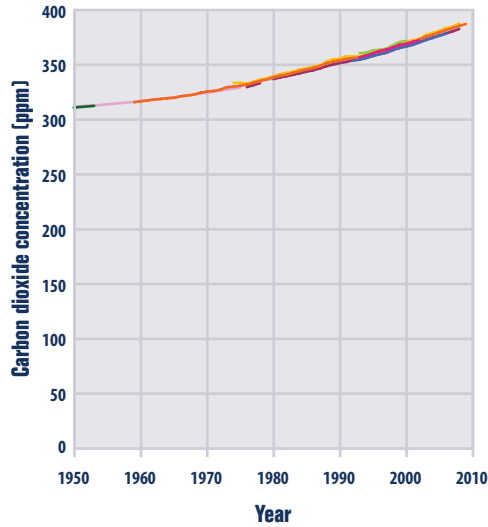
- EPICA Dome C, Antarctica: 646,729 BC to 1888 AD
- Vostok Station, Antarctica: 415,172 BC to 346 BC
- Greenland GISP2 ice core: 87,798 BC to 8187 BC

Concentrations of Greenhouse Gases

10,000 BC to 2009 AD



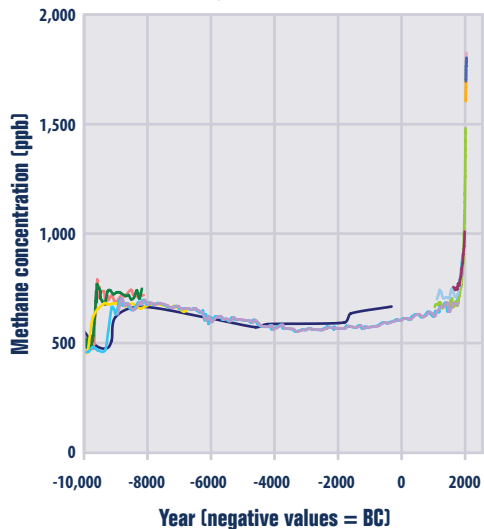
1950 AD to 2009 AD



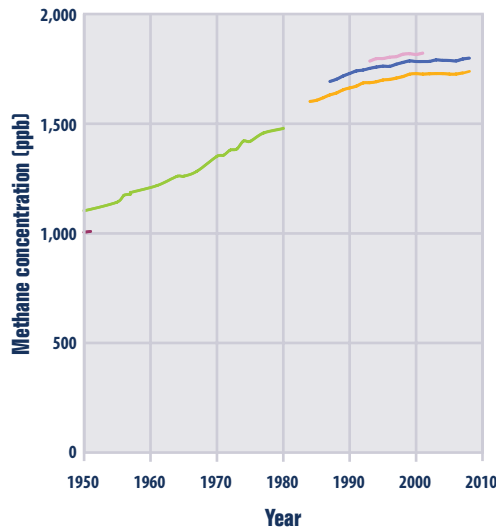
Key Points

- Global atmospheric concentrations of carbon dioxide, methane, nitrous oxide, and certain manufactured greenhouse gases have all risen substantially in recent years (see Figures 1, 2, 3, and 4).
- Before the industrial era began around 1780, carbon dioxide concentrations measured approximately 270–290 ppm. Concentrations have risen steadily since then, reaching 387 ppm in 2009—a 38 percent increase. Almost all of this increase is due to human activities.¹²
- Since 1905, the concentration of methane in the atmosphere has roughly doubled. It is very likely that this increase is predominantly due to agriculture and fossil fuel use.¹³
- Historical measurements show that the current global atmospheric concentrations of carbon dioxide and methane are unprecedented over the past 650,000 years, even after accounting for natural fluctuations (see Figures 1 and 2).
- Over the past 100,000 years, concentrations of nitrous oxide in the atmosphere have rarely exceeded 280 ppb. Levels have risen steadily since the 1920s, however, reaching a new high of 323 ppb in 2009 (see Figure 3). This increase is primarily due to agriculture.¹⁴
- Concentrations of manufactured halocarbons (gases that contain chlorine, fluorine, bromine, or iodine) were essentially zero a few decades ago, but have increased rapidly as they have been incorporated into industrial products and processes (see Figure 4 on page 16). Some of these chemicals are now being phased out of use because they also cause harm to the Earth's ozone layer, causing their concentrations to stabilize. However, concentrations of others continue to increase.

10,000 BC to 2008 AD



1950 AD to 2008 AD



(Continued on page 16)

Indicator Limitations

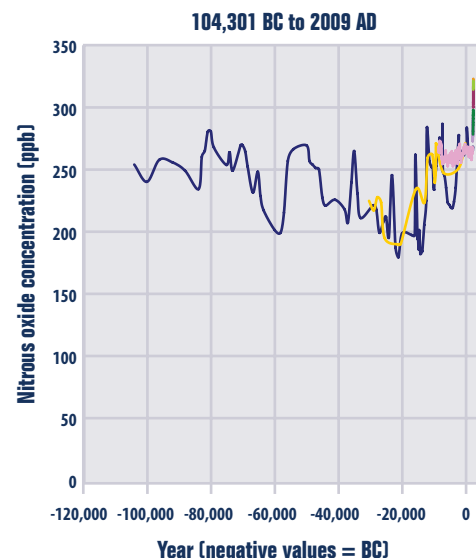
This indicator includes several of the most important greenhouse gases, but some others are not covered. The indicator also does not address certain other pollutants that can affect climate by either reflecting or absorbing energy. For example, sulfate particles can reflect sunlight away from the Earth, while black carbon aerosols (soot) absorb energy.

Data Sources

The data in this indicator came from multiple sources. Summary global atmospheric concentration data for carbon dioxide (Figure 1), methane (Figure 2), and nitrous oxide (Figure 3) were provided by EPA's Office of Atmospheric Programs, based on greenhouse gas concentration measurements reported in a collection of studies published in the peer-reviewed literature. References for the underlying data are included in the corresponding exhibits, and some data sets are also available in electronic format at: www.epa.gov/climatechange/science/recentac.html. Global atmospheric concentration data for selected halocarbons (Figure 4) are a subset of the data depicted in the Intergovernmental Panel on Climate Change's Fourth Assessment Report.¹⁵

Figure 3. Global Atmospheric Concentrations of Nitrous Oxide Over Time

This figure shows concentrations of nitrous oxide in the atmosphere from 100,000 years ago through 2009. The data come from a variety of historical studies and monitoring sites around the world.



Measurement locations:

(Please see Endnotes for complete list of data sources)¹⁶

■ Greenland GISP2 ice core:

104,301 BC to 1871 AD

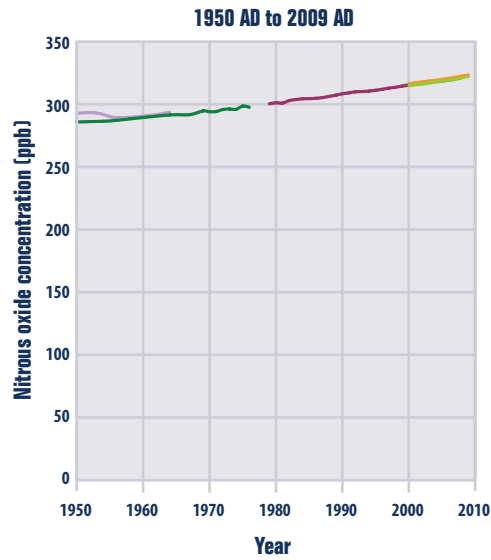
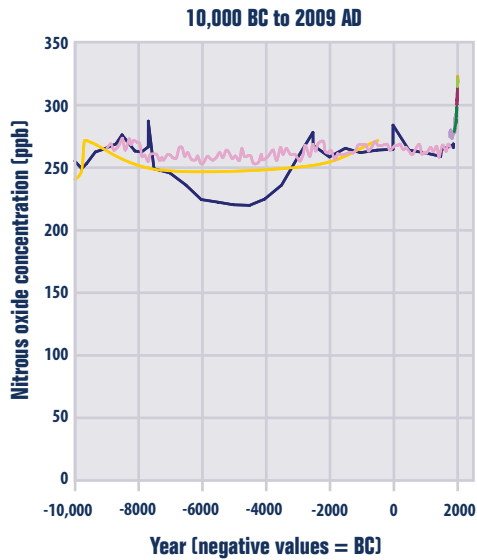
■ Taylor Dome, Antarctica: 30,697 BC to 497 BC

Water Vapor as a Greenhouse Gas

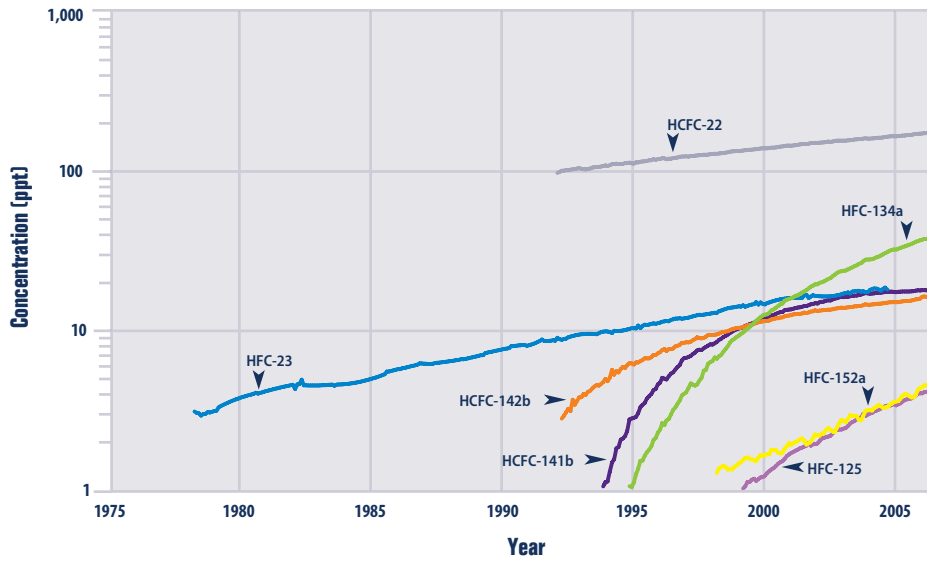
Water vapor is the most abundant greenhouse gas in the atmosphere. Human activities produce only a very small increase in water vapor primarily through irrigation and combustion processes, and so it is not included in this indicator. However, the surface warming caused by human-produced increases in other greenhouse gases leads to an increase in atmospheric water vapor, because a warmer climate increases evaporation and allows the atmosphere to hold more moisture. This creates a “feedback loop” that can lead to more warming.

Figure 4. Global Atmospheric Concentrations of Selected Halocarbons, 1978–2006

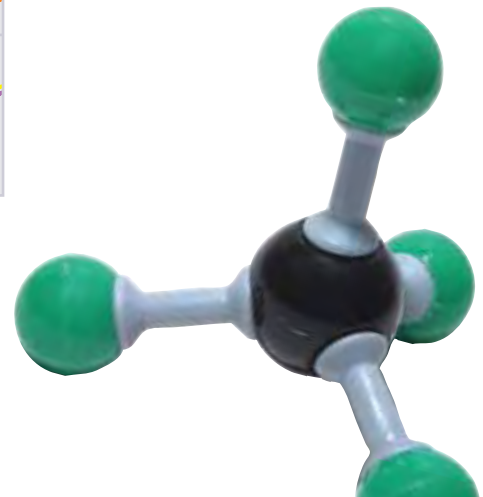
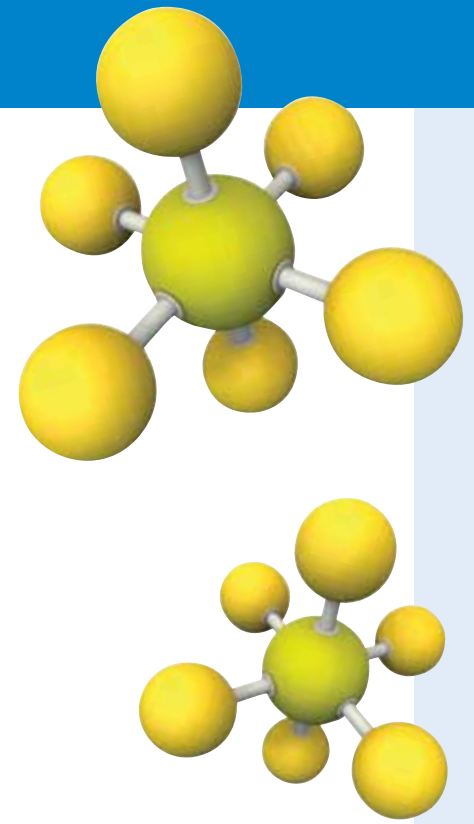
This figure shows concentrations of several man-made halocarbons (gases containing fluorine, chlorine, bromine, or iodine) in the atmosphere. The data come from monitoring sites around the world. Note that the scale is logarithmic, which means it increases by powers of 10. This is because the concentrations of different halocarbons can vary by many orders of magnitude. The numbers following the name of each gas (e.g., HCFC-22) are used to denote specific types of those gases.



- EPICA Dome C, Antarctica: 9000 BC to 1780 AD
- Antarctica: 1756 AD to 1964 AD
- Antarctica: 1903 AD to 1976 AD
- Cape Grim, Australia: 1979 AD to 2008 AD
- South Pole, Antarctica: 1998 AD to 2009 AD
- Barrow, Alaska: 1999 AD to 2009 AD
- Mauna Loa, Hawaii: 2000 AD to 2009 AD



Data source: IPCC, 2007¹⁷



Climate Forcing

This indicator measures the levels of greenhouse gases in the atmosphere based on their ability to cause changes in the Earth's climate.

Background

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. If this energy balance is shifted, the Earth's surface could become noticeably warmer or cooler, leading to a variety of changes in global climate.

A number of natural and man-made mechanisms can affect the global energy balance and force changes in the Earth's climate. Greenhouse gases are one such mechanism. Greenhouse gases in the atmosphere absorb and re-emit some of the outgoing energy radiated from the Earth's surface, causing that heat to be retained in the lower atmosphere. Some greenhouse gases remain in the atmosphere for decades or even centuries, and therefore can affect the Earth's energy balance over a long time period. Factors that influence Earth's energy balance can be quantified in terms of "radiative climate forcing." Positive radiative forcing indicates warming (for example, by increasing incoming energy or decreasing the amount of energy that escapes to space), while negative forcing is associated with cooling.

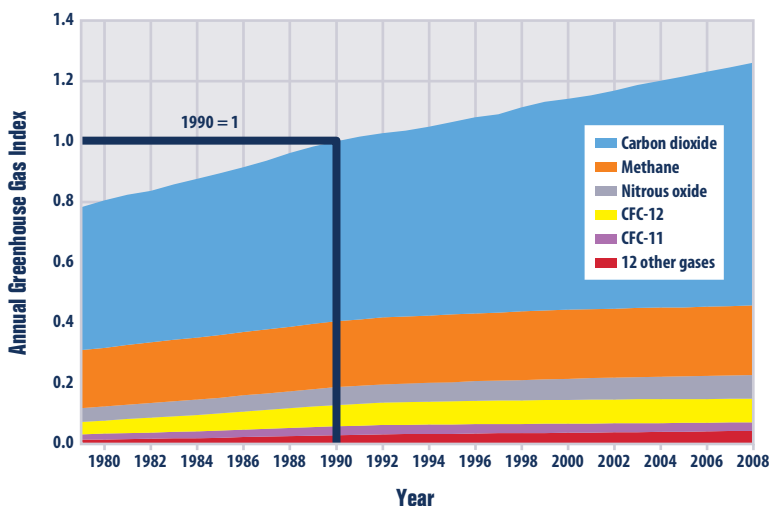
About the Indicator

The Annual Greenhouse Gas Index measures the average total radiative forcing of 17 greenhouse gases, including carbon dioxide, methane, and nitrous oxide. This index was calculated by the National Oceanic and Atmospheric Administration based on measured concentrations of the gases in the atmosphere. Because each gas has a different capacity to absorb heat energy, this indicator converts concentrations into a measure of the total radiative forcing (energy absorption) caused by each gas.

The total radiative forcing of these gases is then translated into one index value. This value represents the ratio of the total radiative forcing for that year compared with the total radiative forcing in 1990.

Figure 1. The Annual Greenhouse Gas Index, 1979–2008

This figure shows the amount of radiative forcing caused by various greenhouse gases, based on the concentrations present in the Earth's atmosphere. Radiative forcing is represented by the Annual Greenhouse Gas Index, which is set to a value of 1 for 1990.



Data source: NOAA, 2009¹⁸

Atmospheric Lifetime and "Global Warming Potential" of Important Greenhouse Gases

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. For example, a molecule of methane emitted today will last an average of 12 years before decaying, while a molecule of sulfur hexafluoride will last for thousands of years. Each gas also has its own unique ability to absorb energy and contribute to climate forcing. By considering both the lifetime of the gas and its ability to absorb energy, scientists have come up with an overall global warming potential for each gas, which is expressed relative to the global warming potential of carbon dioxide.

Greenhouse gas	Average lifetime in the atmosphere	Global warming potential of one molecule of the gas over 100 years (relative to carbon dioxide = 1)
Carbon dioxide	50–200 years*	1
Methane	12 years	21
Nitrous oxide	120 years	310
CFC-12	100 years	10,600
CFC-11	45 years	4,600
HFC-134a	14.6 years	1,300
Sulfur hexafluoride	3,200 years	23,900

* Carbon dioxide's lifetime is poorly defined because the gas is not destroyed over time, but instead moves between 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.

Data source: EPA uses atmospheric lifetimes and global warming potentials from the Intergovernmental Panel on Climate Change's (IPCC's) Second Assessment Report,¹⁹ as countries have agreed to do under current international treaties within the United Nations Framework Convention on Climate Change (UNFCCC). Two exceptions are CFC-11 and CFC-12, which are not covered under the UNFCCC and for which EPA is using values from the IPCC's Third Assessment Report.²⁰

Key Points

- In 2008, the Annual Greenhouse Gas Index was 1.26, an increase in radiative forcing of 26 percent over 1990 (see Figure 1). Carbon dioxide accounts for approximately 80 percent of this increase.
- Of the five most prevalent greenhouse gases shown in Figure 1, carbon dioxide and nitrous oxide are the only two whose contributions to radiative forcing continue to increase at a steady rate. By 2008, radiative forcing due to carbon dioxide was 35 percent higher than in 1990.
- Although the overall Annual Greenhouse Gas Index continues to grow, the rate of increase has slowed somewhat over time. This change has occurred in large part because methane concentrations have remained relatively steady since 1990, and CFC concentrations are declining because most of their uses have been banned (see Figure 1).

Indicator Limitations

There are uncertainties and limitations in the data and models used for deriving radiative forcing values. In addition, the Annual Greenhouse Gas Index does not consider certain other climate forcing mechanisms. For example, reflective aerosol particles in the atmosphere can reduce radiative forcing, while ground-level ozone can increase it.

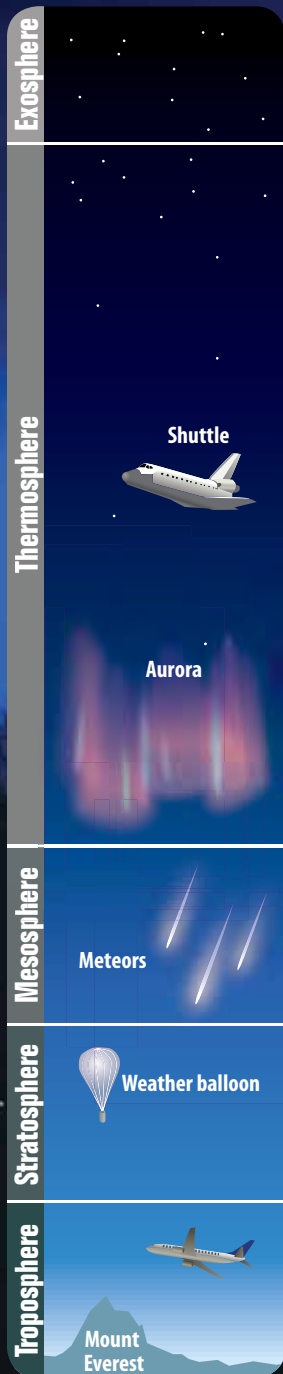
Data Sources

Data for this indicator were provided by the National Oceanic and Atmospheric Administration. This figure and other information are available at: www.esrl.noaa.gov/gmd/aggi.

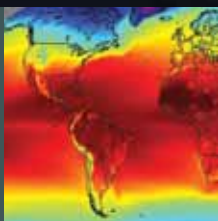


Weather and

Earth's Atmosphere



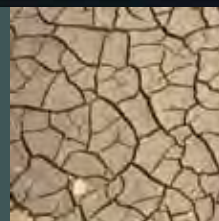
Source: NOAA, 2009¹



**U.S. and Global
Temperature**



Heat Waves



Drought

Climate

Weather is the state of the atmosphere at any given time and place. Most weather takes place in the lower layer of the atmosphere, the troposphere (see diagram of the Earth's atmosphere at left). Familiar aspects of weather include temperature, precipitation, clouds, and wind. Severe weather conditions include hurricanes, tornadoes, and blizzards.

Climate is the average weather in a given place, usually over a period of more than 30 years. While the weather can change in just a few hours, climate changes occur over longer timeframes. Climate is defined not only by average temperature and precipitation, but also by the type, frequency, and intensity of weather events such as heat waves, cold waves, storms, floods, and droughts. Climate has natural year-to-year variations, and extremes in temperatures and weather events have occurred throughout history.

The Earth's climate depends on the balance between the amount of energy received from the sun and the amount of energy that is absorbed or radiated back into space. Natural influences can alter how much heat is reflected or absorbed by the Earth's surface, including changes in the sun's intensity, volcanic eruptions, and multi-year climate cycles such as El Niño. Human activities such as deforestation and the production of greenhouse gases also affect this balance. These alterations, in turn, affect climate on local, regional, and global scales.

Generally, increases in the Earth's surface temperature will increase evaporation from the oceans and land, leading to more overall precipitation. However, this additional precipitation will not be distributed evenly, and shifting storm patterns will likely cause some areas to experience more severe droughts. Scientists have suggested that extreme weather events such as storms, floods, and hurricanes will likely also become more intense. There is natural variability in the intensity and frequency of such events, however, so care must be taken to determine whether observed trends reflect long-term changes in the Earth's climate system.

Climate variations can directly or indirectly affect many aspects of human society—in both positive and disruptive ways. For example, warmer temperatures might reduce heating costs and improve conditions for growing some crops, yet extreme heat can cause illness or death among vulnerable populations. Precipitation can replenish water supplies and nourish crops, but intense storms can damage property, cause loss of life and population displacement, and temporarily disrupt essential services such as transportation, telecommunications, and energy and water supplies.

Shifting storm patterns will likely cause some areas to experience more droughts. Extreme weather events such as storms, floods, and hurricanes will likely also become more intense.



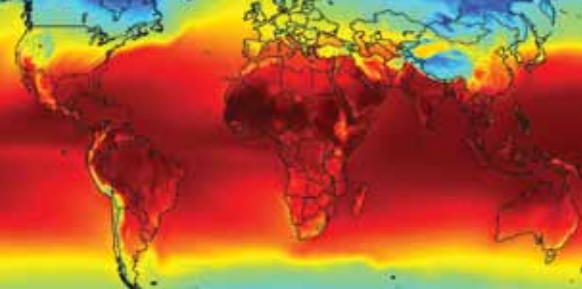
**U.S. and Global
Precipitation**



**Heavy
Precipitation**



**Tropical
Cyclone
Intensity**



U.S. and Global

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

Background

Temperature is a fundamental component of climate, and it can have wide-ranging effects on human life and ecosystems, as many of the other indicators in this report demonstrate. For example, increases in air temperature can lead to more intense heat waves, which can cause illness and death in vulnerable populations. Temperature patterns also determine what types of animals and plants can survive in a particular place. Changes in temperature can disrupt a wide range of natural processes, particularly if these changes occur abruptly and plant and animal species do not have time to adapt.

As greenhouse gases trap more energy in the Earth's atmosphere, average temperatures at the Earth's surface are expected to rise. However, because climate change (both natural and human-driven) can shift the wind patterns and ocean currents that drive the world's climate system, some areas might experience more warming than others, and some might experience cooling. Changes in air temperature can, in turn, cause changes in sea surface temperature, precipitation patterns, and other aspects of climate.

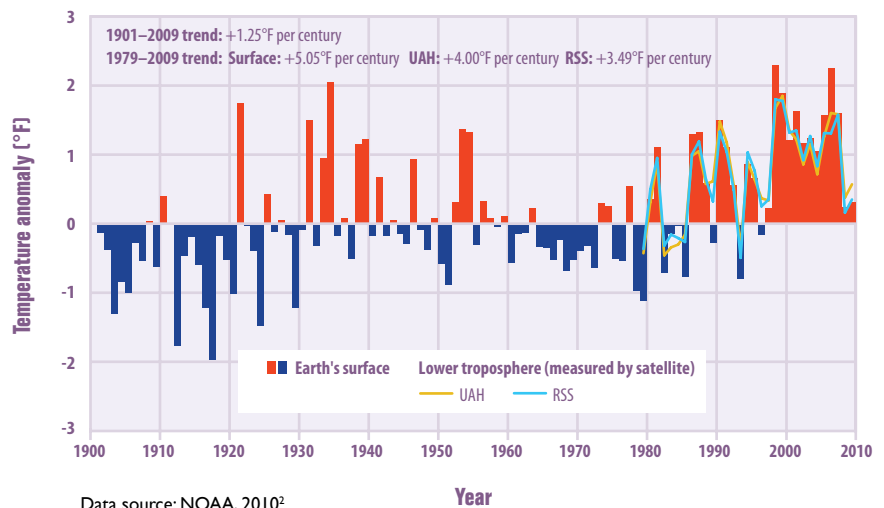
About the Indicator

This indicator examines U.S. and global temperature patterns from 1901 to the present. Data were provided by the National Oceanic and Atmospheric Administration, which keeps historical records from weather stations around the world. U.S. surface measurements come from stations on land, while global surface trends also incorporate observations from buoys and ships on the ocean, thereby providing data from sites spanning the entire surface of the Earth. For comparison, this indicator also displays data from satellites that have measured the temperature of the Earth's lower atmosphere since 1979.

This indicator shows annual anomalies, or differences, compared with the average temperature from 1901 to 2000. Anomalies are calculated in degrees for each location, then averaged together.

Figure 1. Temperatures in the Lower 48 States, 1901–2009

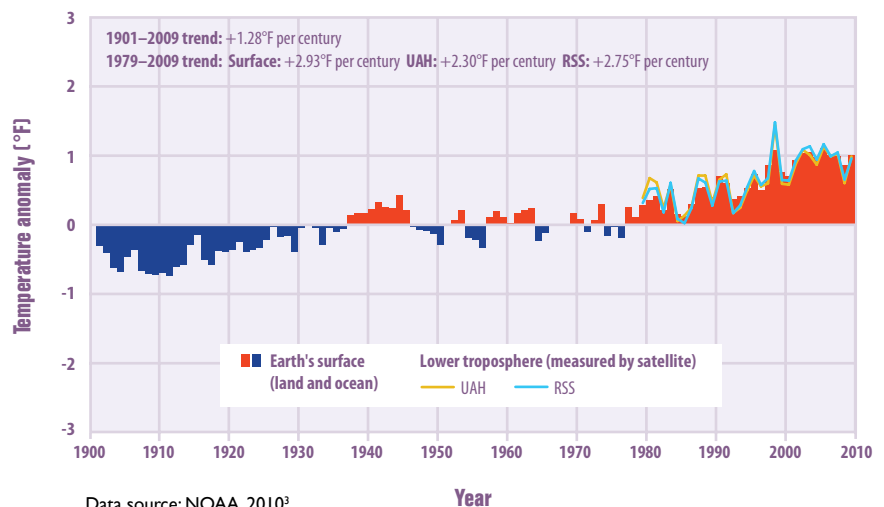
This figure shows how average temperatures in the lower 48 states have changed since 1901. Surface data come from land-based weather stations, while satellite measurements cover the lower troposphere, which is the lowest level of the Earth's atmosphere (see diagram on p. 20). "UAH" and "RSS" represent two different methods of analyzing the original satellite measurements. This graph uses the 1901 to 2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the trend.



Data source: NOAA, 2010²

Figure 2. Temperatures Worldwide, 1901–2009

This figure shows how average temperatures worldwide have changed since 1901. Surface global data come from a combined set of land-based weather stations and sea surface temperature measurements, while satellite measurements cover the lower troposphere, which is the lowest level of the Earth's atmosphere (see diagram on p. 20). "UAH" and "RSS" represent two different methods of analyzing the original satellite measurements. This graph uses the 1901 to 2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the trend.



Data source: NOAA, 2010³

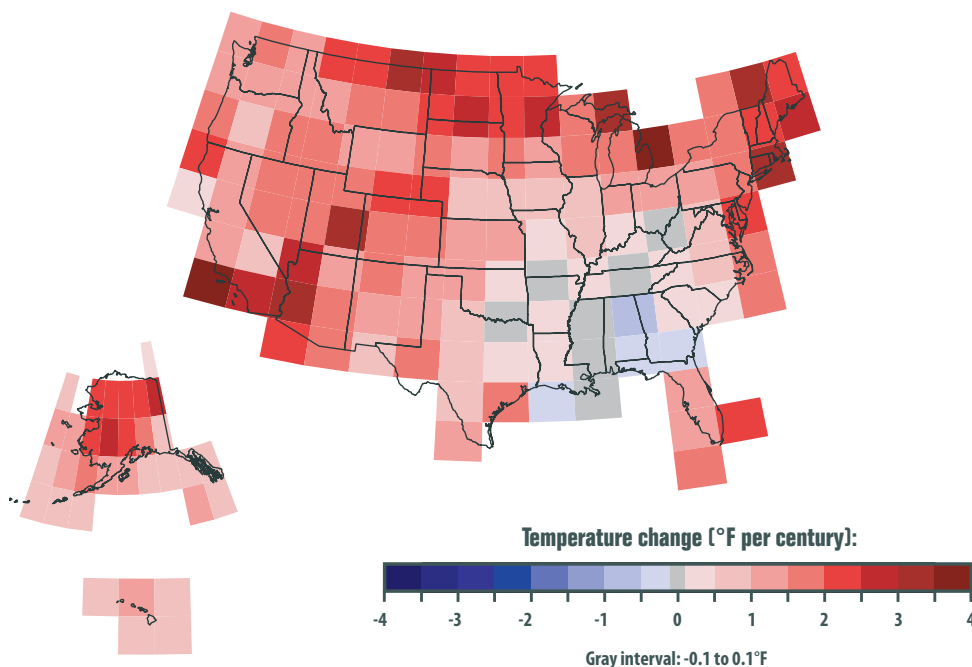
Temperature

Key Points

- Since 1901, temperatures have risen across the lower 48 states at an average rate of 0.13°F per decade (1.3°F per century) (see Figure 1). Average temperatures have risen more quickly since the late 1970s (0.35 to 0.51°F per decade). Seven of the top 10 warmest years on record for the lower 48 states have occurred since 1990, and the last 10 five-year periods have been the 10 warmest five-year periods on record.
- Global average surface temperatures have risen at an average rate of 0.13°F per decade since 1901 (see Figure 2), similar to the rate of warming within the lower 48 states. Since the late 1970s, however, the United States has warmed at nearly twice the global rate. Worldwide, 2000–2009 was the warmest decade on record.
- 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 South have experienced little change. However, not all of these regional trends are statistically meaningful.

Figure 3. Rate of Temperature Change in the United States, 1901–2008

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



Data source: NOAA, 2009⁴

Indicator Limitations

Data from the early 20th century are somewhat less precise because there were fewer stations collecting measurements at the time. However, the overall trends are still reliable. Measurement instruments and methods (for example, the time of day measurements are taken) have also changed over time, and some stations have moved. Where possible, the data have been adjusted to account for these kinds of changes.

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. Surface temperature anomalies were calculated based on monthly values from a network of long-term monitoring stations. Satellite data were analyzed by two independent groups, resulting in the slightly different "UAH" and "RSS" trend lines.



Heat Waves

This indicator tracks the frequency of extreme heat events in the United States.

Background

A heat wave is a prolonged period of abnormally hot weather. With an overall warming of the Earth's climate, heat waves are expected to become more frequent, longer, and more intense in places where they already occur.⁵ Increased frequency and severity of heat waves can lead to more illness and death, particularly among older adults, the young, and other vulnerable groups (see the Heat-Related Deaths indicator on p. 58). Excessive heat also can kill or injure crops and livestock, and can lead to power outages as heavy demands for air conditioning strain the power grid.

About the Indicator

While there is no universal definition of a heat wave, this indicator defines a heat wave as a four-day period with an average temperature that would only be expected to occur once every 10 years, based on the historical record.

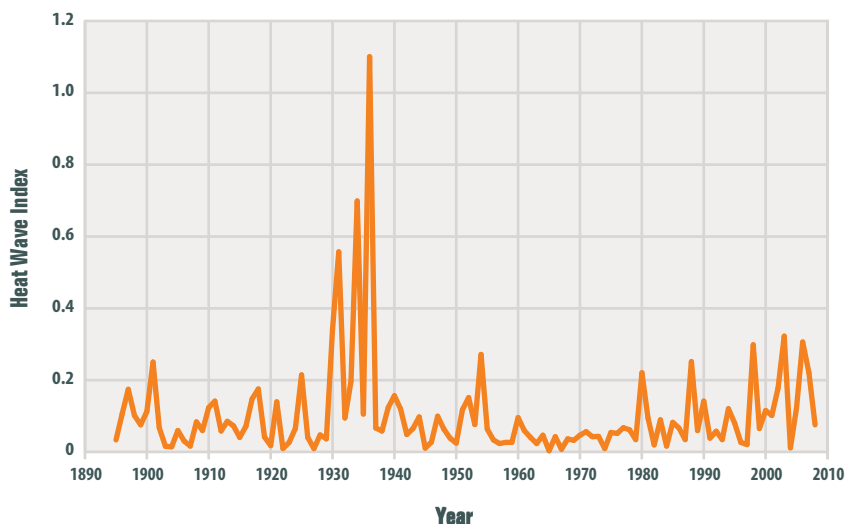
This indicator reviews trends in the U.S. Annual Heat Wave Index between 1895 and 2008. This index tracks the frequency of heat waves across the lower 48 states, but not the intensity of these episodes. The index uses daily maximum temperature data from the National Oceanic and Atmospheric Administration, which keeps records from weather stations throughout the nation. Approximately 300 to 400 stations reported data from 1895 to 1910; over the last 100 years, the number of stations has risen to 700 or more.

The index value for a given year could mean several different things. For example, an index value of 0.2 in any given year could mean that 20 percent of the recording stations experienced one heat wave; 10 percent of stations experienced two heat waves; or some other combination of stations and episodes resulted in this value.

(Continued on page 25)

Figure 1. U.S. Annual Heat Wave Index, 1895–2008

This figure shows the annual values of the U.S. Heat Wave Index from 1895 to 2008. These data cover the lower 48 states.



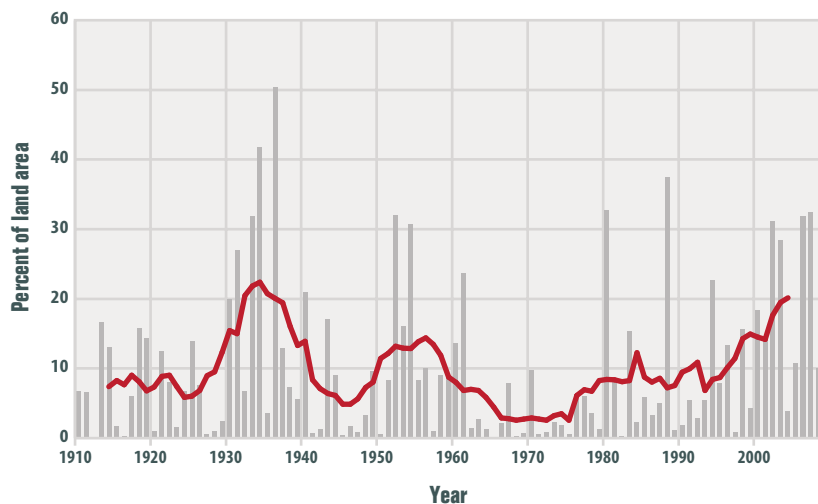
Data source: CCSP, 2009⁶

Key Points

- Heat waves occurred with high frequency in the 1930s, and these remain the most severe heat waves in the U.S. historical record (see Figure 1). Many years of intense drought (the “Dust Bowl”) contributed to these heat waves by depleting soil moisture and reducing the moderating effects of evaporation.⁷
- There is no clear trend over the entire period tracked by the index. Although it is hard to see in Figure 1 (because of the extreme events of the 1930s), heat wave frequency decreased in the 1960s and 1970s but has risen since then (see Figure 1).
- Like the heat wave index, the percentage of the United States affected by heat waves has also risen steadily since the 1970s (see Figures 2 and 3). The recent period of increasing heat is distinguished by a rise in extremely high nighttime temperatures.

Figure 2. Areas of the Lower 48 States With Hot Daily High Temperatures, 1910–2008

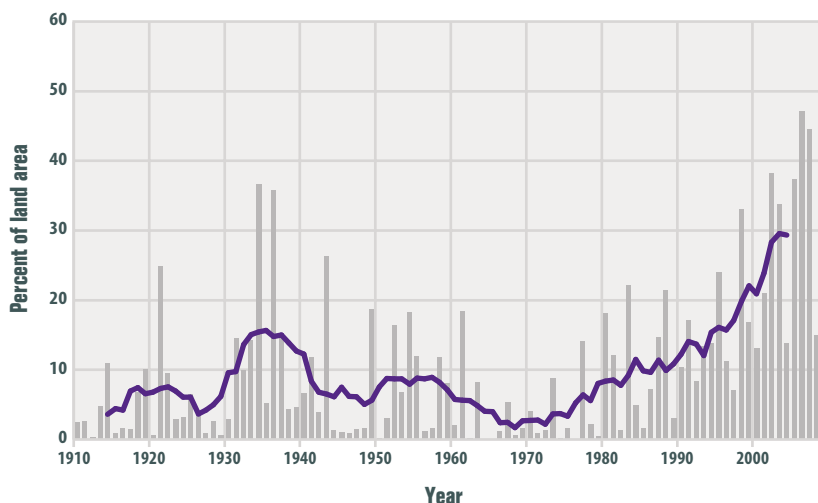
This chart shows the percentage of the land area of the lower 48 states with summer daily high temperatures well above normal. The bars represent individual years, while the line is a smoothed nine-year moving average.



Data source: CCSP,2009⁹

Figure 3. Areas of the Lower 48 States With Hot Daily Low Temperatures, 1910–2008

This chart shows the percentage of the land area of the lower 48 states with summer daily low temperatures well above normal. The bars represent individual years, while the line is a smoothed nine-year moving average.



Data source: CCSP,2009⁹

For additional perspective, this indicator also looks at heat waves in terms of size (percent of area affected) and the difference between trends in daytime high temperatures and trends in nighttime low temperatures.

Indicator Limitations

Temperature data are less certain for the early part of the record because fewer stations were operating at that time. In addition, measurement instruments and procedures have changed over time, and some stations have moved. The data have been adjusted to account for some biases, however, and these uncertainties are not sufficient to change the fundamental trends shown in the figures.

This indicator does not consider humidity, which can have additional health impacts when combined with heat.

Data Sources

The data for this indicator are based on measurements from the National Oceanic and Atmospheric Administration's National Weather Service Cooperative Observer Network. These weather station data are available online at: www.nws.noaa.gov/os/coop/what-is-coop.html.

Drought

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

Background

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, which results in a serious water shortage for some activity, group, or ecological system. Drought can also be thought of as an imbalance between precipitation and evaporation.

As average temperatures rise because of climate change, the Earth's water cycle is expected to speed up, increasing evaporation. Increased evaporation will make more water available in the air for precipitation, but contribute to drying over some land areas. As a result, storm-affected areas are likely to experience increased precipitation (see the U.S. and Global Precipitation indicator on p. 28) and increased risk of flooding (see the Heavy Precipitation indicator on p. 30), while areas located far from storm tracks are likely to experience less precipitation and increased risk of drought. Since the 1970s, drought-affected areas have increased on a global scale—more likely than not as a result of climate change caused by human activities.¹⁰

Drought conditions can 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 to major water shortages. Lower stream flow and ground water levels can also harm plants and animals, and dried-out vegetation increases the risk of wildfires.

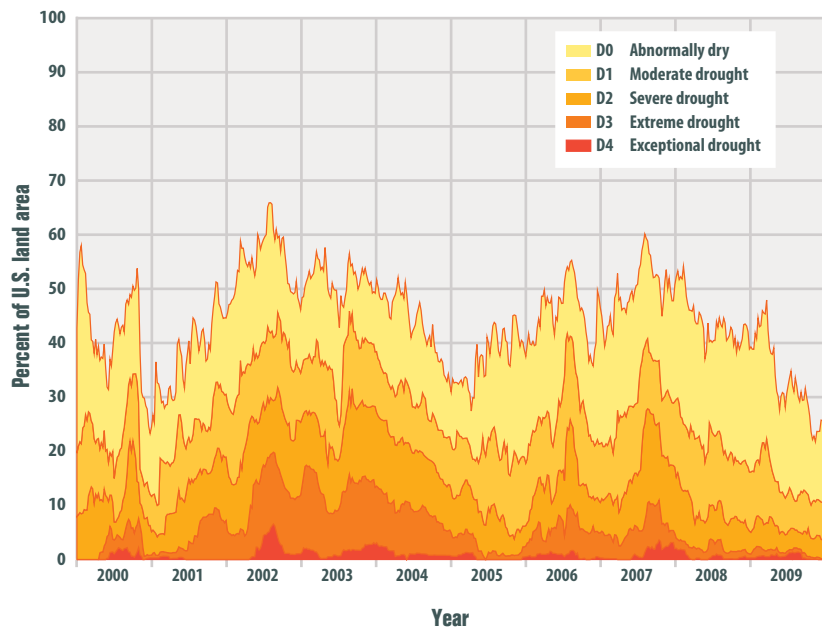
About the Indicator

During the 20th century, many indices were created to measure drought severity by looking at trends in precipitation, soil moisture, stream flow, vegetation health, and other variables.¹¹ This indicator is based on the U.S. Drought Monitor, which integrates several of these indices.

(Continued on page 27)

Figure 1. U.S. Lands Under Drought Conditions, 2000–2009

This chart shows the percentage of U.S. lands classified under drought conditions from 2000 through 2009. The data cover all 50 states plus Puerto Rico.



Data source: National Drought Mitigation Center, 2010¹²

Key Points

- Because data from the U.S. Drought Monitor are only available for the most recent decade, there is no clear long-term trend in this indicator. With continued data collection, future versions of this indicator should be able to paint a more complete picture of long-term trends in drought.
- Over the period from 2000 through 2009, roughly 30 to 60 percent of the U.S. land area experienced drought conditions at any given time (see Figure 1). The years 2002, 2003, and 2007 were relatively high drought years, while 2001, 2005, and 2009 were relatively low drought years.
- “Abnormally dry area” (D0)—the mildest drought event—was the most commonly occurring level of drought in the United States between 2000 and 2009.
- As of early 2010, moderate to severe drought is affecting parts of several western states, along with a small portion of the Upper Midwest.¹³

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 Web site at: www.drought.unl.edu/dm/monitor.html.

The Drought Monitor also considers additional factors such as snow water content, ground water levels, reservoir storage, pasture/range conditions, and other impacts.

The Drought Monitor uses codes from D0 to D4 (see table at left) to classify drought severity. This indicator measures the percent of U.S. land under each of these drought categories from 2000 through 2009. The indicator covers all 50 states and Puerto Rico.

Indicator Limitations

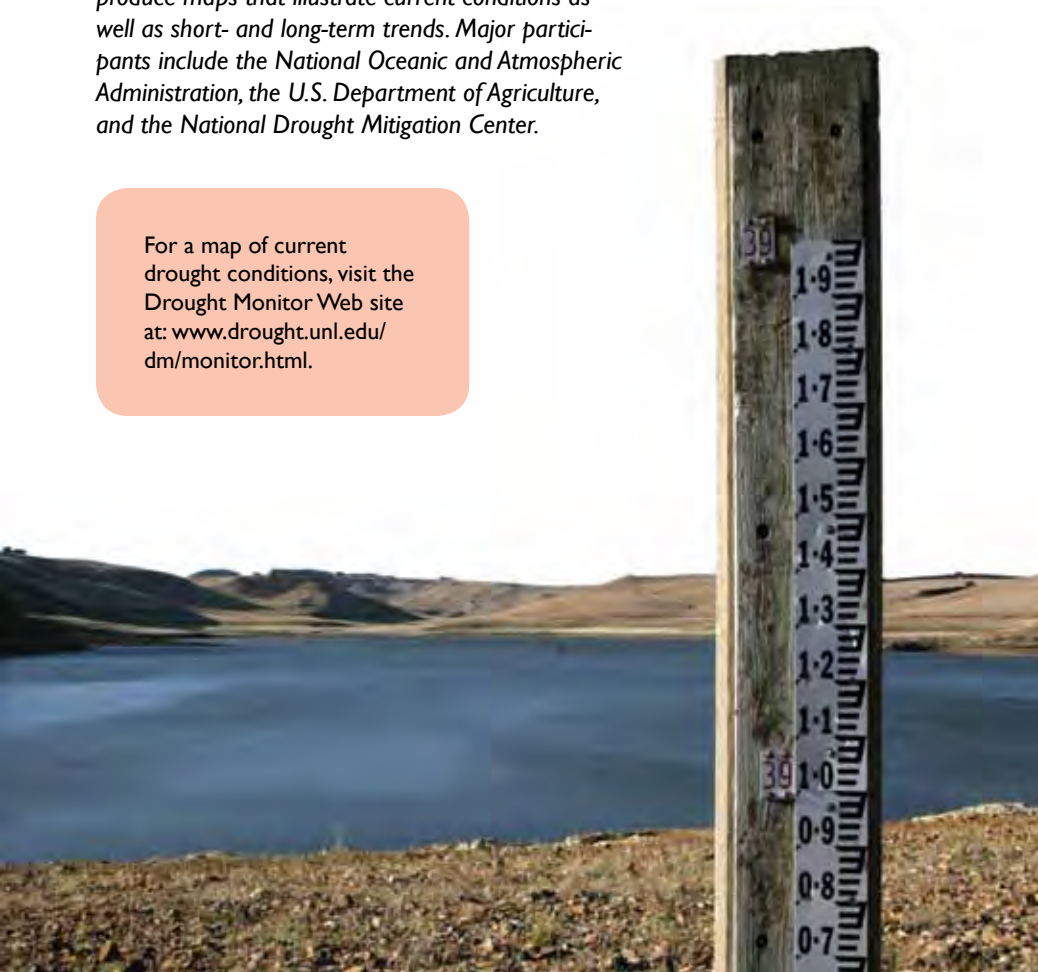
Because of the relative newness of the U.S. Drought Monitor, it cannot be used to assess long-term trends. Other indicators are available that do show historical trends, but they have other weaknesses and cannot be compared across geographic regions or across time.¹⁴

The drought classification scheme used for this indicator is produced by combining data from several different sources. These data are combined to reflect the collective judgment of experts and in some cases are adjusted to reconcile conflicting trends shown by different data sources over different time periods.

The 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 this indicator were provided by the U.S. Drought Monitor. Historical data in table form are available at: www.drought.unl.edu/dm/DM_tables.htm?archive. Maps and current drought information can be found on the main Drought Monitor site at: www.drought.unl.edu/dm/monitor.html.





U.S. and Global

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

Background

Precipitation can have wide-ranging effects on human life and ecosystems. Rainfall, snowfall, and the timing of snow-melt can all affect the amount of water available for drinking and irrigation, 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 abruptly and plant and animal species do not have time to adapt.

As average temperatures at the Earth's surface rise (see the U.S. and Global Temperature indicator on p. 22), more evaporation and cloud formation 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 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.

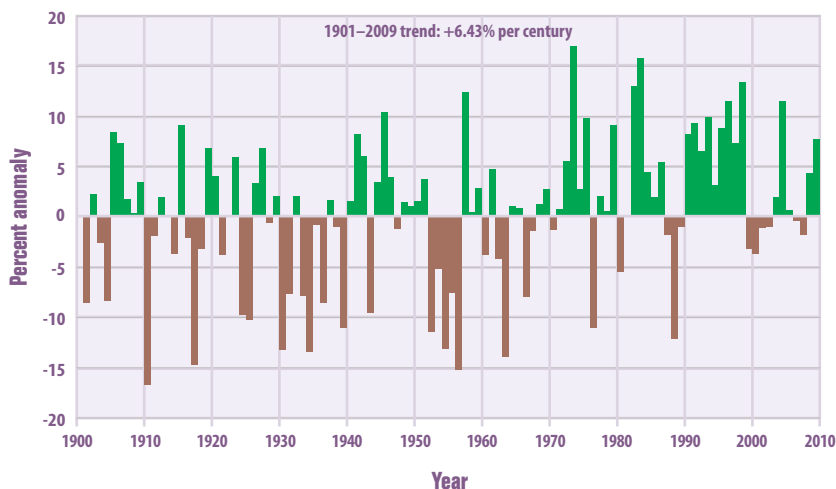
About the Indicator

This indicator examines U.S. and global precipitation patterns from 1901 to the present, based on rainfall and snowfall measurements from land-based stations worldwide. Data were provided by the National Oceanic and Atmospheric Administration, which keeps historical records from weather stations around the world.

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.

Figure 1. Precipitation in the Lower 48 States, 1901–2009

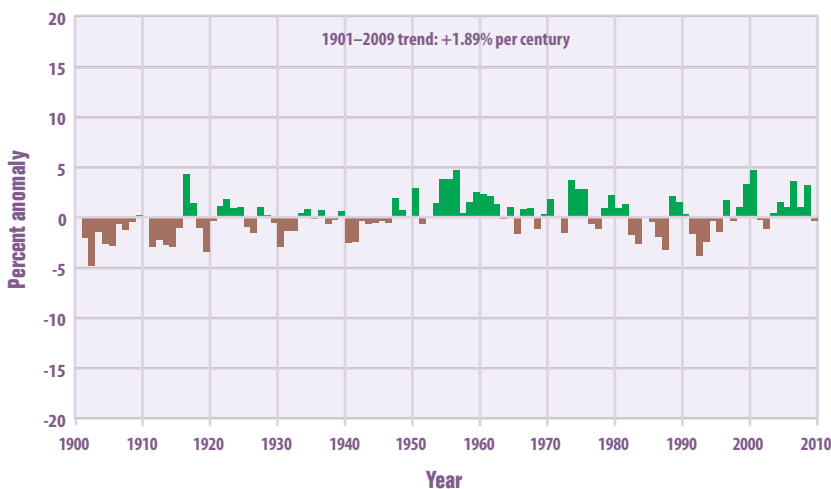
This figure shows how the amount of precipitation in the lower 48 states has changed since 1901. This graph uses the 1901 to 2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the trend.



Data source: NOAA, 2010¹⁵

Figure 2. Precipitation Worldwide, 1901–2009

This figure shows how the amount of precipitation globally has changed since 1901. This graph uses the 1901 to 2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the trend.



Data source: NOAA, 2010¹⁶

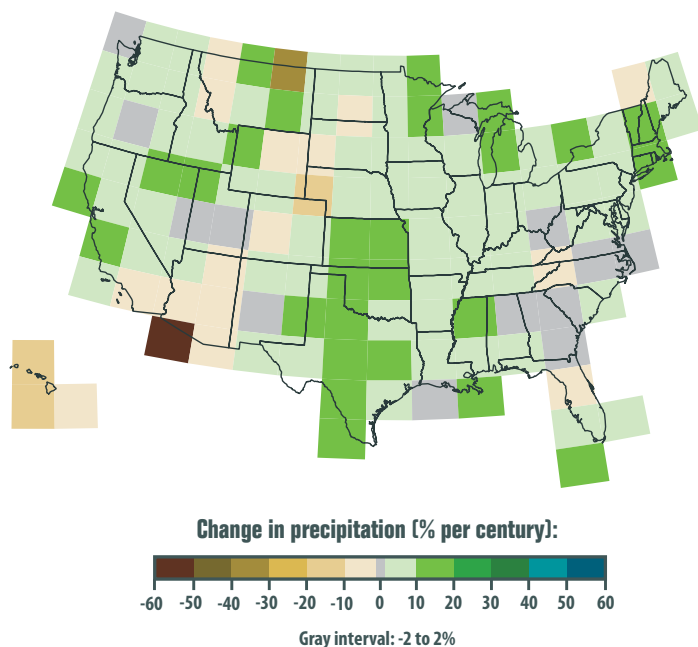
Precipitation

Key Points

- Average precipitation has increased in the United States and worldwide (see Figures 1 and 2). Since 1901, global precipitation has increased at an average rate of 1.9 percent per century, while precipitation in the lower 48 states has increased at a rate of 6.4 percent per century.
- Some parts of the United States have experienced greater increases in precipitation than others. A few areas such as Hawaii and parts of the South-west have seen a decrease (see Figure 3).

Figure 3. Rate of Precipitation Change in the United States, 1901–2008

This figure shows how the amount of precipitation has changed in different parts of the United States since the early 20th century (since 1901 for the lower 48 states; since 1905 for Hawaii). Alaska is not shown because of limited data coverage.



Data source: NOAA, 2009¹⁷

Indicator Limitations

Data from the early 20th century are somewhat less precise because there were fewer stations collecting measurements at the time. However, the overall trends are still reliable. Measurement instruments and methods have also changed over time, and some stations have moved. Where possible, the data have been adjusted to account for these kinds of changes.

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. Global, U.S., and regional precipitation anomalies 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.

Background

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 the location and the season.

Climate change can affect the intensity and frequency of precipitation. Warmer oceans increase the amount of water that evaporates into the air, and warmer air can hold more moisture than cooler air. When this moisture-laden air moves over land, it can produce more intense precipitation—for example, heavier rain and snow storms.¹⁸ 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 hurt 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 can also lead to changes in overall precipitation totals.

About the Indicator

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

(Continued on page 31)

Figure 1. Extreme One-Day Precipitation Events in the Lower 48 States, 1910–2008

This figure shows the percentage of the land area of the lower 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 smoothed nine-year moving average.

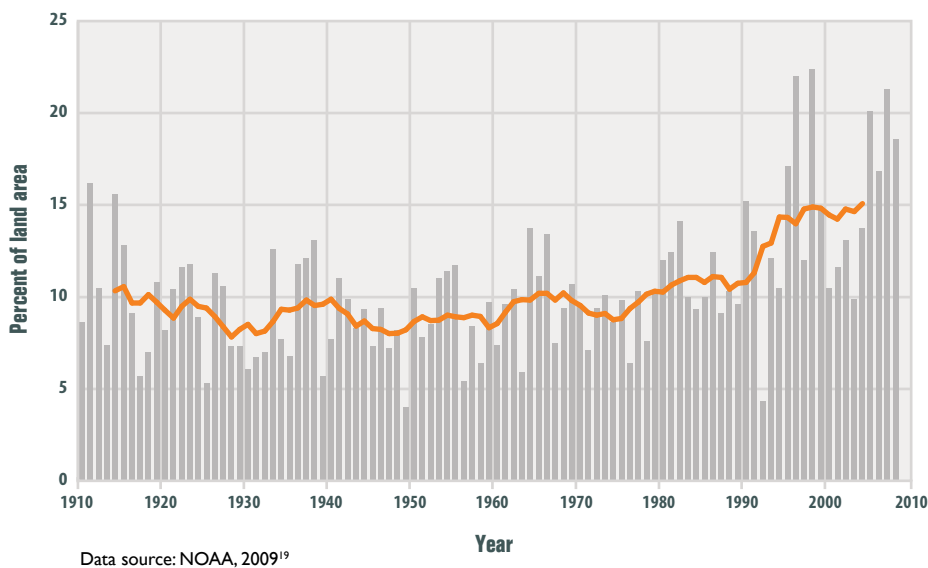
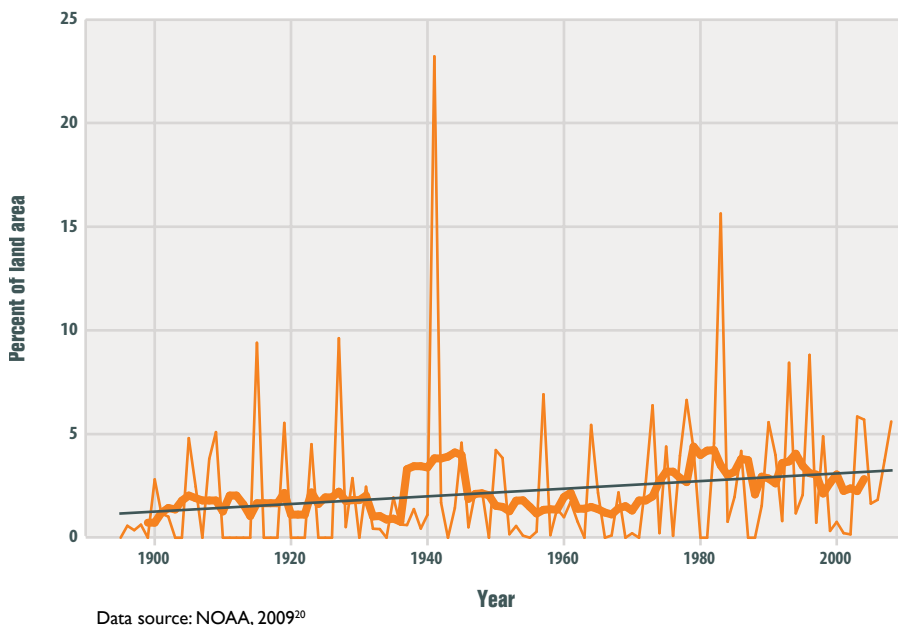


Figure 2. Abnormally High Annual Precipitation in the Lower 48 States, 1895–2008

This figure shows the percentage of the land area of the lower 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 (SPI). The thicker orange line shows a nine-year moving average that smooths out some of the year-to-year fluctuations, while the straight black line is the trend line that fits the data best.



Key Points

- In recent years, a larger percentage of precipitation has come in the form of intense single-day events. Eight 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 2008, the prevalence of extreme single-day precipitation events increased at a rate of about half a percentage point per decade (5 percentage points per century) (see Figure 1).
- The percentage of land area experiencing much greater than normal yearly precipitation totals increased between 1895 and 2008. 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 lower 48 states' land area (see Figure 2).
- Figures 1 and 2 are both consistent with a variety of other studies that have found an increase in heavy precipitation over timeframes ranging from single days to 90-day periods to whole years.²¹ For more information on trends in overall precipitation levels, see the U.S. and Global Precipitation indicator on p. 28.

For added insight, this indicator also tracks the occurrence of abnormally 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 lower 48 states had an annual SPI score of 2.0 or above (well above normal) in any given year.

Both parts of this indicator are based on data from a large national network of weather stations compiled by the National Oceanic and Atmospheric Administration.

Indicator Limitations

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 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.html. 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 and metadata used to construct these maps are available from the National Oceanic and Atmospheric Administration at: <ftp://ftp.ncdc.noaa.gov/pub/data/cirs>.





Tropical Cyclone

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

Background

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. Tropical cyclones get their energy from warm tropical oceans, while extratropical cyclones form outside the tropics, getting their energy from the jet stream and from temperature differences between the north and the south, often involving cold fronts and warm fronts.

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 property damage, loss of life, soil erosion, and flooding. The associated storm surge—the large volume of ocean water pushed ashore by the cyclone’s strong winds—can also cause severe flooding and destruction.

Climate change is expected to affect tropical cyclone intensity by increasing sea surface temperatures, a key factor that influences cyclone formation and behavior. According to the U.S. Global Change Research Program, it is very likely that increased levels of greenhouse gases have contributed to an increase in sea surface temperatures in areas where hurricanes form, suggesting a human contribution to hurricane activity over the last 50 years.²² The U.S. Global Change Research Program and the Intergovernmental Panel on Climate Change project that tropical cyclones will become more intense, with higher wind speeds and heavier rains.²³ However, observations of past cyclone activity and projections of future activity have uncertainties because of changes in monitoring technology, longer-term regional climate patterns, and the limitations of climate models.

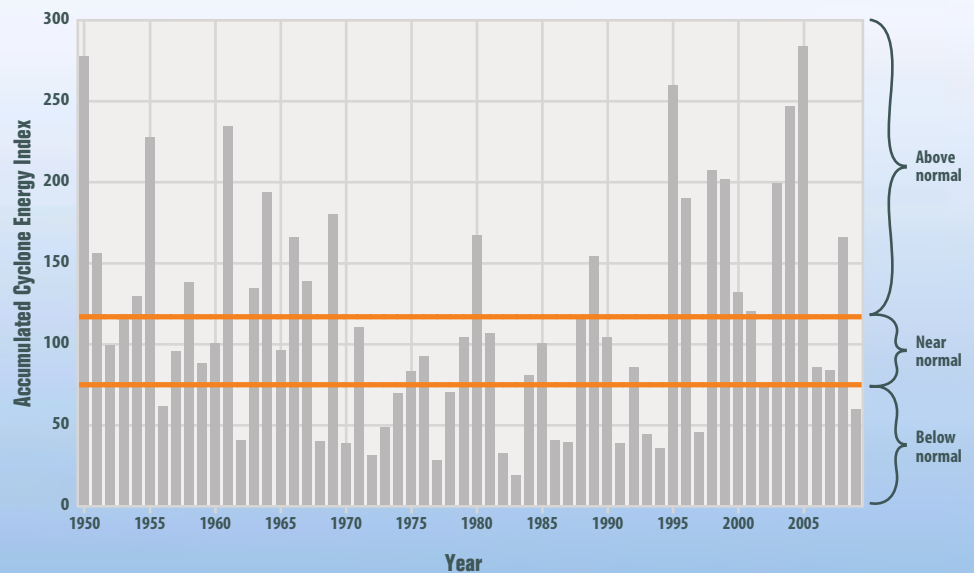
About the Indicator

This indicator uses two related indices: the Accumulated Cyclone Energy (ACE) Index and the Power Dissipation Index (PDI).

The National Oceanic and Atmospheric Administration uses the ACE Index to measure the strength of individual tropical storms as

Figure 1. North Atlantic Cyclone Intensity According to the Accumulated Cyclone Energy Index, 1950–2009

This figure shows total annual Accumulated Cyclone Energy (ACE) Index values from 1950 through 2009. 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 50 years from 1951 to 2000.



Data source: NOAA, 2010²⁴



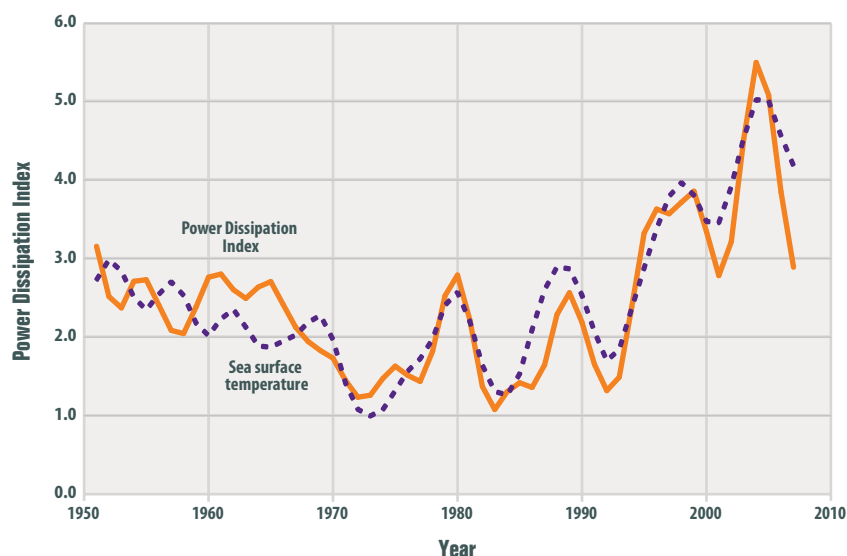
Intensity

Key Points

- When examining the entire ACE Index data series from 1950 to 2009, no clear trends in cyclone intensity are apparent (see Figure 1). However, intensity has risen noticeably over the past 20 years, and six of the 10 most active years have occurred since the mid-1990s. Comparable levels of activity were also seen during the previous high-activity era which spanned the 1950s and 1960s.
- The PDI (see Figure 2) shows a similar trend: fluctuating cyclone intensity for most of the mid- to late 20th century, followed by a noticeable increase since 1995. These trends are closely related to variations in sea surface temperature in the tropical Atlantic (see Figure 2), leading the U.S. Global Change Research Program to conclude that hurricane activity has “increased substantially since the 1950s and ’60s in association with warmer Atlantic sea surface temperatures.”²⁵

Figure 2. North Atlantic Cyclone Intensity According to the Power Dissipation Index, 1949–2009

This figure presents annual values of the Power Dissipation Index (PDI). North Atlantic sea surface temperature trends are provided for reference. Note that sea surface temperature uses different units, but the numbers have been adjusted here to show how the trends are similar. The lines have been smoothed using a five-year weighted average.



Data source: Emanuel, 2010²⁶

well as the total cyclone activity over the course of a hurricane season. An individual storm's ACE Index value is a number based on the storm's maximum wind speed measured at six-hour intervals over the entire time when the cyclone is classified as at least a tropical storm (that is, a storm with a wind speed of at least 39 miles per hour). Therefore, the ACE Index value accounts for both cyclone strength and duration.

The National Oceanic and Atmospheric Administration calculates the ACE Index value for an entire hurricane season by adding the ACE Index values for all named storms in a season, including subtropical storms, tropical storms, and hurricanes. For this indicator, the ACE Index has been converted to a numerical scale where 100 equals the median value (the midpoint) over a base period from 1951 to 2000. The National Oceanic and Atmospheric Administration has set specific thresholds (see Figure 1) to define whether the ACE Index for a given year is close to normal, significantly above normal, or significantly below.

For additional perspective, this indicator also shows trends in the PDI. 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 Limitations

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. How these changes in data gathering technologies might affect data consistency over the life of the indicator is not fully understood.

Data Sources

The ACE Index data (Figure 1) 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



Ocean Heat



**Sea Surface
Temperature**



Sea Level



The oceans and the atmosphere interact constantly—both physically and chemically—exchanging heat, water, gases, and particles. This relationship influences the Earth’s climate on regional and global scales. It also affects the state of the oceans.

Covering nearly 70 percent of the Earth’s surface, the oceans store vast amounts of energy absorbed from the sun and move this energy around the globe through currents. As greenhouse gases trap more energy from the sun, the oceans will absorb more heat, resulting in an increase in sea surface temperatures, rising sea levels, and possible changes to ocean currents. These changes will very likely lead to alterations in climate patterns around the world. For example, warmer waters promote the development of more intense storms in the tropics, which can cause property damage or loss of life.

The oceans are also a key component of the Earth’s carbon cycle. Over geological time, much of the world’s carbon has come to reside in the oceans, either within plants and animals (living or dead) or dissolved as carbon dioxide. Although the oceans can help lessen climate change by

storing a significant fraction of the carbon dioxide that human activities emit into the atmosphere, increasing levels of dissolved carbon dioxide can change the chemistry of seawater and harm certain organisms. 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. The interactions between ocean and atmosphere occur slowly, over many years—even decades. For this reason, even if greenhouse gas emissions are stabilized tomorrow, it will take many more years—decades or centuries—for the oceans to adjust to the climate changes that have already occurred.

Even if greenhouse gas emissions are stabilized tomorrow, it will take many more years—decades or centuries—for the oceans to adjust to the climate changes that have already occurred.

Ocean Heat

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

Background

When sunlight reaches the Earth's surface, the world's oceans absorb some of this energy and store it as heat. The amount of heat in the ocean, or ocean heat content, plays an important role in the Earth's climate system for several reasons. First, the amount of heat absorbed by the ocean affects its temperature. Sea surface temperature is especially important (see the Sea Surface Temperature indicator on p. 38) because surface waters exchange heat with the air and influence weather patterns. Deeper waters also absorb heat, however. Water also 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.

Greenhouse gases are trapping more energy from the sun, and the oceans are currently absorbing a significant fraction of this extra heat.¹ If not for the large heat storage capacity provided by the oceans, the atmosphere would grow warmer at a much faster rate.² Increased heat absorption can change the dynamics of the ocean, however, because many currents are driven by differences in temperature. These currents influence climate patterns and sustain ecosystems—for example, coastal fishing grounds that depend on upwelling currents to bring nutrients to the surface. 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. 40).

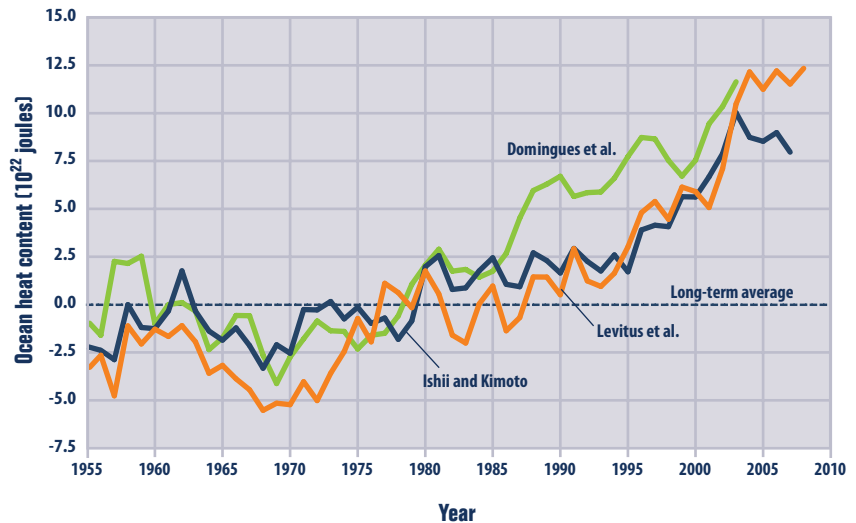
About the Indicator

This indicator shows trends in global ocean heat content to a depth of 700 meters (nearly 2,300 feet) from 1955 to 2008. The indicator measures ocean heat content in joules, which is a unit of energy.

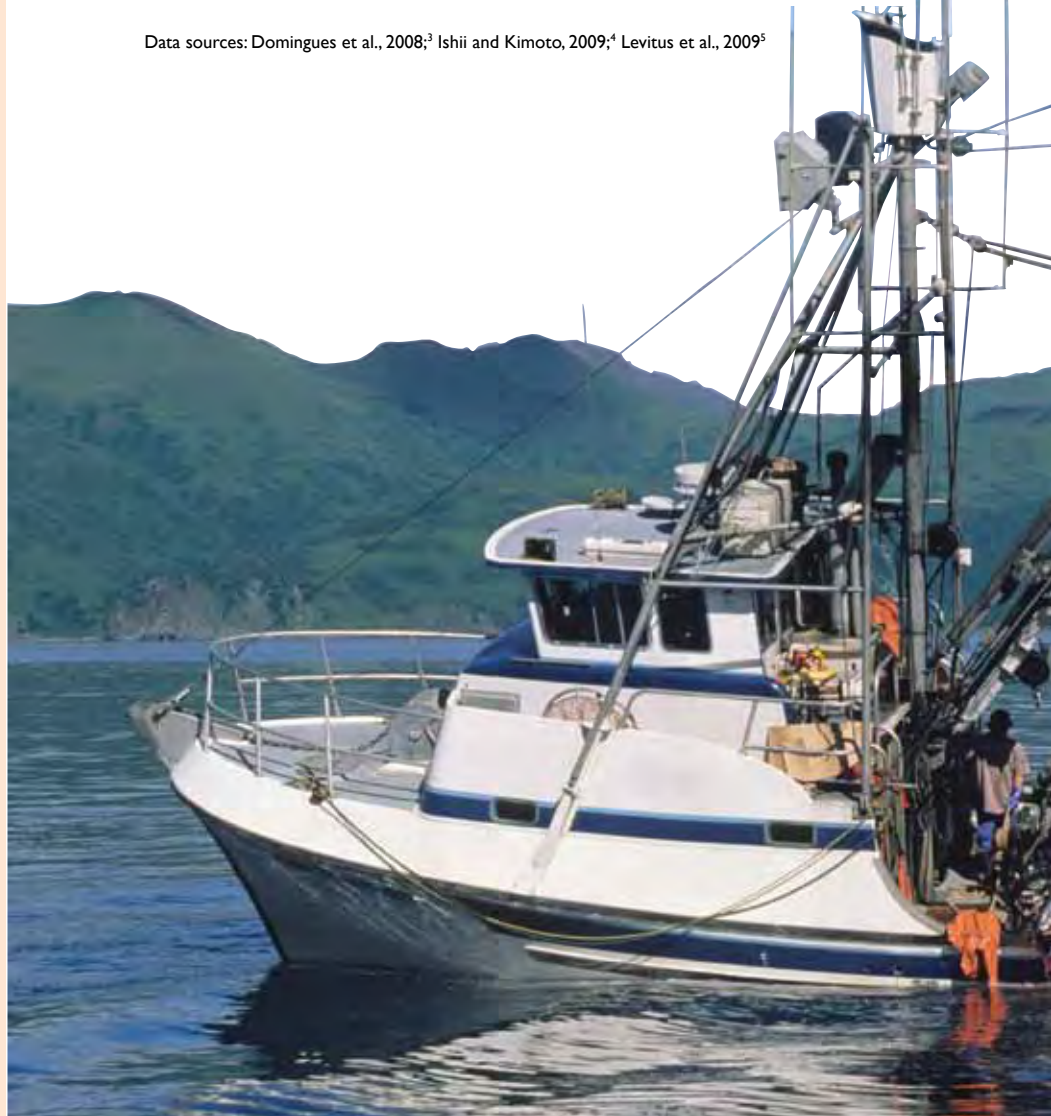
(Continued on page 37)

Figure 1. Ocean Heat Content, 1955–2008

This figure shows changes in ocean heat content between 1955 and 2008. Ocean heat content is measured in joules, a unit of energy, and compared against the long-term average, which is set at zero.



Data sources: Domingues et al., 2008;³ Ishii and Kimoto, 2009;⁴ Levitus et al., 2009⁵



Key Points

- In three different data interpretations, the long-term trend shows that ocean heat content has increased substantially since 1955 (see Figure 1).
- Although concentrations of greenhouse gases have risen at a steady rate over the past few decades (see the Atmospheric Concentrations of Greenhouse Gases indicator on p. 14), the rate of change in ocean heat content can vary greatly 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.

The National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration collected these data using a variety of ocean profiling instruments launched from ships and airplanes and, more recently, underwater robots. Thus, the data must be carefully adjusted to account for different measurement techniques. Scientists' understanding of how to correct the data has evolved over time, leading to changes in the trend line. Figure 1 shows three different interpretations of the same underlying data.

Indicator Limitations

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 the National Aeronautics and Space Administration, and were analyzed by Domingues et al. (2008),⁶ Ishii and Kimoto (2009),⁷ and Levitus et al. (2009).⁸





Sea Surface Temp

This indicator describes global trends in sea surface temperature.

Background

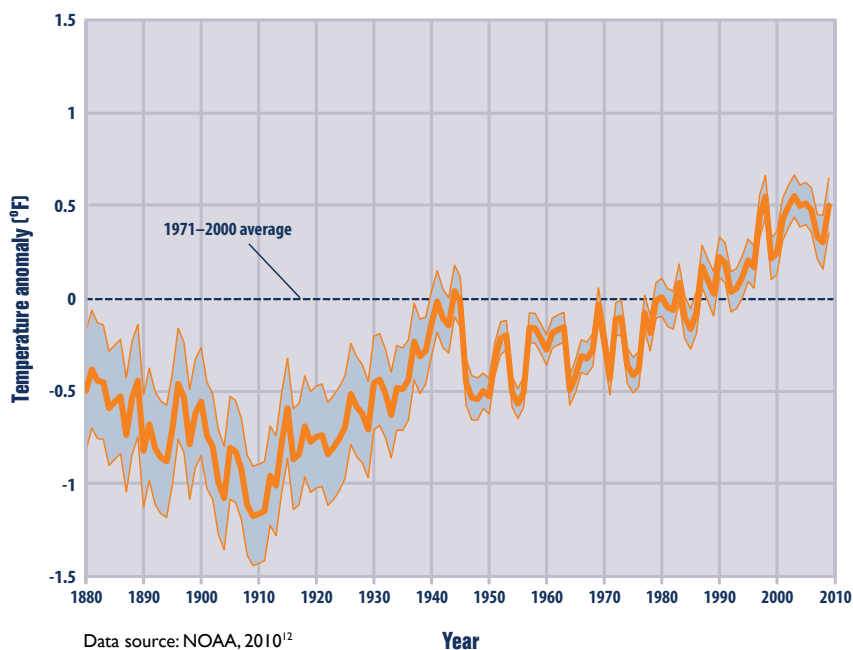
Sea surface temperature—the temperature of the water at the ocean surface—is an important physical attribute of the world’s oceans. The surface temperature of the world’s oceans varies mainly with latitude, with the warmest waters at the equator and the coldest waters in the Arctic and Antarctic regions. As air temperatures change, so can sea surface temperatures, as well as the ocean circulation patterns that transport warm and cold water around the globe.

Changes in sea surface temperature can alter marine ecosystems in several ways. For example, variations in ocean temperature can affect what species of plants and animals are present in a location, alter migration and breeding patterns, threaten fragile ocean life such as corals, and change the frequency and intensity of harmful algal blooms.⁹ Over the long term, increases in sea surface temperature also can reduce the amount of nutrients supplied to surface waters from the deep sea, leading to declines in fish populations.¹⁰

Because the oceans constantly interact with the atmosphere, sea surface temperature also can have profound effects on global climate. Based on changes in sea surface temperature, the amount of atmospheric water vapor over the oceans is estimated to have increased by about 5 percent during the 20th century.¹¹ This water vapor feeds weather systems that produce precipitation, and the increase in water vapor increases the risk of heavy rain and snow (see the Heavy Precipitation and Tropical Cyclone Intensity indicators on p. 30 and p. 32, respectively). Changes in sea surface temperature can also shift precipitation patterns, potentially leading to droughts in some areas.

Figure 1. Average Global Sea Surface Temperature, 1880–2009

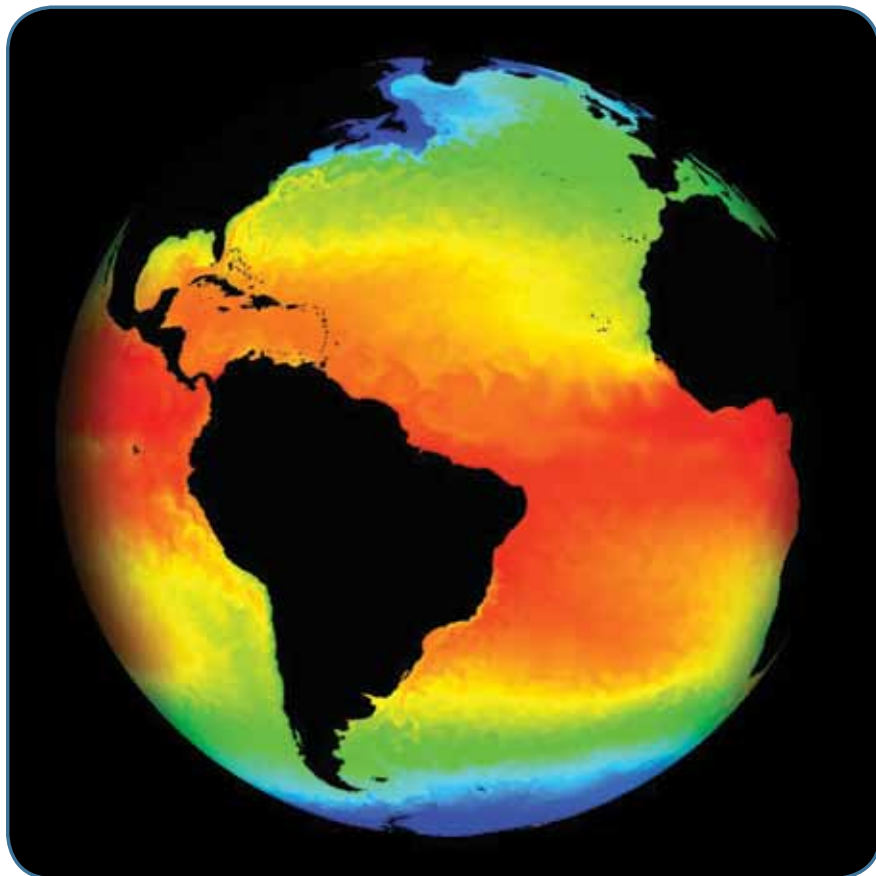
This graph shows how the average surface temperature of the world’s oceans has changed since 1880. This graph uses the 1971 to 2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the trend. The shaded band shows the likely range of values,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



erature

Example of a Sea Surface Temperature Map

This image is an example of a sea surface temperature map based on satellite measurements and computer models. “Warm” colors such as red and orange indicate warmer water temperatures.



Source: NASA, 2008¹³

Key Points

- Sea surface temperature increased over the 20th century. From 1901 through 2009, temperatures rose at an average rate of 0.12 degrees per decade. Over the last 30 years, sea surface temperatures have risen more quickly at a rate of 0.21 degrees per decade (see Figure 1).
- Sea surface temperatures have been higher during the past three decades than at any other time since 1880 (see Figure 1).
- The largest increases in sea surface temperature occurred in two key periods: between 1910 and 1940, and from 1970 to the present. Sea surface temperatures appear to have cooled between 1880 and 1910 (see Figure 1).

About the Indicator

This indicator tracks average global sea surface temperature from 1880 through 2009 using data compiled by the National Oceanic and Atmospheric Administration. 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 buoys.

The data for this indicator have been carefully reconstructed and filtered 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.

Indicator Limitations

Because this indicator tracks sea surface temperature at a global scale, the data cannot be used to analyze local or regional trends.

Due to denser sampling and improvements in sample design and measurement techniques, newer data have more certainty than older data. The earlier trends shown by this indicator are less precise because of lower sampling frequency and less precise sampling methods.

Data Sources

Data for this indicator were provided by the National Oceanic and Atmospheric Administration's National Climatic Data Center and are available online at: www.ncdc.noaa.gov/oa/climate/research/sst/ersstv3.php. These data were reconstructed from actual measurements of water temperature, which are available from the National Oceanic and Atmospheric Administration at: <http://icoads.noaa.gov/products.html>.



Sea Level

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

Background

As the temperature of the ocean changes (see the Sea Surface Temperature indicator on p. 38), 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.
2. As water warms, it expands slightly—an effect that is magnified over the entire surface and depth of the oceans.

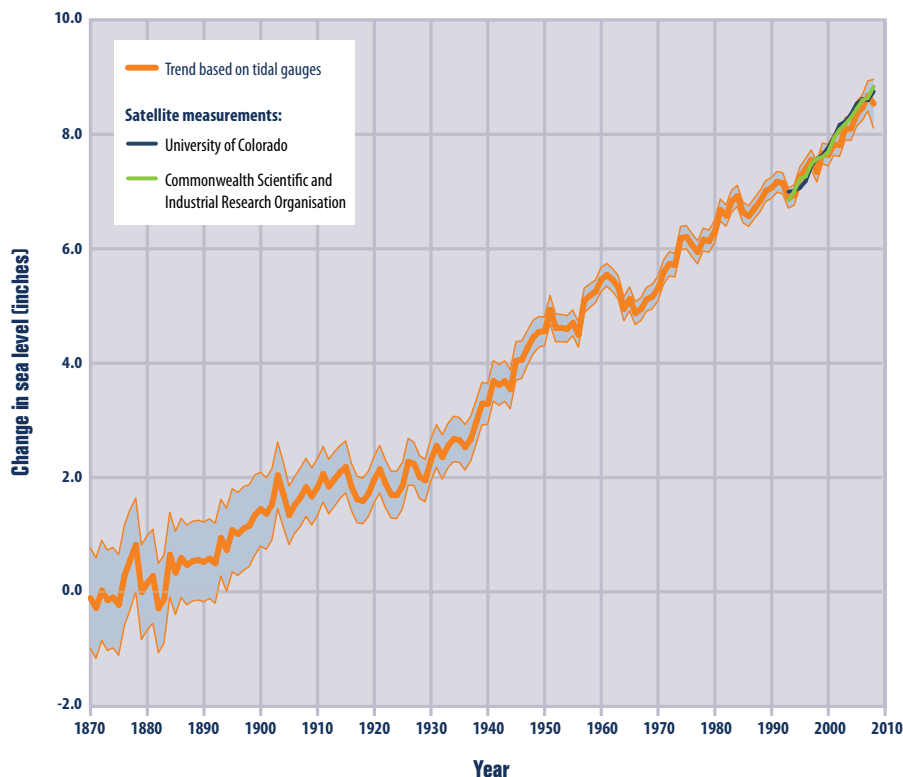
Changing sea levels can affect human activities in coastal areas. For example, rising sea levels can lead to increased flooding and erosion, which is a particular concern in low-lying areas. Sea level rise also can alter ecosystems, transforming marshes and other wetlands into open waters and freshwater systems to salt water.

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 Delta) and geological uplift (for example, over long timeframes as tectonic plates collide and build mountain ranges, and over shorter timeframes 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.

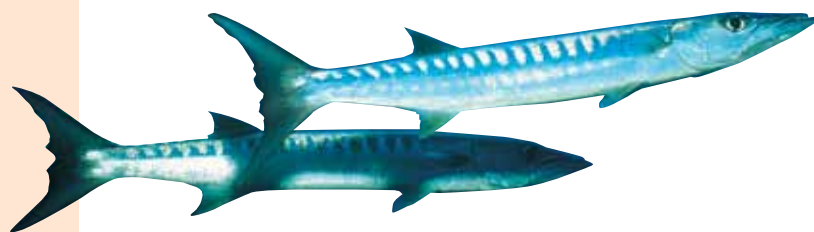
Scientists account for these types of changes by measuring sea level in two different ways. *Relative* sea level is the height of the ocean relative to the land elevation at a particular location. In contrast, *absolute* sea level strictly measures the height of the ocean surface above the center of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

Figure 1. Trends in Global Average Absolute Sea Level, 1870–2008

This graph shows how the average absolute sea level of the world's oceans has changed since 1870, based on a combination of long-term tidal gauge measurements and recent satellite measurements. Absolute sea level does not account for changes in land elevation. 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, 2009;¹⁴ University of Colorado at Boulder, 2009¹⁵





Key Points

- After a period of approximately 2,000 years of little change, average sea levels rose worldwide throughout the 20th century, and the rate of change has accelerated in recent years.¹⁶ When averaged over all the world's oceans, absolute sea level increased at an average rate of 0.06 inches per year from 1870 to 2008 (see Figure 1). From 1993 to 2008, however, average sea level rose at a rate of 0.11 to 0.13 inches per year—roughly twice as fast as the long-term trend.
- Relative sea level rose along much of the U.S. coastline between 1958 and 2008, 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 if absolute sea level has risen, land elevation has apparently risen faster.
- While absolute sea level has increased steadily overall, particularly in recent decades, regional trends vary, and absolute sea level has decreased in some places.¹⁷ 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.

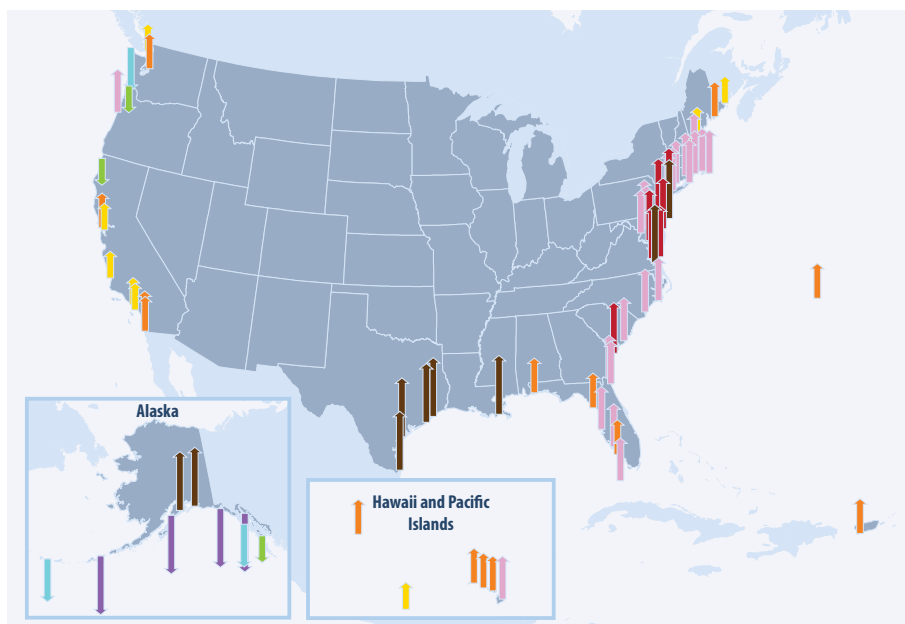
About the Indicator

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

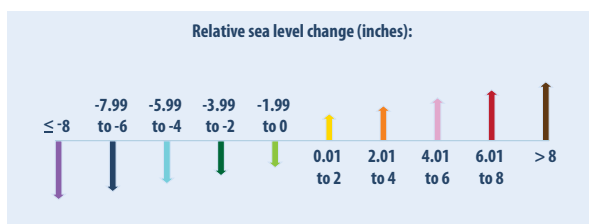
Figure 1 shows trends in absolute sea levels averaged over the entire Earth's ocean surface. The long-term trend is based on tidal gauge data that have been adjusted to show absolute global trends through calibration with recent satellite data. Figure 2 shows trends at a more local scale, highlighting the 1958 to 2008 change in relative sea level at 76 tidal gauges along the Atlantic, Pacific, and Gulf coasts of the United States.

Figure 2. Trends in Relative Sea Level Along U.S. Coasts, 1958–2008

This map shows changes in relative sea level from 1958 to 2008 at tidal gauge stations along U.S. coasts. Relative sea level accounts for changes in sea level as well as land elevation.



Data source: NOAA, 2009¹⁸



Indicator Limitations

Relative sea level trends represent a combination of absolute sea level change and any local land movement. Tidal 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, which affect coastal ocean temperatures; salt content; winds; atmospheric pressure; 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 tidal gauge measurements.

Data Sources

Absolute sea level trends were provided by Australia's Commonwealth Scientific and Industrial Research Organisation and the University of Colorado. These data are based on measurements collected by satellites and tidal 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/slrmap.html>) with links to detailed data for each tidal gauge.



Ocean Acidity

This indicator shows acidity levels in the ocean, which are strongly affected by the amount of carbon dioxide dissolved in the water.

Background

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. 14), the ocean absorbs more carbon dioxide to stay in balance. Because of the slow mixing time of the ocean compared with the atmosphere, it can take hundreds of years to establish a balance between the atmosphere and the ocean.

Although the ocean's ability to take up carbon dioxide is a positive attribute with respect to mitigating climate change, these reactions can have a negative effect on marine life. Carbon dioxide from the atmosphere reacts with sea water to produce carbonic acid. Increasing acidity (measured by lower pH values) reduces the availability of chemicals needed to make calcium carbonate, which corals, some types of plankton, and other creatures rely on to produce their hard skeletons and shells. The effect of declining pH on shell-producing ocean organisms can cause changes in overall ecosystem structure in coastal ecosystems.¹⁹

While changes in ocean pH caused by the uptake of atmospheric carbon dioxide generally occur over long periods of time, some fluctuation in pH can occur over shorter periods, especially in coastal and surface waters. Increased photosynthesis during the day and during summer months, for example, leads to natural fluctuations in pH.

About the Indicator

This indicator presents ocean pH values based on direct observations and modeling. Scientists have only begun to directly measure ocean carbon dioxide and related variables (dissolved organic carbon, alkalinity, and pH) on a global scale during the last few decades.

While direct observations are important in monitoring recent ocean acidity changes, it is even more important to examine trends over longer time spans, given the slow rate at which sea water balances with atmospheric

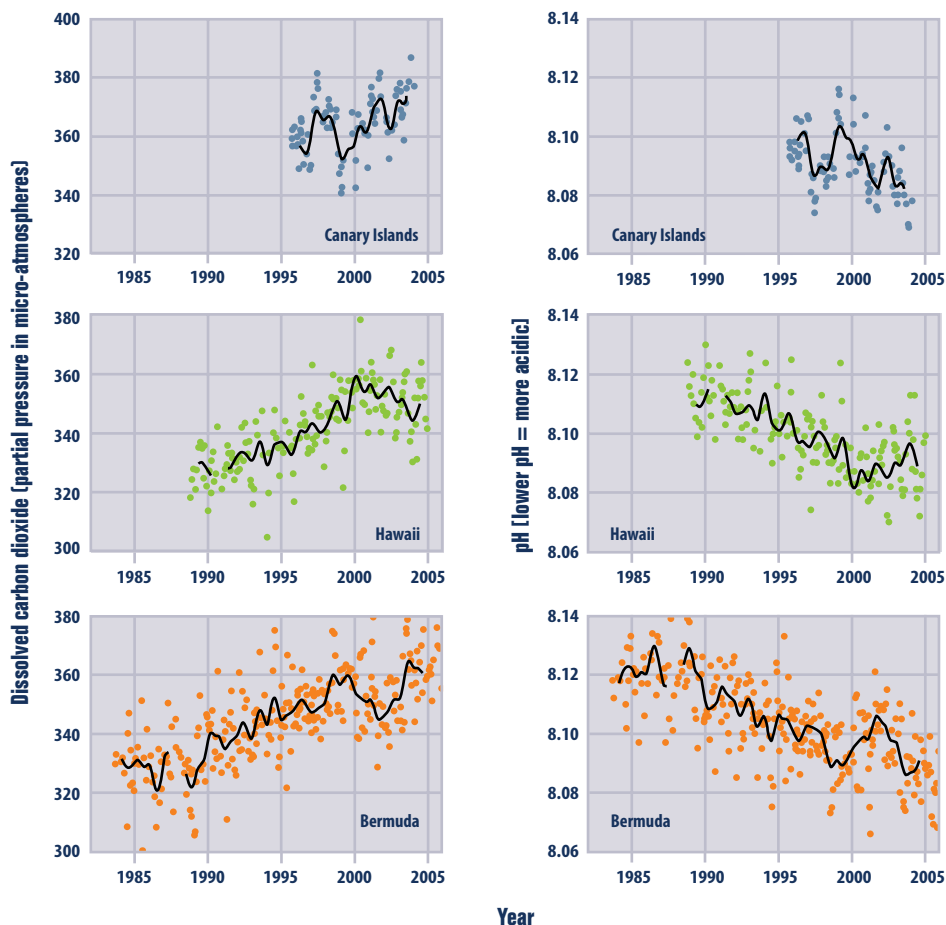
(Continued on page 43)

Key Points

- Measurements made over the last few decades have demonstrated that ocean carbon dioxide levels have risen, accompanied by an increase in acidity (that is, a decrease in pH) (see Figure 1).
- Modeling suggests that over the last few centuries, ocean acidity has increased globally (meaning pH has decreased), most notably in the Atlantic (see Figure 2).
- Direct observations show that pH levels fluctuate more frequently in some areas of the ocean than in others.²⁰ More measurements are needed to better understand the links between these natural fluctuations and long-term changes in ocean acidity.

Figure 1. Ocean Carbon Dioxide Levels and Acidity, 1983–2005

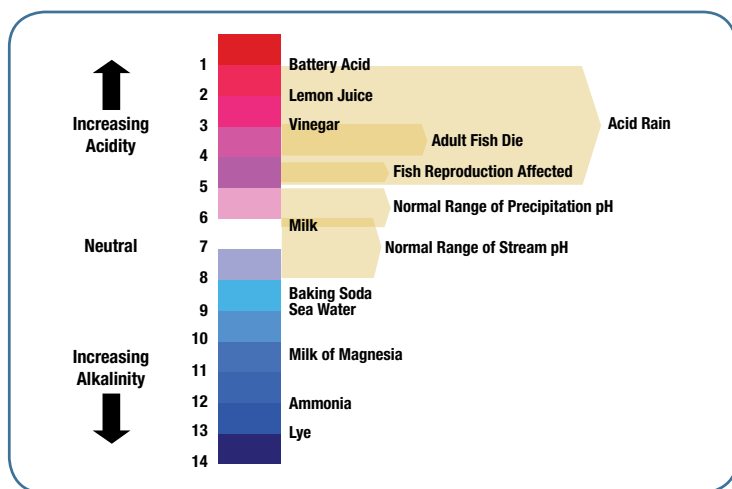
This figure shows changes in ocean carbon dioxide levels (measured as a partial pressure) and acidity (measured as pH). The data come from two observation stations in the North Atlantic Ocean (Canary Islands and Bermuda) and one in the Pacific (Hawaii). Dots represent individual measurements, while the lines represent smoothed trends.



Data source: Bindoff et al., 2007²¹

pH Scale

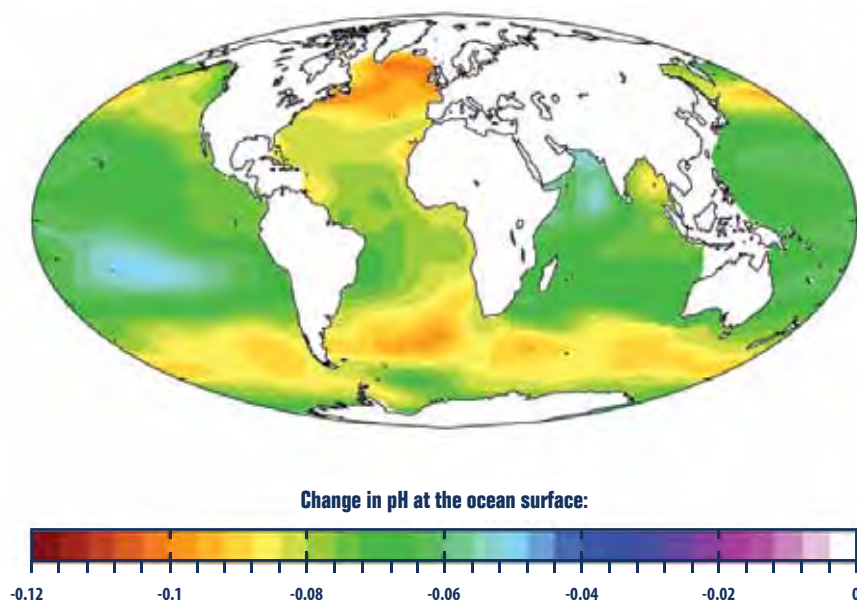
Acidity is commonly measured using the pH scale. Pure water has a pH of about 7, which is considered neutral. A substance with a pH less than 7 is acidic, while a substance with a pH greater than 7 is basic or alkaline. The lower the pH, the more acidic the substance. The pH scale is based on powers 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, 2008²²

Figure 2. Historical Changes in Ocean Acidity, 1700s–1990s

This figure shows changes in ocean pH levels around the world from pre-industrial times to the present based on modeled data.



Data source: Yool, 2007²³

carbon dioxide. Because of the lack of historical observation data, modeling has been used to make comparisons between pre-industrial times and the present.

Indicator Limitations

Changes in ocean pH caused by the uptake of atmospheric carbon dioxide tend to occur slowly relative to natural fluctuations, so the full effect of atmospheric carbon dioxide concentrations on ocean pH may not be seen for many decades, if not centuries.

Ocean chemistry is not uniform throughout the world's oceans, so local conditions could cause a pH measurement to seem incorrect or abnormal in the context of the global data.

Data Sources

Data for Figure 1 came from three ocean time series studies: the Bermuda Atlantic Time-Series Study, the Hawaii Ocean Time-Series, and the European Station for Time-Series in the Ocean (Canary Islands). Bermuda data were analyzed by Bates et al. (2002)²⁴ and Gruber et al. (2002).²⁵ Hawaii data were analyzed by Dore et al. (2003),²⁶ and Canary Islands data were analyzed by Gonzalez-Davila et al. (2003).²⁷ Bermuda and Hawaii data are available at: www1.whoi.edu. The map in Figure 2 was created using Global Ocean Data Analysis Project data, and the figure was provided by the Pacific Science Association Task Force on Ocean Acidification. This map and other information are available at: www.pacificscience.org/tfoceanacidification.html.

Snow and Ice



Arctic Sea Ice



Glaciers



Lake Ice



The Earth's surface contains many forms of snow and ice, including sea ice, lake and river ice, snow cover, glaciers, ice caps and sheets, and frozen ground. Together, these features are sometimes referred to as the “cryosphere,” a term for all parts of the Earth where water exists in solid form.

Snow and ice are an important part of the global climate system. Because snow and ice are highly reflective, much of the sunlight that hits these surfaces is reflected back into space instead of warming the Earth. The presence or absence of snow and ice affects heating and cooling over the Earth's surface, influencing the planet's energy balance.



Source: UNEP, 2007¹

Climate change can dramatically alter the Earth's snow- and ice-covered areas. Unlike other substances found on the Earth, snow and ice exist relatively close to their melting point and can change from solid to liquid and back again. As a result, prolonged warming or cooling trends can result in observable changes across the landscape as snow and ice masses shrink or grow over time.

Changes in snow and ice cover, in turn, affect air temperatures, sea levels, ocean currents, and storm patterns. For example, melting polar ice caps add fresh water to the ocean, increasing sea level and possibly changing currents that are driven by differences in temperature and salinity. Because of their light color, snow and ice 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.

Changes in snow and ice could not only affect communities and natural systems in northern and polar regions, but also have worldwide implications. For example, thawing of frozen ground and reduced sea ice in the Arctic could affect biodiversity on local and global scales, leading to harmful effects not only on polar bears and seals, but also on migratory species that breed or feed in these areas. These same changes could affect human societies in several ways, such as by compromising food availability. 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. Reduced snow cover 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.



Snow Cover



Snowpack



Arctic Sea Ice

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

Background

Sea ice is a key feature in the Arctic Ocean. During the dark winter months, sea ice covers nearly 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 extent in mid-September; then begins expanding again through the winter.

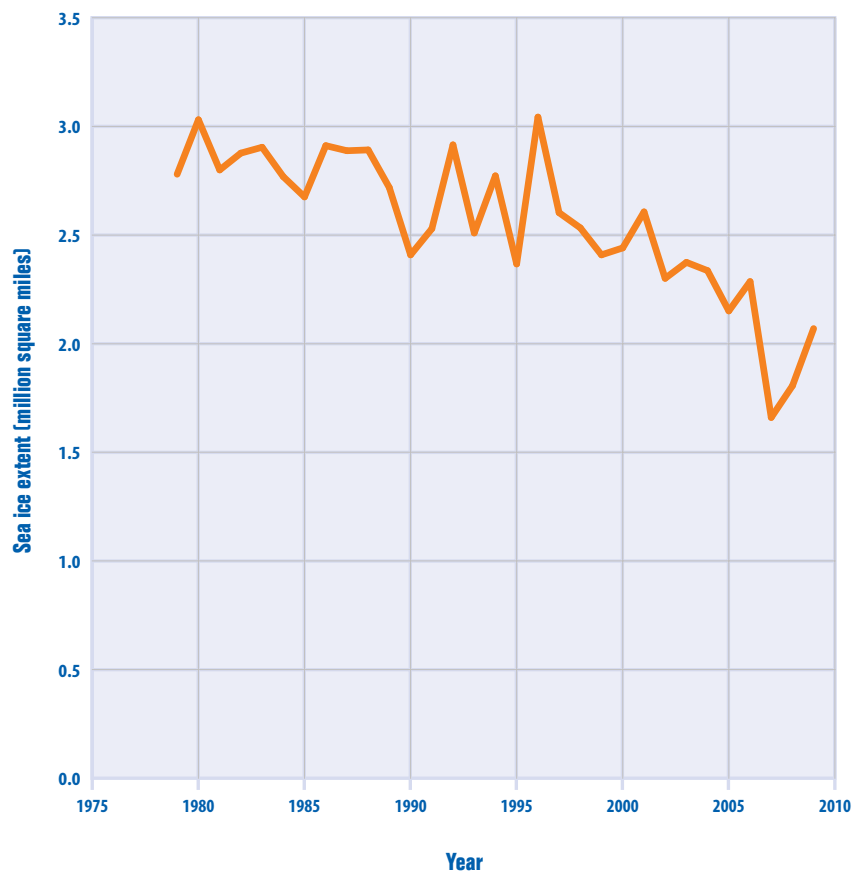
The extent of area covered by Arctic sea ice is considered a sensitive indicator of global climate because a warmer climate will reduce the amount of sea ice present. Because sea ice is more reflective than liquid water, it also plays a role in regulating global climate by keeping polar regions cool. (For more information on the effects of surface color on reflecting sunlight, see the Snow Cover indicator on p. 52.) Thus, as the amount of sea ice decreases because of increased air temperatures, 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.

Arctic mammals, such as polar bears and walrus, rely on the presence of sea ice to preserve their hunting, breeding, and migrating habits. These animals might become threatened if birth rates decline or access to food sources is restricted

(Continued on page 47)

Figure 1. September Average Arctic Sea Ice Extent, 1979–2009

This figure shows Arctic sea ice extent from 1979 through 2009 using data from September of each year, which is when the minimum extent typically occurs.



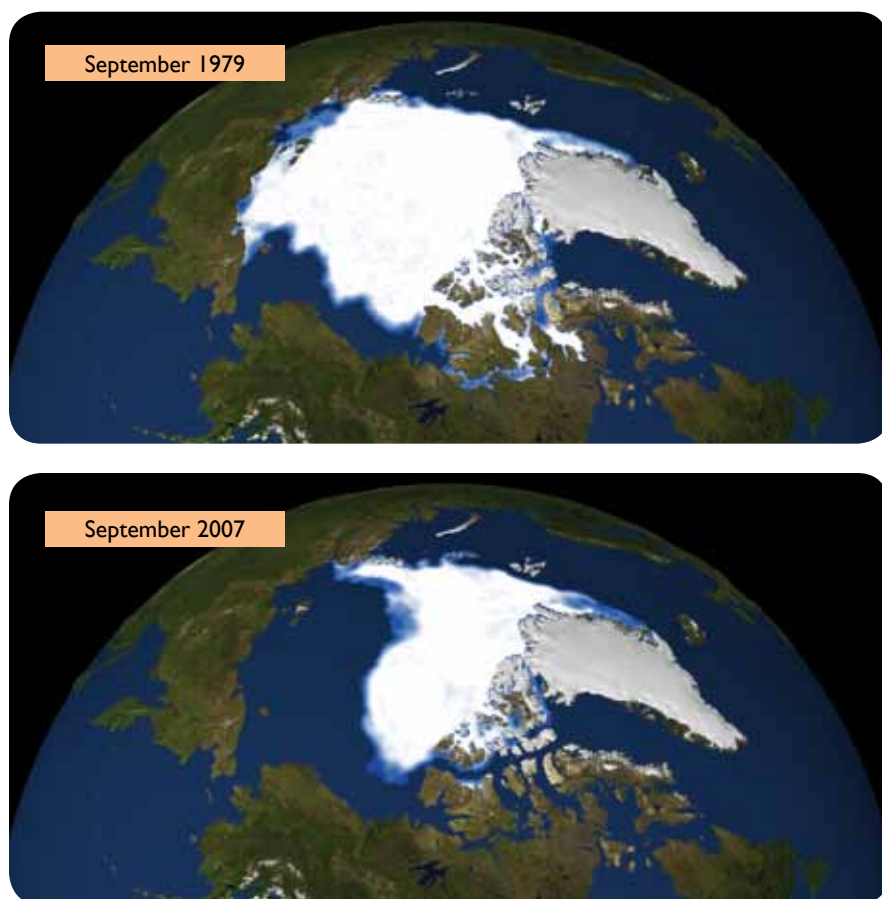
Data source: NSIDC, 2009²



Key Points

- The lowest sea ice extent on record occurred in September 2007. Compared with the previous minimum set in September 2005, the 2007 total reflected a loss of 490,000 square miles of sea ice—an area larger than Texas and California combined (see Figure 1).
- Compared with the 1979 to 2000 average, the extent of Arctic sea ice in 2007 was lower by 1 million square miles—an area approximately the size of Alaska and Texas combined (see Figure 1).
- Although September 2009 saw an increase in sea ice extent compared with 2007 and 2008, the 2009 sea ice extent was still 24 percent below the 1979 to 2000 historical average.
- Although the annual minimum of sea ice extent typically occurs in September, all months have shown a decreasing trend in sea ice extent over time.³

Dwindling Arctic Sea Ice



Source: NASA, 2009⁴

because of diminished sea ice. Impacts on Arctic wildlife, as well as the loss of ice itself, threaten the traditional lifestyle of indigenous Arctic populations such as the Yup'ik, Iñupiat, and Inuit. In addition to reducing the number of animals available to hunt, diminished sea ice extent and earlier melting can severely limit hunting seasons and access to hunting grounds, making traditional subsistence hunting more difficult. While diminished sea ice can have negative ecological effects, it can also present positive commercial opportunities. For instance, reduced sea ice opens shipping lanes and increases access to natural resources in the Arctic region.

About the Indicator

This indicator reviews trends in Arctic sea ice extent from 1979 to 2009. Sea ice extent is defined as the area of ocean where at least 15 percent of the surface is frozen. Data are collected throughout the year, but for comparison, this indicator focuses on sea ice extent data for September of each year. This is because September is typically when the sea ice extent reaches its annual minimum after melting during the summer months. Data for this indicator were gathered by the National Snow and Ice Data Center using satellite imaging technology.

Indicator Limitations

Increasing temperatures associated with climate change are not the only factor contributing to reductions in sea ice. Other conditions, such as fluctuations in oceanic and atmospheric circulation and typical annual and decadal variability, also affect the extent of sea ice. Additionally, changes in the age and thickness of sea ice—a trend toward younger and thinner ice—might also increase the rate at which the ice melts in summer, making year-to-year comparisons more complex.

Data Sources

The data for this indicator were provided by the National Snow and Ice Data Center and are available online at: http://nsidc.org/data/seaice_index/archives/index.html. The National Snow and Ice Data Center also 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 describes how the size of glaciers around the world has changed over time.

Background

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 naturally flows like a river, only much slower. It accumulates snow at higher elevations, which eventually becomes compressed into ice. At lower elevations, the “river” of ice naturally loses volume because of melting and ice breaking off and floating away. When melting is exactly balanced by new snow accumulation, a glacier is in equilibrium and is neither growing nor shrinking.

Glaciers are important to humans and ecosystems because their normal melting process provides a reliable source of stream flow and drinking water, particularly late in the summer when seasonal snowpack has melted away. A large portion of Earth’s fresh water is found in glaciers, including the polar ice sheets. Glaciers are also important as an indicator of climate change. 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 mass to melting and breaking off (particularly the Greenland and Antarctic ice sheets), they ultimately add more water to the oceans, leading to a rise in sea level (see the Sea Level indicator on p. 40).

About the Indicator

This indicator is based on long-term monitoring data collected at glaciers around the world. At many glaciers, scientists collect detailed measurements to determine 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. Looking at cumulative mass balance over time will reveal long-term trends. For example, if cumulative mass balance becomes more negative over time, it means glaciers are melting faster than they can accumulate new snow.

Figure 1 shows the total change in volume of glaciers worldwide since 1960, when widespread measurement began to take place. The overall change in volume was determined by collecting all available measurements, then estimating a global trend based on the total surface area of

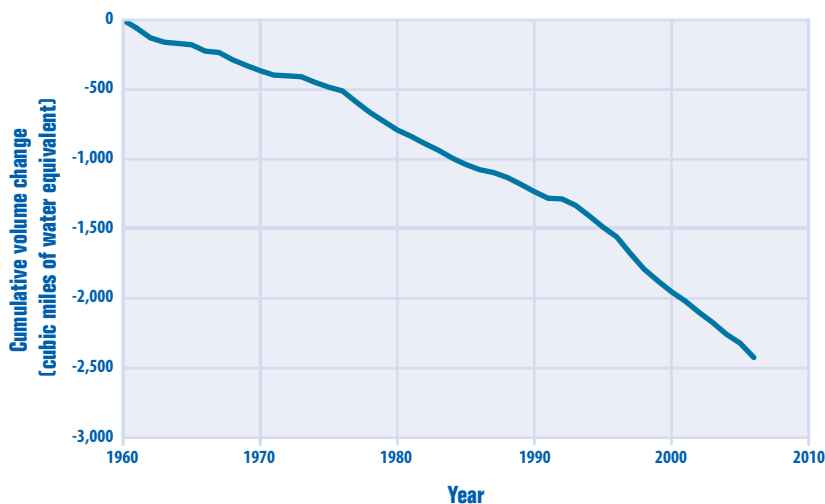
Photographs of Muir Glacier, Alaska, 1941 and 2004



Sources: Field, 1941;⁵ Molnia, 2004⁶

Figure 1. Change in Volume of Glaciers Worldwide, 1960–2006

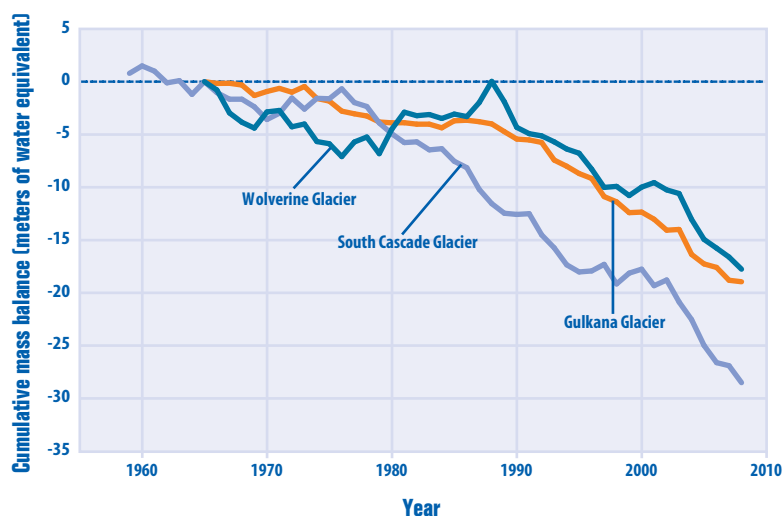
This figure shows the cumulative change in volume of glaciers worldwide beginning in 1960. Negative values in later years indicate a net loss of ice and snow compared with the base year of 1960. For consistency, measurements are in cubic miles of water equivalent, which means the total amount of ice or snow lost has been converted to the equivalent volume of liquid water.



Data source: Dyurgerov, in press⁷

Figure 2. Mass Balance of Three Typical U.S. Glaciers, 1958–2008

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 in later years indicate a net loss of ice and snow compared with the base year. For consistency, measurements are in meters of water equivalent, which means the amount of ice or snow has been converted to the equivalent amount of liquid water.



Data source: USGS, 2009⁸

Key Points

- Since 1960, glaciers worldwide have lost more than 2,000 cubic miles of water (see Figure 1), which in turn has contributed to observed changes in sea level (see the Sea Level indicator on p. 40). The rate at which glaciers are losing volume appears to have accelerated over roughly the last decade.
- All three U.S. benchmark glaciers have shown an overall decline in mass since the 1950s and 1960s (see Figure 2). Year-to-year trends vary, with some glaciers gaining mass in certain years (for example, Wolverine Glacier between 1986 and 1988). However, most of the measurements indicate a loss of 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.⁹ 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. 22).

Glaciers Shown in Figure 2



glaciers worldwide. Figure 2 shows trends for three “benchmark” glaciers that have been extensively studied by the U.S. Geological Survey: 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 are representative of other glaciers in their regions.

Indicator Limitations

The relationship between climate change and glacier mass balance is complex, and the observed changes at the three U.S. benchmark glaciers might reflect a combination of global and local climate variations. Slightly different measurement 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, so the total global trend in Figure 1 is also based in part on some of the best available estimates. The total in Figure 1 does not include the Greenland and Antarctic ice sheets. Other evidence suggests that these ice sheets are also experiencing a net loss in volume.¹⁰

Data Sources

The University of Colorado at Boulder provided the global trend in Figure 1. Its analysis is based on measurements collected from a variety of publications and databases. An older version of this analysis was published by the U.S. Global Change Research Program in 2009,¹¹ and the latest version is expected to be published in the scientific literature sometime in 2010.

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 Web site at: <http://ak.water.usgs.gov/glaciology>.

Lake Ice

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

Background

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 lake ice duration. 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, whereas an ice- and snow-covered lake will reflect the sun's energy rather than absorb it. (For more information on ice and snow reflecting sunlight, see the Snow Cover indicator on p. 52.)

The timing and duration of ice cover on lakes and other bodies of water can also affect society—particularly shipping and transportation, hydroelectric power generation, and fishing. The impacts can be either 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 because of decreased water levels.

About the Indicator

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

(Continued on page 51)

Key Points

- The time that lakes stay frozen has generally decreased since the mid-1800s. For most of the lakes in this indicator, the duration of ice cover has decreased at an average rate of one to two days per decade (see Figure 1).
- The lakes covered by this indicator are generally freezing later than they did in the past. Freeze dates have grown later at a rate of roughly half a day to one day per decade (see Figure 2).
- Thaw dates for most of these lakes show a general trend toward earlier ice breakup in the spring (see Figure 3).
- The changes in 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 at an average rate of 5.8 days per 100 years, and thaw dates have occurred earlier at an average rate of 6.5 days per 100 years.¹²

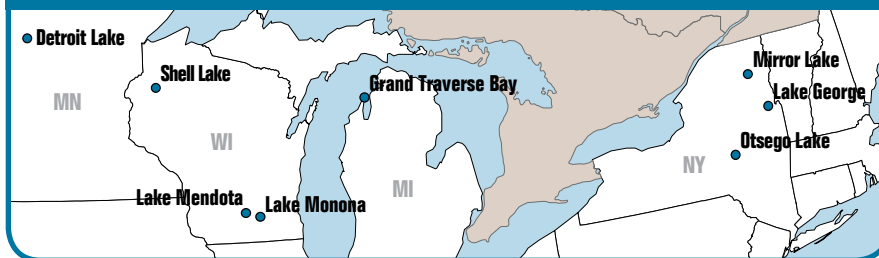


Figure 1. Duration of Ice Cover for Selected U.S. Lakes, 1850–2000

This figure displays the duration (in days) of ice cover for eight U.S. lakes. The data are available from approximately 1850 to 2000, depending on the lake, and have been smoothed using a nine-year moving average.

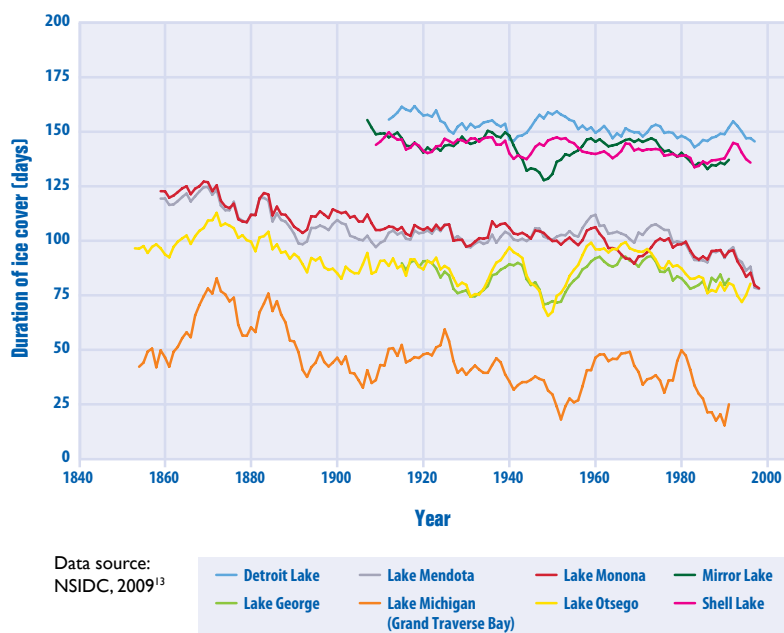


Figure 2. Ice Freeze Dates for Selected U.S. Lakes, 1850–2000

This figure shows the “ice-on” date, or date of first freeze, for eight U.S. lakes. The data are available from approximately 1850 to 2000, depending on the lake, and have been smoothed using a nine-year moving average.

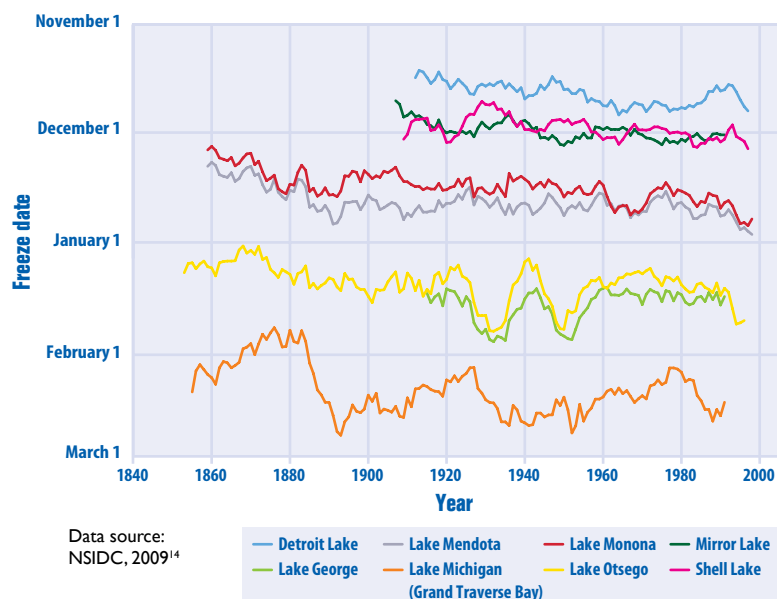
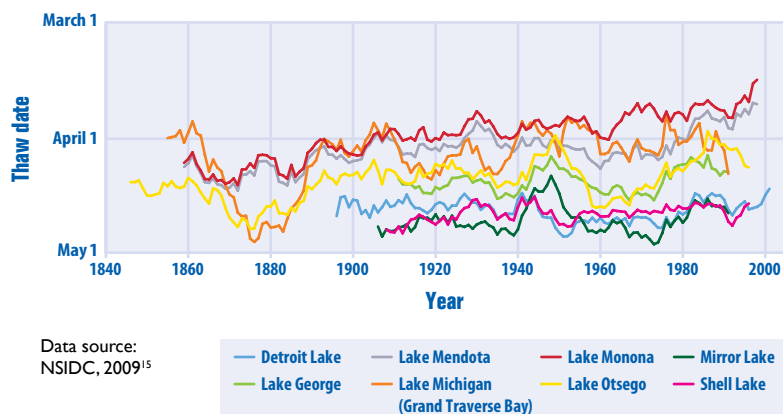


Figure 3. Ice Thaw Dates for Selected U.S. Lakes, 1850–2000

This figure shows the “ice-off” date, or date of ice thawing and breakup, for eight U.S. lakes. The data are available from approximately 1850 to 2000, depending on the lake, and have been smoothed using a nine-year moving average.



Freeze and thaw dates have been recorded through 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 eight lakes within the United States that have the longest and most complete historical records. The lakes of interest are located in Minnesota, Wisconsin, Michigan, and New York.

Indicator Limitations

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, ranging from brief lapses to large gaps in data. This indicator is limited to eight lakes with fairly complete historical records.

Data used in this indicator are all based on visual observations. Records based on 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 the shore, which might not be representative of lakes as a whole or comparable to more recent satellite-based observations.

Data Sources

Data 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.



Snow Cover

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

Background

The amount of land covered by snow at any given time is influenced by many climate factors, such as the amount of snowfall an area receives and the timing of that snowfall. 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 reflects much of the sunlight that hits it. In contrast, darker surfaces such as open water absorb more light 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, while less snow cover means the Earth will absorb more heat and become warmer.

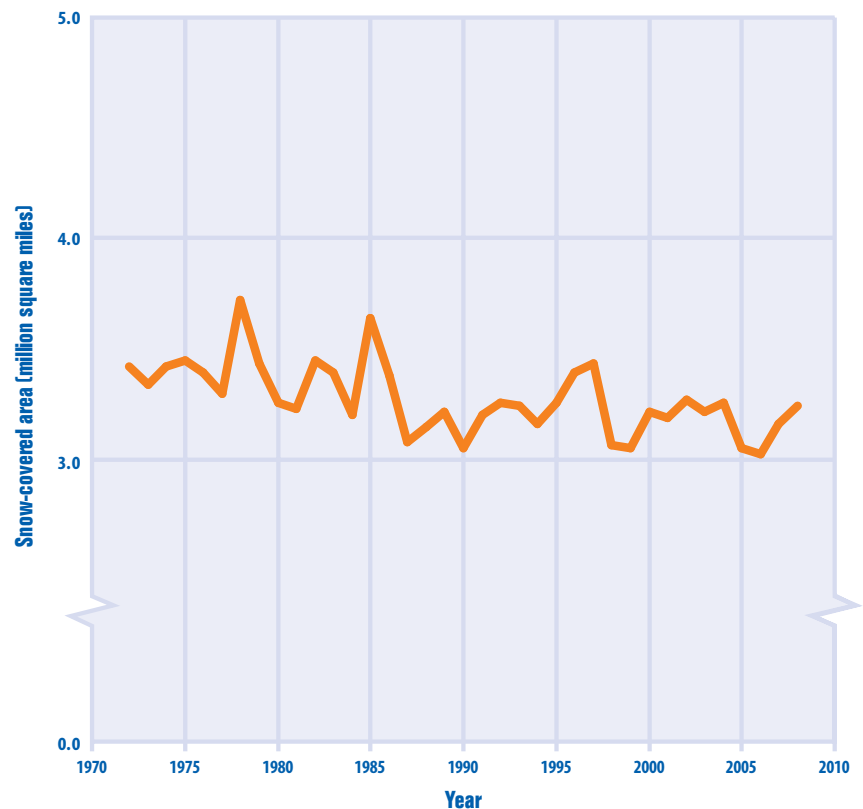
On a more local scale, snow cover is important for many plants and animals. For example, some plants rely on a protective blanket of snow to insulate them from sub-freezing winter temperatures. Humans and ecosystems also rely on snowmelt to replenish streams and ground water.

About the Indicator

This indicator tracks the total area covered by snow across all of North America 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.

Figure 1. Snow-Covered Area in North America, 1972–2008

This graph shows the average area covered by snow in a given year, based on an analysis of weekly maps. The area is measured in square miles. These data cover all of North America.



Data source: Rutgers University Global Snow Lab, 2009¹⁶



Key Points

- Overall, during the period from 1972 to 2008, snow covered an average of 3.3 million square miles of North America (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 3.7 million square miles, with the minimum value occurring in 2006 and the maximum in 1978 (see Figure 1).
- Looking at averages by decade suggests that the extent of North America covered by snow has decreased steadily over time. The average extent for the 1970s (1972 to 1979) was 3.43 million square miles, compared with 3.3 million for the 1980s, 3.21 million for the 1990s, and 3.18 million from 2000 to 2008 (see Figure 1).

Indicator Limitations

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.

Because it examines only yearly averages, this indicator does not show whether trends in overall snow cover are being driven by decreases in winter extent, summer extent (at high elevations and latitudes), or both. An analysis of more detailed weekly and monthly data suggests that the largest decreases have come in spring and summer.¹⁷

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>. It is based on measurements collected by the National Oceanic and Atmospheric Administration's National Environmental Satellite Data and Information Service at: www.nesdis.noaa.gov.





Snowpack

This indicator measures trends in mountain snowpack in western North America.

Background

Temperature and precipitation are key factors affecting snowpack, which is the amount of snow that accumulates on the ground. In a warming climate, more precipitation will be expected to fall as rain, not snow, in most areas—reducing the extent and depth of snowpack. Snow will also melt earlier in the spring.

Mountain snowpack is a key component of the water cycle in western North America, storing water in the winter when the snow falls and releasing it in spring and early summer when the snow melts. Millions of people in the West depend on the springtime melting of mountain snowpack for power, irrigation, and drinking water. In most western river basins, snowpack is a larger component of water storage than man-made reservoirs.¹⁸

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 stream flows.

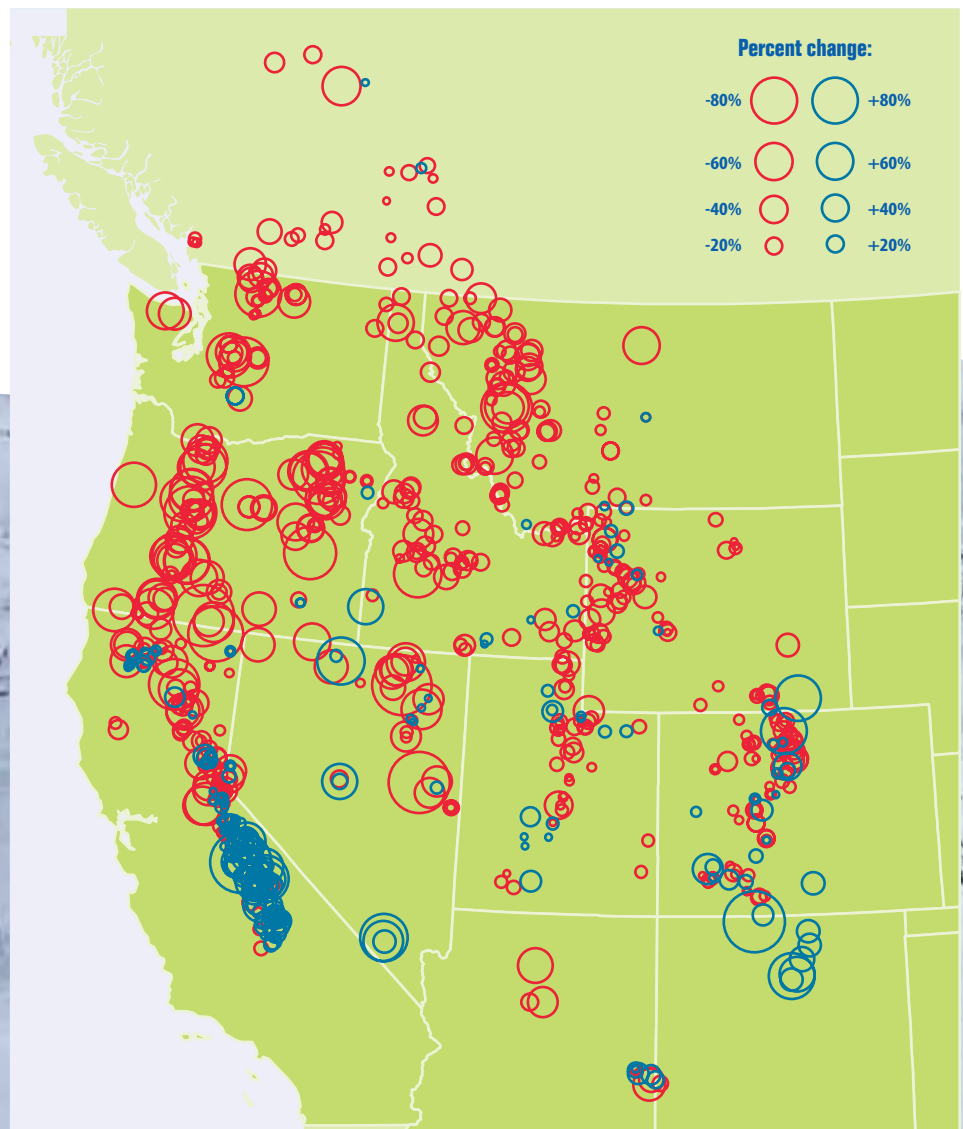
About the Indicator

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 1930s. 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 800 permanent

Figure 1. Trends in April Snowpack in the Western United States and Canada, 1950–2000

This map shows trends in snow water equivalent in the western United States and part of Canada. Negative trends are shown by red circles and positive trends by blue.



Data source: Mote, 2009¹⁹

(Continued on page 55)

Key Points

- From 1950 to 2000, April snow water equivalent declined at most of the measurement sites (see Figure 1), with some relative losses exceeding 75 percent.
- In general, the largest decreases were observed in western Washington, western Oregon, and northern California. April snowpack decreased to a lesser extent in the northern Rockies.
- A few areas have seen increases in snowpack, primarily in the southern Sierra Nevada of California and in the Southwest.

research sites in the western United States and Canada. The indicator shows trends for the month of April, which could reflect changes in winter snowfall as well as the timing of spring snowmelt.

Indicator Limitations

Natural changes in the Earth's climate could affect snowpack in such a way that trends might slightly differ if measured over a different time period. The 1950s registered some of the highest snowpack measurements of the 20th century in the Northwest. While these values could be magnifying the extent of the snowpack decline depicted in Figure 1, 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. 22), snowfall trends may be partially influenced by nonclimatic 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. The map was constructed using methods described in Mote et al. (2005).²⁰ The U.S. Department of Agriculture data are available at: www.wcc.nrcs.usda.gov.



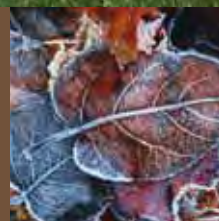
Society and



Heat-Related Deaths



Length of Growing Season



Plant Hardiness Zones

Ecosystems



The indicators in this report show that changes are occurring throughout the Earth's climate system, including increases in air and water temperatures, a rise in sea level, longer growing seasons, and longer ice-free periods on lakes and rivers. Changes such as these are expected to present a wide range of challenges to human society and natural ecosystems.

For society, increases in temperature are likely to increase heat-related illnesses and deaths, especially in urban areas. Changes in precipitation patterns will affect water supplies and quality, while more severe storms and floods will damage property and infrastructure (such as roads, bridges, and utilities) or cause loss of life. Rising sea levels will inundate low-lying lands, erode beaches, and cause flooding in coastal areas. Climate change also will affect agriculture, energy production and use, land use and development, and recreation.

While species have adapted to environmental change for millions of years, climate change could require adaptation on larger and faster scales than current species have successfully achieved in the past.

Climate also plays an important role in natural ecosystems. An ecosystem is an interdependent system of plants, animals, and microorganisms interacting with one another and their environment. Ecosystems provide humans with food, clean water, and a variety of other services that could be affected by climate change. While species have adapted to environmental change for millions of years, climate change could require adaptation on larger and faster scales than current species have successfully achieved in the past. Climate change could also increase the risk of extinction for some species.

The more the climate changes, the greater the risk of harm. The nature and extent of climate change effects, and whether these effects will be harmful or beneficial, will vary by time and place. The extent to which climate change will affect different ecosystems, 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.



**Leaf and
Bloom
Dates**



**Bird
Wintering
Ranges**



Heat-Related Deaths

This indicator reviews trends in heat-related deaths in the United States.

Background

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

Heat waves have become more frequent in most of North America in recent decades (see the Heat Waves indicator on p. 24), and these events can be associated with increases in heat-related deaths.

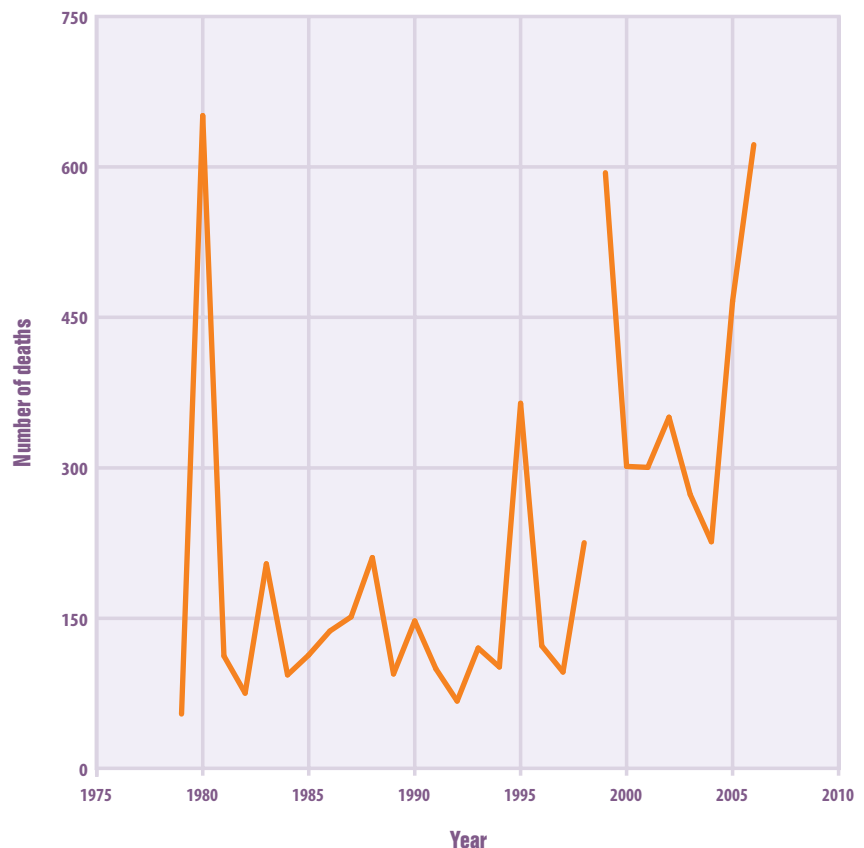
Older adults carry the highest risk of heat-related death. Across North America, the population over the age of 65 is expected to increase slowly until 2010, and then grow dramatically as the baby boom generation ages. People with certain diseases, such as cardiovascular and respiratory illnesses, are especially sensitive to heat.

About the Indicator

This indicator shows the number of heat-related deaths each year in the United States from 1979 to 2006, the years for which national data are available. The indicator is based on data from the U.S. Centers for Disease Control and Prevention, which maintains a database that tracks all deaths nationwide. Data in this indicator include only those deaths for which excessive natural heat was stated as the underlying cause of death on the death certificate. Other studies might consider a broader definition of "heat-related" by also including deaths for which heat has been listed as a contributing factor. For example, even in a case where cardiovascular disease is determined to be the underlying cause of death, heat could have contributed by making the individual more susceptible to the effects of the disease.

Figure 1. Heat-Related Deaths in the United States, 1979–2006

This figure shows the annual number of heat-related deaths occurring in the 50 states and the District of Columbia from 1979 to 2006.*



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

Data source: CDC, 2009¹



Key Points

- Overall, during the 28 years of data collection (1979–2006), 6,367 deaths were classified as heat-related (see Figure 1).
- Considerable year-to-year variability in the number of heat-related deaths makes it difficult to determine whether the United States has experienced a meaningful increase or decrease in heat-related deaths over time.
- Dramatic increases in cases of heat-related mortality are closely associated with the occurrence of heat waves, especially those of 1980 (St. Louis and Kansas City, Missouri), 1995 (Chicago, Illinois), and 1999 (Cincinnati, Ohio, and Chicago).



Indicator Limitations

Just because a death is classified as “heat-related” does not mean that high temperatures were the only factor that caused the death. Pre-existing medical conditions can significantly increase an individual’s vulnerability to heat. This indicator does not include deaths for which heat was listed as a contributing cause but not the official underlying cause of death. Including deaths for which heat was a contributing cause would substantially increase the number of deaths shown in Figure 1. For example, the U.S. Centers for Disease Control and Prevention reported 54 percent more deaths resulting from exposure to extreme heat between 1999 and 2003 (totaling 3,442) when they included deaths for which heat was a contributing cause.²

Heat waves are not the only factor that can affect trends in “heat-related” deaths. Other factors include the vulnerability of the population, the extent to which people have adapted to higher temperatures, the local climate and topography, and the steps people have taken to manage heat emergencies effectively.

Heat response measures can make a big difference in death rates. These measures can include early warning and surveillance systems, air conditioning, health care, public education, infrastructure standards, and air quality management. For example, after a 1995 heat wave, the City of Milwaukee developed a plan for responding to extreme heat conditions in the future. During the 1999 heat wave, this plan cut heat-related deaths nearly in half compared with what was expected.³

Data Sources

Data for this indicator were provided by the U.S. Centers for Disease Control and Prevention (CDC) and are available in the CDC WONDER database in the Compressed Mortality File at: <http://wonder.cdc.gov/mortSQL.html>. In the CDC WONDER database for the period from 1979 to 1998, heat-related mortalities were classified as International Classification of Disease, Ninth Revision (ICD-9) codes E900 “excessive heat—hyperthermia” and E900.0 “due to weather conditions.” For the period from 1999 to 2006, deaths were classified as ICD-10 code X30 “exposure to excessive natural heat—hyperthermia.”



Length of Growing

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

Background

The length of the growing season in any given region represents 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. Moderate warming can benefit crop and pasture yields in mid- to high-latitude regions, yet even slight warming decreases yields in seasonally dry and low-latitude regions.⁴ 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 strain water supplies. 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.

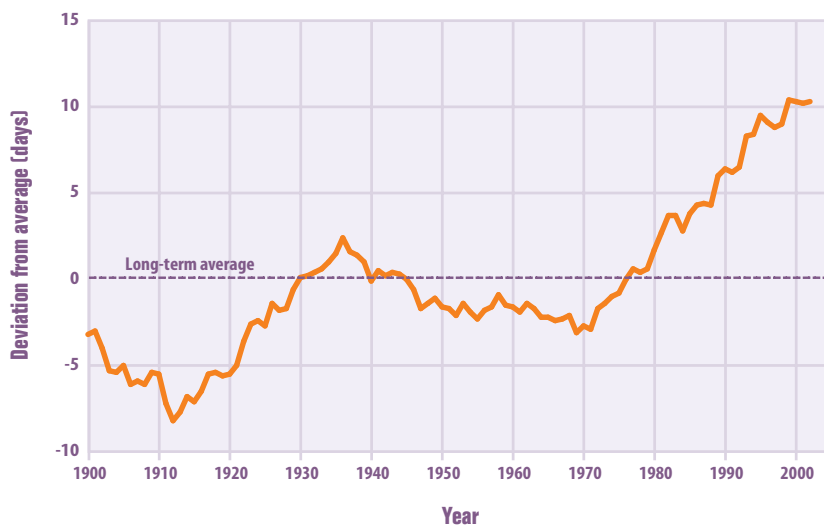
About the Indicator

This indicator looks at the length of the growing season in the lower 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.

Trends in the growing season were calculated using temperature data from 794 weather stations throughout the lower 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 spatially, then compared with a long-term average to determine the deviation from "normal" in any given year.

Figure 1. Length of Growing Season in the Lower 48 States, 1900–2002

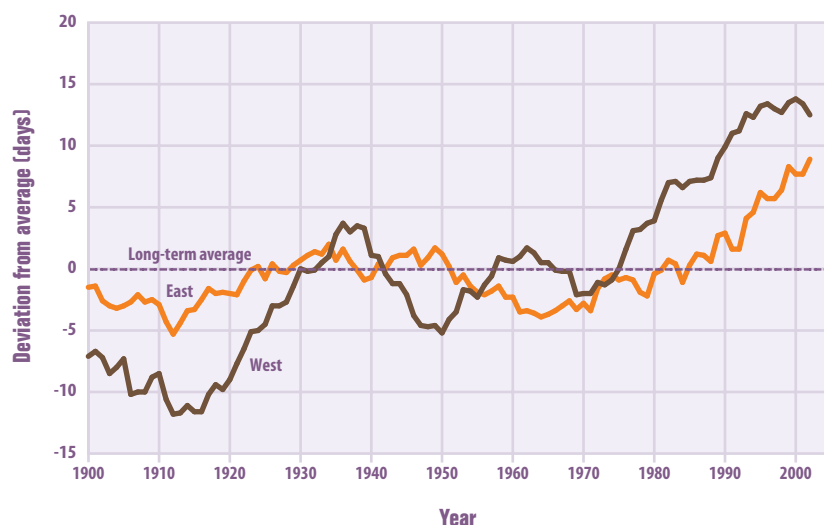
This figure shows the length of the growing season in the lower 48 states compared with a long-term average. For each year, the line represents the number of days shorter or longer than average. The trend line was smoothed using an 11-year moving average. Choosing a different long-term average for comparison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



Data source: Kunkel, 2009⁵

Figure 2. Length of Growing Season in the Lower 48 States, 1900–2002: 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. The trend line was smoothed using an 11-year moving average. Choosing a different long-term average for comparison would not change the shape of the trends.



Data source: Kunkel, 2009⁶

Key Points

- The average length of the growing season in the lower 48 states has increased by about 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 20 days per century since 1900, compared with a rate of about six days per century in the East (see Figure 2).
- The final spring frost is now occurring earlier than at any point since 1900, and the first fall frosts are arriving later. Since 1985, the last spring frost has arrived an average of about four days earlier than the long-term average, and the first fall frost has arrived about three days later (see Figure 3).

Indicator Limitations

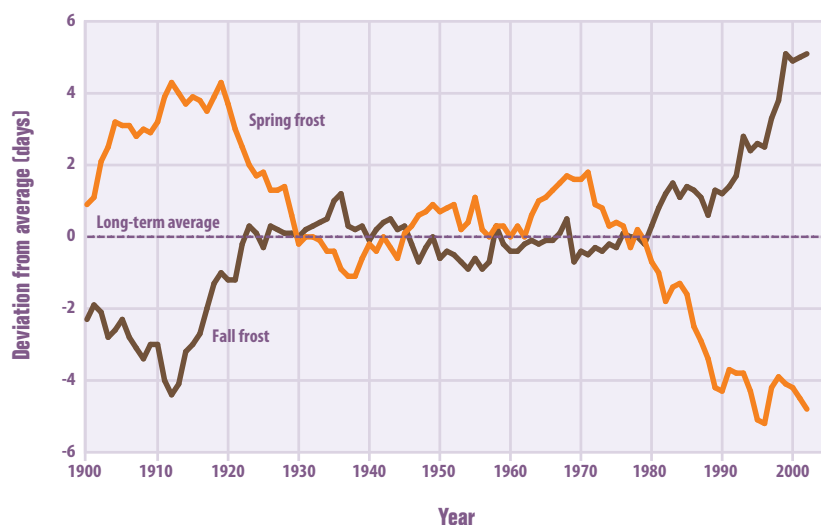
Changes in measurement techniques and instruments over time can affect trends. However, these data were carefully reviewed for quality, and values that appeared invalid were not included in the indicator. This indicator only includes weather stations that did not have many missing data points.

Data Sources

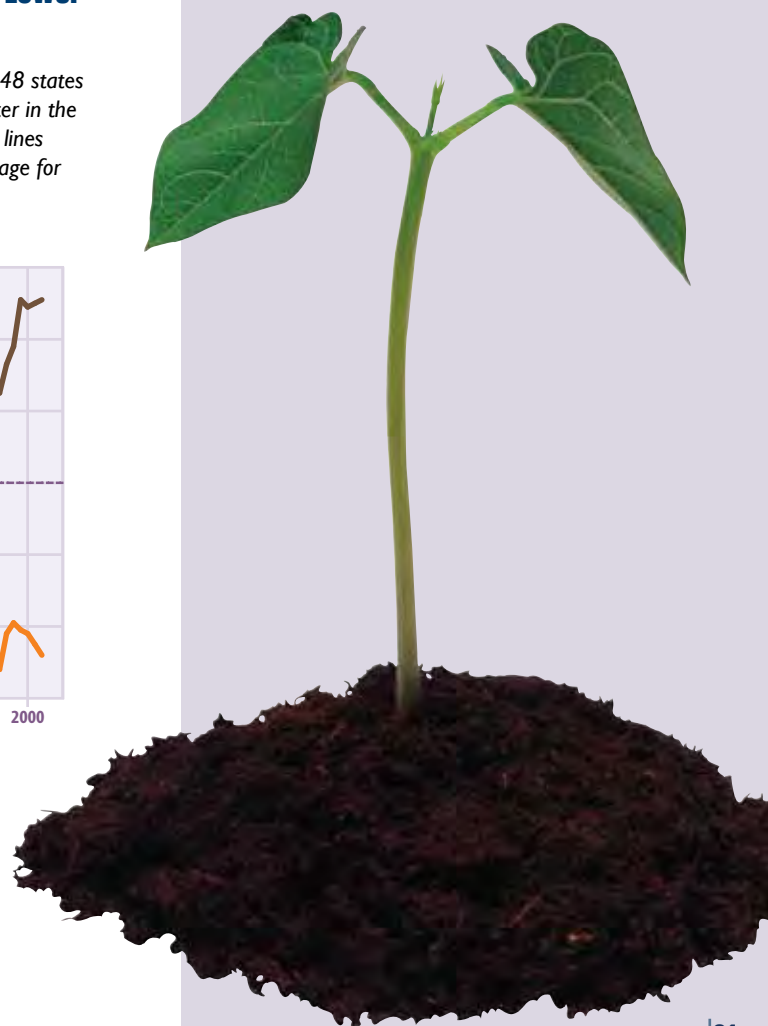
All three figures are based on data compiled by the National Oceanic and Atmospheric Administration's National Climatic Data Center, and these data are available online at: www.ncdc.noaa.gov/oa/ncdc.html. Trends were analyzed by Kunkel (2009).⁸

Figure 3. Timing of Last Spring Frost and First Fall Frost in the Lower 48 States, 1900–2002

This figure shows the timing of the last spring frost and the first fall frost in the lower 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 trend lines were smoothed using an 11-year moving average. Choosing a different long-term average for comparison would not change the shape of the trends.



Data source: Kunkel, 2009⁷





Plant Hardiness

This indicator examines shifts in plant hardiness zones in the lower 48 states.

Background

Plant hardiness zones are regional designations that help farmers and gardeners determine which plant species are expected to survive a typical winter. Locations are assigned a numbered plant hardiness zone based on an average of the lowest temperatures recorded each winter.

Average annual minimum temperature is used to determine hardiness zones because a single low temperature event such as a freeze is far more likely to harm plants than a single high-temperature event, such as an unusually warm day. Minimum temperature is considered a critical factor in a plant's ability to survive in a particular location.

As temperatures increase, plants are able to survive winters in areas that were previously too cold for them to thrive. These changes in growing patterns can influence agricultural production, and changes in wild plant distribution can have wide-ranging effects on ecosystems. For instance, the animal species present in a location could change as the animals move to seek out their preferred food source, or an invasive plant could harm native plant species.

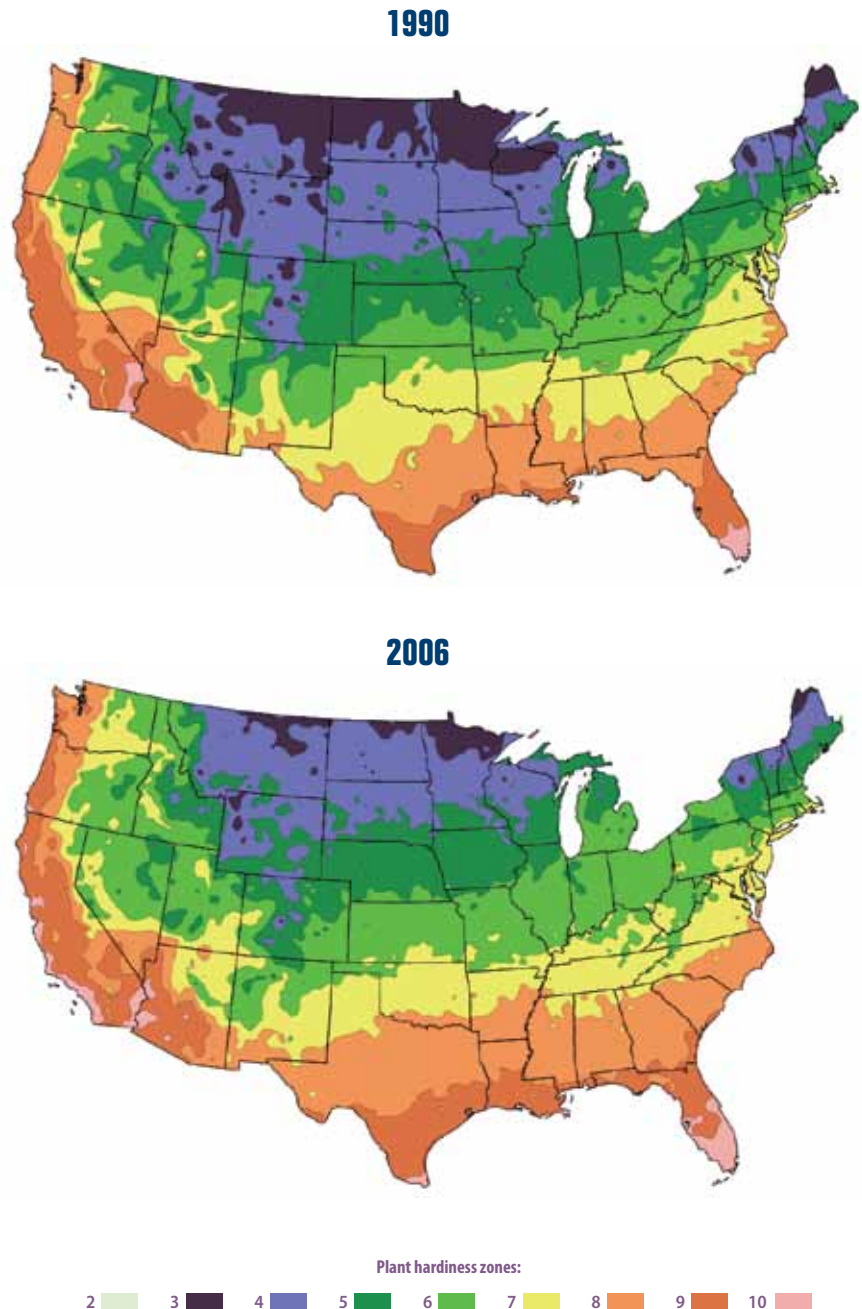
About the Indicator

The U.S. Department of Agriculture first published a plant hardiness zone map of the United States in 1960, and revised the map in 1990. This map is divided into numbered zones based on average annual low temperatures in 10-degree increments. For example, areas in Zone 7 have an average annual minimum temperature of 0 to 10°F, while areas in Zone 8 have an average annual minimum temperature of 10 to 20°F.

In 2006, the Arbor Day Foundation revised the map based on 15 years of temperature data collected by 5,000 National Oceanic and Atmospheric Administration weather stations across the United States. To determine how plant hardiness zones have shifted over time, this indicator compares the 1990 U.S. Department of Agriculture hardiness zone map with the 2006 Arbor Day Foundation hardiness zone map.

Figure 1. United States Plant Hardiness Zones, 1990 and 2006

This figure depicts plant hardiness zones in the lower 48 states in 1990 and 2006.



Data source: Arbor Day Foundation, 2006⁹

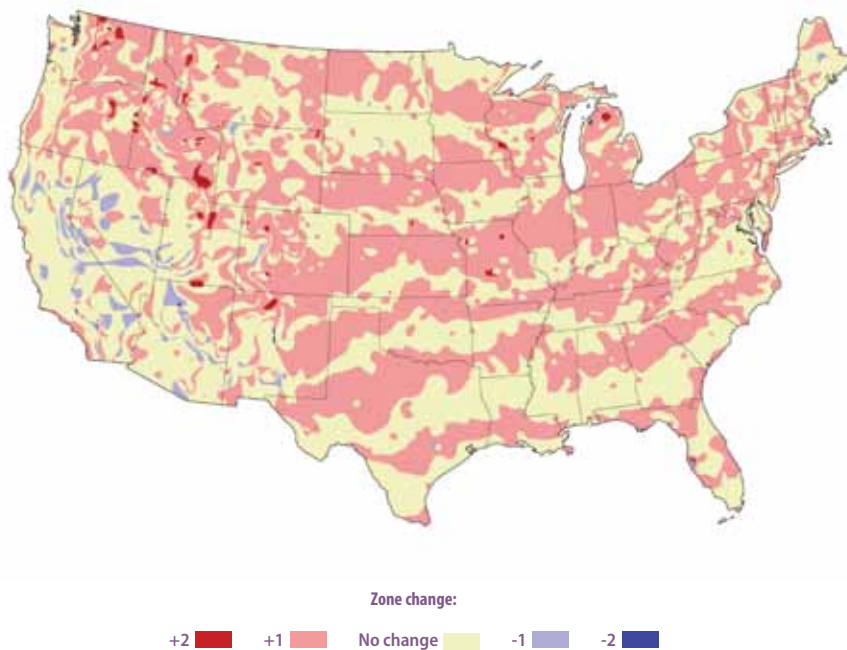
Zones

Key Points

- Between 1990 and 2006, hardiness zones have shifted noticeably northward, reflecting warmer winter temperatures (see Figures 1 and 2).
- Large portions of several states have warmed by at least one hardiness zone; for example, large parts of Illinois, Indiana, Ohio, and Missouri have shifted from Zone 5 to Zone 6, reflecting a sizable increase in average low temperatures (see Figures 1 and 2).
- A few scattered areas, mostly in the West, have cooled by one hardiness zone, while a few smaller areas have cooled by two hardiness zones (see Figure 2).

Figure 2. United States Plant Hardiness Zones, 1990 Versus 2006

This figure depicts changes in plant hardiness zones in the lower 48 states between 1990 and 2006.



Data source: Arbor Day Foundation, 2006¹⁰

Indicator Limitations

Changes in plant hardiness zones do not address maximum temperatures or the amount of precipitation present in a location, which can also affect plants' ability to thrive. Plant hardiness zones also do not take into account the regularity and amount of snow cover, elevation, soil drainage, and the regularity of freeze and thaw cycles. As a result, plant hardiness zone maps are less useful in the western United States, where elevation and precipitation vary widely. For example, both Tucson, Arizona, and Seattle, Washington, are in Zone 9 according to the 2006 map; however, the native vegetation in the two cities is very different.

Data Sources

The maps used in this indicator are available online at: www.arborday.org/media/map_change.cfm. The data used to create the map were provided by the National Oceanic and Atmospheric Administration's National Climatic Data Center, which provides temperature data and maps through its Web site at: www.ncdc.noaa.gov/oa/ncdc.html.





Leaf and Bloom

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

Background

The timing of natural events, such as flower blooms and animal migration, is influenced by changes in climate. Phenology is the study of such important seasonal events. Phenological events are influenced by a combination of climate factors, including light, temperature, rainfall, and humidity.

Scientists have very high confidence that recent warming trends in global climate are linked to an earlier arrival of spring events.¹¹ 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. 60), more abundant invasive species and pests, and earlier and longer allergy seasons.

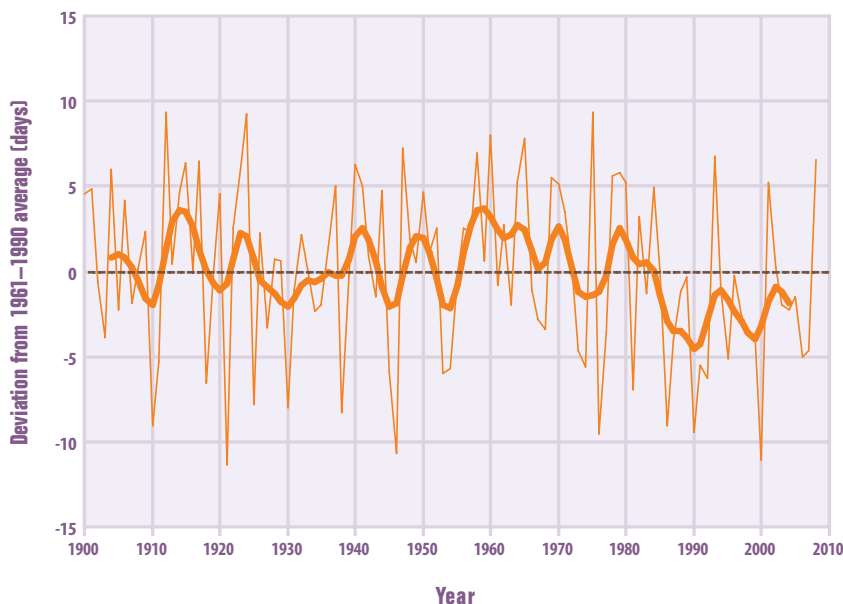
Because of their close connection with climate, the timing of phenological events can be accurate indicators of climate change. Some phenological indicators cover broad trends, such as overall “leaf-on” dates (when trees grow new leaves in the spring), using a combination of satellite data and ground observations. Others rely on ground observations that look at specific types or species of plants or animals. Two particularly useful indicators of the timing of spring events are the first leaf date and the first bloom date of lilacs and honeysuckles, which have an easily monitored flowering season, relatively high survival rate, and large geographic distribution (see map of lilac range at right). The first leaf date in these plants relates to the timing of “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.¹²

About the Indicator

This indicator shows trends in the timing of first leaf dates and first bloom dates in lilacs and honeysuckles across much of the lower 48 states (see map at right). Because many of the phenological observation records in the United States are less than 20 years long, models have been used to provide a more complete understanding of long-term trends.

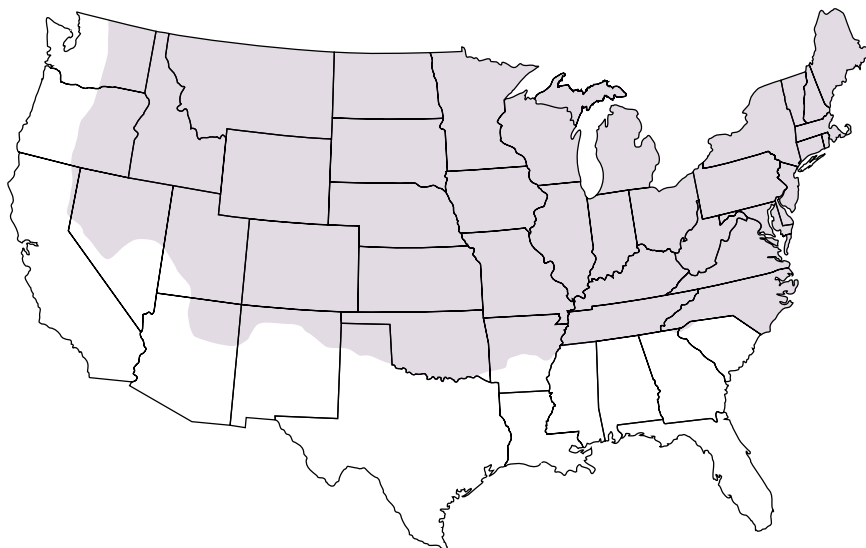
Figure 1. First Leaf Dates in the Lower 48 States, 1900–2008

This figure shows modeled trends in lilac and honeysuckle first leaf dates across the lower 48 states, using the 1961 to 1990 average as a baseline. Positive values indicate that leaf growth began later in the year, and negative values indicate that leafing occurred earlier. The thicker line was smoothed using a nine-year weighted average. Choosing a different long-term average for comparison would not change the shape of the trend.



Data source: Schwartz, 2009¹³

Range of Lilacs Covered in This Indicator



Source: Schwartz, 2009¹⁴

(Continued on page 65)

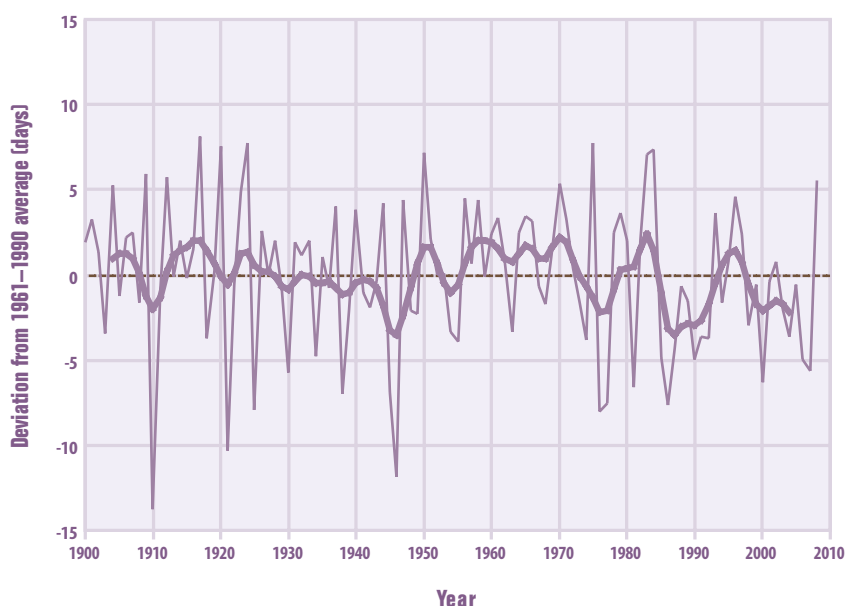
Dates

Key Points

- First leaf growth in lilacs and honeysuckles in the lower 48 states is now occurring a few days earlier than it did in the early 1900s. Although the data show a great deal of year-to-year variability, a noticeable change seems to have begun around the 1980s (see Figure 1).
- Lilacs and honeysuckles are also blooming slightly earlier than in the past. However, the data show a high degree of year-to-year variability, which makes it difficult to determine whether this change is statistically meaningful (see Figure 2).
- Other studies have looked at trends in leaf and bloom dates across all of North America and the entire Northern Hemisphere. These other studies have also found a trend toward earlier spring events, and many of these trends are more pronounced than the trends seen in just the lower 48 states.¹⁵

Figure 2. First Bloom Dates in the Lower 48 States, 1900–2008

This figure shows modeled trends in lilac and honeysuckle bloom dates across the lower 48 states, using the 1961 to 1990 average as a baseline. Positive values indicate that blooming occurred later in the year, and negative values indicate that blooming occurred earlier. The thicker line was smoothed using a nine-year weighted average. Choosing a different long-term average for comparison would not change the shape of the trend.



Data source: Schwartz, 2009¹⁶

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 citizen scientists 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 leaf and bloom dates and climate factors (particularly temperatures), they used this knowledge to estimate leaf and bloom dates for earlier years based on historical weather records.

This indicator uses data from several hundred weather stations throughout the area where lilacs and honeysuckles grow. 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 1961 to 1990 average to determine the number of days’ “deviation from normal.” This indicator presents the average deviation across all stations.

Indicator Limitations

Plant phenological events are studied using several data collection methods, including satellite images, models, and direct observations. The use of varying data collection methods in addition to the use of 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 genetic influences by relying on cloned plant species (that is, plants with no genetic differences).

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. (2006).¹⁷



Bird Wintering

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

Background

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

- Each species of bird has adapted to 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 nonmigratory 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 habitats or habits is seen across a range of bird types, it suggests that a common force might be contributing to that change.

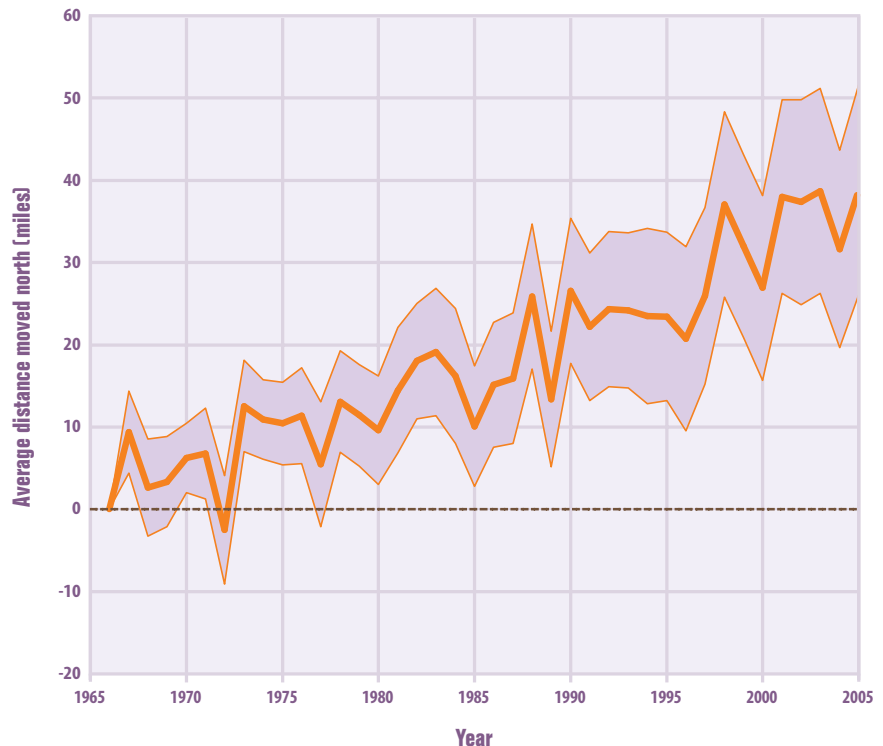
Temperature and precipitation patterns are changing across the United States (see the U.S. and Global Temperature indicator on p. 22 and the U.S. and Global Precipitation indicator on p. 28). Some bird species can adapt to generally warmer temperatures by changing where they live—for example, by migrating further north in the summer but not as far south in the winter, or by shifting inland as winter temperature extremes grow less severe. Nonmigratory 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 might 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

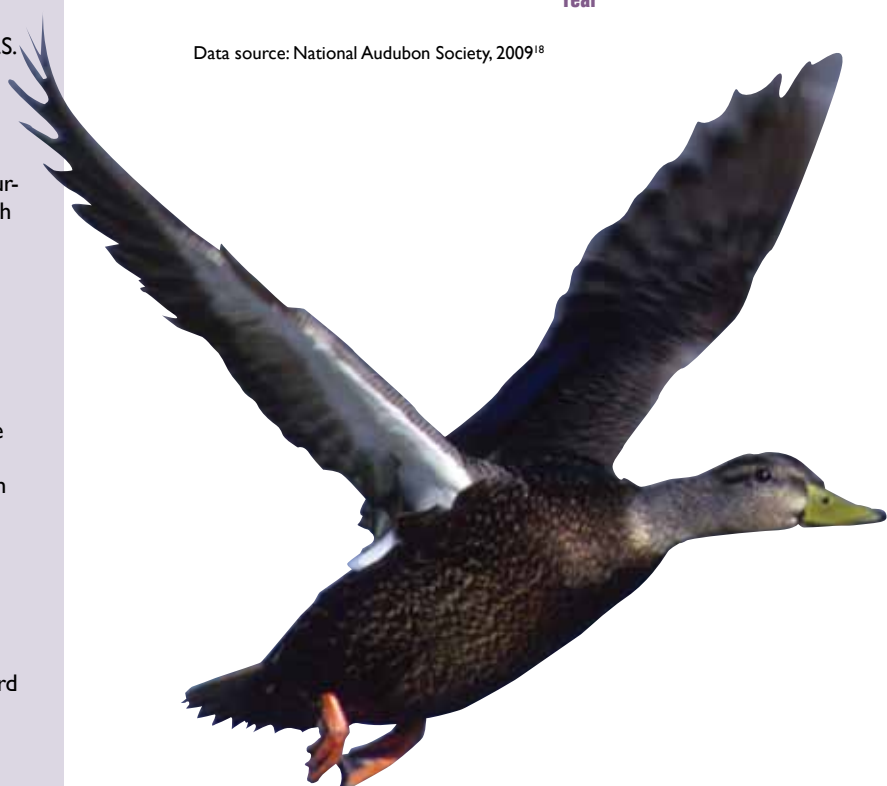
This indicator looks at the “center of abundance” of 305 widespread North American bird species over a 40-year period. The center of

Figure 1. Change in Latitude of Bird Center of Abundance, 1966–2005

This figure shows annual change in latitude of bird center of abundance for 305 widespread bird species in North America from 1966 to 2005. Each winter is represented by the year in which it began (for example, winter 2005–2006 is shown as 2005). 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, 2009¹⁸



(Continued on page 67)

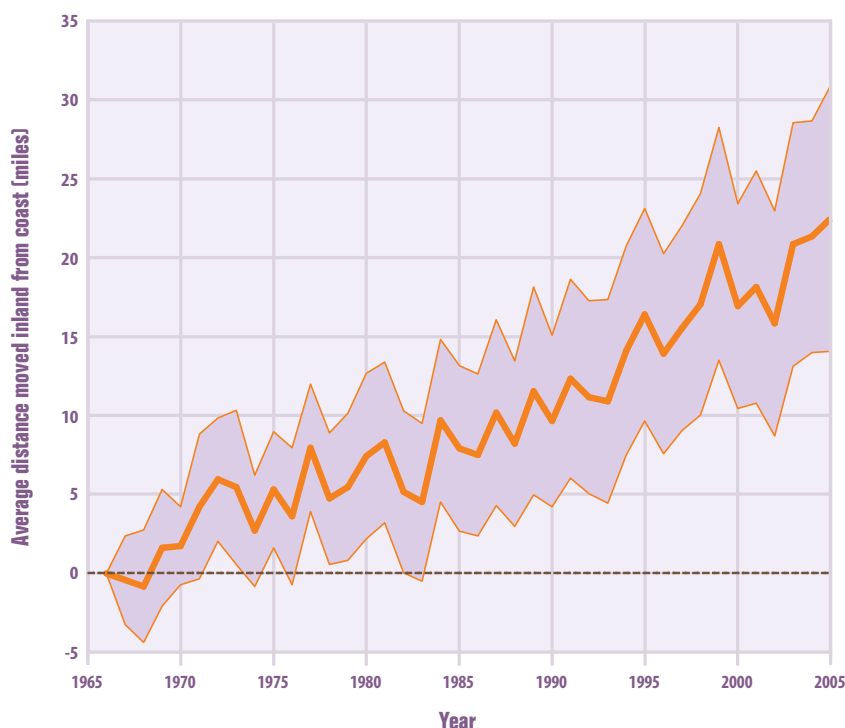
Ranges

Key Points

- Among 305 widespread North American bird species, the average mid-December to early January center of abundance moved northward between 1966 and 2005. The average species shifted northward by 35 miles during this period (see Figure 1). Trends in center of abundance are closely related to winter temperatures.¹⁹
- On average, bird species have also moved their wintering grounds farther from the coast since the 1960s (see Figure 2).
- Some species have moved farther than others. Of the 305 species studied, 177 (58 percent) have shifted their wintering grounds significantly to the north since the 1960s, but some others have not moved at all. A few species have moved northward by as much as 200 to 400 miles.²⁰

Figure 2. Change in Distance to Coast of Bird Center of Abundance, 1966–2005

This figure shows annual change in distance to the coast of bird center of abundance for 305 widespread bird species in North America from 1966 to 2005. Each winter is represented by the year in which it began (for example, winter 2005–2006 is shown as 2005). 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, 2009²¹

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.

Indicator Limitations

Many factors can influence bird ranges, including food availability, habitat alteration, and interactions with other species. As a result, some of the birds covered in this indicator might have moved north for reasons other than changing temperatures. This indicator also 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 between coastal birds, grassland birds, and birds adapted to feeders, which all have varying abilities to adapt to temperature changes.²²

Some data variations can be caused by differences between 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: www.audubon.org/Bird/cbc. Data for this indicator were analyzed by the National Audubon Society in 2009²³ and are available at: www.audubon.org/bird/bacc/index.html.



Conclusion

The indicators in this report present compelling evidence that the composition of the atmosphere and many fundamental measures of climate in the United States are changing. These changes include rising air and water temperatures, more heavy precipitation, and, over the last several decades, more frequent heat waves and intense Atlantic hurricanes. Assessment reports from the Intergovernmental Panel on Climate Change and the U.S. Global Change Research Program have linked many of these changes to increasing greenhouse gas emissions from human activities, which are also documented in this report.

Analysis of the indicators presented here suggests that these climate changes are affecting the environment in ways that are important for society and ecosystems. Sea levels are rising, snow cover is decreasing, glaciers are melting, and planting zones are shifting (see Summary of Key Findings on p. 4). Although the indicators in this report were developed from some of the most complete data sets currently available, they represent just a small sample of the growing portfolio of potential indicators. Considering that future warming projected for the 21st century is very likely to be greater than observed warming over the past century,¹ indicators of climate change should only become more clear, numerous, and compelling.

As new and more complete indicator data become available, EPA plans to update the indicators presented in this report and provide additional indicators that can more comprehensively document climate change and its effects. Identifying and analyzing indicators will improve our understanding of climate change, validate projections of future change, and, importantly, assist us in evaluating efforts to slow climate change and adapt to its effects. Looking ahead, EPA will continue to work in partnership with other agencies, organizations, and individuals to collect useful data and to craft informed policies and programs based on this knowledge.



Climate Change Resources

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

- Learn more about greenhouse gases and the science of climate change.
- Get to know EPA's regulatory initiatives and partnership programs.
- Search EPA's database of frequently asked questions about climate change and ask your own questions.
- Read about greenhouse gas emissions and look through EPA's greenhouse gas inventories.
- Get up-to-date news on climate change.
- Find out what you can do at home, on the road, at work, and at school to help reduce greenhouse gas emissions.
- Discover the potential impacts of climate change on human health and ecosystems.
- Explore U.S. climate policy and climate economics.

Many other government and nongovernment Web sites 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 Web site (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.
- 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 activities at: www.climate.gov.
- NOAA's National Climatic Data Center Web site (www.ncdc.noaa.gov/oa/ncdc.html) helps explore data that demonstrate the effects of climate change on weather, climate, and the oceans.
- The U.S. Geological Survey's Office of Global Change Web site (www.usgs.gov/global_change) 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 Web site (<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 Institute's Web site (www.whoi.edu/page.do?pid=11939) explains how climate change affects the oceans and how scientists measure these effects.
- The Pew Center on Global Climate Change (www.pewclimate.org/global-warming-basics) provides fact sheets on the causes and effects of climate change.
- The World Resources Institute (www.wri.org/climate) has published several publications about climate change mitigation strategies, particularly their relationship to energy use and the economy.

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

Endnotes

Introduction

- 1 IPCC (Intergovernmental Panel on Climate Change). 2007. Summary for Policymakers. In: Climate change 2007: The physical science basis (Fourth Assessment Report). Cambridge, United Kingdom: Cambridge University Press.
- 2 The National Academies. 2008. Understanding and responding to climate change. <http://dels.nas.edu/dels/rpt_briefs/climate_change_2008_final.pdf>
- 3 IPCC (Intergovernmental Panel on Climate Change). 2007. Summary for Policymakers. In: Climate change 2007: The physical science basis (Fourth Assessment Report). Cambridge, United Kingdom: Cambridge University Press.

Greenhouse Gases

- 1 U.S. EPA (U.S. Environmental Protection Agency). 2010. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2008. USEPA #EPA 430-R-10-006. <<http://www.epa.gov/climatechange/emissions/usinventoryreport.html>>
- 2 *ibid.*
- 3 *ibid.*
- 4 *ibid.*
- 5 *ibid.*
- 6 World Resources Institute. 2009. Climate Analysis Indicators Tool (CAIT). Version 6.0. Accessed January 2009. <<http://cait.wri.org>>
- 7 *ibid.*
- 8 *ibid.*
- 9 *ibid.*
- 10 *EPICA Dome C, Antarctica: 647,426 BC to 411,548 BC*
Siegenthaler, U., T. F. Stocker, E. Monnin, D. Lüthi, J. Schwander, B. Stauffer, D. Raynaud, J. M. Barnola, H. Fischer, V. Masson-Delmotte, and J. Jouzel. 2005. Stable carbon cycle-climate relationship during the late Pleistocene. *Science* 310(5752):1313–1317. <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/epica_domec/edc-co2-650k-390k.txt>
Vostok Station, Antarctica: 415,157 BC to 339 BC
Barnola, J. M., D. Raynaud, C. Lorius, and N. I. Barkov. 2003. Historical CO₂ record from the Vostok ice core. In: *Trends: A compendium of data on global change*. Oak Ridge, TN: U.S. Department of Energy. <<http://cdiac.ornl.gov/trends/co2/vostok.html>>
EPICA Dome C, Antarctica: 9002 BC to 1515 AD
Flückiger, J., E. Monnin, B. Stauffer, J. Schwander, T. F. Stocker, J. Chappellaz, D. Raynaud, and J. M. Barnola. 2002. High resolution Holocene N₂O ice core record and its relationship with CH₄ and CO₂. *Global Biogeochem. Cycles* 16(1):10–11. <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/epica_domec/readme_flueckiger2002.txt>
Law Dome, Antarctica, 75-year smoothed: 1010 AD to 1975 AD
Etheridge, D. M., L. P. Steele, R. L. Langenfelds, R. J. Francey, J. M. Barnola, and V. I. Morgan. 1998. Historical CO₂ records from the Law Dome DE08, DE08-2, and DSS ice cores. In: *Trends: A compendium of data on global change*. Oak Ridge, TN: U.S. Department of Energy. <<http://cdiac.ornl.gov/trends/co2/lawdome.html>>
Siple Station, Antarctica: 1744 AD to 1953 AD
Neftel, A., H. Friedli, E. Moor, H. Löttscher, H. Oeschger, U. Siegenthaler, and B. Stauffer. 1994. Historical CO₂ record from the Siple Station ice core. In: *Trends: A compendium of data on global change*. Oak Ridge, TN: U.S. Department of Energy. <<http://cdiac.ornl.gov/trends/co2/siple.html>>
Mauna Loa, Hawaii: 1959 AD to 2009 AD
NOAA (National Oceanic and Atmospheric Administration). 2010. Annual mean CO₂ concentrations for Mauna Loa, Hawaii. <ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_annmean_mlo.txt>
Barrow, Alaska: 1974 AD to 2008 AD
Cape Matatula, American Samoa: 1976 AD to 2008 AD
South Pole, Antarctica: 1976 AD to 2008 AD
NOAA (National Oceanic and Atmospheric Administration). 2009. Monthly mean CO₂ concentrations for Barrow, Alaska, Cape Matatula, American Samoa, and the South Pole. <<http://cdiac.ornl.gov/ftp/ndp005a>>
Cape Grim, Australia: 1992 AD to 2006 AD
Shetland Islands, Scotland: 1993 AD to 2002 AD
Steele, L. P., P. B. Krummel, and R. L. Langenfelds. 2007. Atmospheric CO₂ concentrations (ppmv) derived from flask air samples collected at Cape Grim, Australia, and Shetland Islands, Scotland. Aspendale, Victoria, Australia: Atmospheric, Research, Commonwealth Scientific, and Industrial Research Organisation. <<http://cdiac.esd.ornl.gov/ftp/trends/co2/csiro>>
Lampedusa Island, Italy: 1993 AD to 2000 AD
Chamard, P., L. Ciattaglia, A. di Sarra, and F. Monteleone. 2001. Atmospheric CO₂ record from flask measurements at Lampedusa Island. In: *Trends: A compendium of data on global change*. Oak Ridge, TN: U.S. Department of Energy. <<http://cdiac.ornl.gov/trends/co2/lampis.html>>
II EPICA Dome C, Antarctica: 646,729 BC to 1888 AD
Spahni, R., J. Chappellaz, T. F. Stocker, L. Loulergue, G. Hausamann, K. Kawamura, J. Flückiger, J. Schwander, D. Raynaud, V. Masson-Delmotte, and J. Jouzel. 2005. Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. *Science* 310(5752):1317–1321. <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/epica_domec/edc-ch4-2005-650k.txt>
Vostok Station, Antarctica: 415,172 BC to 346 BC
Petit, J. R., J. Jouzel, D. Raynaud, N. I. Barkov, J. M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V. M. Kotlyakov, M. Legrand, V. Lipenkov, C. Lorius, L. Pépin, C. Ritz, E. Saltzman, and M. Stievenard. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* 399:429–436. <<ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/vostok/ch4nat.txt>>
Greenland GISP2 ice core: 87,798 BC to 8187 BC
Byrd Station, Antarctica: 85,929 BC to 6748 BC
Greenland GRIP ice core: 46,933 BC to 8129 BC
Blunier, T., and E. J. Brook. 2001. Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. *Science* 291:109–112. <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/grip/synchronization/readme_blunier2001.txt>
EPICA Dome C, Antarctica: 8945 BC to 1760 AD
Flückiger, J., E. Monnin, B. Stauffer, J. Schwander, T. F. Stocker, J. Chappellaz, D. Raynaud, and J. M. Barnola. 2002. High resolution Holocene N₂O ice core record and its relationship with CH₄ and CO₂. *Global Biogeochem. Cycles* 16(1):10–11. <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/epica_domec/readme_flueckiger2002.txt>
Law Dome, Antarctica: 1008 AD to 1980 AD
Various Greenland locations: 1075 AD to 1885 AD
Etheridge, D. M., L. P. Steele, R. J. Francey, and R. L. Langenfelds. 2002. Historical CH₄ records since about 1000 AD from ice core data. In: *Trends: A compendium of data on global change*. Oak Ridge, TN: U.S. Department of Energy. <http://cdiac.ornl.gov/trends/atm_meth/lawdome_meth.html>
Greenland Site J: 1598 AD to 1951 AD
WDCGG (World Data Centre for Greenhouse Gases). 2005. Atmospheric CH₄ concentrations for Greenland Site J. <<http://gaw.kishou.go.jp/wdogg>>
Cape Grim, Australia: 1984 AD to 2008 AD
NOAA (National Oceanic and Atmospheric Administration). 2009. Monthly mean CH₄ concentrations for Cape Grim, Australia. <ftp://ftp.cmdl.noaa.gov/ccg/ch4/flask/month/cgo_01D0_mm.ch4>
Mauna Loa, Hawaii: 1987 AD to 2008 AD
NOAA (National Oceanic and Atmospheric Administration). 2009.

Monthly mean CH₄ concentrations for Mauna Loa, Hawaii. <ftp://ftp.cmdl.noaa.gov/ccg/ch4/in-situ/mlo/mlo_01CO_mm.ch4>

Shetland Islands, Scotland: 1993 AD to 2001 AD

Steele, L.P., P.B. Krummel, and R.L. Langenfelds. 2002. Atmospheric CH₄ concentrations from sites in the CSIRO Atmospheric Research GASLAB air sampling network (October 2002 version). In: Trends: A compendium of data on global change. Oak Ridge, TN: U.S. Department of Energy. <http://cdiac.esd.ornl.gov/trends/atm_meth/csiro/csiro-shetlandch4.html>

- 12 IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: The physical science basis (Fourth Assessment Report). Cambridge, United Kingdom: Cambridge University Press.
- 13 IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: Synthesis report (Fourth Assessment Report). Cambridge, United Kingdom: Cambridge University Press.
- 14 *ibid.*
- 15 *ibid.*
- 16 *Greenland GISP2 ice core: 104,301 BC to 1871 AD*
Taylor Dome, Antarctica: 30,697 BC to 497 BC
Sowers, T., R.B. Alley, and J. Jubenville. 2003. Ice core records of atmospheric N₂O covering the last 106,000 years. *Science* 301(5635):945–948. <www.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/taylor/taylor_n2o.txt>
EPICA Dome C, Antarctica: 9000 BC to 1780 AD
Flückiger, J., E. Monnin, B. Stauffer, J. Schwander, T.F. Stocker, J. Chappellaz, D. Raynaud, and J.M. Barnola. 2002. High resolution Holocene N₂O ice core record and its relationship with CH₄ and CO₂. *Global Biogeochem. Cycles* 16(1):10–11. <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/epica_domec/readme_flueckiger2002.txt>
Antarctica: 1756 AD to 1964 AD
Machida, T., T. Nakazawa, Y. Fujii, S. Aoki, and O. Watanabe. 1995. Increase

in the atmospheric nitrous oxide concentration during the last 250 years. *Geophys. Res. Lett.* 22(21):2921–2924. <ftp://daac.ornl.gov/data/global_climate/global_N_cycle/data/global_N_perturbations.txt>

Antarctica: 1903 AD to 1976 AD

Battle, M., M. Bender, T. Sowers, P. Tans, J. Butler, J. Elkins, J. Ellis, T. Conway, N. Zhang, P. Lang, and A. Clarke. 1996. Atmospheric gas concentrations over the past century measured in air from firn at the South Pole. *Nature* 383:231–235. <ftp://daac.ornl.gov/data/global_climate/global_N_cycle/data/global_N_perturbations.txt>

Cape Grim, Australia: 1979 AD to 2008 AD

AGAGE (Advanced Global Atmospheric Gases Experiment). 2009. Monthly mean N₂O concentrations for Cape Grim, Australia. <http://gaw.kishou.go.jp/wdogg>

South Pole, Antarctica: 1998 AD to 2009 AD

Barrow, Alaska: 1999 AD to 2009 AD

Mauna Loa, Hawaii: 2000 AD to 2009 AD

NOAA (National Oceanic and Atmospheric Administration). 2010. Monthly mean N₂O concentrations for Barrow, Alaska, Mauna Loa, Hawaii, and the South Pole. <www.esrl.noaa.gov/gmd/hats/insitu/cats/cats_conc.html>

- 17 IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: Synthesis report (Fourth Assessment Report). Cambridge, United Kingdom: Cambridge University Press.
- 18 NOAA (National Oceanic and Atmospheric Administration). 2009. The NOAA Annual Greenhouse Gas Index. Accessed April 2009. <www.esrl.noaa.gov/gmd/aggi>
- 19 IPCC (Intergovernmental Panel on Climate Change). 1995. Climate change 1995: The science of climate change (Second Assessment Report). Cambridge, United Kingdom: Cambridge University Press.
- 20 IPCC (Intergovernmental Panel on Climate Change). 2001. Climate change 2001: The scientific basis (Third Assessment Report). Cambridge, United Kingdom: Cambridge University Press.

Weather and Climate

- 1 NOAA (National Oceanic and Atmospheric Administration). 2009. Layers of the atmosphere. <http://www.srh.noaa.gov/jetstream/atmos/layers.htm>
- 2 NOAA (National Oceanic and Atmospheric Administration). 2010. National Climatic Data Center. <www.ncdc.noaa.gov/oa/ncdc.html>
- 3 *ibid.*
- 4 NOAA (National Oceanic and Atmospheric Administration). 2009. National Climatic Data Center. <www.ncdc.noaa.gov/oa/ncdc.html>
- 5 Cheng, S., M. Campbell, Q. Li, L. Guilong, H. Auld, N. Day, D. Pengelly, S. Gingrich, J. Klaassen, D. MacIver, N. Comer, Y. Mao, W. Thompson, and H. Lin. 2005. Differential and combined impacts of winter and summer weather and air pollution due to global warming on human mortality in south-central Canada. Technical Report, Health Policy Research Program: Project Number 6795-15-2001/4400011.
- 6 CCSP (U.S. Climate Change Science Program). 2009. Updated version of a figure that originally appeared in the U.S. Climate Change Science Program's 2008 report: Synthesis and Assessment Product 3.3: Weather and climate extremes in a changing climate. <www.climatechange.gov/Library/sap/sap3-3/final-report/sap3-3-final-Chapter2.pdf>
- 7 CCSP (U.S. Climate Change Science Program). 2008. Synthesis and Assessment Product 3.3: Weather and climate extremes in a changing climate. <www.climatechange.gov/Library/sap/sap3-3/final-report/sap3-3-final-Chapter2.pdf>
- 8 CCSP (U.S. Climate Change Science Program). 2009. Updated version of a figure that originally appeared in the U.S. Climate Change Science Program's 2008 report: Synthesis and Assessment Product 3.3: Weather and climate extremes in a changing climate. <www.climatechange.gov/Library/sap/sap3-3/final-report/sap3-3-final-Chapter2.pdf>
- 9 *ibid.*
- 10 IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: Synthesis report (Fourth Assessment Report). <www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html>
- 11 Heim, R.R. 2002. A review of twentieth-century drought indices used in the United States. *Bull. Amer. Meteor. Soc.* 83(8):1149–1165.
- 12 National Drought Mitigation Center. 2010. Drought Monitor archives. Accessed April 2010. <www.drought.unl.edu/dm/archive.html>
- 13 National Drought Mitigation Center. 2010. U.S. Drought Monitor. Accessed April 2010. <www.drought.unl.edu/dm/monitor.html>
- 14 For example, see Heim, R.R. 2002. A review of twentieth-century drought indices used in the United States. *Bull. Amer. Meteor. Soc.* 83(8):1149–1165.
- 15 NOAA (National Oceanic and Atmospheric Administration). 2010. National Climatic Data Center. <www.ncdc.noaa.gov/oa/ncdc.html>
- 16 *ibid.*
- 17 NOAA (National Oceanic and Atmospheric Administration). 2009. National Climatic Data Center. <www.ncdc.noaa.gov/oa/ncdc.html>
- 18 Tebaldi, C., K. Hayhoe, J.M. Arblaster, and G.A. Meehl. 2006. Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Climatic Change* 79:185–211.
- 19 NOAA (National Oceanic and Atmospheric Administration). 2009. U.S. Climate Extremes Index. <www.ncdc.noaa.gov/oa/climate/research/cei/cei.html>
- 20 NOAA (National Oceanic and Atmospheric Administration). 2009. Standardized Precipitation Index data files. Accessed March 2009. <ftp://ftp.ncdc.noaa.gov/pub/data/cirs>
- 21 CCSP (U.S. Climate Change Science Program). 2008. Synthesis and Assessment Product 3.3: Weather and climate extremes in a changing climate. <www.climatechange.gov/Library/sap/sap3-3/final-report/sap3-3-final-Chapter2.pdf>
- 22 *ibid.*
- 23 *ibid.*
- 24 NOAA (National Oceanic and Atmospheric Administration). 2010. The 2009 North Atlantic hurricane season: A climate perspective. <www.cpc.noaa.gov/products/expert_assessment/hursummary_2009.pdf>
- 25 CCSP (U.S. Climate Change Science Program). 2008. Synthesis and Assessment Product 3.3: Weather and climate extremes in a changing climate. <www.climatechange.gov/Library/sap/sap3-3/final-report/sap3-3-final-Chapter2.pdf>
- 26 Emanuel, K.A. 2010 update of data originally published in: Emanuel, K.A. 2007. Environmental factors affecting tropical cyclone power dissipation. *J. of Climate* 20(22):5497–5509.

- 1 Bindoff, N.L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley, and A. Unnikrishnan. 2007. Observations: Oceanic climate change and sea level. In: *Climate change 2007: The physical science basis* (Fourth Assessment Report). Cambridge, United Kingdom: Cambridge University Press.
- 2 Levitus, S., J. Antonov, and T. Boyer. 2005. Warming of the world ocean, 1955–2003. *Geophys. Res. Lett.* 32:L02604.
- 3 Domingues, C.M., J.A. Church, N.J. White, P.J. Gleckler, S.E. Wijffels, P.M. Barker, and J.R. Dunn. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* 453:1090–1093.
- 4 Ishii, M., and M. Kimoto. 2009. Reevaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections. *J. Oceanogr.* 65:287–299.
- 5 Levitus, S., J.I. Antonov, T.P. Boyer, R.A. Locarnini, H.E. Garcia, and A.V. Mishonov. 2009. Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophys. Res. Lett.* 36:L07608.
- 6 Domingues, C.M., J.A. Church, N.J. White, P.J. Gleckler, S.E. Wijffels, P.M. Barker, and J.R. Dunn. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* 453:1090–1093.
- 7 Ishii, M., and M. Kimoto. 2009. Reevaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections. *J. Oceanogr.* 65:287–299.
- 8 Levitus, S., J.I. Antonov, T.P. Boyer, R.A. Locarnini, H.E. Garcia, and A.V. Mishonov. 2009. Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophys. Res. Lett.* 36:L07608.
- 9 For example, see Ostrander, G.K., K.M. Armstrong, E.T. Knobbe, D. Gerace, and E.P. Scully. 2000. Rapid transition in the structure of a coral reef community: The effects of coral bleaching and physical disturbance. *Proc. Natl. Acad. Sci.* 97(10):5297–5302.
- 10 Pratchett, M.S., S.K. Wilson, M.L. Berumen, and M.I. McCormick. 2004. Sublethal effects of coral bleaching on an obligate coral feeding butterflyfish. *Coral Reefs* 23(3):352–356.
- 11 Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tank, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden, and P. Zhai. 2007. Observations: Surface and atmospheric climate change. In: *Climate change 2007: The physical science basis* (Fourth Assessment Report). Cambridge, United Kingdom: Cambridge University Press.
- 12 NOAA (National Oceanic and Atmospheric Administration). 2010. Sea surface temperature (SST) datasets. National Climatic Data Center. <www.ncdc.noaa.gov/oa/climate/research/sst/sst.html#grid>
- 13 NASA (National Aeronautics and Space Administration). 2008. NASA global sea surface temperature model. <<http://sos.noaa.gov/images/fullsize/Ocean/sstNASAModel.jpg>>
- 14 CSIRO (Commonwealth Scientific and Industrial Research Organisation). 2009. Sea level rise. Accessed November 2009. <<http://www.cmar.csiro.au/sealevel>>
- 15 University of Colorado at Boulder. 2009. Sea level change: 2009 release #2. <<http://sealevel.colorado.edu>>
- 16 Titus, J.G., E. K. Anderson, D. R. Cahoon, S. Gill, R.E. Thiel, and J.S. Williams. 2009. Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region. U.S. Climate Change Science Program and the Subcommittee on Global Change Research. <www.climatechange.gov/Library/sap/sap4-1/final-report/default.htm>
- 17 University of Colorado at Boulder. 2009. Sea level change: 2009 release #2. <<http://sealevel.colorado.edu>>
- 18 NOAA (National Oceanic and Atmospheric Administration). 2009 update to data originally published in: NOAA. 2001. Sea level variations of the United States 1854–1999. NOAA Technical Report NOS CO-OPS 36. <<http://tidesandcurrents.noaa.gov/publications/techrpt36.pdf>>
- 19 Wootton, J.T., C.A. Pfister, and J.D. Forester. 2008. Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset. *Proc. Natl. Acad. Sci.* 105(48):18848–18853.
- 20 Pacific Science Association. 2009. Task force on ocean acidification. <www.pacificscience.org/tfoceanacidification.html>
- 21 Bindoff, N.L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley, and A. Unnikrishnan. 2007. Observations: Oceanic climate change and sea level. In: *Climate change 2007: The physical science basis* (Fourth Assessment Report). Cambridge, United Kingdom: Cambridge University Press.
- 22 Recreated from Environment Canada. 2008. The pH scale. <www.ec.gc.ca/eau-water/default.asp?lang=En&n=FDF30C16-1>
- 23 Yool, A. 2007. Change in sea surface pH. Data from Global Ocean Data Analysis Project and analyzed using: R. Zeebe “csys” package. <http://en.wikipedia.org/wiki/File:AYool_GLODAP_del_pH.png>
- 24 Bates, N., A.C. Pequignat, R.J. Johnson, and N. Gruber. 2002. A short-term sink for atmospheric CO₂ in subtropical mode water of the North Atlantic Ocean. *Nature* 420:489–493.
- 25 Gruber, N., C.D. Keeling, N.R. Bates. 2002. Interannual variability in the North Atlantic Ocean carbon sink. *Science* 298:2374–2378.
- 26 Dore, J.E., R. Lukas, D.W. Sadler, and D.M. Karl. 2003. Climate-driven changes to the atmospheric CO₂ sink in the subtropical North Pacific Ocean. *Nature* 424:754–757.
- 27 Gonzalez-Davila, M., J.M. Santana-Casiano, M. Rueda, O. Llinas, and E. Gonzalez-Davila. 2003. Seasonal and interannual variability of sea-surface carbon dioxide species at the European Station for Time Series in the Ocean at the Canary Islands (ESTOC) between 1996 and 2000. *Global Biogeochem. Cy.* 17(3):1076.

Snow and Ice

- 1 UNEP (United Nations Environment Programme). 2007. Global outlook for ice and snow. Cartographer: Hugo Ahlenius, UNEP/GRID-Arendal. <http://www.unep.org/geo/ice_snow>
Map based on the following data sources:
Armstrong, R.L., and M.J. Brodzik. 2005. Northern Hemisphere EASE-Grid weekly snow cover and sea ice extent version 3. National Snow and Ice Data Center.
Armstrong, R.L., M.J. Brodzik, K. Knowles, and M. Savoie. 2005. Global monthly EASE-Grid snow water equivalent climatology. National Snow and Ice Data Center.
Brown, J., O.J. Ferrinas, Jr., J.A. Heginbottom, and E.S. Melnikov. 2001. Circum-Arctic map of permafrost and ground-ice conditions. National Snow and Ice Data Center/World Data Center for Glaciology.
National Geospatial-Intelligence Agency. 2000. Vector map level 0. <http://geoengine.nima.mil/ftpdir/archive/vpf_data/v0soa.tar.gz>
Stroeve, J., and W. Meier. 2005. Sea ice trends and climatologies from SMMR and SSM/I. National Snow and Ice Data Center. <http://nsidc.org/data/smmr_ssmi_ancillary/monthly_means.html>
- 2 NSIDC (National Snow and Ice Data Center). 2009. Archived monthly sea ice data and images. Accessed November 2009. <http://nsidc.org/data/seaice_index/archives/index.html>
- 3 ibid.
- 4 NASA (National Aeronautics and Space Administration). 2009. Sea ice yearly minimum 1979–2007. NASA/Goddard Space Flight Center Scientific Visualization Studio. <<http://svs.gsfc.nasa.gov/vis/a000000/a003400/a003464/index.html>>
- 5 Field, W.O. 1941. Muir Glacier. Glacier photograph collection. Boulder, Colorado: National Snow and Ice Data Center/World Data Center for Glaciology. <<http://nsidc.org/data/g00472.html>>
- 6 Molnia, B.F. 2004. Muir Glacier. Glacier photograph collection. Boulder, Colorado: National Snow and Ice Data Center/World Data Center for Glaciology. <<http://nsidc.org/data/g00472.html>>
- 7 Dyurgerov, M.B. In press. Reanalysis of glacier changes: From the IGY to the IPY, 1960–2008. Materials of Glaciological Studies.
- 8 USGS (U.S. Geological Survey). 2009. Water resources of Alaska—glacier and snow program, benchmark glaciers. Accessed November 2009. <<http://ak.water.usgs.gov/glaciology>>
- 9 Lemke, P., J. Ren, R.B. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R.H. Thomas, and T. Zhang. 2007. Observations: Changes in snow, ice and frozen ground. In: *Climate change 2007: The physical science basis* (Fourth Assessment Report). Cambridge, United Kingdom: Cambridge University Press.
- 10 GCRP (U.S. Global Change Research Program). 2009. Global climate change impacts in the United States. <<http://www.globalchange.gov/usimpacts>>

- 11 *ibid.*
- 12 Magnuson, J.J., D.M. Robertson, B.J. Benson, R.H. Wynne, D.M. Livingstone, T. Arai, R.A. Assel, R.G. Barry, V. Card, E. Kuusisto, N.G. Granin, T.D. Prowse, K.M. Stewart, and V.S. Vuglinski. 2000. Historical trends in lake and river ice cover in the Northern Hemisphere. *Science* 289:1743–1746. Errata 2001. *Science* 1291:1254.
- 13 NSIDC (National Snow and Ice Data Center). 2009. Global lake and river ice phenology. <http://nsidc.org/data/lake_river_ice>
- 14 *ibid.*
- 15 *ibid.*
- 16 Rutgers University Global Snow Lab. 2009. Area of extent data: North America (no Greenland). <<http://climate.rutgers.edu/snowcover>>
- 17 *ibid.*
- 18 Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in Western North America. *Bull. Amer. Meteor. Soc.* 86(1):39–49.
- 19 Mote, P.W. 2009 update to data originally published in: Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in Western North America. *Bull. Amer. Meteor. Soc.* 86(1):39–49.
- 20 Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in Western North America. *Bull. Amer. Meteor. Soc.* 86(1):39–49.

Society and Ecosystems

- 1 CDC (U.S. Centers for Disease Control and Prevention). 2009. CDC WONDER database. Accessed August 2009. <<http://wonder.cdc.gov/mortSQL.html>>.
- 2 CDC (U.S. Centers for Disease Control and Prevention). 2006. Heat-related deaths—United States, 1999–2003. *Morbidity and Mortality Weekly Report* 55(29):796–798. <www.cdc.gov/mmwr/preview/mmwrhtml/mm5529a2.htm>
- 3 Weisskopf, M.G., H.A. Anderson, S. Foldy, L.P. Hanrahan, K. Blair, T.J. Torok, and P.D. Rumm. 2002. Heat wave morbidity and mortality, Milwaukee, Wis, 1999 vs. 1995: An improved response? *Amer. J. Public Health* 92:830–833.
- 4 Easterling, W.E., P.K. Aggarwal, P. Batima, K.M. Brander, L. Erda, S.M. Howden, A. Kirilenko, J. Morton, J.-F. Soussana, J. Schmidhuber, and F.N. Tubiello. 2007. Food, fibre and forest products. In: *Climate change 2007: Impacts, adaptation and vulnerability (Fourth Assessment Report)*. Cambridge, United Kingdom: Cambridge University Press.
- 5 Kunkel, K.E. 2009 update to data originally published in: Kunkel, K.E., D.R. Easterling, K. Hubbard, and K. Redmond. 2004. Temporal variations in frost-free season in the United States: 1895–2000. *Geophys. Res. Lett.* 31: L03201.
- 6 *ibid.*
- 7 *ibid.*
- 8 *ibid.*
- 9 Arbor Day Foundation. 2006. Differences between 1990 USDA hardiness zones and 2006 arborday.org hardiness zones reflect warmer climate. <www.arborday.org/media/map_change.cfm>
- 10 *ibid.*
- 11 IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate change 2007: Synthesis report (Fourth Assessment Report)*. Cambridge, United Kingdom: Cambridge University Press.
- 12 Schwartz, M.D., R. Ahas, and A. Aasa. 2006. Onset of spring starting earlier across the Northern Hemisphere. *Glob. Chang. Biol.* 12:343–351.
- 13 Schwartz, M.D. 2009 update to data originally published in: Schwartz, M.D., R. Ahas, and A. Aasa. 2006. Onset of spring starting earlier across the Northern Hemisphere. *Glob. Chang. Biol.* 12:343–351.
- 14 Schwartz, M.D. 2009 map provided to accompany update to data originally published in: Schwartz, M.D., R. Ahas, and A. Aasa. 2006. Onset of spring starting earlier across the Northern Hemisphere. *Glob. Chang. Biol.* 12:343–351.
- 15 For example, see: Schwartz, M.D., R. Ahas, and A. Aasa. 2006. Onset of spring starting earlier across the Northern Hemisphere. *Glob. Chang. Biol.* 12:343–351.
- 16 Schwartz, M.D. 2009 update to data originally published in: Schwartz, M.D., R. Ahas, and A. Aasa. 2006. Onset of spring starting earlier across the Northern Hemisphere. *Glob. Chang. Biol.* 12:343–351.
- 17 Schwartz, M.D., R. Ahas, and A. Aasa. 2006. Onset of spring starting earlier across the Northern Hemisphere. *Glob. Chang. Biol.* 12:343–351.
- 18 National Audubon Society. 2009. Northward shifts in the abundance of North American birds in early winter: A response to warmer winter temperatures? <www.audubon.org/bird/bacc/techreport.html>
- 19 *ibid.*
- 20 *ibid.*
- 21 *ibid.*
- 22 *ibid.*
- 23 *ibid.*

Conclusion

- 1 IPCC (Intergovernmental Panel on Climate Change). 2007. Summary for policymakers. In: *Climate change 2007: The physical science basis (Fourth Assessment Report)*. Cambridge, United Kingdom: Cambridge University Press.





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