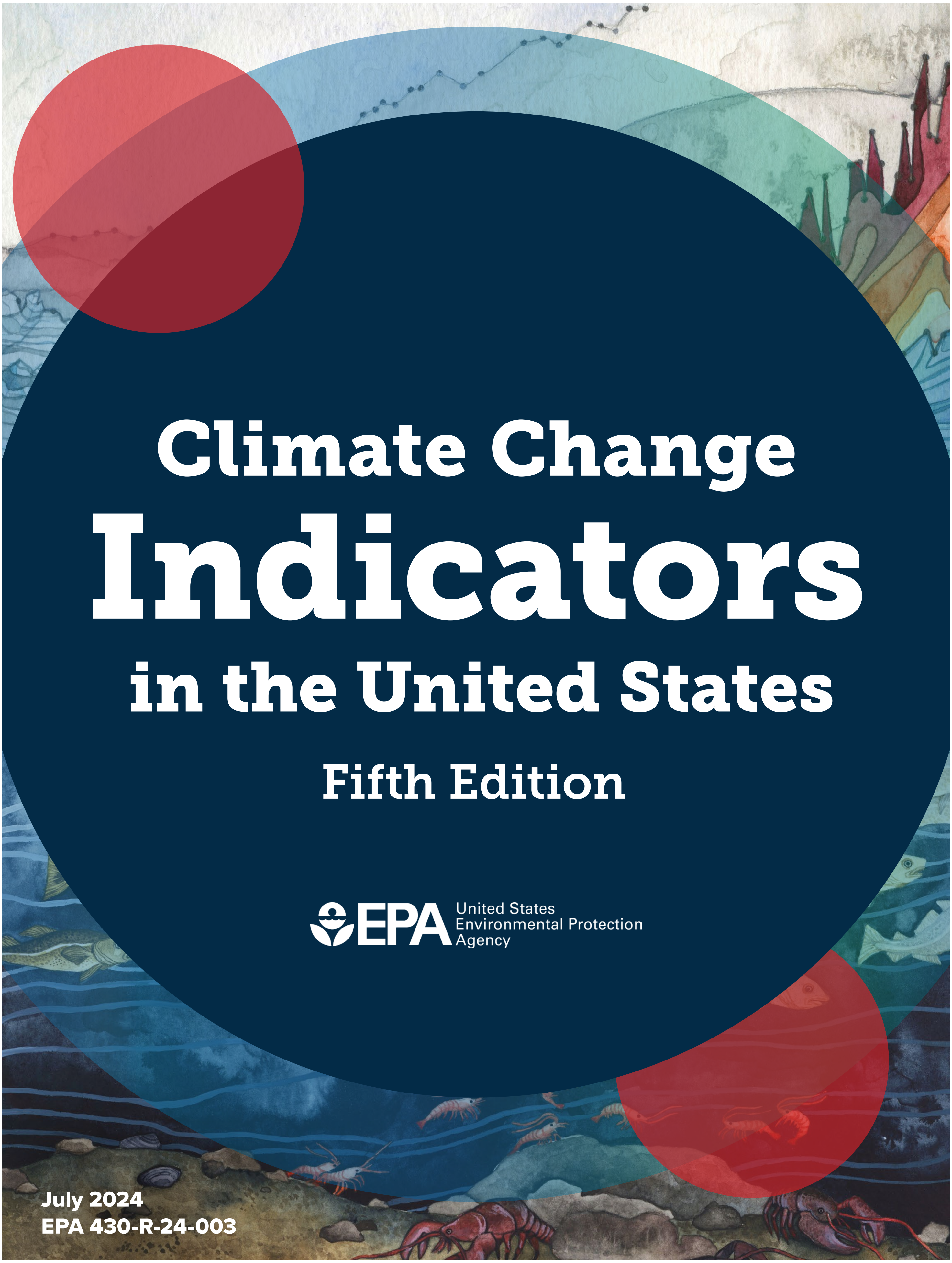


Climate Change Indicators in the United States

Fifth Edition

United States Environmental Protection Agency

July 2024
EPA 430-R-24-003

Find Us Online

Please visit EPA's website at: www.epa.gov/climate-indicators to:

- View the latest information about EPA's climate change indicators
- View additional graphs and background information
- Explore the Climate Indicator Map Viewer
- Access technical documentation
- Download figures and data

Questions? Suggestions? Please email: climateindicators@epa.gov.

Suggested Citation

U.S. Environmental Protection Agency. (2024). *Climate change indicators in the United States* (Fifth ed., EPA 430-R-24-003). www.epa.gov/climate-indicators

Corrigenda

This report was updated in September 2024 with minor corrections. For more information, please see the corrigenda at www.epa.gov/system/files/documents/2024-09/corrigenda.pdf.

Contents

Acknowledgments

Data contributors and indicator reviewers

EPA wishes to thank the federal government agencies, nongovernmental organizations, and other institutions that have contributed in the past and who currently contribute to the climate change indicator suite. Their commitment, contributions, and collaboration have helped make the website and this report possible.

U.S. governmental organizations

- Centers for Disease Control and Prevention: C. Ben Beard, Paul Mead, Alison Hinckley, and Ambarish Vaidyanathan
- National Aeronautics and Space Administration: Walt Meier and Trent Schindler
- National Oceanic and Atmospheric Administration: Analise Keeney, Scott Applequist, Bailey Armos, Boyin Huang, Chris Zervas, Jessica Blunden, and Yin Xungang
- National Park Service
- U.S. Department of Agriculture
- U.S. Department of Energy
- U.S. Department of Labor
- U.S. Geological Survey: Louis Sass, Michael McHale, Matt Bachmann, and Dan Fagre

Universities, nongovernmental organizations, and international institutions

- Bermuda Institute of Ocean Sciences: Nick Bates
- Commonwealth Scientific and Industrial Research Organisation: Catia Domingues, Didier Paolo Monselesan, and Benoit Legresy
- Colorado State University: Phil Klotzbach
- Friends of Cooper Island: George Divoky
- Japan Agency for Marine-Earth Science and Technology: Masayoshi Ishii
- Massachusetts Institute of Technology: Kerry Emanuel
- National Audubon Society
- North Carolina State University: Ken Kunkel
- Princeton University: Gabriele Villarini
- Rutgers University: David Robinson and Thomas Estilow
- University of Alaska Fairbanks: Vladimir Romanovsky
- University of Colorado: Mark Tschudi
- University of Montana: John Kimball and Youngwook Kim
- University of Wisconsin–Milwaukee: Mark Schwartz
- WestWide Drought Tracker: University of Idaho, Western Regional Climate Center, and Desert Research Institute
- World Glacier Monitoring Service: Michael Zemp
- World Resources Institute: Mengpin Ge

Peer review

The indicators highlighted in this report have been independently peer reviewed. In addition, this report was peer reviewed by four external experts in a process independently coordinated by ICF International and an EPA peer review leader. EPA gratefully acknowledges the four peer reviewers for their useful comments and suggestions: Andrew Christ, Lesley-Ann Dupigny-Giroux, Michael Mendez, and Paul Schramm. The information and views expressed in this report do not necessarily represent those of the peer reviewers, who also bear no responsibility for any remaining errors or omissions. The technical documentation provides more information about the peer review.

Report development and production

Overall coordination and development of this report was provided by EPA's Office of Atmospheric Protection, Climate Change Division. Support for content development, data analysis, and report design and production was provided by Eastern Research Group, Inc. (ERG).

Introduction

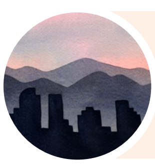
Multiple lines of evidence reveal the far-reaching impacts of climate change on the people and environment of the United States. Tracking observations over time reveals valuable data about what people are experiencing today. These data can help guide climate actions that are effective, are equitable, and will address challenges into the future. Understanding and addressing climate change is critical to the Environmental Protection Agency's (EPA's) mission of protecting human health and the environment.

A roadmap to this report

Climate Change Indicators in the United States is the fifth edition of a report first published by EPA in 2010. This report is intended to help readers understand how climate change has affected and continues to affect the United States; the magnitude and significance of the changes; and their possible consequences for people, the environment, and society.

This report presents highlights from 39 of EPA's total of 57 indicators, supported by an extensive review of relevant scientific literature. It has eight chapters:

Greenhouse Gases. As greenhouse gas emissions from human activities increase, they build up in the atmosphere and warm the climate, leading to many other changes around the world—in the atmosphere, on land, and in the oceans. The indicators presented in other chapters of this report and on EPA's website illustrate many of these changes and their effects on people, society, and the environment.



Heat on the Rise. As the concentrations of heat-trapping greenhouse gases in the atmosphere continue to increase, the United States has experienced warming temperatures, more unusually hot summer days, and more frequent heat waves that threaten people's health and strain the electric power grid.

Extreme Events. Rising global average temperature is associated with widespread changes in weather patterns. Extreme events such as heavy rainstorms, hurricanes, floods, droughts, and wildfires have happened throughout history, but human-induced climate change is expected to make these events more frequent and/or intense. While risks vary across the country, these events are among the nation's costliest disasters, sometimes causing great damage to ecosystems, communities, and the economy.

Water Resources at Risk. Clean fresh water is essential to life on the Earth, and climate change is affecting the planet's water resources. As the climate warms, changing precipitation patterns, drought, decreasing amounts of snow, and earlier snowmelt all pose risks to water supplies in the United States, affecting communities, livelihoods, and ecosystems.

Changing Seasons. Although the timing, duration, and intensity of the seasons vary naturally from year to year, climate change is driving longer-term changes in seasonality and fundamentally altering the ways in which humans and natural systems experience and interact with seasonal events. These changes lead to wide-ranging impacts such as warmer winters, lakes thawing earlier, longer growing seasons, and worsening allergies for people.

Ocean Impacts. The heat-trapping greenhouse gases that humans have added to the atmosphere are making the Earth's oceans warmer and more acidic. Changes in the oceans affect the Earth's climate and weather patterns and threaten marine ecosystems and biodiversity and the people whose livelihoods depend on them.

Rising Seas. As the temperature of the Earth changes, so does sea level throughout the world's oceans. Water from melting ice sheets and glaciers on land ultimately flows into the ocean. Also, as water in the ocean warms, it expands slightly, increasing the volume of water in the ocean. Both of these factors contribute to sea level rise, which increases coastal flooding and other coastal risks.

Alaska's Warming Climate. The Arctic is warming more quickly than the rest of the world, as is Alaska—the northernmost U.S. state. Alaska is also uniquely vulnerable to climate change due to its frozen features. Alaska is the only state with widespread permafrost (underlying 80 percent of its land) and significant sea ice extent, which are an integral part of life. Entire ecosystems, communities, and Indigenous ways of life could vanish as these frozen features shrink or disappear.

Indicators related to **human health** and **societal impacts** of climate change cut across chapter themes and are integrated throughout the report. Each chapter includes information on why these impacts matter, including examples and discussion of the disproportionate impacts of climate change. The report also provides examples of what people and communities can do and are doing to address climate change.

What is climate change?

"Climate change" refers to any substantial change in measures of climate (such as temperature or precipitation) lasting for decades or longer. Natural factors have caused the climate to change during previous periods of the Earth's history, but human activities are the main cause of the changes that are being observed now.

What is a climate change indicator?

One important way to track and communicate the causes and effects of climate change is through indicators. An indicator represents the state or trend of certain environmental or societal conditions in a given place and time period. EPA's indicators are designed to help readers understand observed long-term trends related to the causes and effects of climate change. In other words, they provide important evidence of how our climate is changing all around us.

About EPA's climate change indicators

EPA partners with more than 50 data contributors from various U.S. and international government agencies, academic institutions, and other organizations to compile and communicate key indicators related to the causes and effects of climate change. EPA's indicators generally cover broad geographic scales and as many years as the underlying data allow, to show large-scale and long-term trends relevant to climate change. Although the climate is continually changing, not every indicator shows a pattern of steady change over the period of record. The Earth is a complex system, and conditions naturally vary from one year to the next—for example, a very warm year can be followed by a colder year. The Earth's climate also goes through other natural cycles that can play out over years or even decades.

The indicators have a relationship to climate change grounded in science, though some indicators are more directly influenced by a warming climate than others. This report does not attempt to identify the extent to which trends for observed indicators are attributable to climate change. Connections between human activities, climate change, and observed indicators are explored in more detail elsewhere in the scientific literature.[1,2] The indicators presented here do not cover all possible measures of the causes and effects of climate change or all of their interconnections to human health, society, and environmental justice, nor do they capture all possible climate change indicators found in the full body of scientific assessment literature. Instead, EPA's indicators represent a wide-ranging set of high-quality, long-term data that show observed changes in the Earth's climate system and climate-relevant impacts.

Climate equity and EPA's climate change indicators

Climate change does not affect all people equally. Some communities experience disproportionate impacts because of existing vulnerabilities, historical patterns of inequity, socioeconomic disparities, and systemic environmental injustices. People who already face the greatest burdens are often the ones affected most by climate change.

Climate equity is the goal of recognizing and addressing the unequal burdens made worse by climate change, while ensuring that all people share the benefits of climate protection efforts. Achieving equity means that all people—regardless of their race, color, gender, age, sexuality, national origin, ability, or income—live in safe, healthy, and fair communities.

While EPA's current suite of indicators does not specifically measure the equity and justice dimensions of climate change, understanding these impacts is critically important. With more inclusive information on the range and magnitude of climate change impacts, solutions can be better tailored to the people and communities most at risk.

EPA follows an established framework to identify data sets, choose indicators, obtain independent expert review, and publish the online resource and reports.

- **Data sources:** All of EPA's indicators are based on peer-reviewed, publicly available data from government agencies, academic institutions, and other organizations. These data sets have been published in the scientific literature and in other government or academic reports. EPA also receives input from scientists, researchers, and communications experts in nongovernmental and private sectors as it compiles and updates indicators. EPA's indicators are based on records that are as current as data availability allows and go back in time as far as possible without sacrificing data quality, so each indicator's time scale varies.
- **Indicator selection:** EPA carefully screened and selected each indicator using a standard set of criteria that consider data availability and quality, transparency of the analytical methods, and the indicator's relevance to climate change. This process ensures that all indicators chosen are consistently evaluated, are based on credible data, and can be transparently documented.
- **Expert review:** All of EPA's climate change indicators and supporting documentation were peer reviewed by independent technical experts.
- **Presentation:** The indicators and accompanying detailed technical documentation have been designed to ensure that the indicators are presented and documented clearly, transparently, and objectively.

EPA's climate change indicator website

This report presents excerpts from a larger set of indicators. EPA's full suite of 57 indicators is available on the web at: www.epa.gov/climate-indicators.

The online resource includes detailed background information for each indicator, additional graphs and maps, downloadable data, interactive maps and animations for some indicators, and important notes to help readers interpret the data. EPA also provides technical documentation for every indicator to fully explain the data sources, origin, calculation, and nuanced factors involved in each indicator metric. These materials enable every indicator's derivation to be transparent and their results to be replicable by readers.

Greenhouse Gases

As greenhouse gas emissions from human activities increase, they build up in the atmosphere and warm the climate, leading to many other changes around the world—in the atmosphere, on land, and in the oceans. The indicators presented in other chapters of this report and on EPA's website illustrate many of these changes and their effects on people, society, and the environment.

Indicators featured in this chapter:
Global Greenhouse Gas Emissions, U.S. Greenhouse Gas Emissions, Atmospheric Concentrations of Greenhouse Gases

Why it matters

Excess heat trapped in the atmosphere by greenhouse gases leads to higher air temperatures near the Earth's surface, alters weather patterns, and raises the temperature of the oceans. The scale, pace, and geographic extent of observed climatic changes affect people and the environment in important ways. For example, sea levels are rising, glaciers are melting, and plant and animal life cycles are changing. These types of changes can bring about fundamental disruptions in ecosystems, affecting plant and animal populations, communities, and biodiversity. Such changes can also affect people's health and quality of life, where people can live, what kinds of crops are most viable, what kinds of businesses can thrive in certain areas, and the condition of buildings and infrastructure. The other chapters of this report explore several of these types of impacts in more depth, along with their effects on people's health and well-being.

The atmosphere has higher concentrations of greenhouse gases now than it did at any other point in human history. Human civilization has never existed with such a strong greenhouse effect controlling the Earth's temperature. As fossil fuel burning and other activities continue to add greenhouse gases to the atmosphere, humanity will continue into uncharted conditions.

The world's greenhouse gas emissions have increased substantially in the last 30 years.

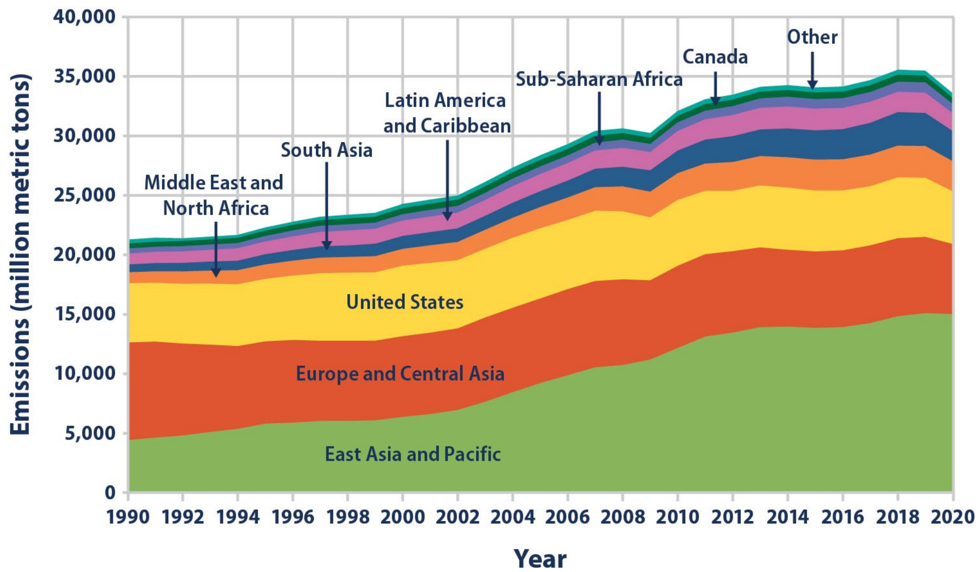
What's happening

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

- EPA's Global Greenhouse Gas Emissions indicator shows that between 1990 and 2015, global emissions of all major greenhouse gases increased. Between 1990 and 2020, gross emissions of carbon dioxide increased by 58 percent, which is particularly important because carbon dioxide accounts for about three-fourths of total global emissions.
- Carbon dioxide emissions are increasing faster in some parts of the world (for example, East Asia and the Pacific) than in others. The majority of emissions come from three regions: East Asia and Pacific, Europe and Central Asia, and the United States, which together accounted for 75 percent of total global emissions in 2020 (Figure 1).

Figure 1. Global Carbon Dioxide Emissions by Region, 1990–2020

This graph shows carbon dioxide emissions from 1990 to 2020 for different regions of the world. These totals do not include emissions or sinks related to land-use change or forestry. Inclusion of land-use change and forestry would increase the apparent emissions from some regions while decreasing the emissions from others. Data source: Climate Watch, 2023.[1]



Human activities produce greenhouse gases that stay in the atmosphere for many years

The major greenhouse gases emitted into the atmosphere are **carbon dioxide, methane, nitrous oxide, and fluorinated gases**. Some of these gases are produced almost entirely by human activities; others come from a combination of natural sources and human activities. The sources from human activities include burning of fuels for electricity, transportation, and heat as well as agricultural and industrial processes.

Many of the major greenhouse gases can remain in the atmosphere for tens to thousands of years after being released. They become globally mixed in the lower part of the atmosphere, called the troposphere (the first several miles above the Earth's surface), reflecting the combined contributions of emissions sources worldwide from the past and present. Due to this global mixing, the impact of emissions of these gases does not depend on where in the world they are emitted. Also, concentrations of these gases are similar regardless of where they are measured, as long as the measurement is far from any large sources or sinks of that gas.

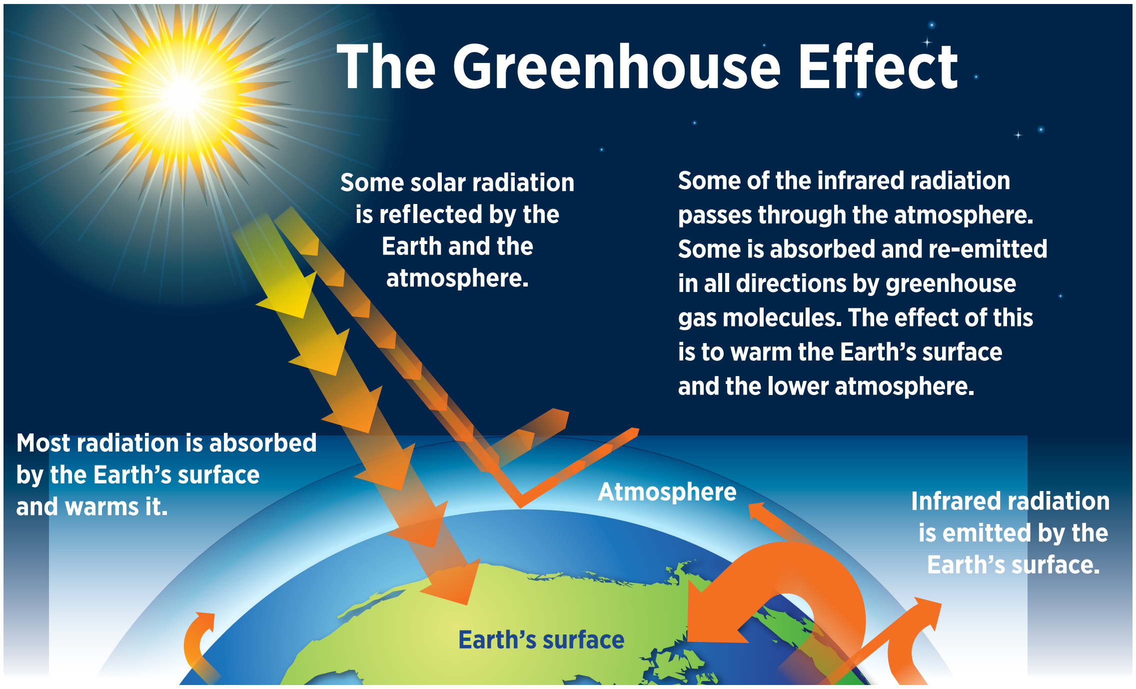
Some other substances have much shorter atmospheric lifetimes (less than a year) but are still relevant to climate change. Important short-lived substances that affect the climate include water vapor, ozone in the troposphere, pollutants that lead to ozone formation, and aerosols (atmospheric particles) such as black carbon and sulfates. Water vapor, tropospheric ozone, and black carbon contribute to warming, while other aerosols produce a cooling effect. Because these substances are short-lived, their climate impact can be influenced by the location of their emissions, with concentrations varying greatly from place to place.

Learn more at: www.epa.gov/ghgemissions.

Greenhouse gases trap heat in the atmosphere

The Earth's temperature depends on the balance between energy entering and leaving the planet's system. That balance is controlled by the interactions between sunlight and the atmosphere. When sunlight reaches the Earth's surface, it can either be reflected back into space or be absorbed by the Earth. Solar energy that is reflected back into space does not warm the Earth. Incoming energy that is absorbed by the Earth warms the surface. Earth's warmed surface then releases some of that absorbed energy back into the atmosphere as infrared radiation.

Certain gases in the atmosphere absorb infrared radiation, which traps that energy as heat instead of letting it escape to outer space. Those gases are known as greenhouse gases. They act like a blanket, making the Earth warmer than it would otherwise be. This process, commonly known as the greenhouse effect, is natural and necessary to support life. However, the recent buildup of greenhouse gases in the atmosphere from human activities has tipped the balance of heat for the planet. As a result, the Earth's climate is changing with increasingly dangerous effects on human health and well-being and on ecosystems.



The greenhouse effect helps trap heat from the sun, which keeps the temperature on the Earth comfortable. But people's activities are increasing the amount of heat-trapping greenhouse gases in the atmosphere, causing the Earth to warm up.

U.S. greenhouse gas emissions have decreased slightly since 1990, but still make up a sizable share of the world's emissions.

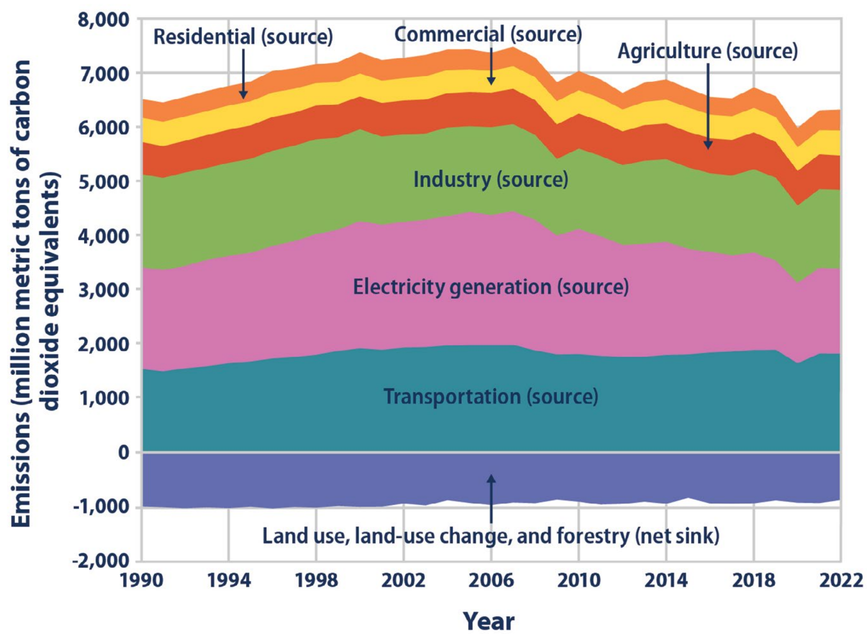
What's happening

EPA's U.S. Greenhouse Gas Emissions indicator shows that in 2022, U.S. greenhouse gas emissions totaled 6,343 million metric tons (14.0 trillion pounds) of carbon dioxide equivalents. This is a 3 percent decrease since 1990, due to factors such as increased energy efficiency and decreased carbon intensity of energy sources (mainly in non-transport sectors). Although overall emissions have decreased slightly since 1990, the United States still accounted for 13 percent of global carbon dioxide emissions in 2020 (see Figure 3 of EPA's Global Greenhouse Gas Emissions indicator) despite having only about 4 percent[2] of the world's population then.

- Everyday activities like using electricity or driving vehicles contribute to climate change. Among the various sectors of the U.S. economy, transportation accounts for the largest share—28 percent—of 2022 emissions, followed by electric power (power plants) (25 percent), industry (23 percent), agriculture (10 percent), the commercial sector (7 percent), and the residential sector (6 percent) (Figure 2).
- Removals or sinks represent the opposite of emissions: the absorption or sequestering of carbon dioxide from the atmosphere. In 2022, 13 percent of U.S. greenhouse gas emissions were offset by net sinks resulting from land use and forestry practices. One major sink is the net growth of forests, including urban trees, which remove carbon from the atmosphere. Other carbon sinks are associated with how people manage and use the land, including the practice of depositing yard trimmings and food scraps in landfills (Figure 2).
- The sharp decline in emissions from 2019 to 2020 was largely due to the impacts of the coronavirus (COVID-19) pandemic on travel and economic activity. Emissions increased 5.7 percent from 2020 to 2022 as the economy rebounded (Figure 2).

Figure 2. U.S. Greenhouse Gas Emissions and Sinks by Economic Sector, 1990–2022

This graph shows greenhouse gas emissions and sinks (negative values) by source in the United States from 1990 to 2022. For consistency, emissions are expressed in million metric tons of carbon dioxide equivalents. All electric power emissions are grouped together in the "Electricity generation" sector, so other sectors such as "Residential" and "Commercial" are only showing non-electric sources, such as burning oil or gas for heating. The economic sectors shown here do not include emissions from U.S. territories outside the 50 states. EPA publishes supplementary tables and charts online that show sector- and gas-specific data broken out by individual state. Data source: U.S. EPA, 2024.[3]



Sources of data on U.S. greenhouse gas emissions

EPA has two key programs that provide data on greenhouse gas emissions in the United States. The programs are complementary, providing both a higher-level perspective on the nation's total emissions and detailed information about the sources and types of emissions from individual facilities.

- EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks tracks trends in total annual U.S. emissions by source (or sink), economic sector, and greenhouse gas going back to 1990. This inventory fulfills the nation's obligation to provide an annual emissions report under the United Nations Framework Convention on Climate Change.
- EPA's Greenhouse Gas Reporting Program collects annual emissions data from industrial sources that directly emit large amounts of greenhouse gases. The program helps EPA and the public understand where greenhouse gas emissions are coming from and helps inform policy, business, and regulatory decisions.

The amount of carbon dioxide in the atmosphere is higher than it has been at any time in at least the last 800,000 years.

What's happening

When greenhouse gases are emitted into the atmosphere, many remain there for periods ranging from a decade to many millennia. Over time, these gases are removed from the atmosphere by chemical reactions or by emission sinks, such as the oceans and vegetation, which absorb greenhouse gases from the atmosphere. As a result of human activities, however, these gases are entering the atmosphere more quickly than they are being removed from it, and thus their concentrations are increasing.

EPA's Atmospheric Concentrations of Greenhouse Gases indicator describes concentrations of greenhouse gases in the atmosphere, focusing on the major greenhouse gases that result from human activities. For carbon dioxide, the most prominent greenhouse gas, recent measurements come from monitoring stations around the world, while measurements of older air come from air bubbles trapped in layers of ice from Antarctica and Greenland. By determining the age of the ice layers and the concentrations of gases trapped inside, scientists can learn what the atmosphere was like thousands of years ago.

- The global atmospheric concentration of carbon dioxide has risen significantly over the last few hundred years. Since the beginning of the industrial era, carbon dioxide concentrations have risen from an annual average of 280 parts per million (ppm) in the late 1700s to 419 ppm in 2023. Almost all of this increase is due to human activities (Figure 3).[4]
- Historical measurements show that the current global atmospheric concentration of carbon dioxide is unprecedented compared with the past 800,000 years (Figure 3).

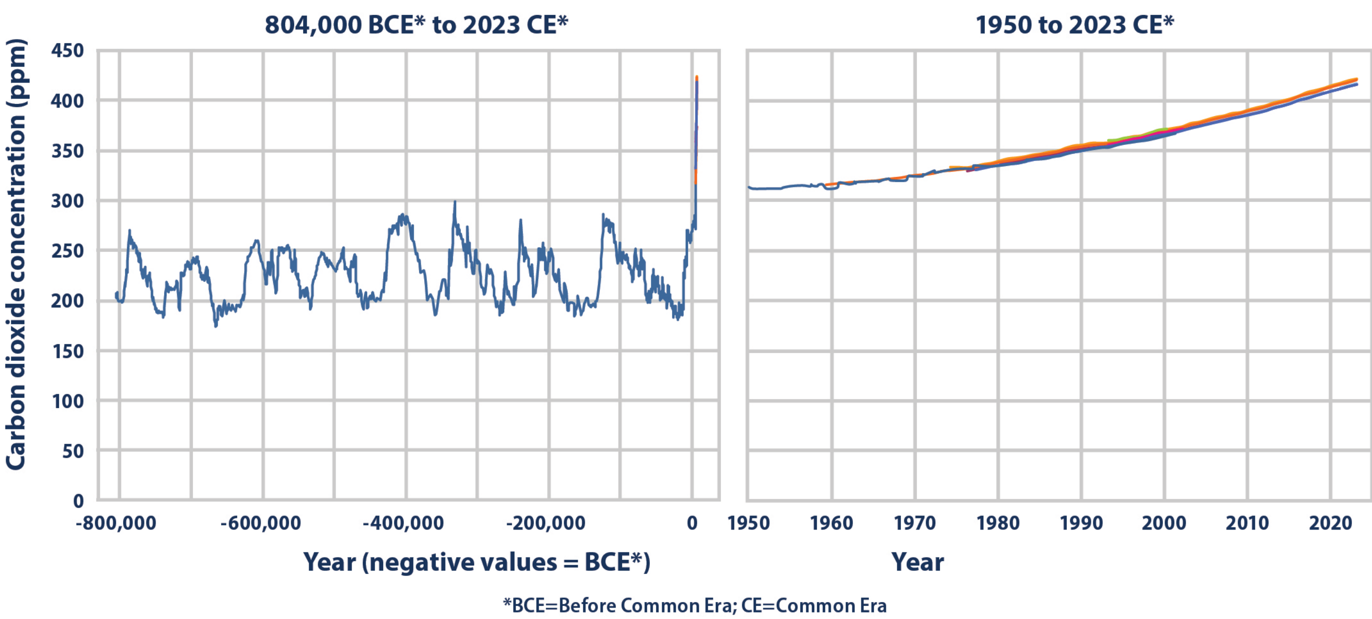


Figure 3. Global Atmospheric Concentrations of Carbon Dioxide over Time

This figure shows concentrations of carbon dioxide in the atmosphere from hundreds of thousands of years ago through 2023, measured in parts per million (ppm). The data come from a variety of historical ice core studies and recent air monitoring sites around the world. Each line represents a different data source. Data source: Compilation of eight underlying data sets.[5]

Taking action: what EPA is doing about climate change

Climate change is real and happening all around us. Taking action to fight the urgent threat of climate change offers an opportunity to build more resilient infrastructure, protect public health, advance environmental justice, strengthen America's working communities, and spur American technological innovations.

EPA's work is improving society's understanding of climate change and its impacts on human health and the environment. The data, tools, and resources that EPA develops can also be used by other agencies, organizations, states, Tribes, and communities to help tackle the climate crisis effectively, equitably, and sustainably.

Specific actions EPA undertakes to address climate change include:

- **Measuring emissions.** EPA is responsible for measuring and estimating greenhouse gas emissions through the Inventory of U.S. Greenhouse Gas Emissions and Sinks and Greenhouse Gas Reporting Program to help the public and policymakers understand the nation's total emissions as well as the sources and types of these emissions at individual facilities.
- **Reducing emissions.** EPA works with industry, states, and others to reduce greenhouse gas emissions through regulatory initiatives and partnership programs. EPA also uses a range of strategies to reduce its own greenhouse gas emissions, increase its energy efficiency, and take other steps to reduce its carbon footprint.
- **Investing in our future.** Through the Bipartisan Infrastructure Law and Inflation Reduction Act, EPA is making historic investments to tackle climate change, protect public health, create jobs in communities across the country, and deliver a more equitable future. Many of these investments are specifically targeted toward communities that have faced underinvestment in the past.
- **Evaluating policy options, costs, and benefits.** EPA conducts analyses to understand the physical and economic impacts of climate change under different emission scenarios and to quantify the economic impacts and effectiveness of proposed climate policies. EPA also provides free tools to state, local, and Tribal governments to help them evaluate their own clean energy policies and programs.
- **Advancing the science.** EPA conducts research on climate change to understand its impacts and help manage its risks. EPA partners with other federal agencies and international organizations to coordinate research. EPA's research includes efforts to better understand the links between climate change and air quality, water quality, ecosystems, and public health.
- **Partnering internationally.** EPA is engaged in a variety of international activities to advance climate change science, monitor the environment, and promote activities that reduce greenhouse gas emissions.
- **Helping communities reduce emissions and adapt.** Climate change is happening and affecting communities, livelihoods, and environments. In response, EPA is providing technical assistance, tools, and resources to help state, local, and Tribal governments in planning, adapting, and building climate resilience. These include grant programs and technical assistance centers specifically adapted to the needs and challenges of communities with environmental justice concerns.

Learn more about actions EPA is taking to address climate change.

Heat on the Rise

As the concentrations of heat-trapping greenhouse gases in the atmosphere continue to increase, the United States has experienced warming temperatures, more unusually hot summer days, and more frequent heat waves that threaten people's health and strain the electric power grid.

Indicators featured in this chapter:

U.S. and Global Temperature, High and Low Temperatures, Heat Waves, Heat-Related Deaths, A Closer Look: Heat-Related Workplace Deaths, Heating and Cooling Degree Days, Residential Energy Use

The United States has warmed more quickly than the global rate. Some parts of the country are warming more than others.

Why it matters

Temperature is a fundamental measurement for describing the climate. In particular places, temperature can have wide-ranging effects on human life and ecosystems. Hotter days and nights and heat waves can not only increase people's discomfort, but also harm physical and mental health and well-being. When people are exposed to extreme heat, they can suffer from potentially deadly illnesses, such as heat exhaustion and heat stroke. Hot temperatures can also contribute to deaths from heart attacks, strokes, and other forms of cardiovascular disease. Less "cooling off" at night can be particularly bad for people's health because it gives less opportunity to recover from daytime heat. Certain populations such as older adults, children, people with chronic diseases, and outdoor workers face higher risks of heat-related illnesses and death (see the "Extreme heat: who's most at risk?" box on p. 17).

What's happening

EPA's U.S. and Global Temperature indicator shows that global average surface temperature has risen at an average rate of 0.17°F per decade since 1901, similar to the rate of warming within the contiguous 48 states. Since the late 1970s, however, the United States has warmed more quickly than the planet as a whole.

- For the contiguous United States, nine of the 10 warmest years on record have occurred since 1998, and 2012 and 2016 were the two warmest years (Figure 4).
- Worldwide, 2023 was the warmest year on record, 2016 was the second warmest, and 2014–2023 was the warmest decade on record since thermometer-based observations began (Figure 5).

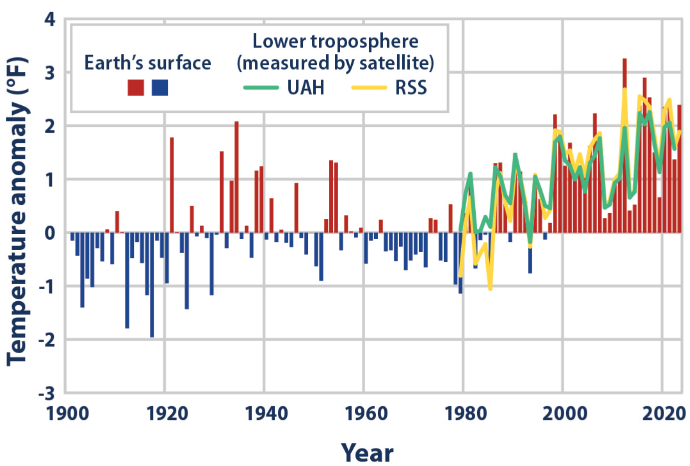


Figure 4. Temperatures in the Contiguous 48 States, 1901–2023

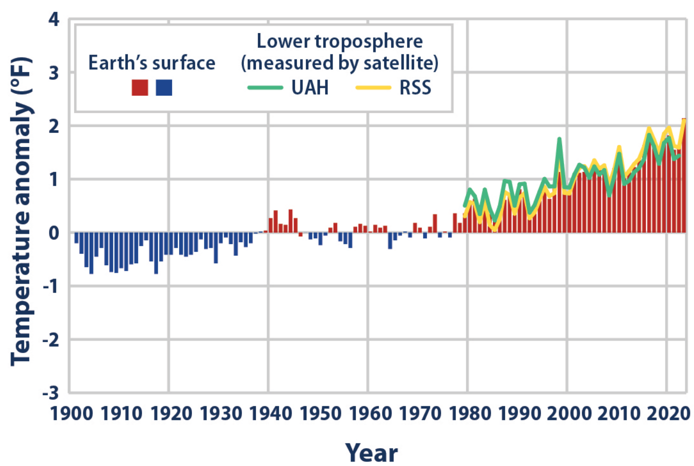


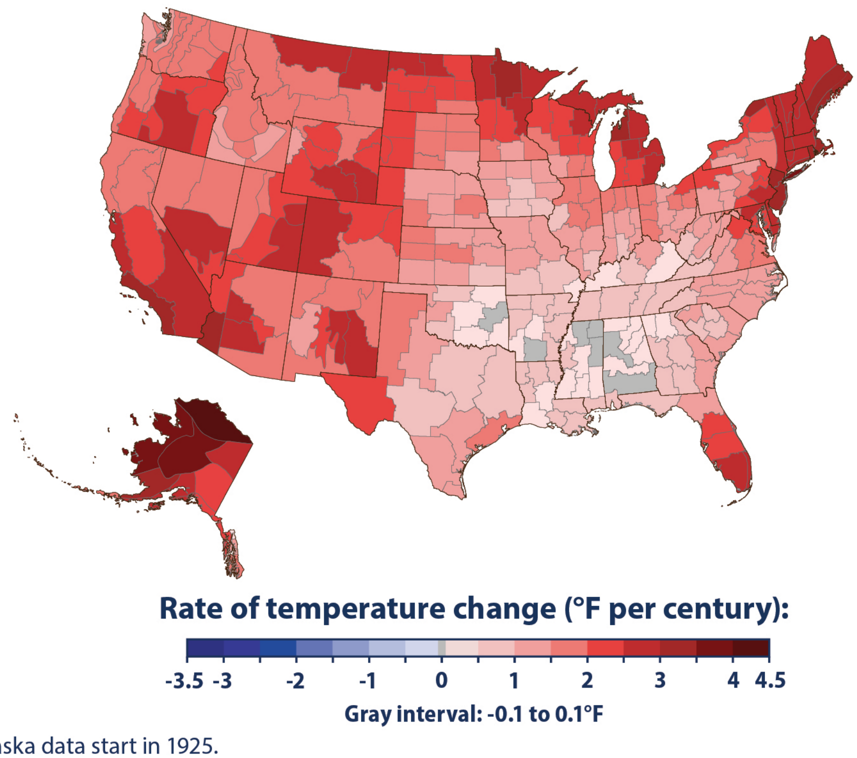
Figure 5. Temperatures Worldwide, 1901–2023

These graphs show how annual average temperatures in the contiguous 48 states and worldwide have changed since 1901. Surface data come from land-based weather stations. Satellite measurements cover the lower troposphere, which is the lowest level of the Earth's atmosphere. "UAH" and "RSS" represent two different methods of analyzing the original satellite measurements. These graphs use the 1901–2000 average as a baseline for showing change. Choosing a different baseline period would not change the shape of the data over time. Data source: NOAA, 2024.[1]

- Warming is happening across the United States. Some parts, such as the North, West, and Alaska, have experienced more pronounced warming, while some parts of the Southeast have experienced little change (Figure 6). Alaska's Warming Climate examines how the most rapid climate change is affecting life in a state whose culture, ecosystems, and infrastructure are uniquely vulnerable to warming.

Figure 6. Rate of Temperature Change in the United States, 1901–2023

This map shows how annual average air temperatures have changed in different parts of the United States since the early 20th century (since 1901 for the contiguous 48 states and 1925 for Alaska). The data are shown for climate divisions, as defined by the National Oceanic and Atmospheric Administration. Data source: NOAA, 2024.[2]



"Unusually hot" summer days and nights are not that unusual anymore.

What's happening

Record-setting temperatures are a natural part of day-to-day variation in weather. However, as the Earth's climate warms overall, temperatures that are unusually hot for a given location are expected to increase.[3]

- EPA's High and Low Temperatures indicator shows that, nationwide, unusually hot summer days (highs) have become more common over the last few decades. The occurrence of unusually hot summer nights (lows) has increased at an even faster rate, which indicates less "cooling off" at night (Figure 7).
- The 20th century also had many winters with widespread patterns of unusually low temperatures, including a particularly large spike in the late 1970s. Since the 1980s, though, unusually cold winter temperatures have become less common—particularly very cold nights (lows) (Figure 8).

Figure 7. Area of the Contiguous 48 States with Unusually Hot Summer Temperatures, 1910–2023

This graph shows the percentage of the land area of the contiguous 48 states with unusually hot daily high and low temperatures during the months of June, July, and August. The lines show a nine-year weighted average. The red line represents daily highs, while the orange line represents daily lows. The term "unusual" in this case is based on the long-term average conditions at each location. Data source: NOAA, 2024.[4]

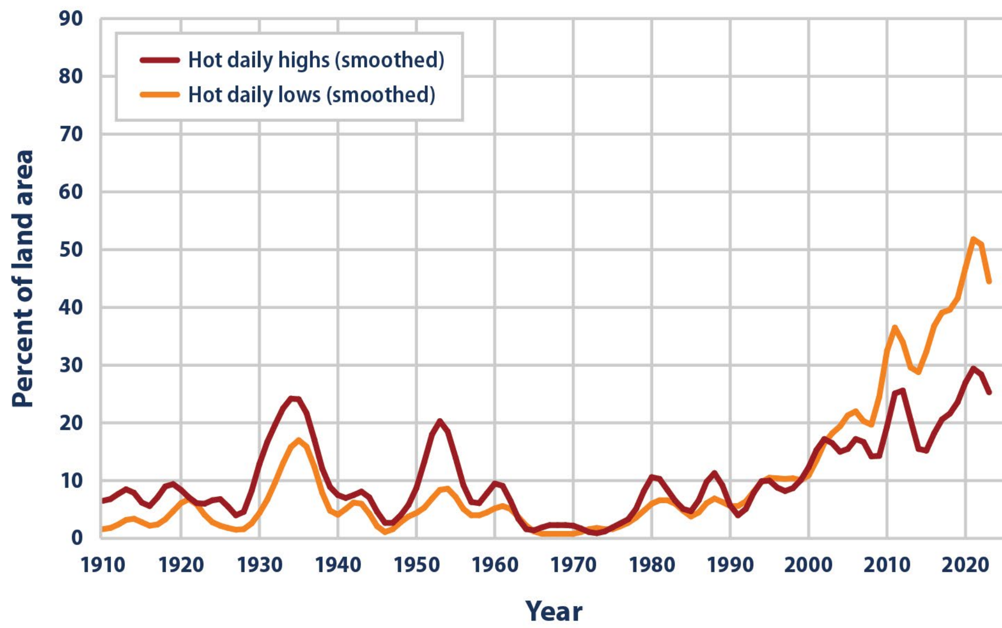
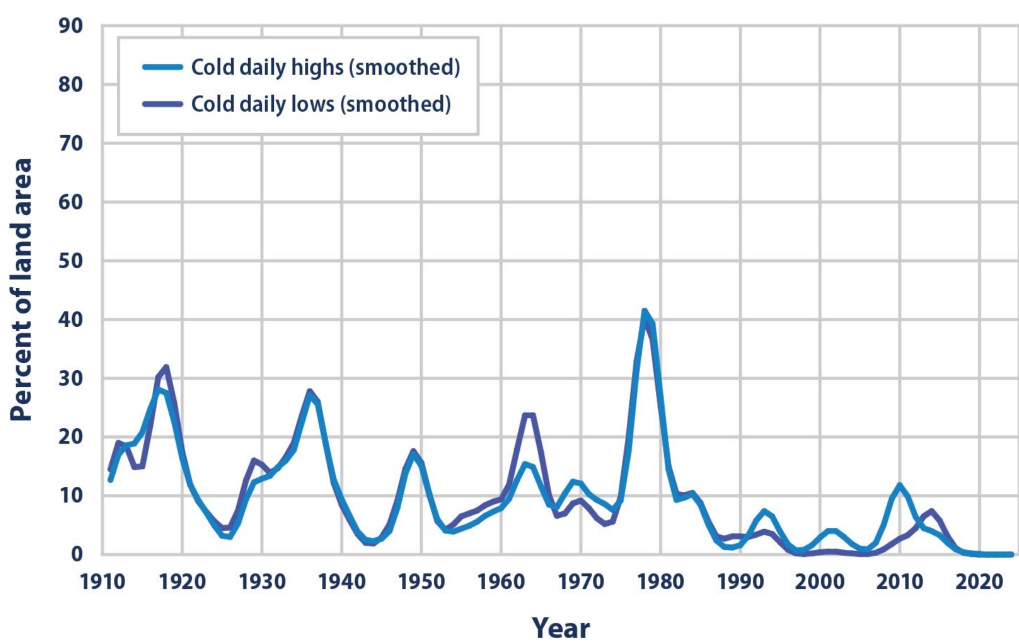


Figure 8. Area of the Contiguous 48 States with Unusually Cold Winter Temperatures, 1911–2024

This graph shows the percentage of the land area of the contiguous 48 states with unusually cold daily high and low temperatures during the months of December, January, and February. The lines show a nine-year weighted average. The blue line represents daily highs, while the purple line represents daily lows. The term "unusual" in this case is based on the long-term average conditions at each location. Data source: NOAA, 2024.[5]



Extreme heat: who's most at risk?

A person's chances of being harmed by extreme heat depend on a combination of exposure, sensitivity, and capacity to adapt. Depending on these factors, certain populations face higher risks of heat-related illness and death. Increases in the frequency and intensity of heat waves due to climate change will raise this risk. Specifically:

- The population of adults aged 65 and older, which is expected to continue to grow, has a higher-than-average risk of heat-related illness and death due to factors such as underlying health conditions.[6] This group accounted for more heat-related hospitalizations than any other age group in EPA's Heat-Related Illnesses indicator.
- Children are at higher risk because their bodies are less able to adapt to heat than adults', and they must rely on others to help keep them safe. They also tend to spend more time outdoors than adults.[7]
- People with certain chronic diseases, such as cardiovascular and respiratory illnesses, are at higher risk for heat-related health impacts. Data also suggest a higher incidence of heat-related illnesses among non-Hispanic Black people.[8]
- People who lack access to cool spaces or air conditioning, either due to poor housing or from experiencing homelessness, are at higher risk. The risk increases in neighborhoods where hot temperatures are magnified by the heat island effect.
- Many workers face higher exposure to extreme heat because they work outdoors in industries like agriculture, landscaping, construction, and delivery services or work in hot indoor environments that lack adequate air conditioning, such as manufacturing plants, warehouses, and other facilities.[9] For instance, OSHA has found that workers in agriculture are 35 times more likely to die from heat exposure than the average American worker.[10]

Learn more about who's most at risk from extreme heat on EPA's website, Climate Change and Human Health: Who's Most at Risk?, as well as in the "Human Health" chapter of the Fifth National Climate Assessment.

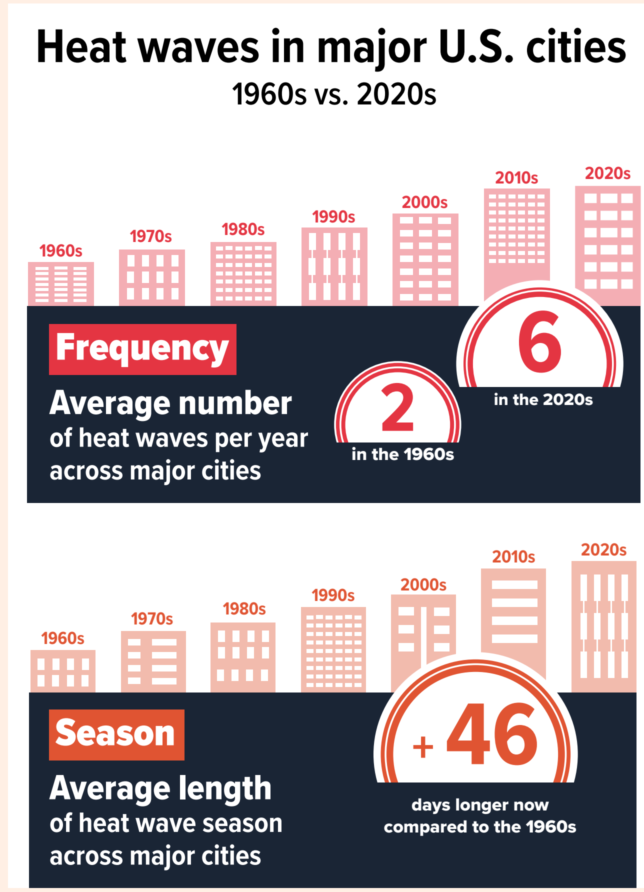
Heat waves are more frequent, long-lasting, and intense than they used to be.

What's happening

A period of several unusually hot days in a row is referred to as an extreme heat event or a heat wave. Unusually hot days and heat wave events are a natural part of day-to-day variation in weather, but as the Earth's climate warms, heat waves are expected to become more frequent and intense. High humidity adds to this hazard. EPA's Heat Waves indicator uses more than 60 years of detailed data on apparent temperatures (actual temperature plus humidity, similar to the heat index) to examine how heat wave frequency, duration, season length, and intensity have changed. In this indicator, a heat wave is defined as a period of two or more consecutive days when the daily minimum apparent temperature in a particular city exceeds the 85th percentile of historical July and August temperatures (1981–2010) for that city.

- Heat waves are occurring more often than they used to across 50 major cities measured, including Chicago, Dallas, Miami, Boston, Phoenix, Memphis, and Seattle. Their frequency has increased steadily, from an average of two heat waves per year during the 1960s to six per year during the 2010s and 2020s (Figure 9).
- The average heat wave season (the number of days between the first heat wave of the year and the last) across the 50 cities measured is about 46 days longer now than it was in the 1960s (Figure 9).
- In recent years, the average heat wave in major U.S. urban areas has been about four days long. This is about a day longer than the average heat wave in the 1960s.
- Heat waves have become more intense over time. Compared with the 1960s, the average heat wave in the 2010s and 2020s is hotter across the 50 cities measured.

Figure 9. Heat Waves in Major U.S. Cities, 1960s vs. 2020s



Data source: NOAA, 2024.[11]

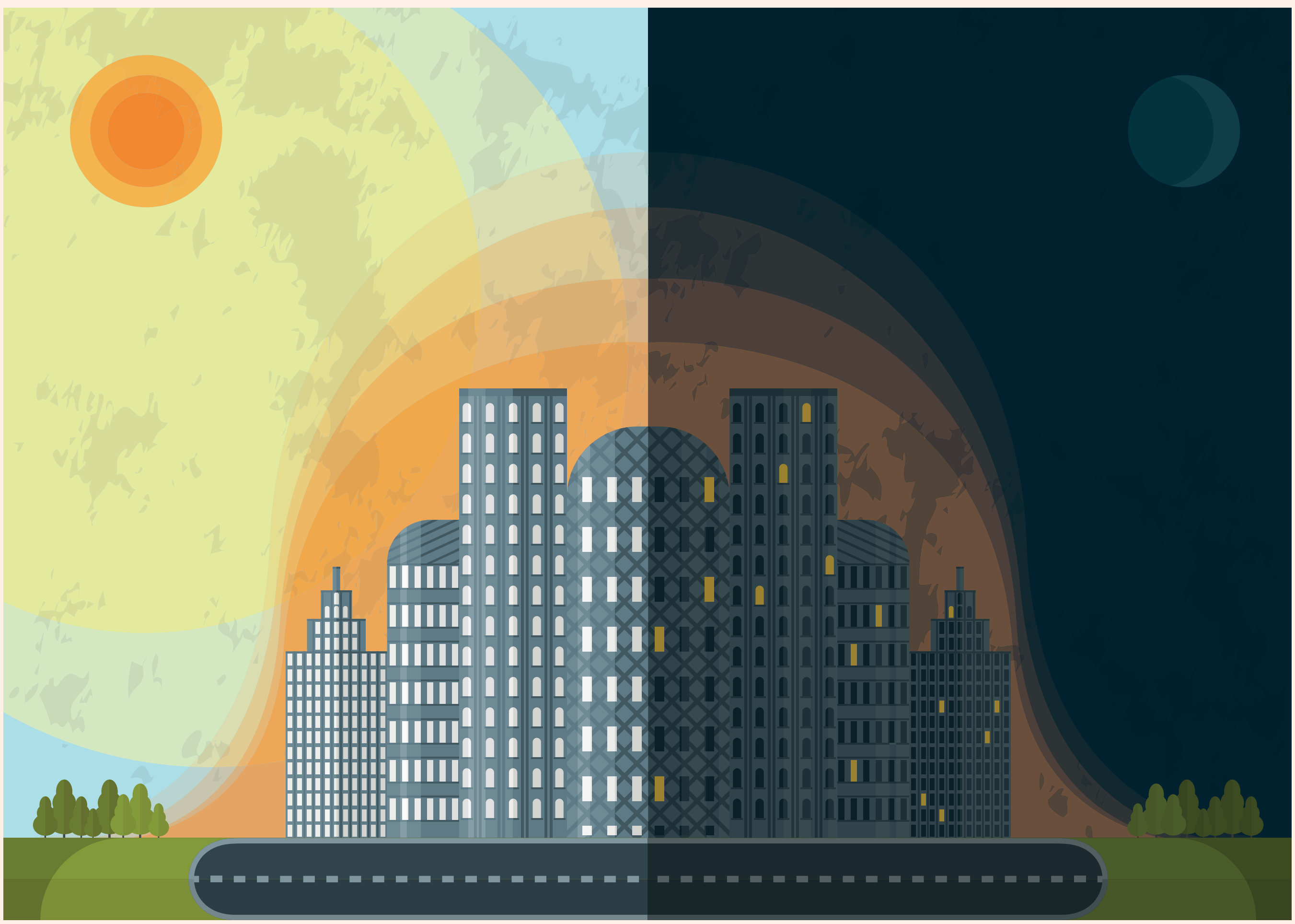
The timing of heat waves can matter. Extreme heat events that occur earlier in the spring or later in the fall can catch people off-guard and increase exposure to the health risks associated with extreme heat. For instance, people who live in multi-family buildings might not have control of when their air conditioning operates.

The heat island effect

Cities have buildings, pavement, and other infrastructure that absorbs and re-emits the sun's heat more than natural landscapes such as forests and water bodies. As a result, urban areas can become "islands" that are warmer than surrounding areas and can hold that heat for longer into the night. This phenomenon is known as the heat island effect. Heat islands heighten the risk of heat-related illness and death. They also increase energy demand for cooling, which can increase greenhouse gas emissions and air pollution and can pose a financial burden for many people—particularly low- or fixed-income households.

The heat island effect is heightened in neighborhoods that lack tree cover and green space. In many urban areas, this contributes to disproportionate impacts on lower-income communities and people of color, populations who already face other burdens and challenges. Studies have found that heat island effects are often more severe in neighborhoods with lower median incomes and a higher proportion of people of color. Some of this can be traced back to the legacy of "redlining" that began in the 1930s—a discriminatory practice in which the federal government labeled many non-white neighborhoods as undesirable for real estate investment. Public and private lenders often withheld loans and other services from people in those areas, depriving residents of opportunities to grow their wealth. Even though redlining was outlawed in 1968 with the Fair Housing Act, it contributed to residential segregation patterns, homeownership disparities, and deteriorating infrastructure that are still present today. Current neighborhoods that were once redlined continue to have less tree cover, higher temperatures, and greater proportions of residents with lower income.[12]

Learn more about heat islands, and about how strategies such as investing in cooler infrastructure have been used to mitigate the effects of heat islands, at EPA's Heat Islands website.



Warmer temperatures increase the risk of heat-related illnesses and deaths.

What's happening

According to the National Weather Service, heat is a leading weather-related killer in the United States,[13] even though most heat-related deaths are preventable through outreach and intervention. Extreme heat can exacerbate underlying health conditions including cardiovascular disease, respiratory diseases like asthma, and diabetes. EPA's [Heat-Related Deaths indicator](#) tracks annual deaths classified as "heat-related" by medical professionals in the 50 U.S. states and the District of Columbia.

- Between 1979 and 2022, the rate of deaths directly resulting from exposure to heat (the underlying cause of death) generally hovered between 0.5 and 2 per million people; this number spiked in certain years (Figure 10).
- Overall, more than 14,000 Americans have died from heat-related causes since 1979, according to death certificates.
- It is difficult to determine if the United States has experienced a meaningful increase or decrease in deaths classified as "heat-related" over time. While dramatic increases in heat-related deaths are closely associated with the occurrence of hot temperatures and heat waves, deaths may not be reported as "heat-related" on death certificates and there is considerable year-to-year variability in the data.
- While heat-related deaths are the more severe outcome, heat-related conditions such as heat exhaustion and heat stroke send more Americans to the hospital every year. EPA's Heat-Related Illnesses indicator shows that from 2001 to 2010, annual heat-related hospitalization rates ranged up to nearly four cases per 100,000 people in some states.
- EPA's Cold-Related Deaths indicator notes that rising winter temperatures are expected to reduce the number of cold-related deaths, but the decrease is projected to be smaller than increases in heat-related deaths.[14]

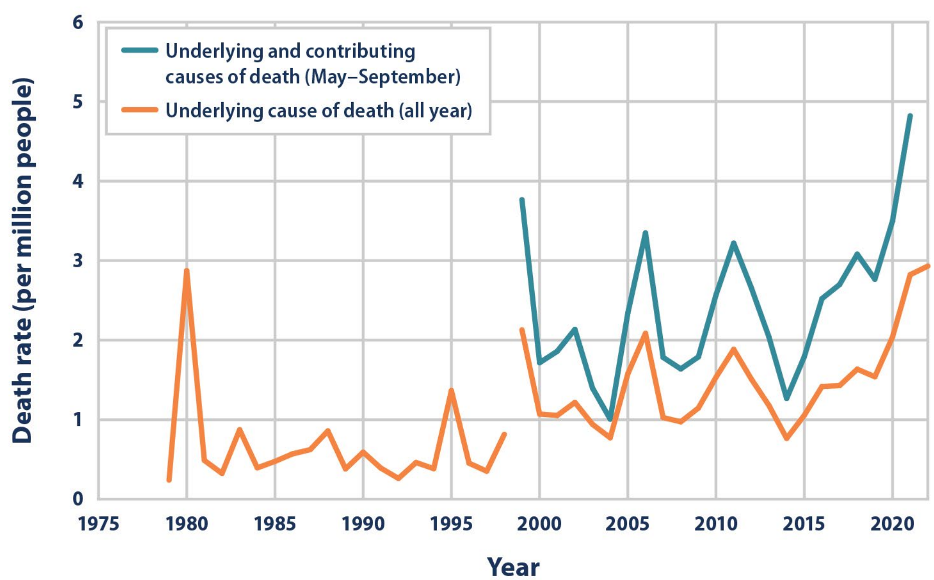


Figure 10. Deaths Classified as "Heat-Related" in the United States, 1979–2022

This graph shows the annual rates for deaths classified as "heat-related" by medical professionals in the 50 states and the District of Columbia. The orange line shows deaths for which heat was listed as the main (underlying) cause. The way causes of death are classified changed between 1998 and 1999, so data before 1999 cannot be easily compared with data from 1999 and later. The blue line shows deaths for which heat was listed as either the underlying or the contributing cause of death in May–September, based on a broader set of data that became available in 1999 and could be updated through 2021. Data source: CDC, 2024.[15,16]

Outdoor workers, particularly those engaging in strenuous physical activity, disproportionately face heat-related health threats.[17] EPA's A Closer Look: Heat-Related Workplace Deaths tracks the number of workers who have died as a result of heat exposure on the job in the United States.

- From 1992 to 2022, a total of 986 workers across all industry sectors in the United States died from exposure to heat. This represents an average of 34 deaths per year (Figure 11).
- The construction sector accounted for about 34 percent of all occupational heat-related deaths from 1992 to 2022. During this time frame, 334 construction workers died due to heat exposure on the job.
- The total number of heat-related worker deaths per year has ranged from 11 (reported in 1992) to 61 (2011). The number of heat-related deaths in the construction sector peaked at 18 in 2010 (and 18 again in 2011).

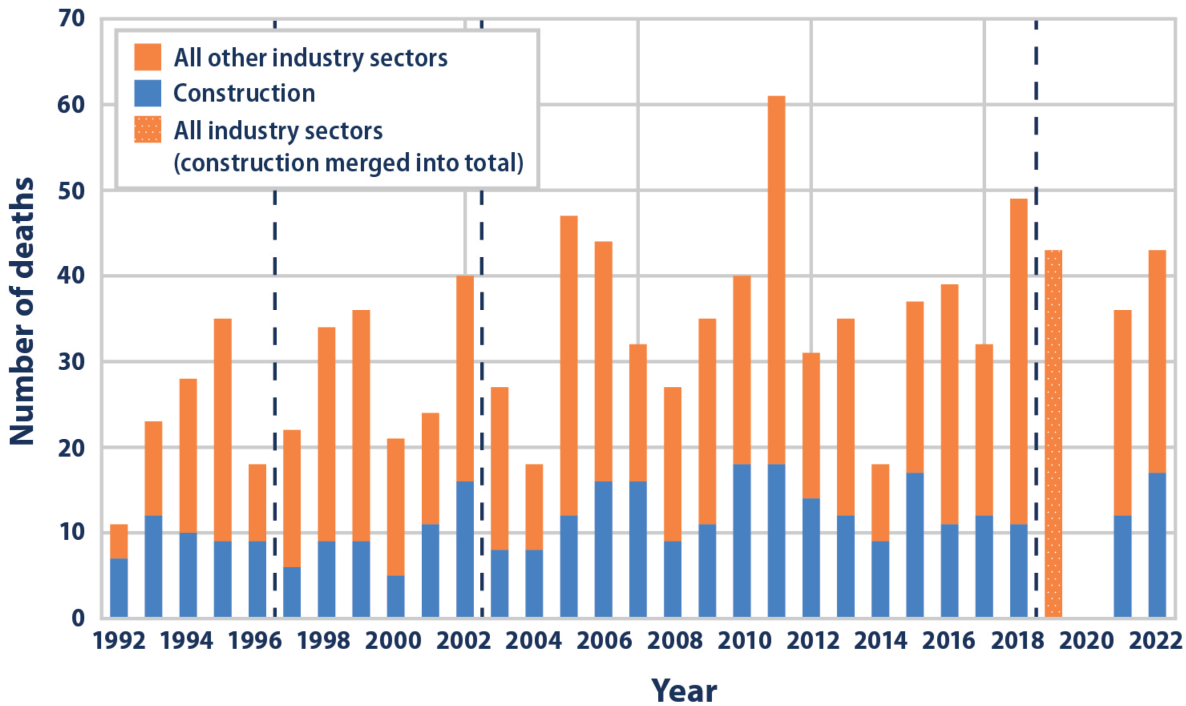


Figure 11. Heat-Related Workplace Deaths in the United States, 1992–2022

This graph shows the number of reported heat-related workplace deaths in the United States each year. The blue portions of the bars show deaths in the construction sector and the orange portions show deaths in all other sectors of the economy. The dashed lines indicate when the U.S. Bureau of Labor Statistics (BLS) changed how it classifies "construction" (1996/1997 and 2002/2003) or changed its thresholds for reporting individual industry totals (2018/2019). Total construction sector deaths in 2019 fell below the new threshold; for that year, BLS combined construction into a single "all-industry" total rather than reporting a sector total. BLS has indicated that data collection for 2020 fell below reporting thresholds. Data source: BLS, 2024.[18]

Taking action: adapting to extreme heat

With unusually hot summer temperatures becoming more common and heat waves becoming more frequent and intense, the risk of heat-related deaths and illness is expected to increase unless people take steps to adapt.

The best defense against extreme heat is to be prepared, and remember:

- **Get ready.** Take steps now to prepare your home, workplace, and community for future heat events. Consider ways to avoid or postpone outdoor activities, especially during the hottest part of the day.
- **Get set.** Know the symptoms of heat-related illnesses and what to do in an emergency.
- **Go.** Check on those who may be most at risk during an extreme heat event, like children, older adults, people with disabilities, homebound neighbors, outdoor workers, people with chronic medical conditions, and pregnant people.

Communities across the United States are taking steps to prepare for extreme heat and protect their residents. In response to several severe heat waves in the early 1990s—one of which, in 1993, led to more than 100 deaths—Philadelphia, Pennsylvania, formed a "Heat Task Force" that implemented several successful strategies that are still protecting lives today. These strategies include:

- **"Heatline" activation.** A special helpline is available for residents to call for assistance during a heat emergency.
- **Home visits by health department staff.** Mobile heat health teams can be dispatched to help people in need.
- **Halt to service shutoffs.** Residential electric and water shutoffs are stopped during a heat health emergency.
- **Cooling centers/senior refuge.** Hours of operation at air-conditioned senior centers are extended to provide a refuge for those otherwise lacking access to air conditioning.

For more information, see:

- www.heat.gov (offering resources from multiple federal agencies).
- EPA's *Excessive Heat Events Guidebook*.
- EPA and CDC's *Climate Change and Extreme Heat: What You Can Do to Prepare*.
- CDC's extreme heat resources.
- Philadelphia's hot weather preparedness website.

Warmer temperatures increase the demand for cooling.

Why it matters

Temperature affects our health, comfort level, and demand for heating and air conditioning. Collectively, heating and cooling the spaces in which we live accounts for about half of the energy that American households use every year. Heating and cooling degree days suggest how much energy people might need to use to heat and cool their homes and workplaces, thus providing a sense of how climate change could affect people's daily lives and finances.

What's happening

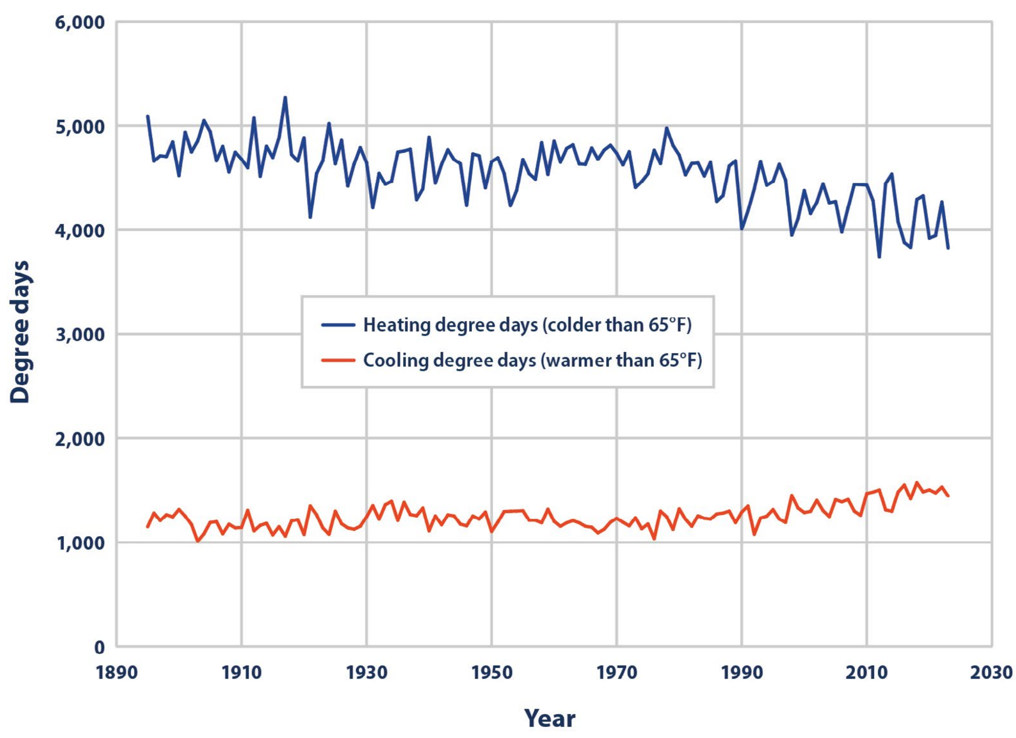
As climate change drives an increase in average temperatures, an increase in unusually hot days, and a decrease in unusually cold days, the overall demand for heating is expected to decline and the demand for cooling is expected to increase.

One way to measure the influence of temperature change on energy demand is using heating and cooling degree days. EPA's Heating and Cooling Degree Days indicator measures the difference between outdoor temperatures and a temperature that people generally find comfortable indoors. These differences in temperature suggest how much energy people might need to use to heat and cool their homes and workplaces.

- Heating degree days have declined overall in the contiguous United States, particularly in recent years, as the climate has warmed (Figure 12).
- Overall, cooling degree days have increased over the past 100 years. The increase is most noticeable over the past few decades (Figure 12).

Figure 12: Heating and Cooling Degree Days in the Contiguous 48 States, 1895–2023

This graph shows the average number of heating and cooling degree days per year across the contiguous 48 states. Data source: NOAA, 2024.[19]



More cooling can require more electricity use.

Why it matters

As the need for air conditioning increases, people will likely have to spend more money on electricity for cooling. Increased use of air conditioning could also lead to more greenhouse gas emissions and further climate change, as more electricity must be generated to meet this increased demand. Hot days are also the most vulnerable days for the nation's power grid: increased electricity demand for cooling on these days can increase the likelihood of brownouts or blackouts.

What's happening

As climate change contributes to an increase in average temperatures and unusually hot days, Americans are expected to use more energy—mostly electricity for air conditioning. EPA's Residential Energy Use indicator examines trends related to home air conditioning and heating by tracking the amount of electricity used by U.S. homes in the summer and energy used in the winter.

- The amount of electricity used by the average American at home during the summer has nearly doubled since 1973. It appears to have leveled off somewhat in recent years, concurrent with increases in energy efficiency (Figure 13).
- Year-to-year fluctuations in electricity use generally follow changes in cooling degree days (see Heating and Cooling Degree Days). Total cooling degree days have also increased since 1973, though they have not increased as dramatically as electricity use (Figure 13).
- The amount of natural gas used by the average American at home during the winter has decreased since 1974. Total heating degree days have also decreased since 1974, though they have not decreased as dramatically as natural gas use.

As temperatures continue to rise, Americans are expected to use less fuel energy for heating their homes during the winter and more electricity for cooling buildings in the summer.[20]

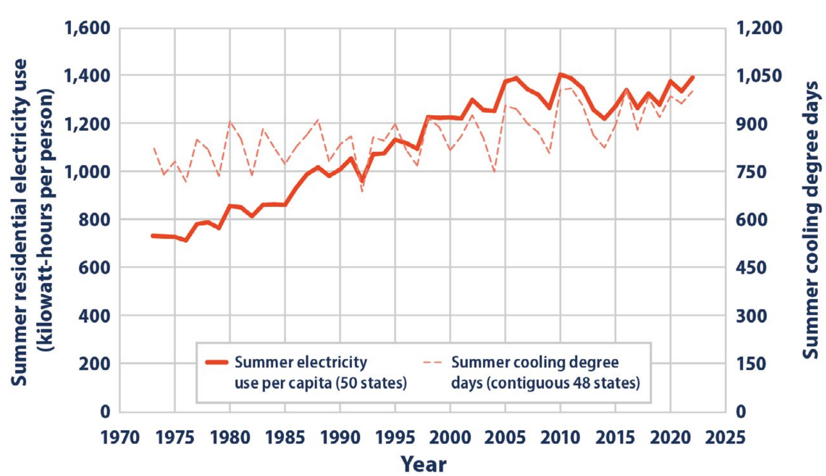
Extreme heat and equity

Extreme heat can have a variety of effects on people's physical and cognitive health. Impacts are not felt equally and can have a greater effect on populations who are most at risk. Extreme heat can also have economic implications and be a financial burden. Rising energy costs make it difficult for people, especially low-income households, to afford to cool their homes.

This energy burden can also affect children's learning, which in turn means lost future income. A recent report found that installing air conditioning in schools generally costs less than this lost income, but still only partially mitigates the effect on learning. Rather, A/C in homes is also necessary to reduce learning losses from extreme heat. Low-income households and communities are more likely to have lower rates of A/C usage and access, making them more likely to experience impacts from extreme heat disproportionately.

Figure 13. Residential Summer Electricity Use per Capita and Summer Cooling Degree Days in the United States, 1973–2022

This graph shows the amount of electricity used by the average American during the summer months (June, July, and August) of each year from 1973 to 2022. The solid line shows average summer electricity use per capita. It represents all 50 states plus D.C. For reference, the dashed line shows the average number of cooling degree days for the same months across the contiguous 48 states plus D.C. Data sources: EIA, 2022;[21] BEA, 2022;[22] NOAA, 2022.[23]



Extreme Events

Rising global average temperature is associated with widespread changes in weather patterns. Extreme events such as heavy rainstorms, hurricanes, floods, droughts, and wildfires have happened throughout history, but human-induced climate change is expected to make these events more frequent and/or intense. While risks vary across the country, these events are among the nation's costliest disasters, sometimes causing great damage to ecosystems, communities, and the economy.

Indicators featured in this chapter:
Heavy Precipitation, Drought, Tropical Cyclone Activity, Wildfires

Heavy precipitation events are becoming more common.

Why it matters

Heavy precipitation events can cause crop damage, soil erosion, and flooding. An increase in flood risk due to heavy rains can lead to injuries, drownings, respiratory health impacts from exposure to mold, and other flood-related health effects.[1] Heavy precipitation also can overwhelm drainage systems, and the runoff can wash pollutants from land into water bodies, which can reduce water quality and affect the health of people and ecosystems.

What's happening

Climate change can affect the intensity and frequency of precipitation. Warmer oceans increase the amount of water that evaporates into the air. When more moisture-laden air moves over land or converges into a storm system, it can produce more intense precipitation—for example, heavier rain and snowstorms.[2] As warmer temperatures cause more water to evaporate from the land and oceans, changes in the size and frequency of heavy storms could in turn affect the size and frequency of river flooding (see EPA's River Flooding indicator).

"Heavy precipitation" refers to storms that deliver much more rain or snow in a short period than a particular location is used to. EPA's Heavy Precipitation indicator tracks the frequency of heavy precipitation events in the United States. The exact amount that counts as "heavy" varies by location and season, depending on what is normal. An increase in heavy precipitation does not necessarily mean the total amount of precipitation at a location has increased—just that more of it is falling in more concentrated periods of time.

Climate change increases the odds of extreme weather

There have been changes in extreme weather events in the United States over the last several decades, including more extreme heat, less extreme cold, more heavy precipitation, and an increased potential for intense hurricanes. This rise in extreme weather events fits a pattern one can expect with a warming planet, where average temperatures are increasing and the atmosphere holds more moisture. Scientists project that climate change will make some of these extreme weather events more likely to occur and/or more likely to be severe.

Establishing the most likely causes behind an extreme weather event can be challenging, since these events are due to combinations of factors, some of which occur naturally. Nevertheless, scientists have been able to draw a connection between some types of extreme climate patterns—and even some individual events—and climate change. The movement of heat in the atmosphere drives weather patterns, so because added heat is a key feature of climate change, weather patterns are expected to shift with this increase in energy. A good way to think about this connection is to focus on whether an extreme weather event was made more likely by climate change.

Climate change also increases the likelihood of "whiplash," where conditions shift abruptly between opposite extremes. For example, a shift from intense drought to a deluge of rain can heighten the risk of flooding and landslides if the drought leaves the ground so hardened that it can't absorb much of the rainwater. Landslides can also occur if heavy rain follows a wildfire. When extremely wet seasons that lead to plant overgrowth are followed by drier periods, this creates conditions conducive to wildfires.[3]

See the Water Resources at Risk chapter for more information about changing precipitation patterns, including information from EPA's U.S. and Global Precipitation indicator.

- The prevalence of extreme single-day precipitation events remained fairly steady between 1910 and the 1980s, but has risen substantially since then (Figure 14).
- In recent years, a larger percentage of precipitation has come in the form of intense single-day events. Looking at more than 100 years of data, nine of the top 10 years for extreme one-day precipitation events have occurred since 1995 (Figure 14).

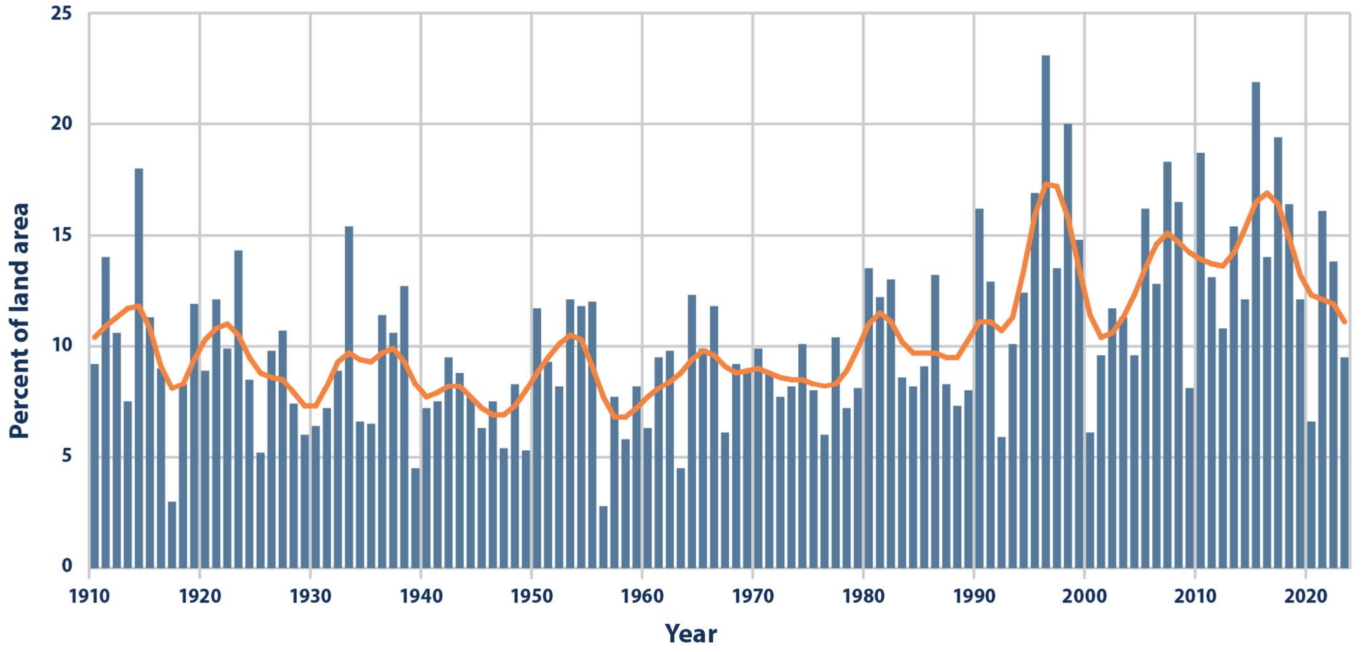


Figure 14. Extreme One-Day Precipitation Events in the Contiguous 48 States, 1910–2023

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.

This graph shows the percentage of the land area of the contiguous 48 states where a much greater than normal portion of total annual precipitation has come from extreme single-day precipitation events. The bars represent individual years, while the orange line is a nine-year weighted average. Data source: NOAA, 2024.[4]

Historically dry areas in the West are at increased risk of drought.

Why it matters

Drought conditions can negatively affect agriculture, water supplies, energy production, human health, 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, threatening the livelihoods of farmers and farm workers. Water supply impacts can range from lowered reservoir levels and dried-up streams to major water shortages that affect access to drinking water. Lower streamflow and groundwater levels can also harm ecosystems more broadly, by harming plants and animals and increasing the risk of wildfires.

What's happening

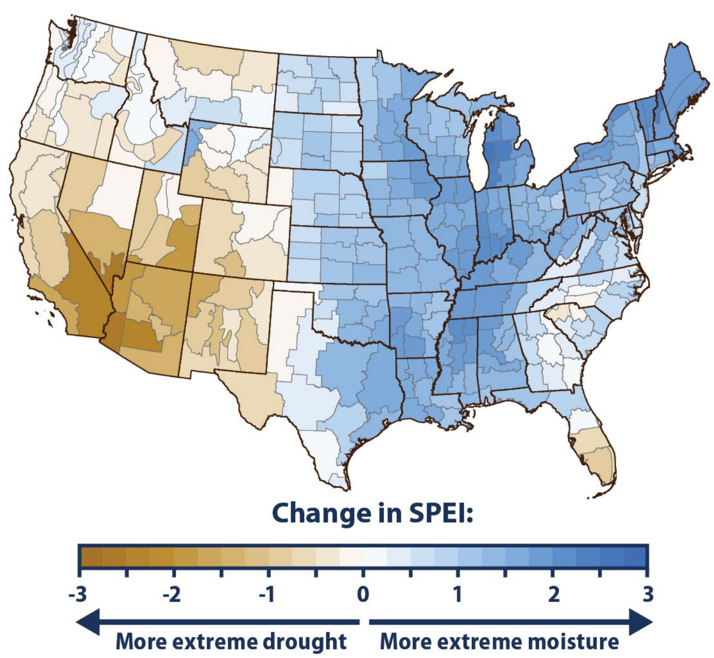
Meteorologists generally define drought as a prolonged period of dry weather caused by a lack of precipitation that results in a serious water shortage for some activity, population, or ecological system.

As average temperatures have risen because of climate change, the rate of water evaporation from the Earth's surface (including soil, lakes, and reservoirs) and transpiration (the process of losing water) from plants has risen as well. This has sped up the Earth's water cycle. An increase in evapotranspiration (the transfer of water from land to the atmosphere) makes more water available in the air for precipitation, but it also leaves less moisture in the soil.

- EPA's Drought indicator shows that from 1900 to 2023, drought conditions have increased in southwestern states such as California, Arizona, and New Mexico. Over the same period, the eastern United States—particularly the Midwest and Northeast—has experienced generally wetter conditions. From 2000 through 2023, roughly 10 to 70 percent of the U.S. land area experienced conditions that were at least abnormally dry at any given time (Figure 15).
- EPA's A Closer Look: Temperature and Drought in the Southwest has more information about drought in the U.S. Southwest. For example, for extended periods from 2002 to 2005 and from 2012 to 2020, nearly the entire region experienced abnormal drought conditions. The region's rapid population growth has added to the challenge of managing water.

Figure 15. Average Change in Drought (Five-Year SPEI) in the Contiguous 48 States, 1900–2023

This map shows the total change in drought conditions across the contiguous 48 states, based on the long-term average rate of change in the five-year Standardized Precipitation Evapotranspiration Index (SPEI) from 1900 to 2023. SPEI measures the combination of water supply (precipitation) and atmospheric water demand (evapotranspiration, which is based on temperature) to determine whether a certain area is experiencing extreme drought, extreme moisture, or conditions in between. Data are displayed for small regions called climate divisions. Blue areas represent increased moisture; brown areas represent decreased moisture or drier conditions. Data sources: Abatzoglou et al., 2017;[5] Western Regional Climate Center, 2024.[6]



Drought: elevated risks for Indigenous Peoples

Prolonged droughts pose a particular threat to the health and well-being of Indigenous Peoples because of their economic and cultural connection to the land and water, and because historical actions moved many Tribes to lands that were already water-stressed.

Warming and drought can reduce water quality and availability, increasing the risk of waterborne illnesses, and can threaten medicinal and culturally important plants and animals. These climate threats intersect with other challenges, like a lack of access to drinking water and wastewater infrastructure on some Tribal lands.

Tribes and Indigenous Peoples are leading action to prepare for and adapt to these changes. For example, in 2018, the Navajo Nation released its first climate adaptation plan, which outlines strategies to preserve and enhance natural resources and provide a resilient future for the Navajo communities.[7]

For more information, see the "Tribes and Indigenous Peoples" chapter of the *Fifth National Climate Assessment* and the *Status of Tribes and Climate Change Report*.

Tropical cyclones have become more intense in recent years.

Why it matters

The effects of hurricanes and other tropical cyclones are numerous and well known. At sea, storms disrupt and endanger shipping traffic. When cyclones make landfall, their intense rains and high winds can cause severe property and infrastructure damage, loss of life, soil erosion, and flooding. The associated storm surge—the large volume of ocean water pushed toward shore by the cyclone's strong winds—can cause severe flooding, erosion, and destruction.

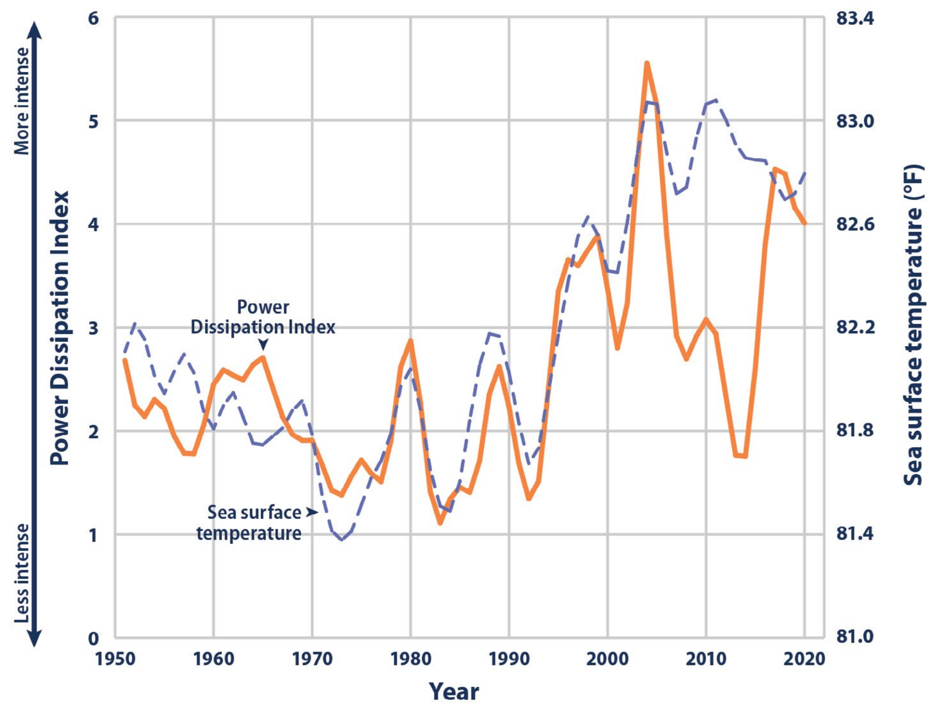
What's happening

Hurricanes, tropical storms, and other intense rotating storms fall into a general category called cyclones. There are two main types of cyclones: tropical and extratropical (those that form outside tropical regions like Nor'easters). Tropical cyclones get their energy from warm tropical oceans. They are most common during the Atlantic hurricane season, which runs from June through November. Climate change is expected to affect tropical cyclones by increasing sea surface temperature, which is a key factor that influences the formation and behavior of these storms.

- EPA's Tropical Cyclone Activity indicator focuses on tropical cyclones in the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. It shows that while there is no clear trend for the number of tropical cyclones per year, tropical cyclones are becoming more intense.
- The Power Dissipation Index is one method of measuring tropical cyclone frequency, strength, and duration using wind speed measurements. It shows that cyclone intensity has risen noticeably over the past 20 years (Figure 16).

Figure 16. North Atlantic Tropical Cyclone Activity According to the Power Dissipation Index, 1949–2022

This graph shows annual values of the Power Dissipation Index, which accounts for cyclone strength, duration, and frequency. Sea surface temperature trends from the tropical Atlantic are provided for reference. Note that sea surface temperature is measured in different units, but the values have been plotted alongside the index to show how they compare. The lines have been smoothed using a five-year weighted average, plotted at the middle year. The most recent average (2018–2022) is plotted at 2020. Data source: Emanuel, 2023.[8]



Wildfires are burning more land.

Why it matters

Wildfires can harm property, livelihoods, and public health. Wildfire-related threats are increasing, especially as more people live in and near forests, grasslands, and other natural areas.[9] According to the National Oceanic and Atmospheric Administration, between 1980 and 2023 the United States had 22 wildfire events that individually caused more than $1 billion in damage; 18 of those have occurred since 2000.[10] Over the past few decades, the United States has routinely spent more than $1 billion per year to fight wildfires, including $3.5 billion in 2022.[11] These efforts have resulted in the deaths of hundreds of firefighters.[12] Even in communities far downwind, wildfire smoke has been directly linked to poor air quality that can lead to significant health effects and costs to society including emergency department visits, hospital admissions, and deaths.[13]

What's happening

While wildfires occur naturally and play a long-term role in the health of ecosystems such as forests, shrubland, and grassland, changing wildfire patterns threaten to upset the status quo. Many studies have found that climate change has already led to an increase in wildfire season length, wildfire frequency, and burned area.[14,15] This is a result of factors such as higher temperatures, longer summer dry seasons and increased drought conditions, and warmer spring weather with less snowpack to supply water throughout the summer.[16]

Wildfires and climate-warming emissions

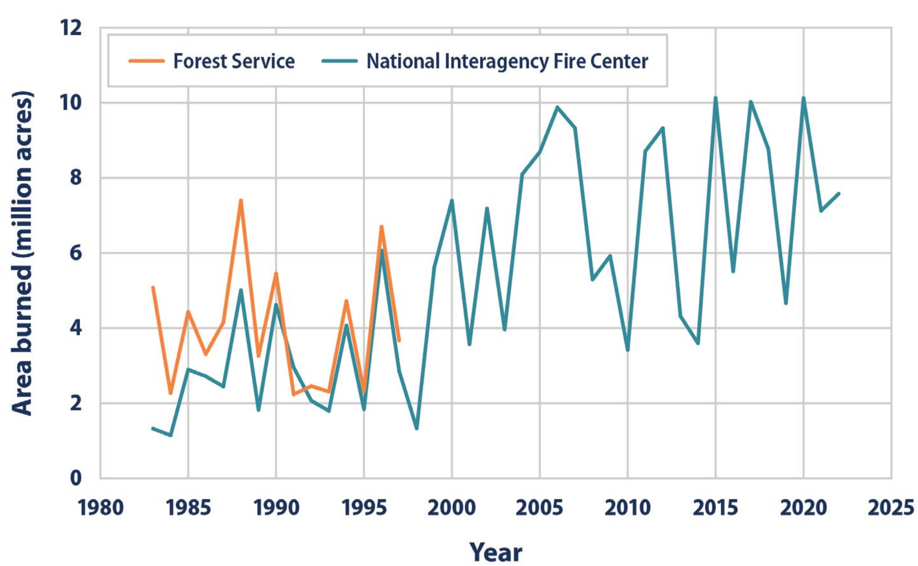
Beyond the human and societal impacts, wildfires also affect the Earth's climate. Forests in particular store large amounts of carbon. When they burn, they immediately release carbon dioxide and other gases into the atmosphere, which in turn contributes to climate change. After burning, forests also release carbon dioxide more gradually through decomposition.

Factors other than climate change also play an important role in wildfire frequency and intensity: land use, large-scale insect infestation, fuel availability (including availability of invasive species such as highly flammable cheatgrass), and management practices (including fire suppression). All these factors vary greatly by region and over time, as do precipitation, wind, temperature, vegetation types, and landscape conditions.

- EPA's Wildfires indicator shows that the extent of area burned by wildfires in the United States has increased since the 1980s (Figure 17), with the largest increases occurring in the West and Southwest.
- According to National Interagency Fire Center data, of the 10 years with the largest acreage burned, all have occurred since 2004, including peak years in 2015 and 2020 (Figure 17). This period coincides with many of the warmest years on record nationwide (see the Heat on the Rise chapter). The largest increases have occurred during the spring and summer months.

Figure 17. Wildfire Extent in the United States, 1983–2022

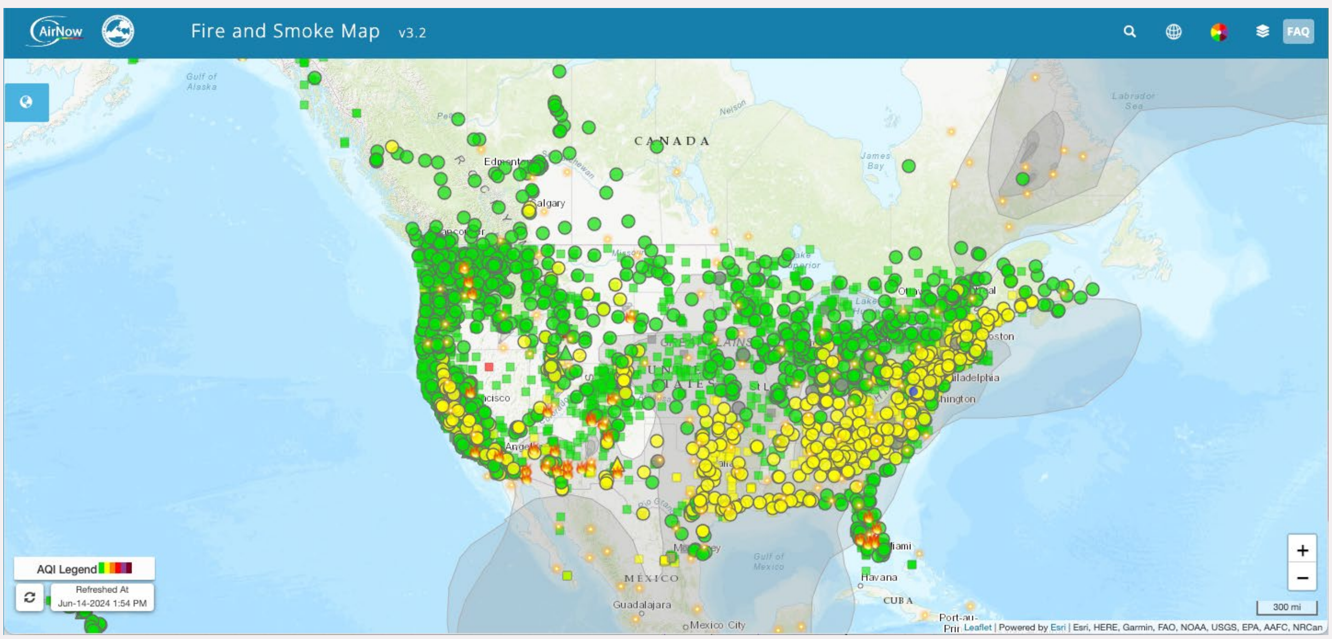
This graph shows annual wildfire-burned area (in millions of acres) from 1983 to 2022. The two lines represent two different reporting systems, though the orange line is shown only for comparison in the early part of the graph. (The U.S. Forest Service stopped collecting statistics in 1997 and is not planning to update them.) Data sources: NIFC, 2024;[17] Short, 2015.[18]



Taking action: preparing for wildfire smoke

Wildfire smoke can harm people's health. Microscopic particles in the smoke can get into people's eyes and respiratory systems, where they can cause problems such as burning eyes, runny nose, and illnesses like bronchitis. Smoke can also aggravate chronic heart and lung diseases—and is even linked to premature deaths in people with these conditions.

To help people know when they may be at risk from wildfire smoke, EPA and the U.S. Forest Service have built on the popular AirNow program to create the [AirNow Fire and Smoke Map], which provides comprehensive data on where wildfire smoke is affecting air quality in real time. The map leverages hourly air quality data provided by AirNow's state, local, and Tribal air agency partners; crowd-sourced data from low-cost air sensors; and satellite data. It uses these data to show information about whether air quality is getting better or worse, fire locations, smoke plumes, smoke forecast outlooks (where available), and steps people can take to reduce their exposure to smoke.



AirNow is a partnership between EPA and state, local, and Tribal air agencies; the U.S. Forest Service; the National Oceanic and Atmospheric Administration; the National Park Service; the National Aeronautics and Space Administration; the Centers for Disease Control and Prevention; and the U.S. Department of State.

Visit AirNow's wildfires page to learn what to do before, during, and after a fire.

Water Resources at Risk

Clean fresh water is essential to life on the Earth, and climate change is affecting the planet's water resources. As the climate warms, changing precipitation patterns, drought, decreasing amounts of snow, and earlier snowmelt all pose risks to water supplies in the United States, affecting communities, livelihoods, and ecosystems.

Indicators featured in this chapter:

U.S. and Global Precipitation, Snowpack, Streamflow,
A Closer Look: Temperature and Drought in the Southwest

Precipitation is increasing in some parts of the country and decreasing in others.

Why it matters

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

What's happening

As the Earth becomes warmer (see the Heat on the Rise chapter), more evaporation and transpiration (water loss from plants) occur. Increased evaporation adds more moisture to the atmosphere and, in turn, generally increases precipitation. Therefore, a warming climate is expected to increase precipitation in many areas. Just as precipitation patterns vary across the world, so do the effects of climate change on precipitation. By shifting the wind patterns and ocean currents that drive the world's climate system, climate change will also cause some areas to experience decreased precipitation. In addition, areas with increased precipitation will not necessarily have more water available for people and ecosystems, because higher temperatures also lead to more evaporation.

- EPA's U.S. and Global Precipitation indicator shows that total annual precipitation has increased in the United States and worldwide (Figure 18). Since 1901, precipitation in the contiguous 48 states has increased at a rate of 0.18 inches per decade and global precipitation has increased at an average rate of 0.03 inches per decade.

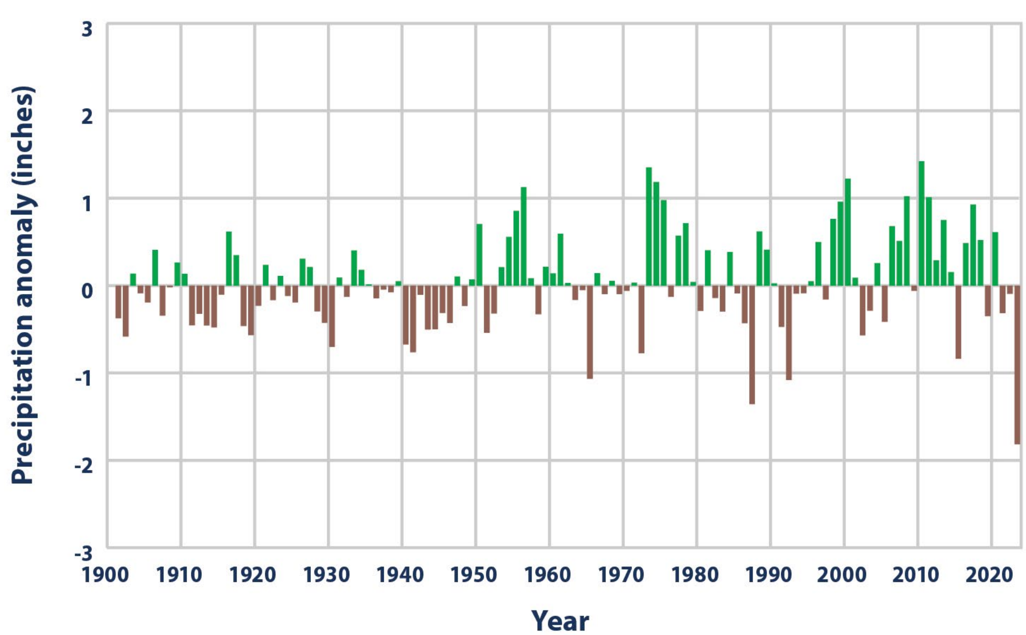
Precipitation and water quality

Precipitation patterns don't just affect water quantity—they also affect water quality. For example, runoff from heavy rain can wash pollutants from land into water bodies, impairing water quality.

EPA's Office of Water is taking actions to address climate change impacts in the water sector.

Figure 18. Precipitation Worldwide, 1901–2023

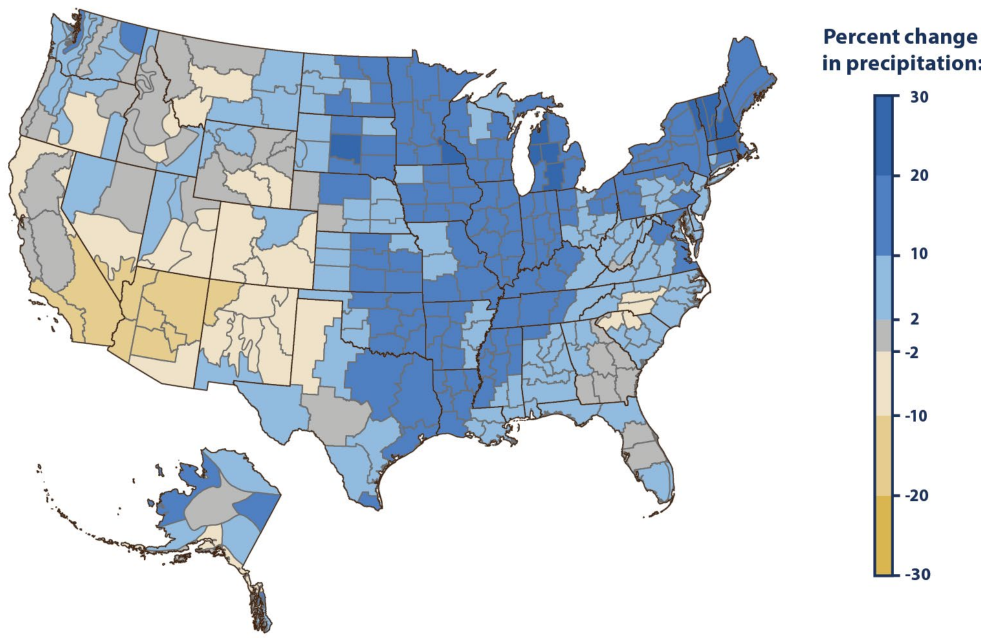
This graph shows how the total annual amount of precipitation over land worldwide has changed since 1901. This graph uses the 1901–2000 average as a baseline for showing change. Choosing a different baseline period would not change the shape of the data over time. Data source: NOAA, 2024.[1]



- Because precipitation changes vary by region, some parts of the country have experienced greater increases in precipitation than others. A few areas, such as the Southwest, have seen a decrease in precipitation (Figure 19).

Figure 19. Change in Precipitation in the United States, 1901–2023

This map shows the percent change in total annual precipitation in different parts of the United States since the early 20th century (since 1901 for the contiguous 48 states and 1925 for Alaska). The data are shown for climate divisions, as defined by the National Oceanic and Atmospheric Administration. Data source: NOAA, 2024.[2]



The effect of temperature on water quality

EPA's Great Lakes Water Levels and Temperatures indicator explores how climate change is affecting water temperatures in the Great Lakes, which supply drinking water to more than 30 million people.[3] It shows that average temperatures at the water's surface are rising slightly in each of the Great Lakes. This rise is mostly driven by warming during the spring and summer.

Rising temperatures can affect water quantity by increasing drought risk and reducing resources like snowpack. However, like precipitation, temperature also affects the quality of water resources. Warmer water promotes the growth of algae and bacteria, including some that produce toxins. These toxins can cause illnesses and contaminate drinking water supplies.

For example, increases in harmful algae growth already threaten Lake Erie's ecosystems and drinking water supplies. The lake provides drinking water to 12 million people in the United States and Canada, and it is especially at risk from harmful algae because of nutrient pollution from urban, industrial, and agricultural runoff. As water temperatures rise, this risk could increase.[4] Toledo, Ohio, is one city that has experienced contamination in its water supply from these algal blooms. The National Oceanic and Atmospheric Administration produces harmful algal bloom forecasts for Lake Erie for July to October, when water temperatures are warmest.

Snowpack is decreasing.

Why it matters

Snowpack is the amount or thickness of snow that accumulates on the ground. Mountain snowpack plays a key role in the water cycle in western North America, storing water in the winter when the snow falls and releasing it as runoff in spring and summer when the snow melts. Millions of people in the West depend on the melting of mountain snowpack for hydropower, irrigation, and drinking water. In most western river basins, snowpack stores more water than human-constructed reservoirs.

What's happening

As the climate warms, more precipitation is falling as rain rather than snow in most areas—reducing the extent and depth of snowpack. With warmer winter and spring weather, the seasonality of snowpack is also changing. Higher temperatures cause snow to melt earlier, which in turn affects the timing and availability of water. In other words, less snowpack and earlier melting mean less water is stored in snowpack that will last long enough to feed streams and reservoirs in the summer.

- April 1 is a date that is often used to measure snowpack for spring and summer water supply forecasting. EPA's Snowpack indicator shows that large and consistent decreases in April snowpack have been observed throughout the western United States. Decreases have been especially prominent in Washington, Oregon, northern California, and the northern Rocky Mountains (Figure 20).
- Almost 80 percent of the sites this indicator covers have experienced a shift toward earlier peak snowpack. This earlier trend is especially pronounced in southwestern states like Colorado, New Mexico, and Utah. Across all stations, peak snowpack has shifted earlier by an average of nearly seven days since 1982.
- From 1982 to 2023, the snowpack season became shorter at 80 percent of the sites where snowpack was measured. Across all sites, the length of the snowpack season decreased by about 15 days, on average (Figure 21).

Figure 20. Trends in April Snowpack in the Western United States, 1955–2023

This map shows trends in April snowpack in the western United States, measured in terms of snow water equivalent. Blue circles represent increased snowpack; red circles represent a decrease. Data source: USDA Natural Resources Conservation Service, 2024.[5]

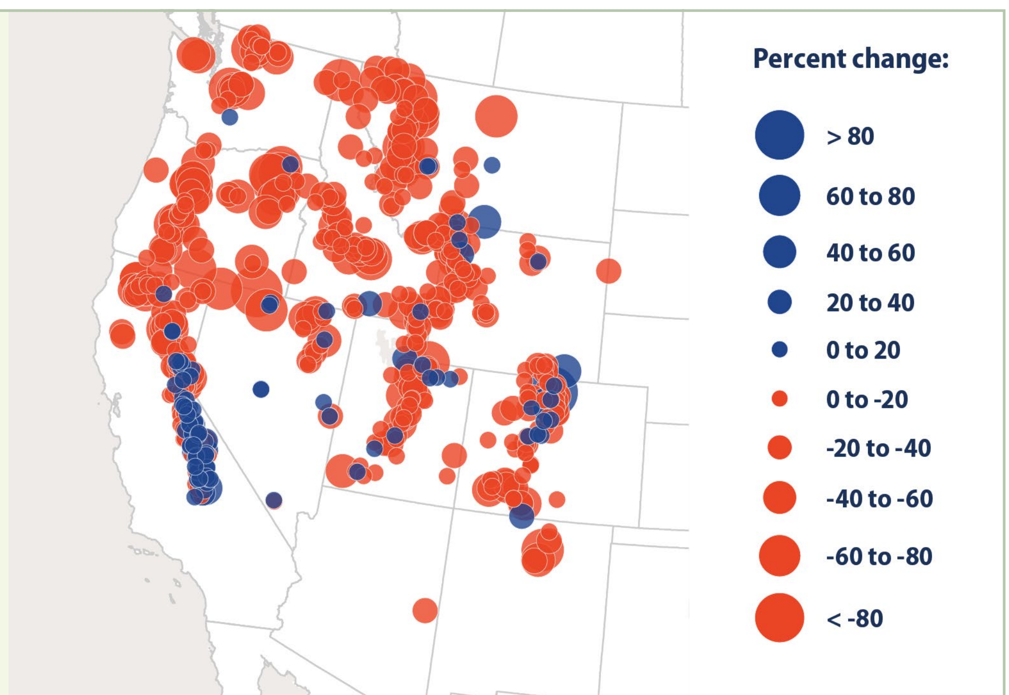
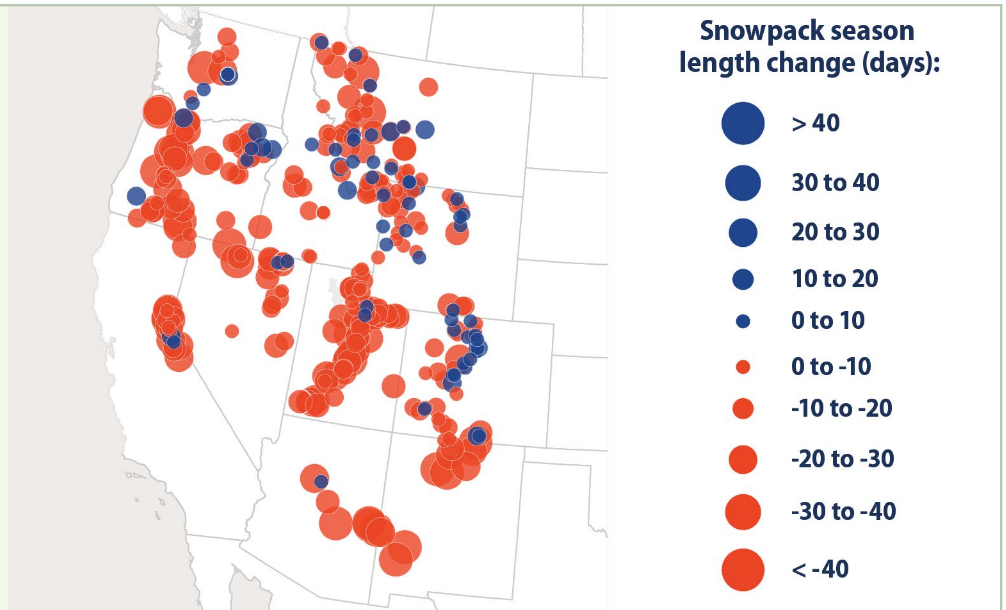


Figure 21. Change in Snowpack Season Length in the Western United States, 1982–2023

This map shows trends in the length of the snowpack season across the western United States, in days. Blue circles show where the season has grown longer; red circles show where it has become shorter. Data source: USDA Natural Resources Conservation Service, 2023.[6]



Streamflow levels and timing are changing in response to warming conditions.

Why it matters

Streamflow naturally varies over the course of a year. For example, rivers and streams in many parts of the country have their highest flow when snow melts in the spring and their lowest flow in late summer. The amount of streamflow is important because very high flows can cause erosion and damaging floods, while very low flows can diminish water quality, harm fish, reduce the amount of water available for people to use, and disrupt economic activities like river shipping. The timing of the high flows is important for water supplies because it affects the ability of reservoir managers to store water to meet needs later in the year.

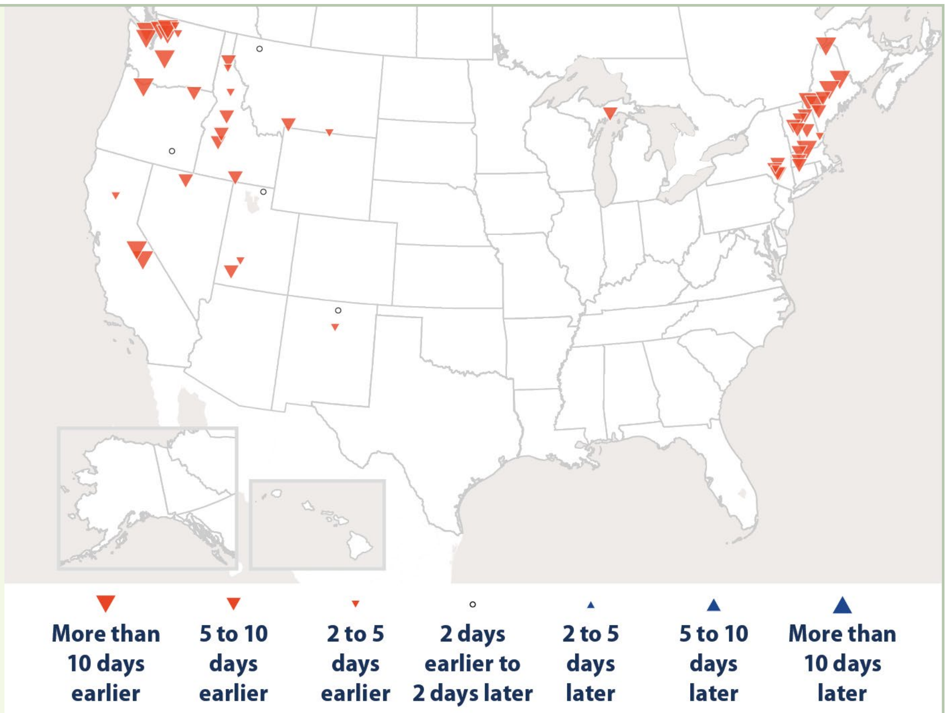
What's happening

Climate change can affect streamflow in several ways. Less spring snowpack and earlier melting of snow can reduce high spring streamflows and shift them earlier. This is especially an issue for western areas that rely on snowpack as a water source. Elsewhere, more precipitation is expected to cause higher average streamflow in some places, while heavier storms could lead to larger peak flows. More frequent or severe droughts could reduce streamflow in certain areas.

- EPA's Streamflow indicator describes trends in the amount of water carried by streams across the United States, as well as the timing of runoff associated with snowmelt. In parts of the country that have substantial snowmelt, winter-spring runoff is generally happening at least five days earlier than in the mid-20th century (Figure 22).
- The Pacific Northwest and the Northeast have experienced the largest changes in runoff timing (Figure 22).

Figure 22. Timing of Winter-Spring Runoff in the United States, 1940–2022

This map shows changes in the timing of annual high winter-spring flow carried by rivers and streams from 1940 to 2022. This analysis focuses on parts of the country where streamflow is strongly influenced by snowmelt. Trends are based on the winter-spring center of volume, which is the date when half of the total January 1–July 31 streamflow (in the West) or half of the total January 1–May 31 streamflow (in the East) has passed by each streamflow gauge, reflecting the timing of spring snowmelt. Data source: USGS, 2023.[7]



Taking action: creating resilient water utilities in Hershey, Nebraska

Climate change has prompted the Village of Hershey, Nebraska, to examine the drought resilience of its drinking water system, which serves about 660 community residents. Hershey has already experienced challenges due to drought, with an extended dry period from 2011 to 2021. The utility is concerned that, under more intense drought conditions, the system could experience reduced water supply due to aquifer withdrawal restrictions, as well as decreased water quality.

These concerns led Hershey officials to investigate strategies to increase the system's drought resilience using EPA's Climate Ready Evaluation and Assessment Tool (CREAT). CREAT helps water sector utilities assess climate-related risks to their assets and operations, allowing them to evaluate future climate change for their local area and evaluate the cost-effectiveness of different adaptive measures under these future changes. Hershey based its CREAT results on climate model projections that predict hotter and drier conditions, and the utility assessed financial impacts on its system under this future climate scenario. The utility identified several adaptive measures that could reduce drought impacts, including installing water use meters, building new groundwater wells, and developing a drought contingency plan, all of which CREAT indicated could be cost-effective.

Hershey's story is one of many adaptation case studies available from EPA's Creating Resilient Water Utilities initiative. For case studies focused on equitable water utility climate adaptations, see the initiative's new Building Equity and Environmental Justice StoryMap, which includes a dashboard bringing together socioeconomic and climate data as well as other resources to inform equitable adaptation.

In the Southwest, rising temperatures and drought threaten already scarce water supplies.

Why it matters

The impacts of drought on water supplies can range from lowered reservoir levels and dried-up streams to major water shortages. In the Southwest, water is already scarce, so every drop is a precious resource. People in the Southwest are particularly dependent on surface water supplies like Lake Mead, which are vulnerable to losing water from evaporation. Thus, even a small increase in temperature (which drives evaporation) or a decrease in precipitation in this already arid region can seriously threaten natural systems and society.

What's happening

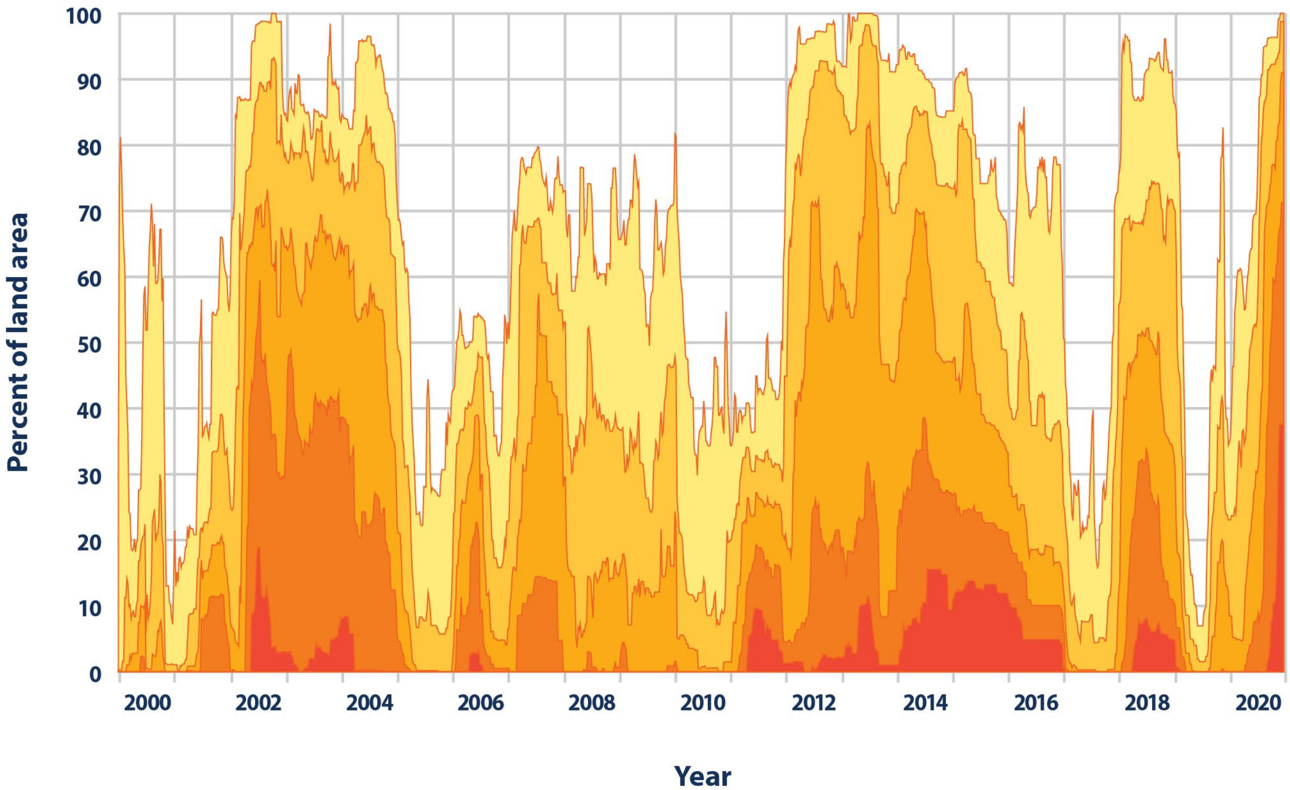
Drought risk is increasing in the Southwest. EPA's A Closer Look: Temperature and Drought in the Southwest indicator focuses on six states that are commonly thought of as "southwestern" and characterized at least in part by arid landscapes and scarce water supplies: Arizona, California, Colorado, Nevada, New Mexico, and Utah.

- Every part of the Southwest experienced higher average temperatures between 2000 and 2020 than the long-term average (1895–2020).
- Large portions of the Southwest have experienced drought conditions since weekly Drought Monitor records began in 2000. For extended periods from 2002 to 2005 and from 2012 to 2020, nearly the entire region was abnormally dry or even drier (Figure 23).
- While drought conditions in the Southwest have varied since 1895, the Southwest has seen some of the most persistent droughts on record since 1990.

To learn more about climate change and drought in the United States, see the Extreme Events chapter.

The Southwestern landscape

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



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.

Figure 23. Southwestern U.S. Lands Under Drought Conditions, 2000–2020

This graph shows the percentage of land area in six southwestern states (Arizona, California, Colorado, Nevada, New Mexico, and Utah) classified under drought conditions from 2000 through 2020. This figure uses the U.S. Drought Monitor classification system, which is described in the table. Data source: National Drought Mitigation Center, 2021.[8]

Changing Seasons

Although the timing, duration, and intensity of the seasons vary naturally from year to year, climate change is driving longer-term changes in seasonality and fundamentally altering the ways in which humans and natural systems experience and interact with seasonal events. These changes lead to wide-ranging impacts such as warmer winters, lakes thawing earlier, longer growing seasons, and worsening allergies for people.

Indicators featured in this chapter:

Seasonal Temperature, Snowfall, Lake Ice, Leaf and Bloom Dates, Community Connection: Cherry Blossom Bloom Dates in Washington, D.C., Length of Growing Season, Growing Degree Days, Ragweed Pollen Season

Temperatures are increasing in all seasons, with winter warming the most.

Why it matters

Warming temperatures have profound, wide-ranging effects throughout the year—from reducing critical water supplies to disrupting seasonal patterns that animals and plants rely on to survive. Hotter summers can lead to higher energy costs and risk of wildfires, while milder winters can reduce snowfall; allow ticks to spread, exposing more people to Lyme disease; and threaten winter recreation and tourism. These changes will increasingly affect people and ecosystems as warming continues.

What's happening

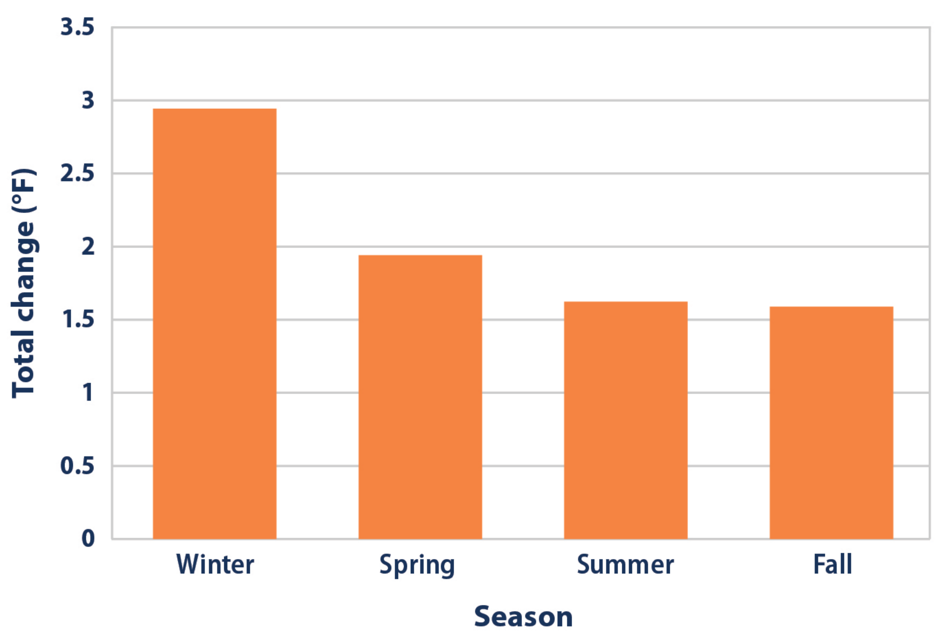
As the Earth warms, average temperatures increase throughout the year, but the increases may be larger in certain seasons and regions than in others.

The winter is particularly sensitive to rising temperatures, because overall, minimum temperatures have increased at a higher rate than average maximum temperatures.[1] Much of the observed warming in the United States has taken place when and where it is usually the coldest—namely, during winter,[2] at night, and in the northern parts of the country.

- EPA's Seasonal Temperature indicator shows that average winter temperatures across the contiguous 48 states have increased by about 3°F since 1896. Spring temperatures have increased by about 2°F, while summer and fall temperatures have increased by about 1.6°F (Figure 24).
- Temperature changes vary by state, with larger seasonal increases across the northern states and the Mountain West, and smaller increases in the South and Southeast (Figure 25).
- All 48 states experienced winter warming from 1896 to 2021. Most states experienced warming in the spring, summer, and fall, but a few states (for example, Alabama) had little to no overall change or cooled slightly during those months (Figure 25).

Figure 24. Temperature Change by Season in the Contiguous 48 States, 1896–2023

This graph shows changes in the average annual temperature by season for the contiguous 48 states from 1896 to 2023, in degrees Fahrenheit. Seasons are defined as follows: December, January, and February for winter; March, April, and May for spring; June, July, and August for summer; and September, October, and November for fall. Data source: NOAA, 2024.[3]



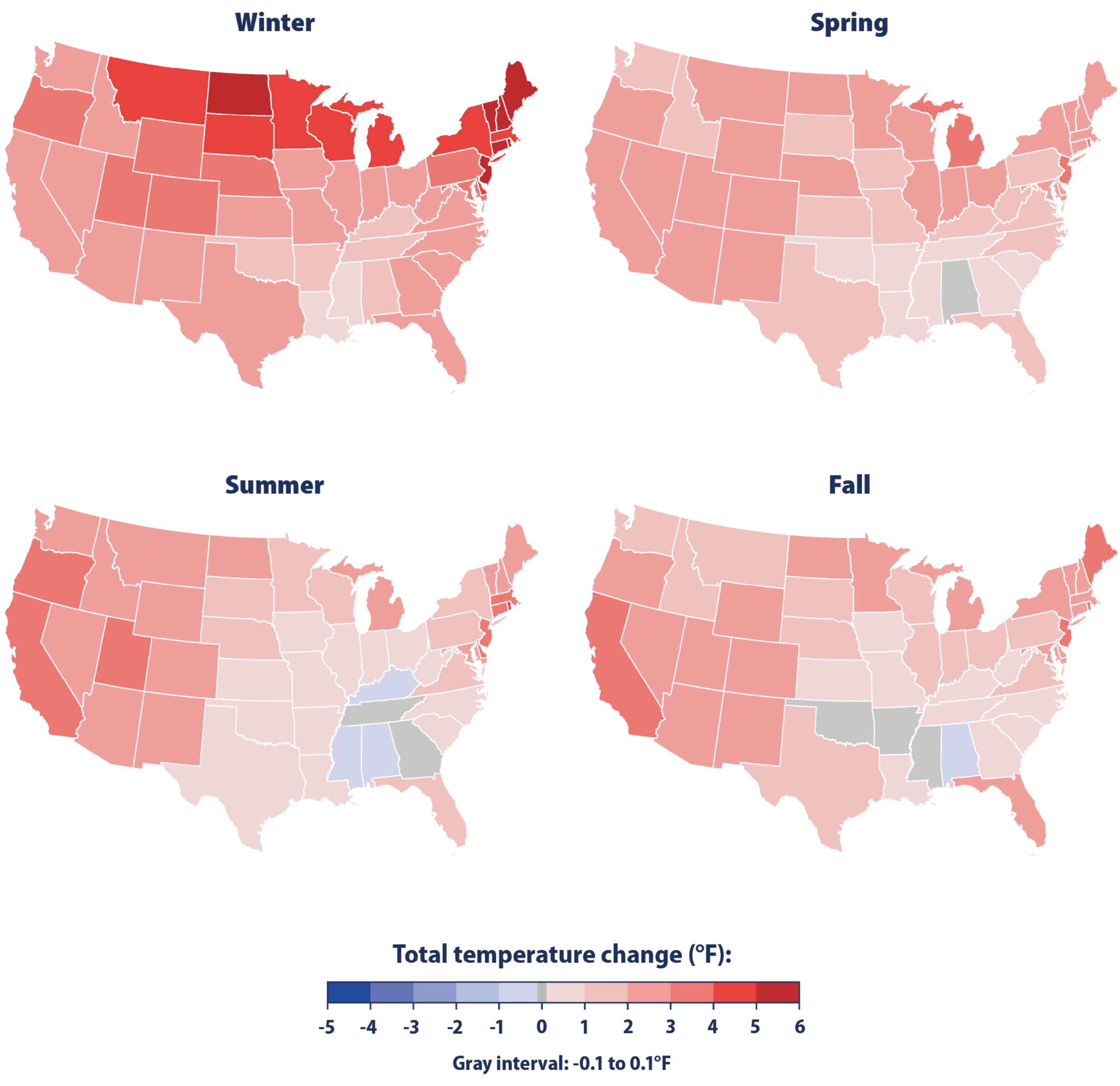


Figure 25. Change in Seasonal Temperatures by State, 1896–2023

These maps show the total change in the average seasonal temperature for each of the contiguous 48 states from 1896 to 2023, in degrees Fahrenheit. Total change in temperature was calculated from the long-term average rate of change. Seasons are defined as follows: December, January, and February for winter; March, April, and May for spring; June, July, and August for summer; and September, October, and November for fall. Data source: NOAA, 2024.[4]

More winter precipitation is falling as rain instead of snow.

Why it matters

The amount of snow that falls in an area directly influences both snow cover and snowpack (snow that accumulates on the ground). Many people depend on spring snowmelt to provide their drinking water and support other uses such as irrigation, especially in the western United States. (Visit the Water Resources at Risk chapter for details about water quantity and quality.) Many communities also rely on snow for winter recreation activities, like skiing, that support their local economies. Some plants and animals depend on snow and snowmelt for survival. Changes in the amount of snow versus rain could raise or lower streamflows at times that affect fish migration and spawning.

What's happening

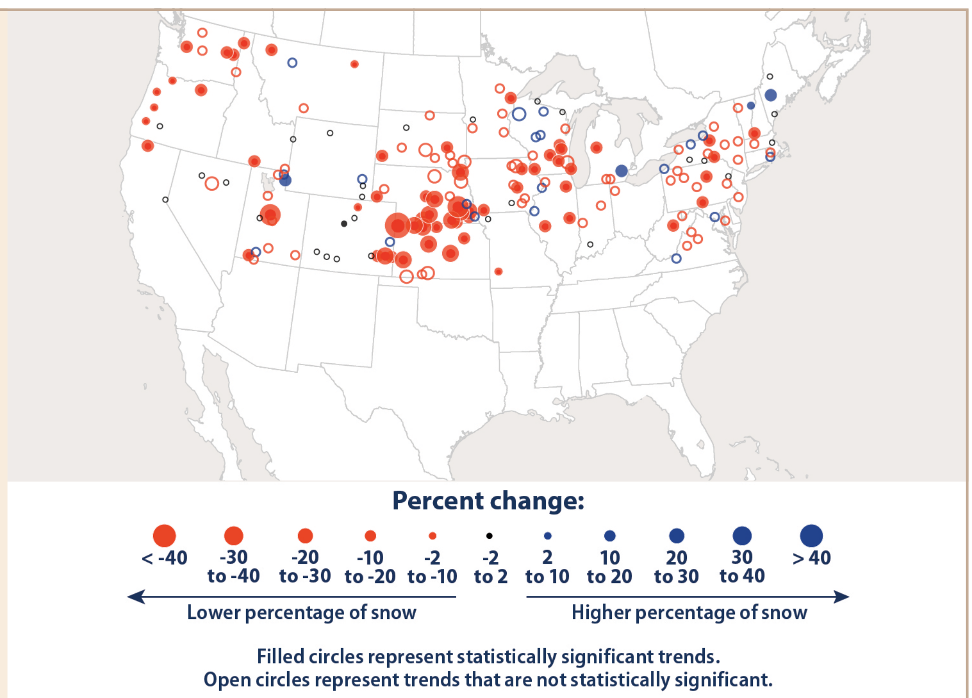
Warmer temperatures cause more water to evaporate from the land and oceans, which leads to more precipitation, larger storms, and more variation in precipitation in some areas. In general, a warmer climate causes more of this precipitation to fall in the form of rain instead of snow. Some places could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

EPA's Snowfall indicator shows that total snowfall has decreased in many parts of the country since widespread observations became available in 1930.

- Nearly 80 percent of the locations studied across the contiguous 48 states have experienced a decrease in the proportion of precipitation falling as snow (Figure 26).
- Snowfall trends vary by region. The Pacific Northwest has seen a decline in both total snowfall and the proportion of precipitation falling as snow. Parts of the Midwest have also experienced a decrease, particularly in terms of the snow-to-precipitation ratio. A few regions have seen modest increases, including some areas near the Great Lakes that now receive more snow than in the past (Figure 26).

Figure 26. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2020

This map shows the percentage change in winter snow-to-precipitation ratio from 1949 to 2020 at 177 weather stations in the contiguous 48 states. This ratio measures what percentage of total winter precipitation falls in the form of snow. A decrease (red circle) indicates that more precipitation is falling in the form of rain instead of snow. Solid-color circles represent stations where the trend was statistically significant. Data source: NOAA, 2021.[5]



Lake ice is thawing earlier in the spring.

Why it matters

Changes in ice cover can affect the physical, chemical, and biological characteristics of a lake. For example, ice influences heat and moisture transfers between a lake and the atmosphere. Reduced lake ice cover leads to increased evaporation and lower water levels, as well as an increase in water temperature and sunlight penetration. These changes, in turn, can affect plant and animal life cycles and the availability of suitable habitat. Additionally, ice cover affects the amount of heat that is reflected from the Earth's surface. Exposed water will absorb and retain heat, making the Earth's surface warmer, whereas an ice- and snow-covered lake will reflect more of the sun's energy and absorb less. Less lake ice also reduces opportunities for winter recreation, such as ice fishing, curling, and hockey.

What's happening

The formation of ice cover on lakes in the winter and its disappearance the following spring depend on climate factors such as air temperature, cloud cover, and wind. A warming climate causes lake ice to thaw and break up earlier. EPA's Lake Ice indicator shows the change in ice thaw dates for selected lakes in the United States with the longest and most complete historical records.

- Thaw dates for most of these lakes show a trend toward earlier ice breakup in the spring. Spring ice thaw is happening up to 24 days earlier since 1905 (Figure 27).
- Nearly all of the lakes selected were found to be thawing earlier in the year (Figure 27).

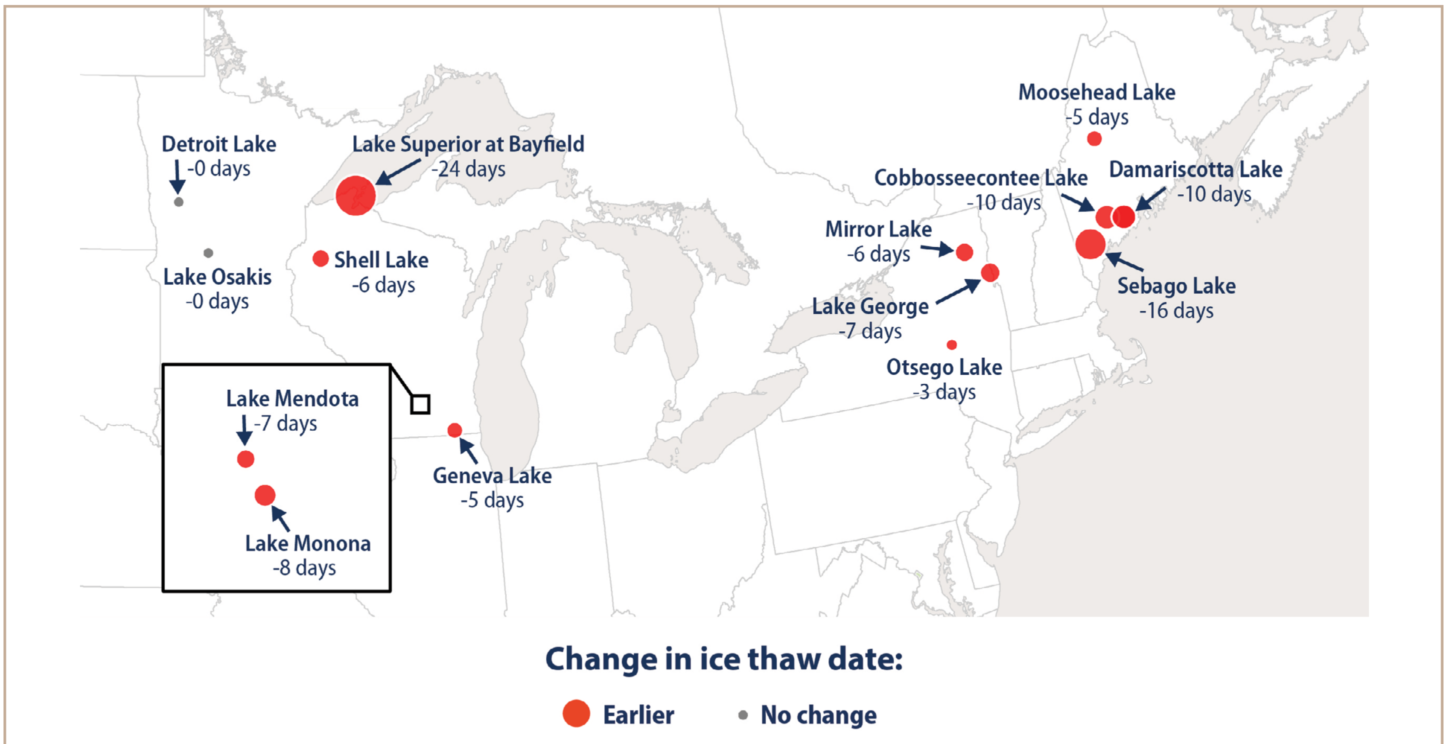


Figure 27. Change in Ice Thaw Dates for Selected U.S. Lakes, 1905–2019

This map shows the change in the "ice-off" date, or date of ice thawing and breakup, for 14 U.S. lakes during the period from 1905 to 2019. Twelve of the lakes have red circles with negative numbers, which represent earlier thaw dates. Larger circles indicate larger changes. Two of the lakes had no change in thaw dates. Data source: Various organizations.[6]

Learn more about seasonality and climate change

For more information on shifting seasons, EPA's *Seasonality and Climate Change: A Review of Observed Evidence in the United States* explores in greater detail the science behind seasonal events and how climate change can influence seasonal trends. Published in December 2021, the report uses EPA's climate change indicators to summarize changes that have been observed in the United States and describes the implications of these changes. The report focuses on the following topics:

- Seasonal changes in temperature and precipitation
- Effects of warmer, shorter winters
- Biological responses and phenology in a warming world
- Seasonality and extreme events

Spring events, such as leaf emergence and flower blooms, are starting earlier in the year.

Why it matters

Earlier spring events can have a variety of impacts on ecosystems and human society. For example, an earlier spring might lead to longer growing seasons, more abundant invasive species and pests, and earlier and longer allergy seasons. Unusually warm weather in late winter can create a "false spring" that triggers the new growth of plants too early, leaving them vulnerable to any subsequent frosts. Because different plant and animal species respond differently to changes in seasonality, seasonal interactions among species can become un-synchronized. Earlier springs can therefore increase the risk of mismatch in the life cycles of different plants and animals. For example, the emergence of pollinators may no longer match the timing of plant flowering.

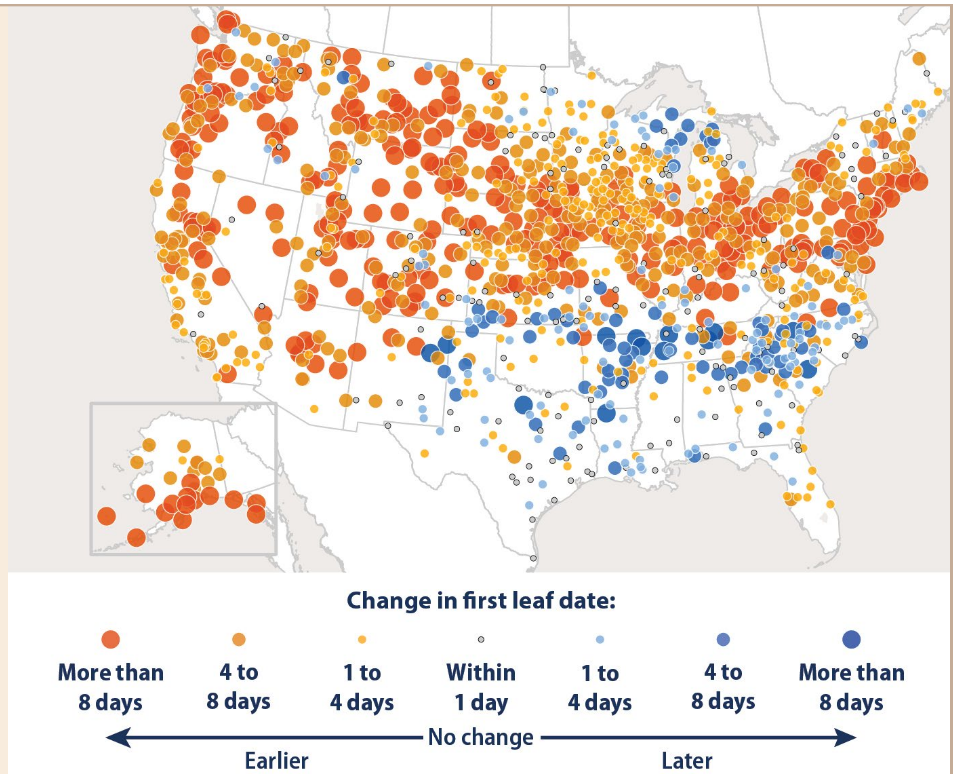
What's happening

The timing of natural events, such as flower blooms and animal migration, is influenced by a combination of environmental factors, including temperature, light, rainfall, and humidity. A warming climate is causing spring events to arrive earlier. Two particularly useful markers of the timing of spring events are the first leaf emergence and the first flower bloom of the season in lilacs and honeysuckles, two plants that are widely distributed across the United States. The first leaf date in these plants relates to the timing of events that occur in early spring, while the first bloom date is consistent with the timing of later spring events, such as the start of growth in forest vegetation.[7] EPA's Leaf and Bloom Dates indicator examines changes in the timing of the first leaf dates and the first bloom dates in lilacs and honeysuckles.

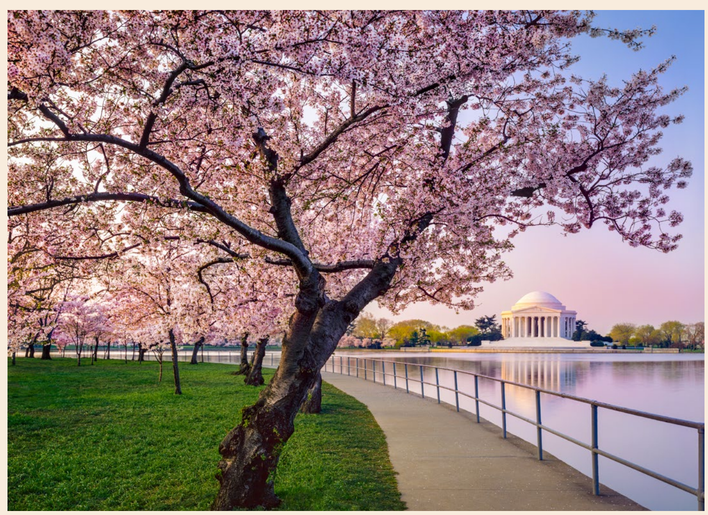
- In general, leaf and bloom events in lilacs and honeysuckles in the United States are happening earlier throughout most of the contiguous 48 states and Alaska, but later in the South and part of the Upper Midwest (Figure 28). This observation is consistent with many of the regional differences in temperature change (see U.S. and Global Temperature in the Heat on the Rise chapter).

Figure 28. Change in First Leaf Date Between 1951–1960 and 2014–2023

This map shows modeled trends in lilac and honeysuckle first leaf dates at weather stations across the contiguous 48 states and Alaska. This map compares the average first leaf date for two 10-year periods. Data source: 2024 update by M. Schwartz to data from Schwartz et al., 2013.[8]



The timing of peak cherry blossom bloom in Washington, D.C., is shifting earlier



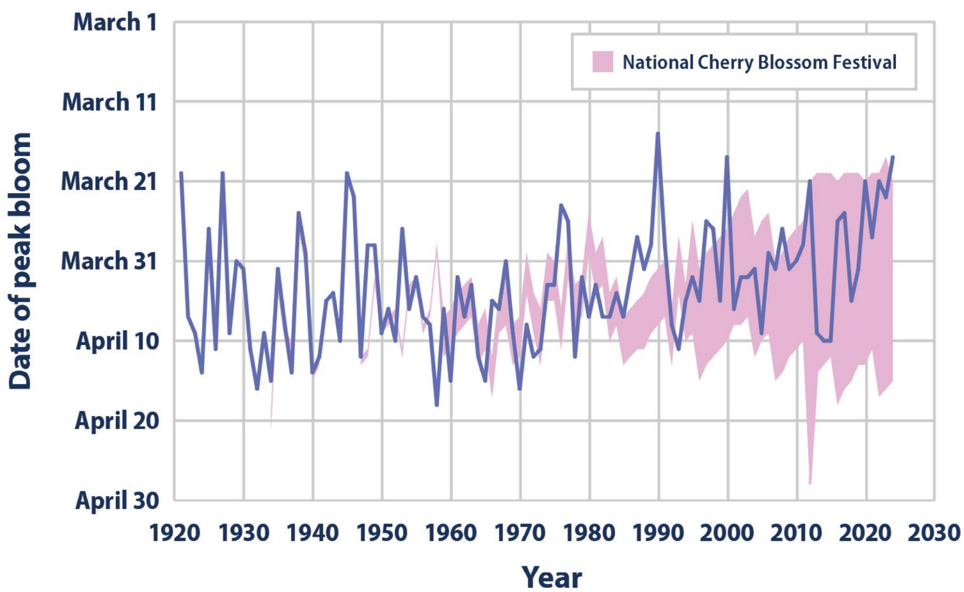
Washington has enjoyed cherry blossoms each year dating back to 1912, when Japan gave about 3,000 cherry trees to the United States as a gift of friendship. These trees attract more than 1.5 million visitors to the area every year during the National Cherry Blossom Festival, which is planned to coincide with the peak bloom of the cherry trees. However, earlier bloom dates can result in the annual festival being out of sync with the peak cherry blossom bloom and thus could affect tourism and the local economy.

EPA's Community Connection: Cherry Blossom Bloom Dates in Washington, D.C., tracks how the annual peak bloom date of Washington cherry trees has changed over time.

- Based on the entire 104 years of data, the average peak bloom date for Washington's cherry blossoms is April 3 (Figure 29).
- Peak bloom date for the cherry trees is occurring earlier than it did in the past. Since 1921, peak bloom dates have shifted earlier by about eight days. The peak bloom date has occurred before April 3 in 15 of the past 20 years (Figure 29).
- While the length of the National Cherry Blossom Festival has expanded over time, the cherry trees have bloomed near the beginning of the festival in recent years. During some years, like 2024, the festival missed early peak bloom dates entirely.

Figure 29. Peak Bloom Date for Cherry Trees Around Washington, D.C.'s Tidal Basin, 1921–2024

This graph shows the timing of peak bloom each year for the cherry trees around the Tidal Basin in Washington, D.C. The peak bloom date occurs when 70 percent of the blossoms are in full bloom. The shaded band shows the timing of the annual National Cherry Blossom Festival. The festival began in 1934 but was not held during World War II. Data source: National Cherry Blossom Festival, 2024;[9] National Park Service, 2024.[10]



Taking action: citizen scientists track ecological change

The USA National Phenology Network (USA-NPN) is a national-scale monitoring and research initiative advancing the science of phenology. Phenology is the study of seasonal plant and animal lifecycle events and how environmental factors such as climate change influence them. The USA-NPN brings together all kinds of people across the country, including volunteer observers, policymakers, research scientists, educators, and students, to collect, organize, and share phenology data and information. As part of their citizen science program, volunteer observers can participate in plant and animal phenology monitoring and contribute to the USA-NPN database.

Additional information comes from the Indigenous Phenology Network, a grassroots organization focused on observing the phenology of lands and species of importance to Indigenous communities. Their efforts include combining phenology observations with learning from local knowledge holders and elders.

The length of the growing season has increased in almost every state.

Why it matters

Changes in the length of the growing season can have both positive and negative effects on the yield and prices of particular crops. A longer growing season could allow farmers to diversify crops or have multiple harvests from the same plot. However, longer growing seasons could also limit the types of crops grown, encourage invasive species or weed growth, and increase demand for irrigation. A longer growing season could also disrupt the function and structure of a region's ecosystems and could alter the range and types of animal species in the area.

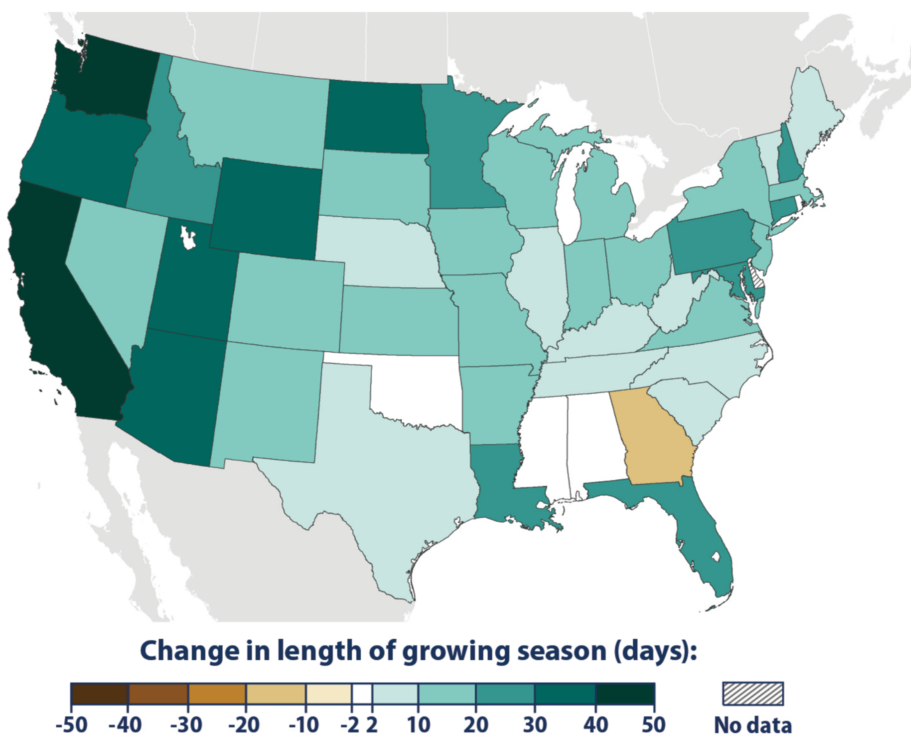
What's happening

The length of the growing season in any given region refers to the number of days when plant growth takes place. The growing season often determines which crops can be grown in an area, as some crops require longer growing seasons than others. 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. Warming in winter, spring, and fall can mean an increase in growing season length. EPA's Length of Growing Season indicator measures the length of the growing season in the contiguous 48 states.

- Between 1895 and 2023, the length of the growing season has increased in almost every state. States in the West (for example, California and Washington) have seen the most dramatic increase. In contrast, the growing season has become slightly shorter in Georgia (Figure 30).
- The average length of the growing season in the contiguous 48 states has increased by more than two weeks since the beginning of the 20th century. A particularly large and steady increase has occurred since the 1970s.

Figure 30. Change in Length of Growing Season by State, 1895–2023

This map shows the total change in length of the growing season from 1895 to 2023 for each of the contiguous 48 states. Data source: Kunkel, 2024.[11]



The number of growing degree days is increasing, worsening allergy season.

Why it matters

Plants typically grow only when the temperature is high enough; this makes growing degree days a useful way to look at temperature changes from the perspective of plant growth and development. Temperature changes affect plant growth, agricultural production, and the spread and impact of plant diseases and pests. One notable effect of warming temperatures is pollen seasons that begin earlier and last longer, which can trigger allergies and asthma in people. These health effects can lead to economic costs from medical expenses and missed workdays. An estimated 15.5 percent of all Americans are sensitive to ragweed pollen,[12] making it one of the most common environmental allergens. It can cause hay fever and trigger asthma attacks, especially in children and older adults.[13] Non-Hispanic Black and Non-Hispanic American Indian/Alaska Native populations are particularly sensitive to longer pollen seasons because they have the highest rates of asthma in the United States, and urban Black and Hispanic children tend to experience more symptoms of allergic rhinitis (hay fever).[14]

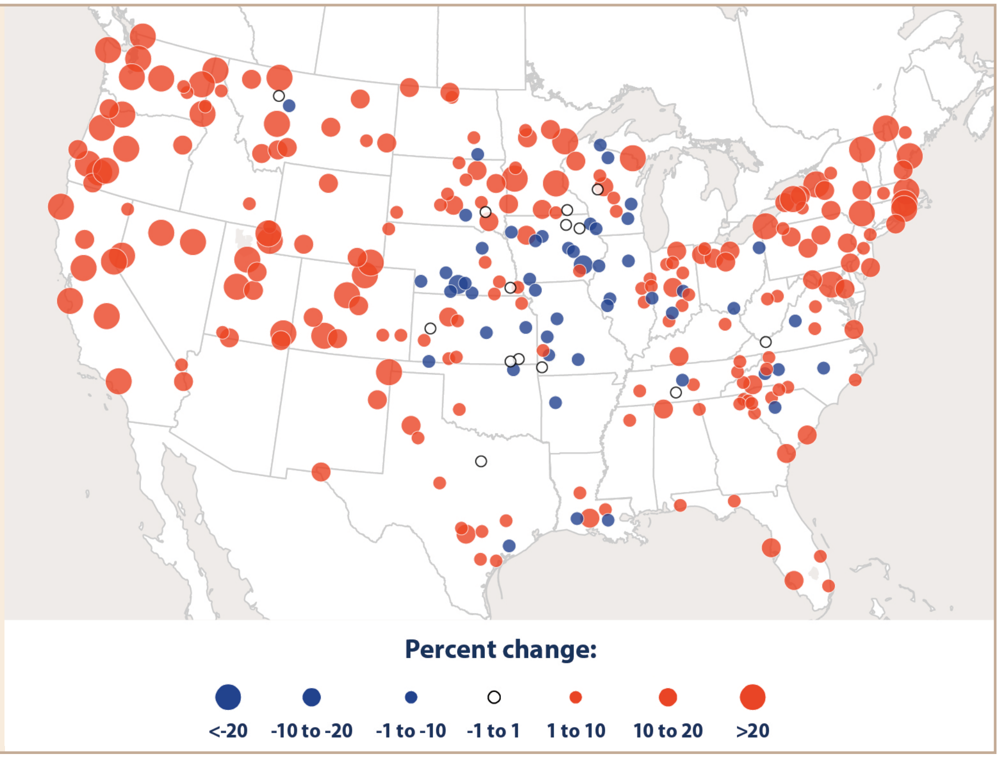
What's happening

Like growing season length, growing degrees days are a widely used measure for tracking plant growth and development. EPA's Growing Degree Days indicator shows changes in growing degree days in the in the contiguous 48 states.

- Between 1948 and 2023, the number of growing degree days increased at 221 of the 280 long-term stations measured (79 percent) across the contiguous 48 states. The average change across all stations represents an increase of about 10 percent (Figure 31).
- The largest increases in growing degree days from 1948 to 2023 occurred in the West and the Northeast. Fifty stations, mostly in the West, have experienced an increase of 20 percent or more (Figure 31).

Figure 31. Change in Growing Degree Days in the Contiguous 48 States, 1948–2023

This map shows trends in the total number of growing degree days per year at 280 weather stations. Growing degree days are defined as the difference in average daily temperature and a baseline of 50°F. For example, a day with an average temperature of 70°F represents 20 growing degree days. The color and size of the symbols represent percent change between 1948 and 2023, based on the long-term average rate of change. Data source: NOAA, 2024.[15]



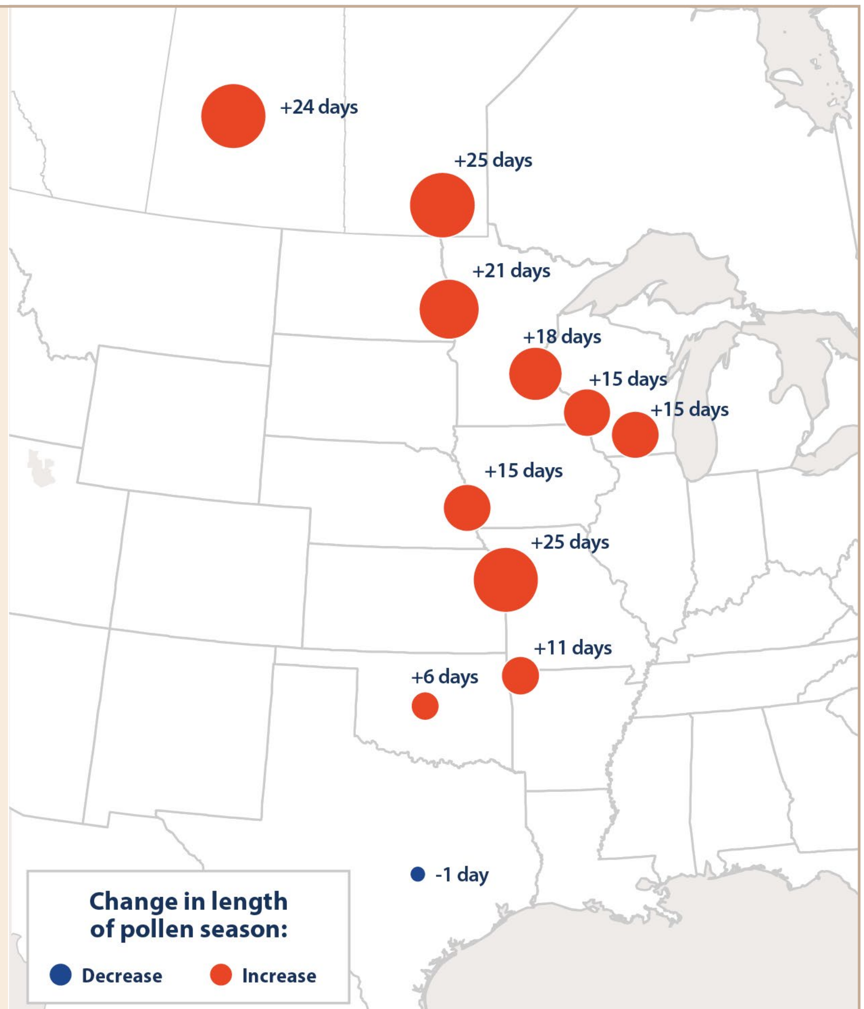
As the climate warms and growing degree days increase, many locations could experience longer and more intense allergy seasons. Multiple regions in the U.S. have experienced longer and more intense pollen seasons.[16]

Ragweed plants mature in mid-summer and produce small flowers that generate pollen. Ragweed pollen season usually peaks in late summer and early fall, but these plants often continue to produce pollen until the first frost. Warmer fall temperatures extend the growing season for ragweed and prolong pollen production. Warmer temperatures and increased carbon dioxide concentrations also lead ragweed and other plants to produce more pollen, and the pollen they produce is more allergenic. EPA's Ragweed Pollen Season indicator shows changes in the length of the ragweed pollen season in 11 cities in the central United States and Canada between 1995 and 2015.

- Since 1995, ragweed pollen season has grown longer at 10 of the 11 locations studied (Figure 32).
- The increase in ragweed season length generally becomes more pronounced from south to north (Figure 32). This trend is consistent with many other observations showing that climate is changing more rapidly at higher latitudes.[17]
- These trends are strongly related to changes in the length of the frost-free season and the timing of the first fall frost. Northern areas have seen fall frosts happening later than they used to, with the delay in first frost closely matching the increase in pollen season. Meanwhile, some southern stations have experienced only a modest change in frost-free season length since 1995.[18]

Figure 32. Change in Ragweed Pollen Season, 1995–2015

This map shows how the length of ragweed pollen season changed at 11 locations in the central United States and Canada between 1995 and 2015. Red circles represent a longer pollen season; the blue circle represents a shorter season. Larger circles indicate larger changes. Data source: Ziska et al., 2016.[19]



Ocean Impacts

The heat-trapping greenhouse gases that humans have added to the atmosphere are making the Earth's oceans warmer and more acidic. Changes in the oceans affect the Earth's climate and weather patterns and threaten marine ecosystems and biodiversity and the people whose livelihoods depend on them.

Indicators featured in this chapter:

Ocean Heat, Sea Surface Temperature, Marine Species Distribution, Marine Heat Waves, Ocean Acidity

Earth's oceans are warming.

Why it matters

Oceans regulate the Earth's climate by absorbing heat and transferring it around the world. Ocean temperature affects this function—particularly sea surface temperature—because heat from ocean surface waters provides energy for storms and thereby influences weather patterns. As water warms, it also expands slightly, causing the sea level to rise (see the Rising Seas chapter). Increased heat absorption also changes ocean currents, which influence climate patterns and sustain ecosystems that depend on certain temperature ranges and movement of nutrients.

What's happening

When sunlight and energy trapped by greenhouse gases reach the Earth's surface, oceans absorb some of this energy and store it as heat. Water is much better at storing heat than air, meaning the oceans can absorb larger amounts of heat energy with only a slight increase in temperature. As greenhouse gases trap more energy, the oceans are absorbing more heat. This heat is initially absorbed at the surface, but some of it eventually spreads to deeper waters. Ocean currents move this heat around the world, influencing climate patterns.

- The total amount of heat stored by the oceans is called "ocean heat content," and measurements of water temperature reflect the amount of heat in the water at a particular time and location.
- EPA's Ocean Heat indicator shows a long-term trend of oceans becoming warmer since 1955. Four different organizations analyzed ocean heat data, and all reached the same conclusion (Figure 33).

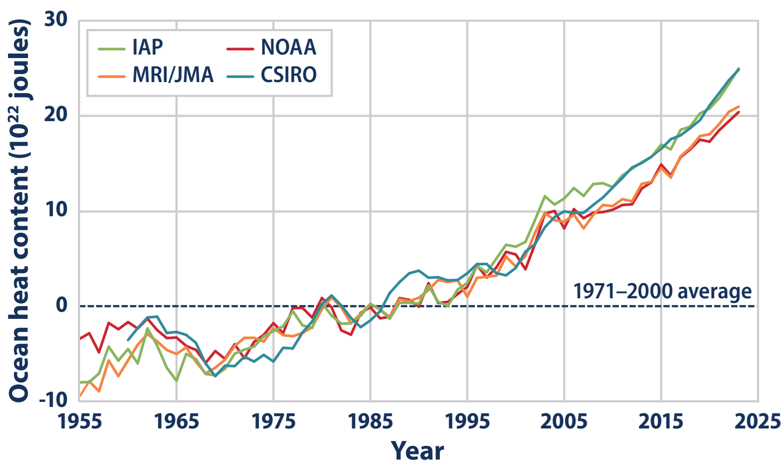


Figure 33. Heat Content in the Top 700 Meters of the World's Oceans, 1955–2023

This figure shows changes in heat content of the top 700 meters of the world's oceans between 1955 and 2023. Ocean heat content is measured in joules, a unit of energy, and compared against the 1971–2000 average, which is set at zero for reference. Choosing a different baseline period would not change the shape of the data over time. The lines were independently calculated using different methods by government organizations in four countries: the United States' National Oceanic and Atmospheric Administration (NOAA), Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), China's Institute of Atmospheric Physics (IAP), and the Japan Meteorological Agency's Meteorological Research Institute (MRI/JMA). For reference, an increase of 1 unit on this graph (1 × 1022 joules) is equal to approximately 17 times the total amount of energy used by all the people on the Earth in a year (based on a total global energy supply of 606 exajoules in the year 2019, which equates to 6.06 × 1020 joules).[1] Data sources: CSIRO, 2024;[2] IAP, 2024;[3] MRI/JMA, 2024;[4] NOAA, 2024.[5]

As the oceans absorb more heat, sea surface temperature is rising.

Why it matters

Higher sea surface temperatures have led to an increase in evaporation over the oceans. This extra evaporation and the associated heat fuel the formation of heavy rain and snow. Warmer surface waters can also promote the growth of certain bacteria that can contaminate seafood and cause people to get sick. This results in beach and fishery closures and affects ocean ecosystems and the people and communities—including Tribes and Indigenous Peoples—who rely on them for jobs or subsistence.[6,7] Many coastal areas have a large share of people who depend on income from fishing, tourism, or both. This is especially common in areas that have fewer economic alternatives, including rural counties and the United States' Caribbean and Pacific island commonwealths and territories.[8]

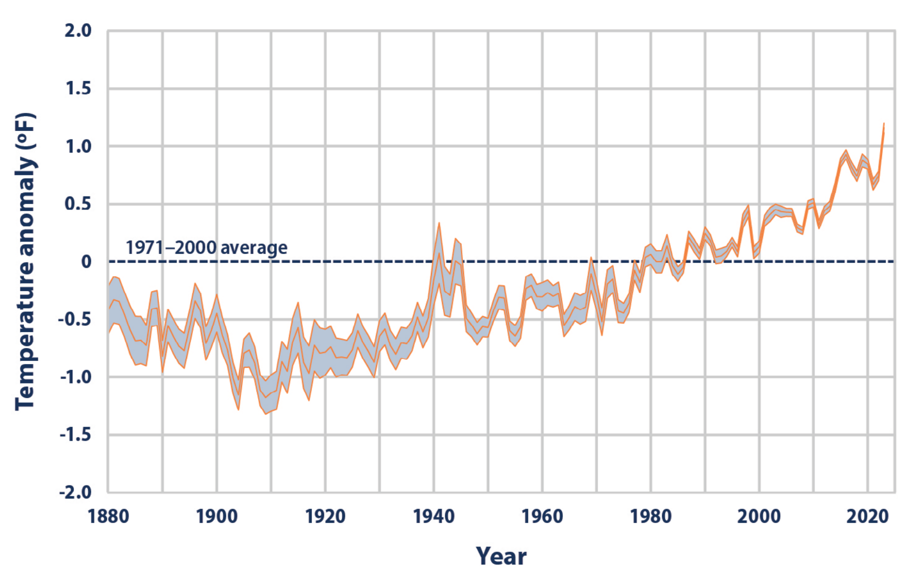
What's happening

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

- EPA's Sea Surface Temperature indicator shows that sea surface temperature increased during the 20th century and continues to rise. From 1901 through 2023, temperature rose at an average rate of 0.14°F per decade (Figure 34).
- Sea surface temperature has also been consistently higher during the past three decades than at any other time since reliable observations began in 1880. The year 2023 was the warmest ever recorded (Figure 34).

Figure 34. Average Global Sea Surface Temperature, 1880–2023

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 showing change. Choosing a different baseline period would not change the shape of the data over time. The shaded band shows the range of uncertainty in the data, based on the number of measurements collected and the precision of the methods used. Data source: NOAA, 2024.[9]



How sea surface temperature affects marine ecosystems

Changes in sea surface temperature can alter marine ecosystems in several ways. For example, variations in ocean temperature can affect what species of plants, animals, and microbes are present in a location, change migration and breeding patterns, threaten sensitive ocean life such as corals, and change the frequency and intensity of harmful algal blooms.[10] Over the long term, increases in sea surface temperature could also disrupt the circulation patterns that bring nutrients from the deep sea to surface waters. Changes in reef habitat and nutrient supply could dramatically alter ocean ecosystems and lead to declines in fish populations, which in turn could affect people who depend on fishing for food or livelihoods.[11]

Warmer oceans affect marine life.

Why it matters

The world's oceans support an abundance of biodiversity, and rising water temperatures can affect the environments where fish, shellfish, and other marine species live. The movement of species based on their preferred temperature conditions can affect commercial and recreational fisheries, altering where species are available, resulting in reduced catch, complicating fisheries management, and affecting livelihoods in communities that depend on these industries. Climate-related fishery losses have already resulted in billions of dollars of lost catch in recent years, directly harming jobs, livelihoods, and local culture.[12]

What's happening

Certain fish species migrate in response to seasonal temperature changes, moving to deeper, cooler waters in the summer and migrating back during the winter. As climate change causes the oceans to become warmer year-round, however, populations of some species may adapt by shifting away from areas that have become too warm and toward areas that were previously cooler. Along U.S. coasts, this means a shift northward or to deeper waters that may have a more suitable temperature. As smaller prey species shift their geographic range, larger predator species may follow them.

- EPA's Marine Species Distribution indicator shows that the average center of biomass for 157 marine fish and invertebrate species shifted northward by nearly 17 miles between 1989 and 2019. These species also moved an average of 0.6 feet deeper (Figure 35).
- Several marine species have shifted northward since the 1970s or 1980s, including several economically important species. In waters off the northeastern United States, American lobster, red hake, and black sea bass have moved northward by an average of 145 miles (Figure 36). In waters off the southeastern United States, Atlantic croaker, banded drum, and smooth butterfly ray have moved northward by an average of 169 miles (Figure 37). In the Bering Sea, walleye pollock, snow crab, and Pacific halibut have generally shifted away from the coast since the early 1980s and moved northward by an average of 41 miles (Figure 38).

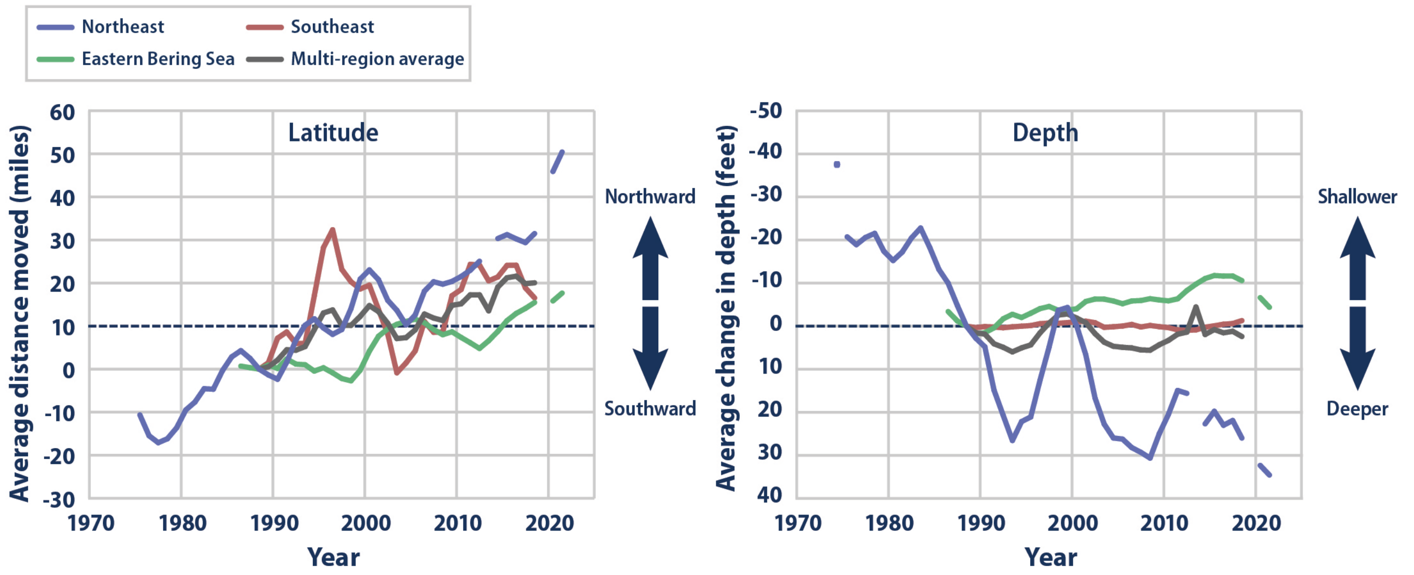


Figure 35. Change in Latitude and Depth of Marine Species, 1974–2022

These graphs show the annual change in latitude (movement in miles) and depth (feet) of 41 marine species along the Northeast coast, 58 in the eastern Bering Sea, and 58 along the Southeast coast. The multi-region average consists of 157 unique species. Changes in the centers of biomass have been aggregated across all species and by region. For each region, the change in latitude and change in depth are set at zero for a base year, 1989. Data source: NOAA, 2024.[13]

Figure 36. Average Locations of Three Fish and Shellfish Species in the Northeast, 1974–2022

In waters off the northeastern United States, several economically important species (American lobster, red hake, and black sea bass) have moved northward by an average of 145 miles since the early 1970s. Dots are shaded from light to dark to show change over time. Data source: NOAA, 2024.[14]

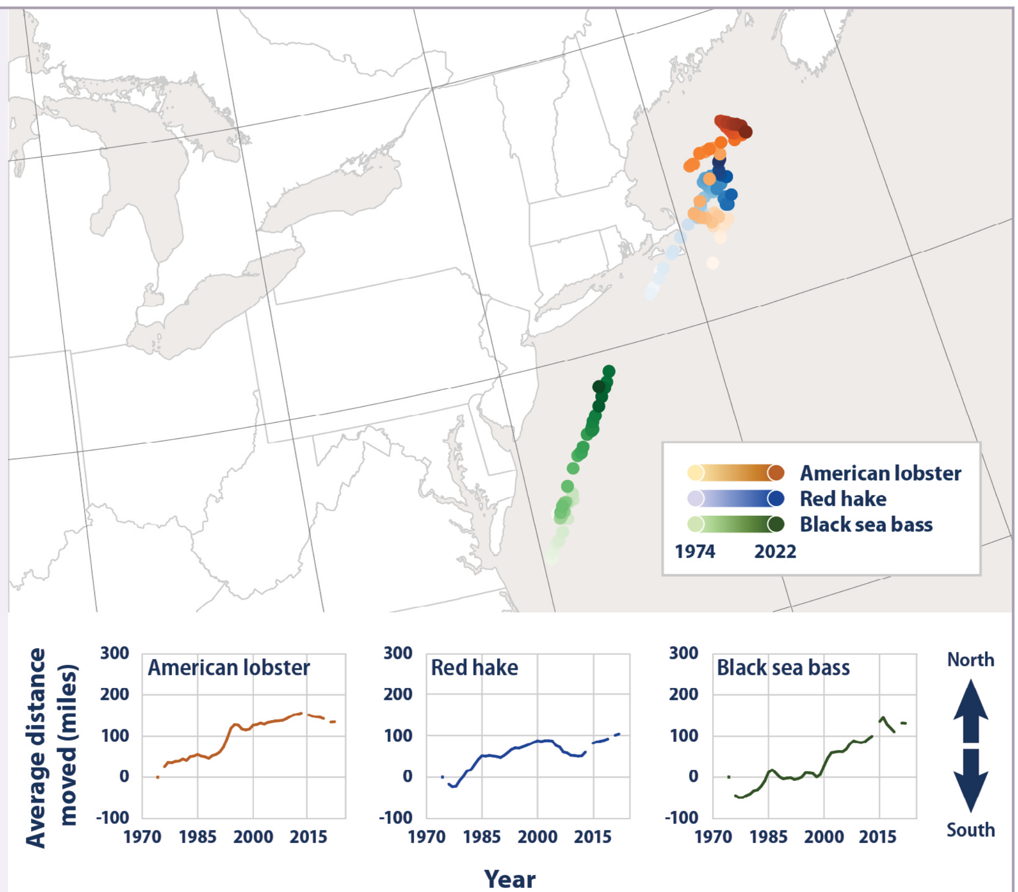


Figure 37. Average Locations of Three Fish Species in the Southeast, 1989–2019

In waters off the southeastern United States, several species (Atlantic croaker, banded drum, and smooth butterfly ray) have shifted northward by an average of 169 miles since the late 1980s. Dots are shaded from light to dark to show change over time. Data source: NOAA, 2024.[15]

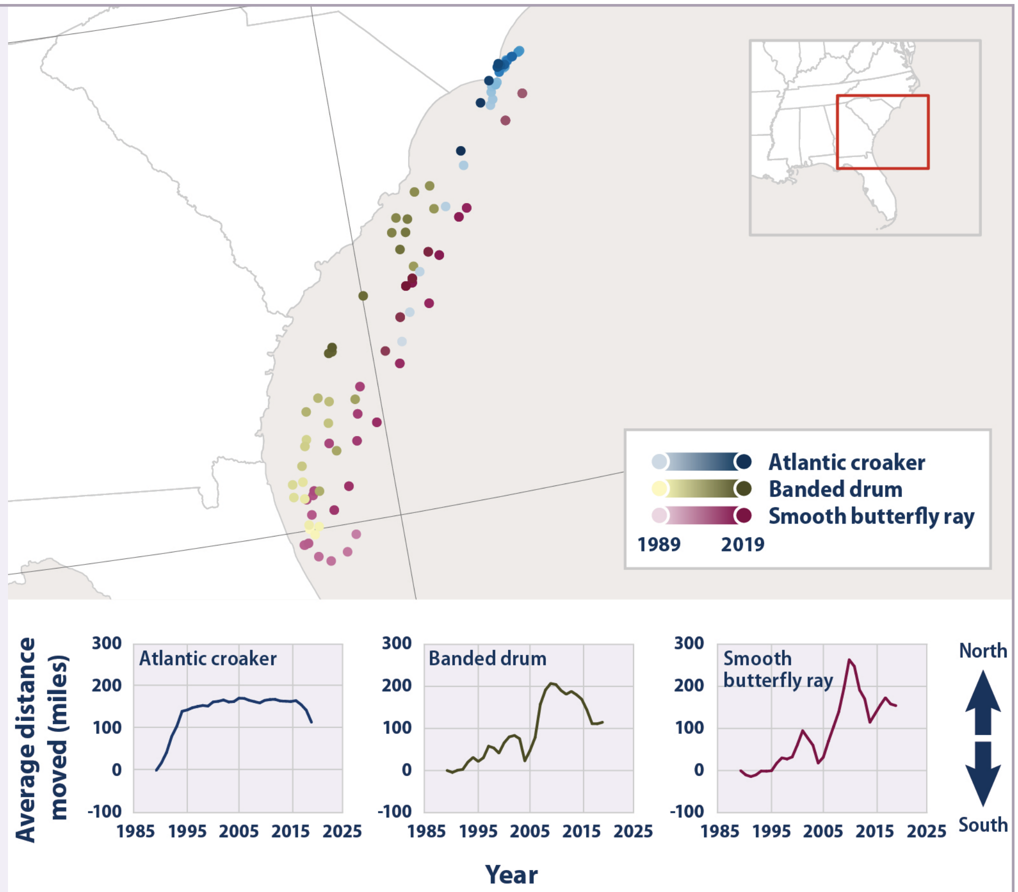
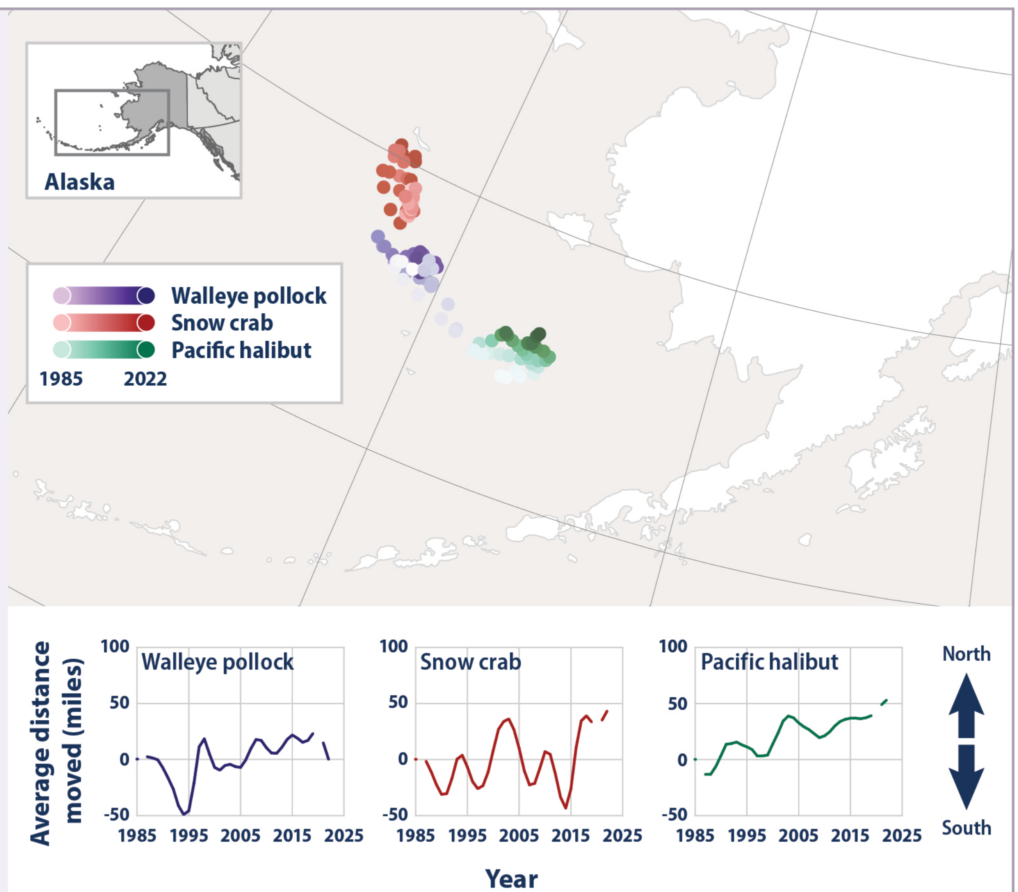


Figure 38. Average Locations of Three Fish and Shellfish Species in the Bering Sea, 1985–2022

In the Bering Sea, walleye pollock, snow crab, and Pacific halibut have generally shifted away from the coast since 1985. They have also moved northward by an average of 41 miles. Dots are shaded from light to dark to show change over time. Data source: NOAA, 2024.[16]



Marine heat waves are occurring more often, lasting longer, and becoming more intense.

Why it matters

Unusually hot ocean waters pose a risk to many creatures, especially those that cannot move, such as corals. These organisms cannot escape or tolerate waters that become too warm for several days or more. Marine heat waves are associated with some of the largest disruptions to marine life in recent years. For example, persistent marine heat wave conditions in the northern Pacific have fed blooms of harmful algae that have affected food chains. Algal blooms have led to the deaths of sea lions by contaminating the fish and squid they eat. Toxins from algae also accumulated in Dungeness crabs and other types of shellfish, rendering them hazardous for human consumption and leading to fishery closures. In 2015–2016, harmful-algal-bloom-related closures of the Dungeness fishery resulted in millions of dollars in lost revenue.[17]

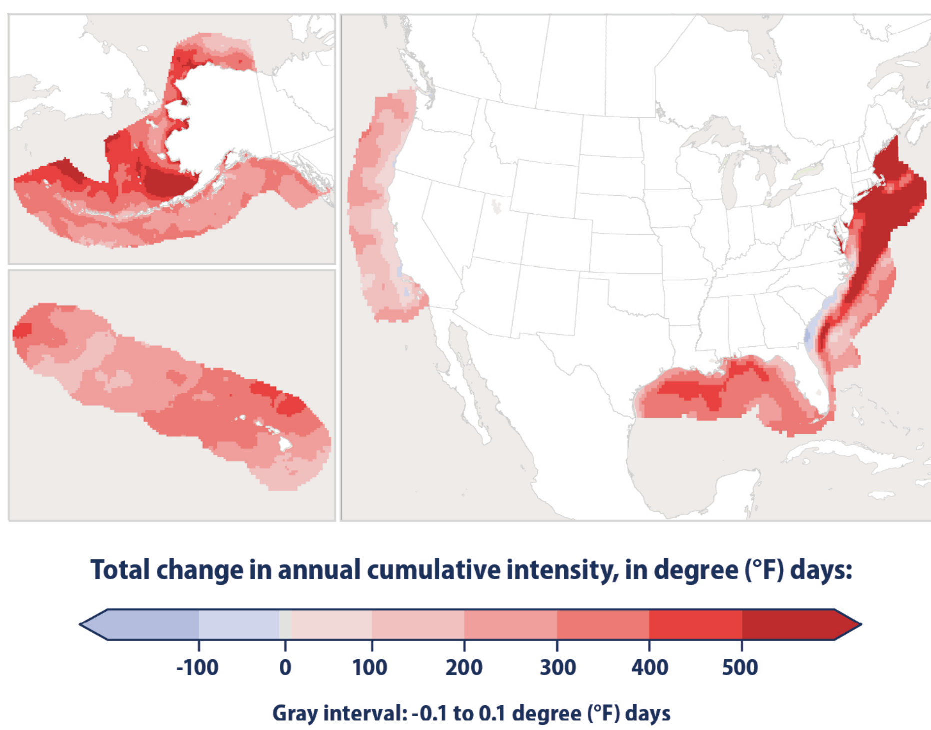
What's happening

Along with the overall trend of warming oceans, short-term spikes in ocean temperatures, known as marine heat waves, are also becoming more prevalent. A marine heat wave is defined as a period of at least five days in a row during which the sea surface temperature is much warmer than usual over a given location. Just like heat waves based on air temperature, marine heat waves are an extreme condition that can severely disrupt life, especially for creatures that cannot move out of harm's way.

- EPA's Marine Heat Waves indicator combines the duration, intensity, and frequency of marine heat waves into a single metric called cumulative intensity, measured in degree-days. If a location experiences an increase in annual cumulative intensity over time, that means marine heat waves are becoming either more common, longer, more intense (hotter), or some combination of the three.
- Between 1982 and 2023, the annual cumulative intensity of marine heat waves has increased in most coastal U.S. waters, with the largest changes in waters off the northeastern U.S. and Alaskan coasts (Figure 39).

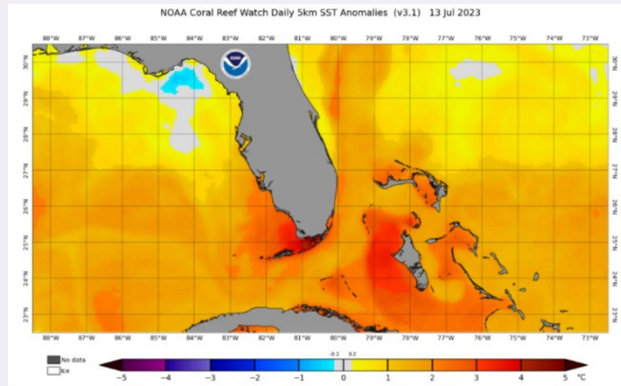
Figure 39. Change in Annual Cumulative Intensity of Marine Heat Waves in the United States, 1982–2023

This map shows the change in annual cumulative intensity of marine heat waves along U.S. coasts from 1982 to 2023. Cumulative intensity is measured in degree days—marine heat wave intensity multiplied by duration. Areas with increases are shown in red, with darker colors indicating greater change. The map shows total change, which is the annual rate of change multiplied by the number of years analyzed. The boundaries include the area within the U.S. exclusive economic zone. Data source: NOAA, 2024.[18]



Florida's marine heat wave of 2023: corals, fish, and human health at risk

The Florida marine heat wave of 2023 caused unprecedented warm ocean temperatures in the region, which harmed coral reefs and other marine life and posed risks to human health and safety. According to the National Oceanic and Atmospheric Administration, the sea surface temperatures around Florida reached the highest levels on record for July since satellites began collecting ocean data.[19] For example, Manatee Bay in southwest Florida reached over 101°F.[20] The heat wave exposed corals and other marine organisms to prolonged, intense thermal stress. The extreme heat triggered widespread coral bleaching, which occurs when corals expel their algal food source and turn white. Coral bleaching occurred in several locations in Florida.[21] Coral damage and death threaten the many ecological benefits that coral reefs provide, including support for biodiversity, fishing, and tourism and recreation.



This map of the ocean waters around Florida shows the difference between sea surface temperature on July 13, 2023 (during Florida's marine heat wave) and the long-term average. Positive values indicate the temperature is warmer than average, and negative values indicate the temperature is cooler than average.[22]

Higher levels of carbon dioxide are making the oceans more acidic.

Why it matters

Rising levels of carbon dioxide dissolved in the water can harm ocean creatures. Carbon dioxide reacts with sea water to produce carbonic acid, and the resulting increase in acidity changes the balance of minerals in the water. This makes it more difficult for corals, some types of plankton, and other creatures to produce a mineral called calcium carbonate, which is the main ingredient in their hard skeletons or shells. Thus, rising ocean acidity can make it more difficult for these animals to thrive. This can lead to broader changes in the overall structure of ocean and coastal ecosystems and can ultimately affect fish and shellfish populations and the people and communities, including Tribes and Indigenous Peoples, who depend on them for jobs or subsistence.[23]

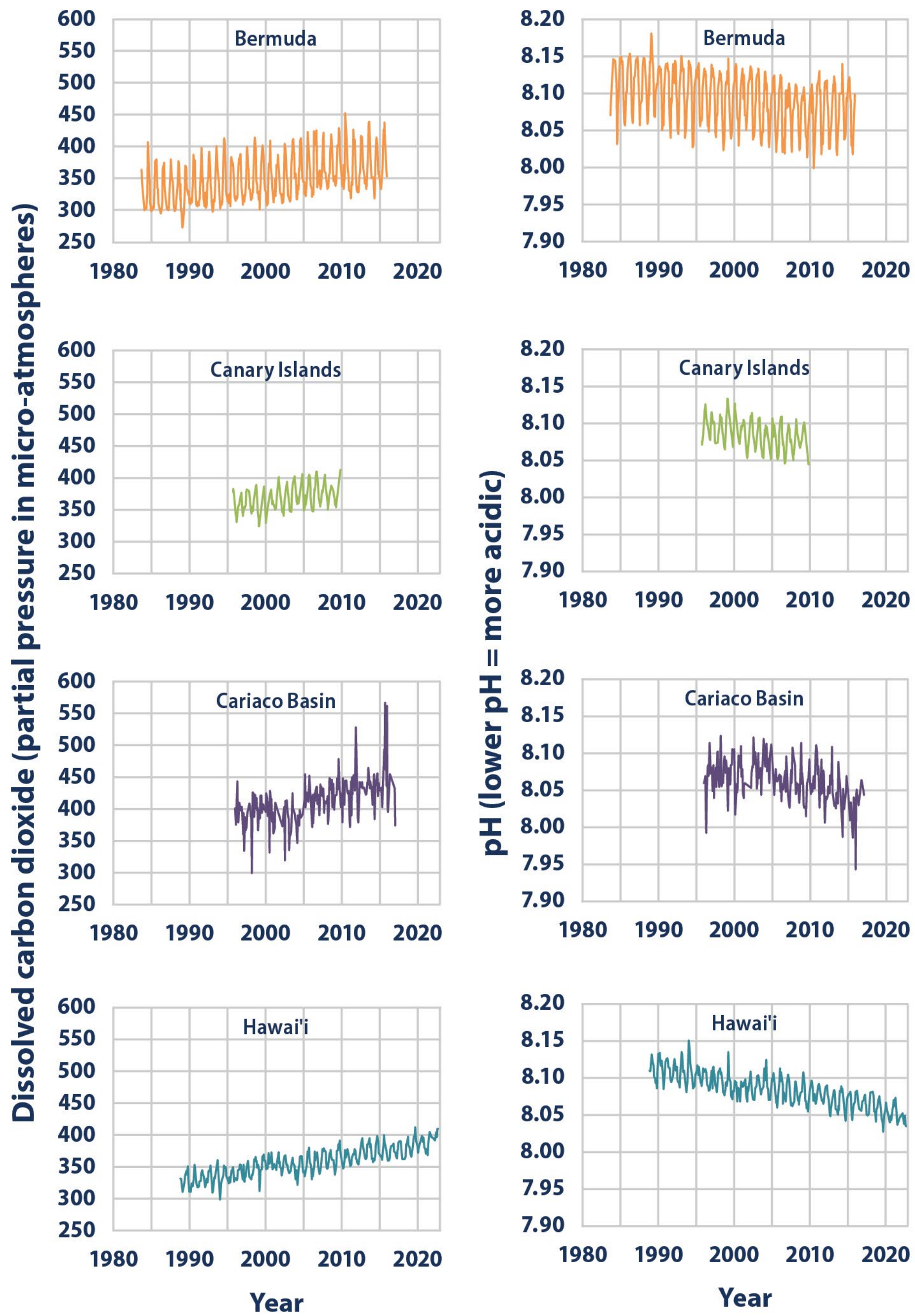
What's happening

Oceans play an important role in regulating the amount of carbon dioxide in the atmosphere. As concentrations of carbon dioxide in the atmosphere increase, some of this additional carbon dioxide dissolves in the ocean. Because of the slow mixing time between surface waters and deeper waters, it can take hundreds to thousands of years to establish this balance. From 1750 to 2019, oceans absorbed about 25 percent of the carbon dioxide emitted into the atmosphere by human activities.[24]

- Although the oceans help to slow the pace of climate change by storing large amounts of carbon dioxide, increasing levels of dissolved carbon dioxide are changing the chemistry of sea water and making it more acidic.
- EPA's Ocean Acidity indicator demonstrates that ocean carbon dioxide levels have risen in response to increased carbon dioxide in the atmosphere, leading to an increase in ocean acidity (Figure 40).

Figure 40. Ocean Carbon Dioxide Levels and Acidity, 1983–2022

This figure shows the relationship between changes in ocean carbon dioxide levels (measured in the left column as a partial pressure—a common way of measuring the amount of a gas) and acidity (measured as pH in the right column; lower pH means more acidity). The data come from two observation stations in the North Atlantic Ocean (Bermuda and Canary Islands), one in the Caribbean Sea (Cariaco), and one in the Pacific (Hawai'i). The up-and-down pattern shows the influence of seasonal variations. Data sources: Bates, 2016;[25] González-Dávila, 2012;[26] University of South Florida, 2021;[27] University of Hawai'i, 2023.[28]



Taking action: building resilience in the face of ocean acidification

Alaska's marine environment plays a critical role in the state's economy and traditional way of life. Many Native Alaskans depend on aquaculture for their livelihoods and for cultural practices. Ocean acidification leads to lower saturation levels of aragonite—the form of carbonate that shellfish need to build and maintain their shells. As the ocean has become more acidic, shellfish hatcheries in the Pacific Northwest and Alaska have experienced challenges maintaining the health of their shellfish. Some have nearly collapsed due to economic losses.

In 2012, the University of Alaska Fairbanks Ocean Acidification Research Center and NOAA's Pacific Marine Environmental Laboratory partnered with the Alutiiq Pride Shellfish Hatchery in Seward, Alaska, to develop a rapid response program to monitor ocean acidification impacts on shellfish. Alutiiq Pride uses the data gathered to determine when aragonite levels are too low in their hatcheries so they can take mitigating steps to keep their shellfish healthy. One such strategy used by Alutiiq Pride is to make the water less acidic by adding soda ash.

Learn more about how the Alutiiq Pride Shellfish Hatchery is collaborating with federal and academic partners to measure the impacts of ocean acidification on shellfish and develop possible adaptation strategies.

Rising Seas

As the temperature of the Earth changes, so does sea level throughout the world's oceans. Water from melting ice sheets and glaciers on land ultimately flows into the ocean. Also, as water in the ocean warms, it expands slightly, increasing the volume of water in the ocean. Both of these factors contribute to sea level rise, which increases coastal flooding and other coastal risks.

Indicators featured in this chapter:

Glaciers, Ice Sheets, Sea Level, Coastal Flooding

Glaciers in the United States and around the world are shrinking.

Why it matters

In many parts of the world, glaciers provide a reliable source of fresh water to support ecosystems and give people drinking water. This water is especially important in times of extended drought and late in the summer when seasonal snowpack has melted away. When glaciers lose ice, they ultimately add more water to the oceans, leading to a rise in sea level.

What's happening

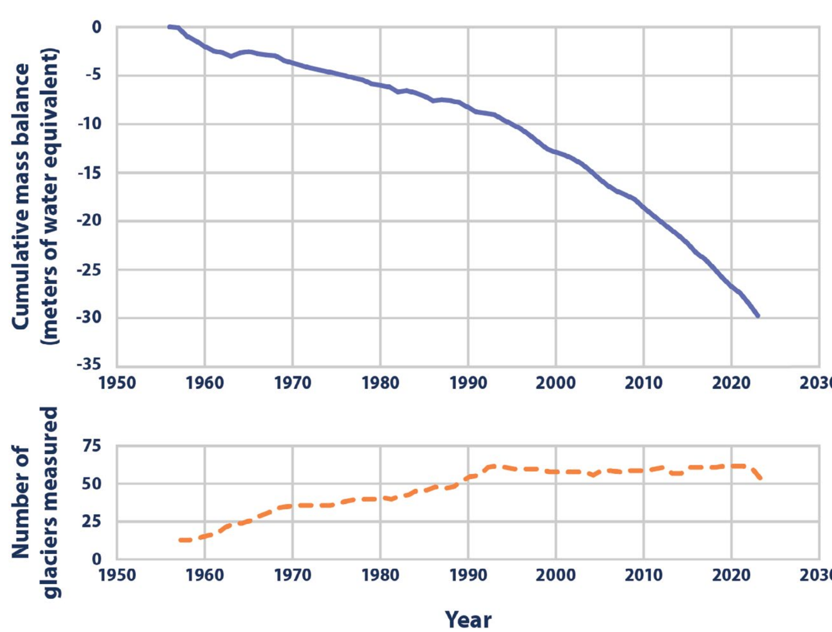
A glacier is a large mass of snow and ice that has accumulated over many years and is present year-round. Glaciers tend to be smaller and narrower than ice sheets. They can occur at any latitude if the temperature conditions are right, usually at high elevations and in well-shaded mountain valleys. At higher elevations, a glacier accumulates snow, which eventually becomes compressed into ice. At lower elevations, the glacier naturally loses mass as the ice melts and as chunks break off (which is called calving and is common in glaciers that end in a lake or at the ocean). Glacier mass balance is the net gain or loss of snow and ice over the course of the year. If glaciers lose more ice through melting and calving than they can accumulate through new snowfall, they add more water to the oceans, increasing sea level.

The world's small glaciers hold less ice than the two giant ice sheets that cover Greenland and Antarctica, but they are melting more quickly. Between 1971 and 2018, glaciers added more water overall to the oceans than the ice sheets.[1]

- EPA's Glaciers indicator shows that glaciers worldwide have been losing mass since at least the 1970s, which in turn has contributed to observed changes in sea level (Figure 41).
- A longer measurement record from a smaller number of glaciers suggests that they have been shrinking since the 1950s.
- The rate at which glaciers are losing mass appears to have accelerated since the early 2000s (Figure 41).

Figure 41. Average Cumulative Mass Balance of "Reference" Glaciers Worldwide, 1956–2023

This figure shows the cumulative change in mass balance of a set of "reference" glaciers worldwide beginning in 1956. The line on the upper graph represents the average of all the glaciers that were measured. Negative values indicate a net loss of ice and snow compared with the base year of 1956. For consistency, measurements are in meters of water equivalent, which represent changes in the average thickness of a glacier. The small chart below shows how many glaciers were measured in each year. Some glacier measurements have not yet been finalized for the last few years, hence the smaller number of sites. Data source: WGMS, 2024.[2]



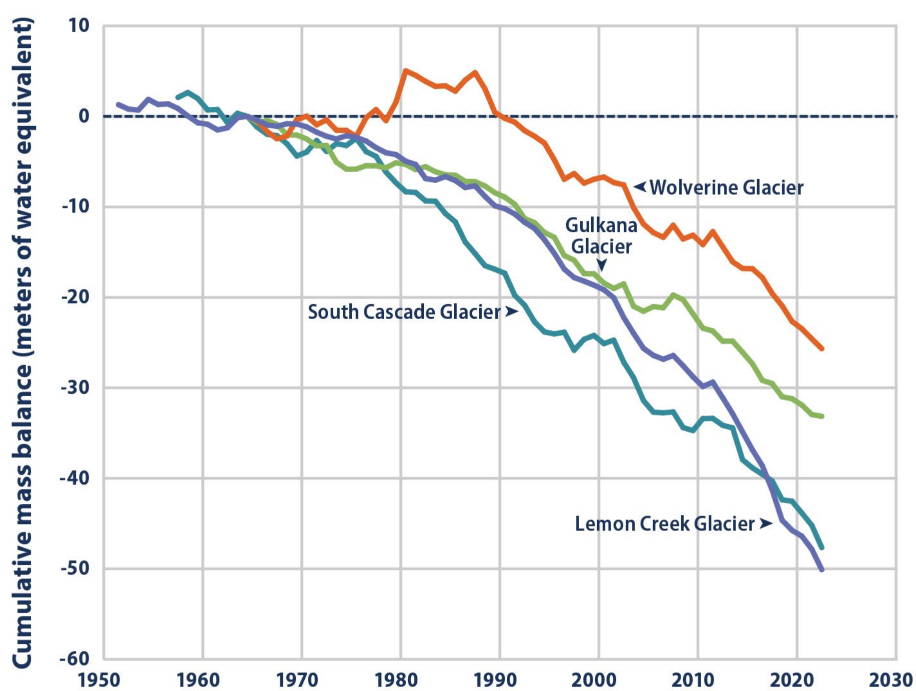
In the United States, glaciers can be found in the Rocky Mountains, in the Sierra Nevada, in the Cascades, and throughout Alaska. Four glaciers in the United States have been studied extensively for many years and are thought to be representative of other glaciers nearby: South Cascade Glacier in Washington State, Lemon Creek Glacier in southeastern Alaska, Wolverine Glacier near Alaska's southern coast, and Gulkana Glacier in Alaska's interior (Figure 42).

- These four U.S. reference glaciers have shown an overall decline in mass balance since the 1950s and 1960s and an accelerated rate of decline in recent years. Year-to-year trends vary, with some glaciers gaining mass in certain years (for example, Wolverine Glacier during the 1980s), but the measurements clearly indicate a loss of glacier mass over time (Figure 43).
- Trends for the four U.S. reference glaciers are consistent with the retreat of glaciers observed throughout the western United States, Alaska, and other parts of the world.[3,4]

Figure 42. Four Reference Glaciers Studied in the United States

Figure 43. Cumulative Mass Balance of Four U.S. Glaciers, 1952–2023

This graph shows the cumulative mass balance of four U.S. reference glaciers since measurements began in the 1950s or 1960s. For each glacier, the mass balance is set at zero for the base year of 1965. Negative values indicate a net loss of ice and snow compared with the base year. For consistency, measurements are in meters of water equivalent, which represent changes in the average thickness of a glacier. Data source: USGS, 2024.[5]



Greenland and Antarctica's ice sheets are also shrinking.

Why it matters

The vast ice sheets of Greenland and Antarctica are losing ice more quickly than new snowfall can replenish it. This overall loss of ice adds fresh water to the ocean, increasing sea level and possibly changing ocean circulation that is driven by differences in temperature and salinity. Because ice reflects more sunlight than bare ground due to its light color, the melting of the ice sheets also causes the Earth's surface to absorb more energy from the sun and become warmer.

What's happening

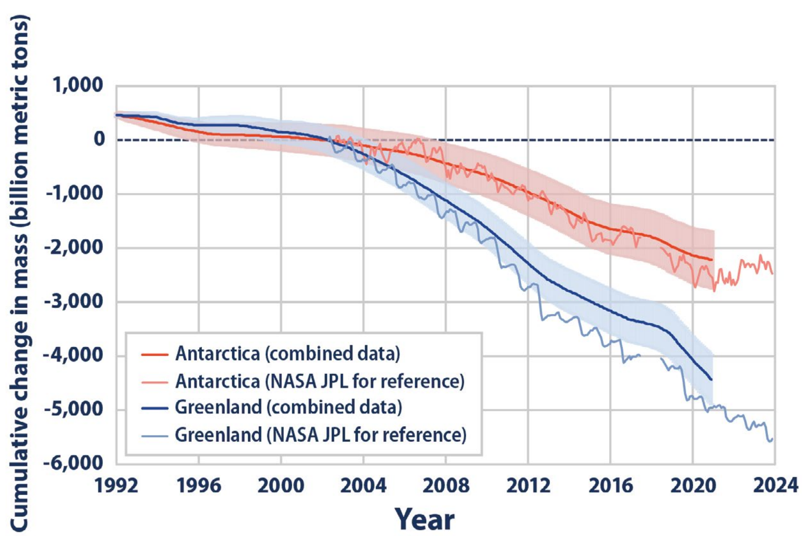
Ice sheets are large bodies of ice on land that cover hundreds of thousands of square miles on Greenland and Antarctica. Greenland and Antarctica's ice sheets together hold nearly 70 percent of the world's fresh water. When an ice sheet is in equilibrium, new snow accumulation is balanced by melting at the surface, runoff, and calving (ice breaking off to form icebergs) into the ocean.

However, a warmer climate is affecting ice sheets in several ways. Warmer air is causing the ice sheets to melt more quickly and flow more rapidly into the sea. Warmer ocean waters are melting the edge and underside of the ice sheets and accelerating the process of calving. EPA's Ice Sheets indicator shows that Greenland and Antarctica have both lost ice overall since 1992, with Greenland losing an average of about 175 billion metric tons of ice per year and Antarctica losing more than 90 billion metric tons of ice per year (Figure 44).

- The total amount of ice lost by Greenland and Antarctica from 1992 to 2020 was enough to raise sea level worldwide by an average of roughly three-quarters of an inch or more.[6] By comparison, when factoring all contributions to sea level rise, global average sea level increased by about 3 inches overall during this period.
- Although ice sheets naturally fluctuate with seasonal variations in temperature, precipitation, and other factors, the overall shrinking of the ice sheets far exceeds seasonal and year-to-year variations.
- Observations of ice sheets losing mass are consistent with trends in small glaciers.

Figure 44. Cumulative Mass Balance of Greenland and Antarctica, 1992–2023

This graph shows the cumulative change in mass in the ice sheets of Greenland and Antarctica since 1992. The dark "combined" lines are based on more than 20 different studies that have been combined for each region. Shading shows the uncertainty estimates from the various data sets that feed into the combined average. The two "NASA JPL" lines have been added to show results from one commonly cited analysis, including seasonal variations. All estimates are centered at zero in 2002 to provide a consistent point of reference. Thus, a downward slope indicates a net loss of ice and snow. For reference, 1,000 billion metric tons is equal to about 260 cubic miles of ice—enough to raise sea level by about 3 millimeters.[7] Data sources: Otosaka et al., 2023;[8] NASA, 2024.[9]



Measuring the changing mass of glaciers and ice sheets

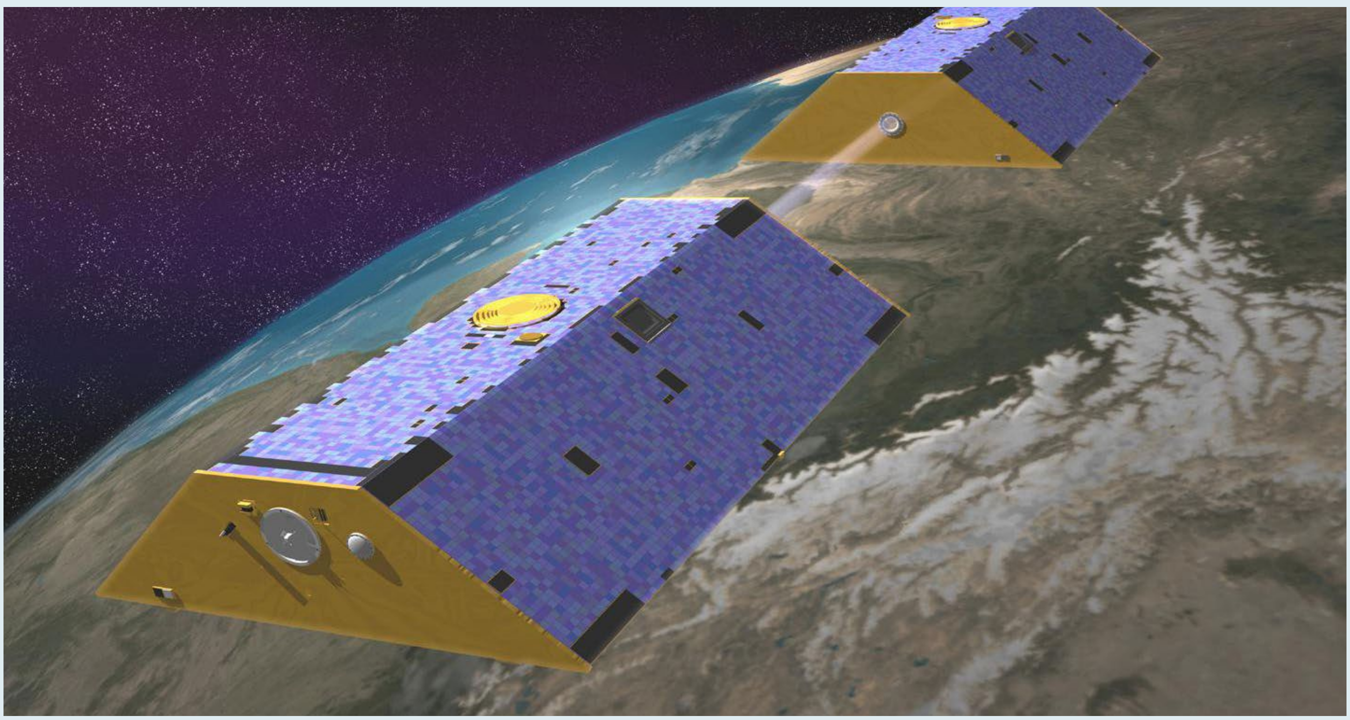
EPA's Glaciers indicator and Ice Sheets indicator draw from decades of data collection. Scientists use a variety of methods to measure how glaciers and ice sheets have changed over time.

Field measurements. Scientists visit glaciers to collect measurements of snow depth and snow density on the glacier surface. Comparing measurements from the same locations over time allows scientists to see changes in snow and ice accumulation and loss. Scientists report these changes in meters of water equivalent. Because snow and ice can vary in density, converting to the equivalent amount of liquid water provides a more consistent way to track and compare results.

Satellites. Unlike small glaciers, the vast ice sheets of Greenland and Antarctica are so large and remote that scientists cannot visit them regularly and collect reliable field measurements. Satellites offer the most effective way to measure changes in these ice sheets.

To get a more complete picture of how ice sheet mass balance has changed, scientists have combined many different estimates. These estimates are based on three main measurement techniques:

- Measuring the height of the ice sheet surface relative to sea level. This technique is called altimetry, and it typically uses radar or laser instruments mounted on aircraft or satellites. Increasing or decreasing ice surface elevation can show areas of the ice sheet that are gaining or losing mass, respectively.
- Measuring changes in the weight of the ice on Greenland and Antarctica. Changes in the density of the Earth's crust and the amount of ice or water overlying it will cause slight variations in the Earth's gravitational field. This technique uses a pair of satellites, known as the GRACE Mission, which are orbiting next to each other and continually measuring the distance between them. As the satellites pass over regions with different gravitational pulls, the distance between the two satellites slightly changes. As ice sheets melt over time, the gravitational pull decreases, allowing a calculation of the mass lost from ice sheets due to climate warming. Learn more about how the GRACE Mission measures changes in the Earth's gravity.
- Using the "input-output" method, which combines various sources of information on ice accumulation (for example, models of surface mass balance) and discharge into the ocean based on radar, satellite images, and other data.



Sea level is rising around the world.

Why it matters

Changing sea levels can affect people and ecosystems in coastal areas. As sea level rises, coastal flooding happens more often (even with high tide on a sunny day) and storm surge becomes higher and more damaging. Low-lying wetlands and dry land can turn into open water, putting coastal ecosystems and the people living in coastal areas at risk. Rising sea levels erode shorelines and increase the flow of salt water into estuaries and nearby groundwater aquifers, threatening some aquatic plants and animals and contaminating freshwater supplies.

What's happening

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

1. Changes in the volume of water and ice on land (namely glaciers and ice sheets) can increase or decrease the volume of water in the ocean.
2. As water warms, it expands slightly—an effect that is cumulative over the entire depth of the oceans. (See the Ocean Impacts chapter to learn more about warming oceans.)

Sea level changes that affect coastal systems involve more than just expanding oceans

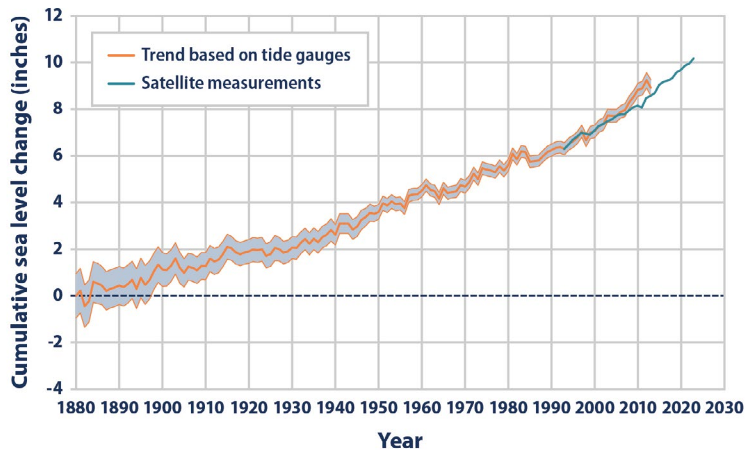
Sea level can be affected by more than just melting glaciers and ice sheets and warming waters. Land can also rise and fall relative to the oceans through geologic processes. Land can rise through processes such as sediment accumulation (the process that built the Mississippi River delta) and geological uplift (for example, as glaciers melt, the land below can rebound upward as it is no longer weighed down by heavy ice). In other areas, land can sink because of erosion, sediment compaction, natural subsidence, groundwater withdrawal, 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.

Scientists account for these types of changes by measuring sea level change in two different ways. "Relative sea level change" refers to how the height of the ocean rises or falls relative to the land at a particular location. In contrast, "absolute sea level change" refers to the height of the ocean surface above the center of the Earth, without regard to whether nearby land is rising or falling. EPA's Sea Level indicator describes how absolute sea level averaged over the entire Earth's surface and relative sea level along the U.S. coastline have changed over time.

- After a period of about 2,000 years of little change (not shown in the figure below),[10] global average sea level rose roughly 6 inches through the 20th century, and the rate of change has accelerated in recent years (Figure 45).
- While absolute sea level has increased steadily overall, particularly in recent decades, regional trends vary, and absolute sea level has decreased in some places.[11]
- Relative sea level rose along much of the U.S. coastline between 1960 and 2023, particularly the Mid-Atlantic Coast and parts of the Gulf Coast, where some stations recorded increases of more than 8 inches (Figure 46). Meanwhile, relative sea level fell at some locations in Alaska and the Pacific Northwest. At those sites, even though absolute sea level has risen, land elevation has risen more rapidly.
- Relative sea level has not risen uniformly because of regional and local changes in land movement and long-term changes in coastal circulation patterns.

Figure 45. Global Average Absolute Sea Level Change, 1880–2023

This graph shows cumulative changes in sea level for the world's oceans since 1880, based on a combination of long-term tide gauge measurements and recent satellite measurements. This figure shows average absolute sea level change, which refers to the height of the ocean surface, regardless of whether nearby land is rising or falling. Satellite data are based solely on measured sea level, while the long-term tide gauge data include a small correction factor because the oceans slowly change in size and shape over time. (On average, the ocean floor has been gradually sinking since the last Ice Age peak, 20,000 years ago.) The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used. Data sources: CSIRO, 2017;[12] NOAA, 2024.[13]



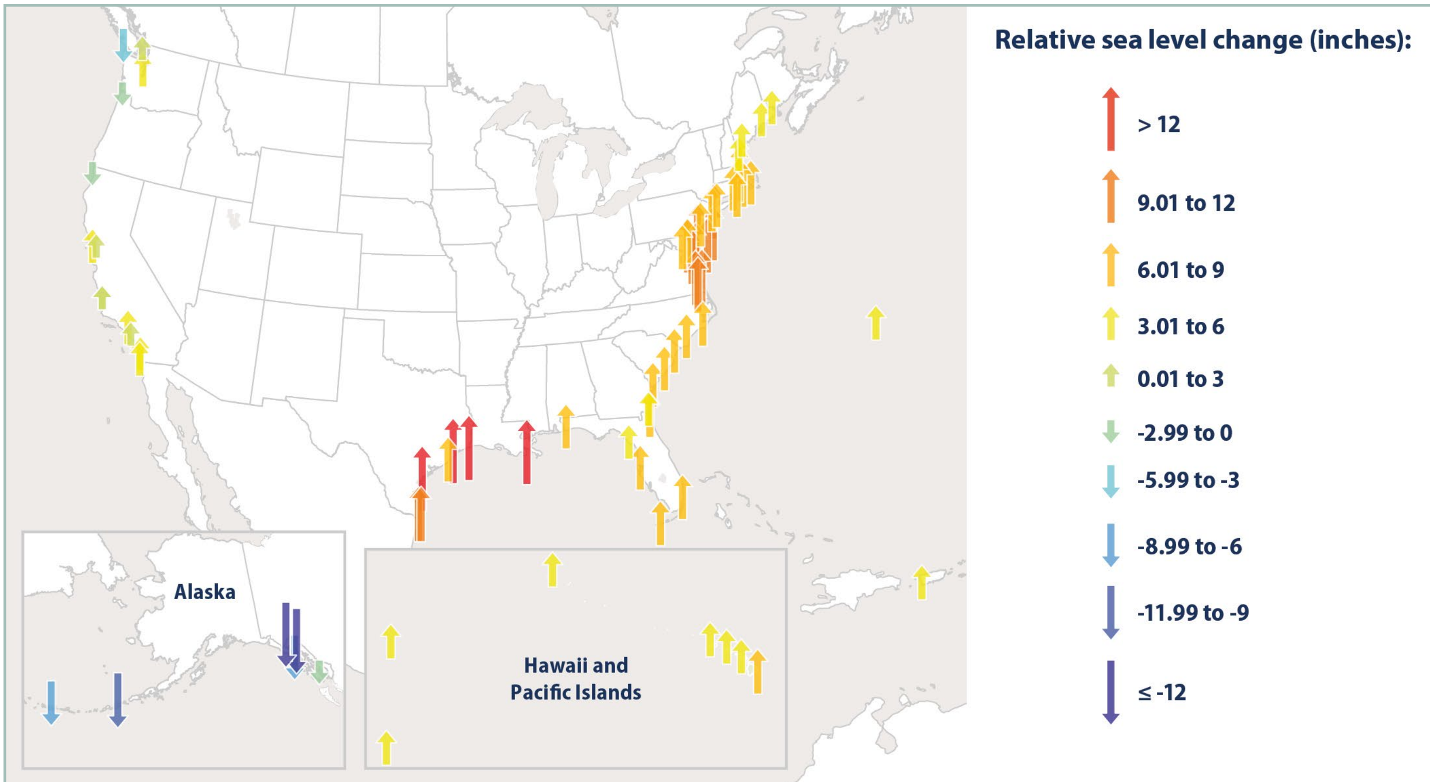


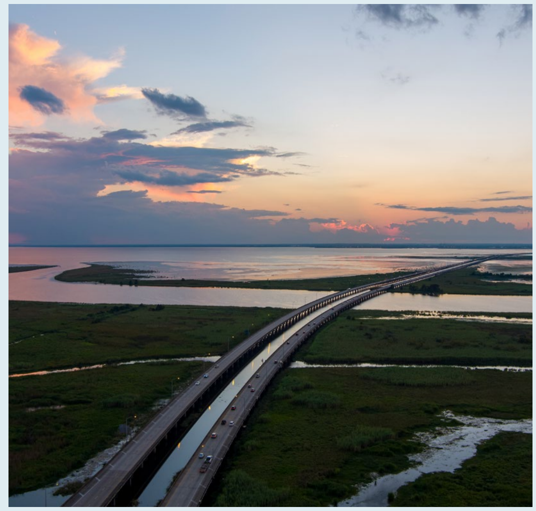
Figure 46. Relative Sea Level Change Along U.S. Coasts, 1960–2023

This map shows cumulative changes in relative sea level from 1960 to 2023 at tide gauge stations along U.S. coasts. Relative sea level reflects changes in sea level as well as land elevation. Data source: NOAA, 2024.[14]

Climate ready estuaries

Coastal communities face many effects of climate change, including sea level rise and coastal flooding. EPA's Climate Ready Estuaries program works to support National Estuary Programs and coastal communities in becoming "climate ready" by helping them assess their vulnerability to climate change and plan ways to adapt. The program provides technical guidance and assistance about climate change adaptation.

For example, the Mobile Bay National Estuary Program in Alabama is implementing strategies in the Three Mile Creek watershed to address climate vulnerabilities in low-lying, historically underserved communities where residents are predominantly people of color. Strategies include improving stormwater management, streambank restoration, and other measures to increase the communities' resilience to flooding.



Flooding is becoming more frequent along the U.S. coastline.

Why it matters

Coastal flooding can damage homes, businesses, and infrastructure that is not designed to withstand frequent inundation or exposure to salt water. Repeated flooding can result in frequent road closures, affecting the ability of people to get to work or school, obtain food and supplies, and receive medical care. Coastal flooding can also make storm drains ineffective and cause drinking water and wastewater treatment systems to fail, putting people at risk of exposure to harmful chemicals and pathogens.

What's happening

As sea level rises, one of the most noticeable consequences is an increase in coastal flooding. Flooding typically occurs during high tides and storms that push water toward the shore. In recent years, however, coastal cities are increasingly flooding on days with less extreme tides or little wind, even on sunny days. Over time, recurrent coastal flooding can lead to permanent inundation. Dry land can turn into wetlands or open water, as described in EPA's feature on land loss along the Atlantic Coast. EPA's Coastal Flooding indicator demonstrates how flooding along the U.S. coastline has changed over time.

- Flooding is becoming more frequent along much of the U.S. coastline. EPA's indicator looks at 42 locations with long-term records, and most of them have experienced an increase in coastal flooding since the 1950s (Figure 47).
- At more than half of the sites, floods are now at least five times more common than they were in the 1950s (Figure 47).
- The average number of flood events per year has progressively accelerated across the decades since 1950. The rate of increase of flood events per year is the largest at most locations in Hawaiʻi and along the East and Gulf Coasts (Figure 48).
- Flooding has increased less dramatically in places where relative sea level has not risen as quickly as it has elsewhere in the United States. Two sites in Alaska and three sites along the West Coast have experienced a decrease in coastal flooding (Figures 47 and 48), coinciding with decreasing relative sea level as the land itself is rising.

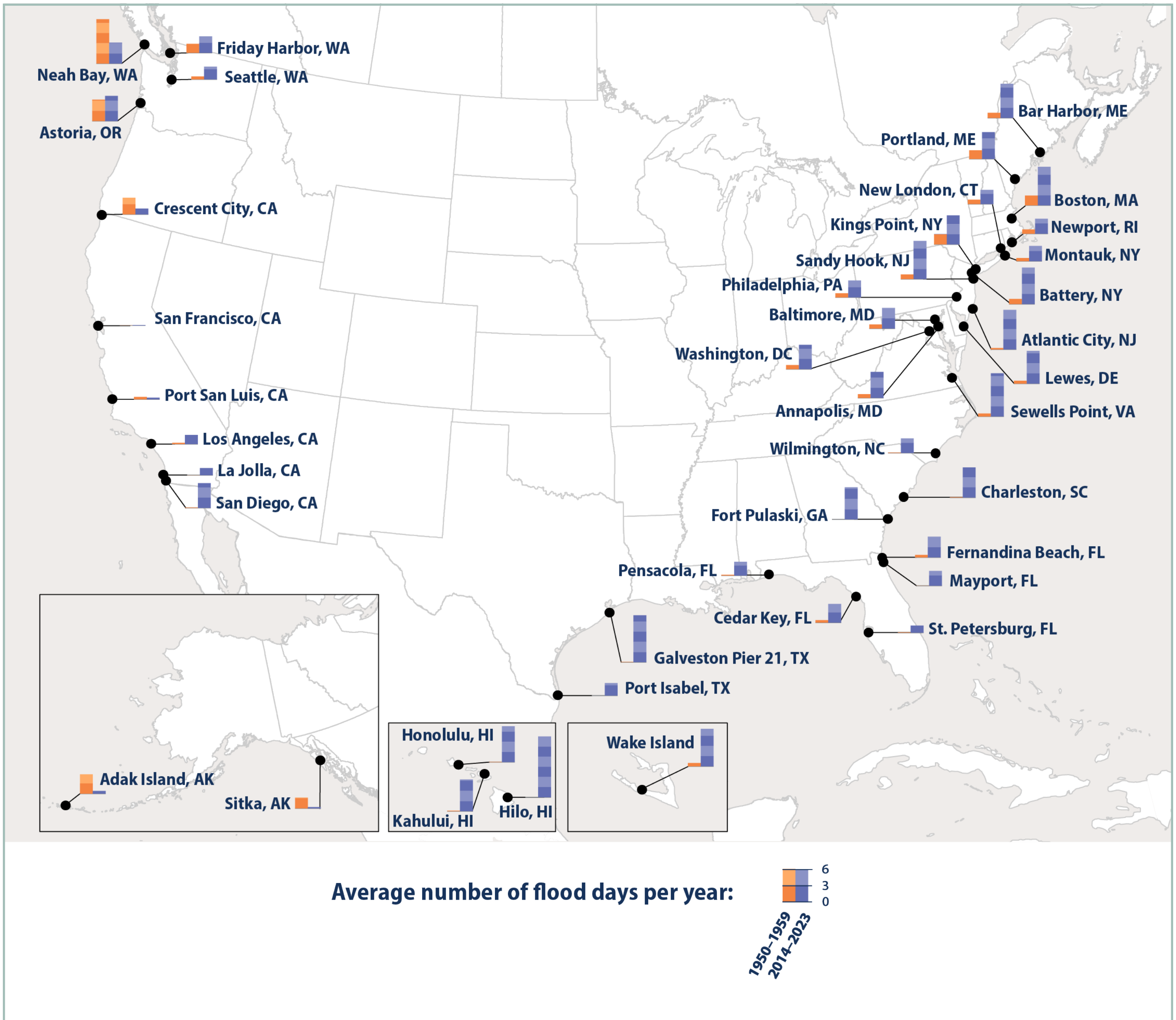


Figure 47. Frequency of Flooding Along U.S. Coasts, 2014–2023 Versus 1950–1959

This map shows the average number of days per year in which coastal waters rose above a local threshold for flooding at 42 sites along U.S. coasts. Each small bar graph compares the first decade of widespread measurements (1950–1959, in orange) with the most recent decade (2014–2023, in purple). Data source: NOAA, 2024.[15,16]

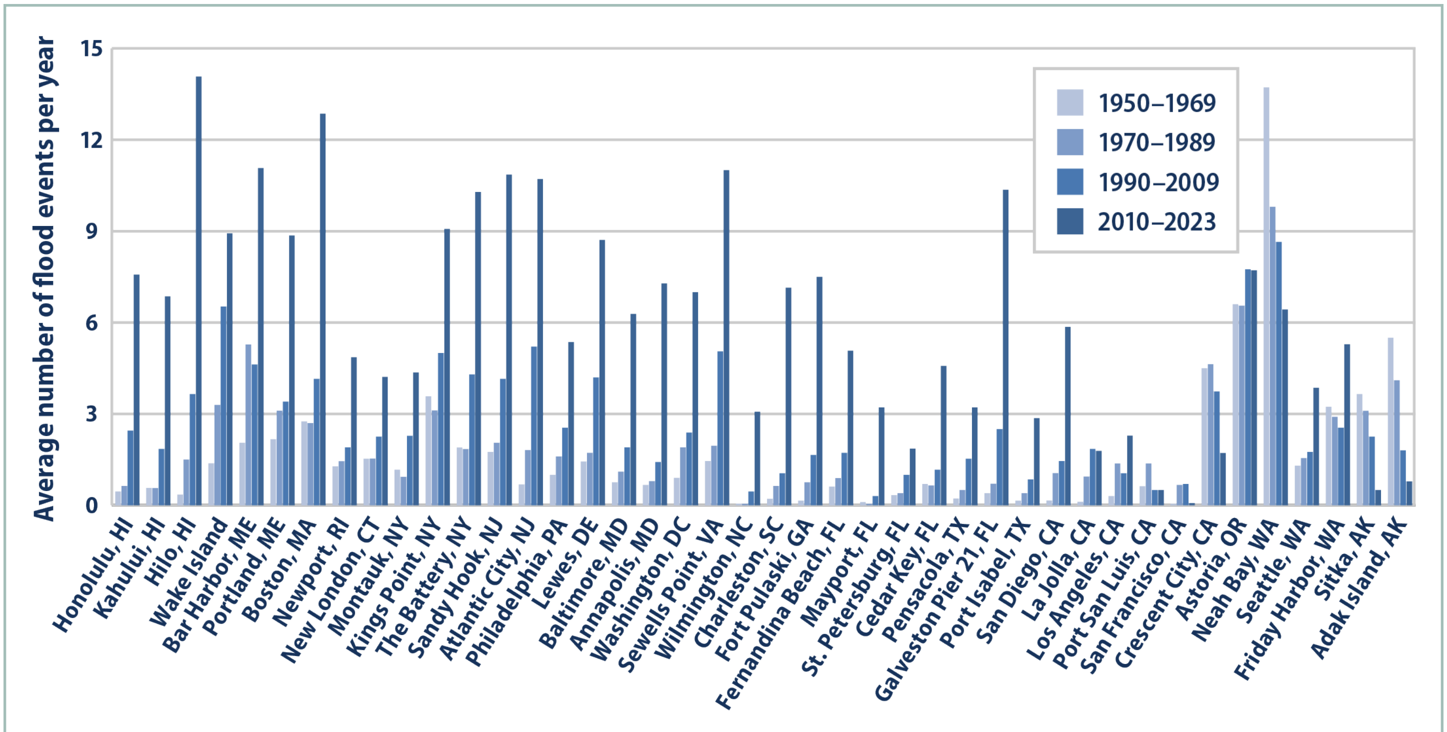


Figure 48. Average Number of Coastal Flood Events per Year, 1950–2023

This graph shows the average number of days per year in which coastal waters rose above a local threshold for flooding at 42 sites along U.S. coasts. The data have been averaged over multi-year periods for comparison. Data source: NOAA, 2024.[17,18]

Taking action: oyster reefs as resilience tools

Restoration of oyster reefs is an effective nature-based approach to increasing shoreline resilience. Oysters cluster on underwater structures, such as rocks, and fuse together as they grow, forming reefs. As a protective barrier, oyster reefs guard coastal communities by reducing wave energy that causes erosion. In contrast to structures like bulkheads and seawalls, communities can create "living shorelines" using oyster reefs as natural barriers that benefit the shoreline ecosystem while buffering waves.

U.S. military leaders have started implementing oyster reef restoration efforts to better protect coastal military assets. Naval Weapons Station Earle is working to restore oyster reefs in New Jersey's Raritan Bay. The naval station is repopulating oysters in the estuary through the creation of a 10-acre oyster reef, located under the station's pier, that will protect the shoreline from erosion. Marine Corps Recruit Depot Parris Island in South Carolina is also stabilizing its shorelines with oyster reefs. The construction of oyster reefs at Parris Island will reduce wave energy and erosion, in addition to benefitting the water quality and other wildlife.

Alaska's Warming Climate

The Arctic is warming more quickly than the rest of the world, as is Alaska—the northernmost U.S. state. Alaska is also uniquely vulnerable to climate change due to its frozen features. Alaska is the only state with widespread permafrost (underlying 80 per cent of its land) and significant sea ice extent, which are an integral part of life. Entire ecosystems, communities, and Indigenous ways of life could vanish as these frozen features shrink or disappear.

Indicators featured in this chapter:

U.S. and Global Temperature, Arctic Sea Ice, A Closer Look: The Black Guillemots of Cooper Island, Permafrost, Community Connection: Ice Breakup in Three Alaskan Rivers, Leaf and Bloom Dates

Alaska is warming more quickly than the rest of the country.

Why it matters

The temperature in particular places can have wide-ranging effects on human life and ecosystems (see the Heat on the Rise chapter to learn more). Temperature patterns affect what types of plants and animal species can survive in particular locations. In Alaska, where snow and ice are key features of the environment, warming can have a large impact on ecosystems, infrastructure, and the people who depend on the landscape for sustenance and cultural survival—particularly Alaska Native communities.

What's happening

Average temperatures at the Earth's surface are increasing and are expected to continue rising. Some parts of the country—including Alaska—are warming more rapidly than others.

- EPA's U.S. and Global Temperature indicator shows that Alaska has warmed more quickly than any other state over the past century. Regionally, Alaska's North Slope has warmed at the fastest rate of all (Figure 49).
- Alaska has also warmed much more quickly than the global average.

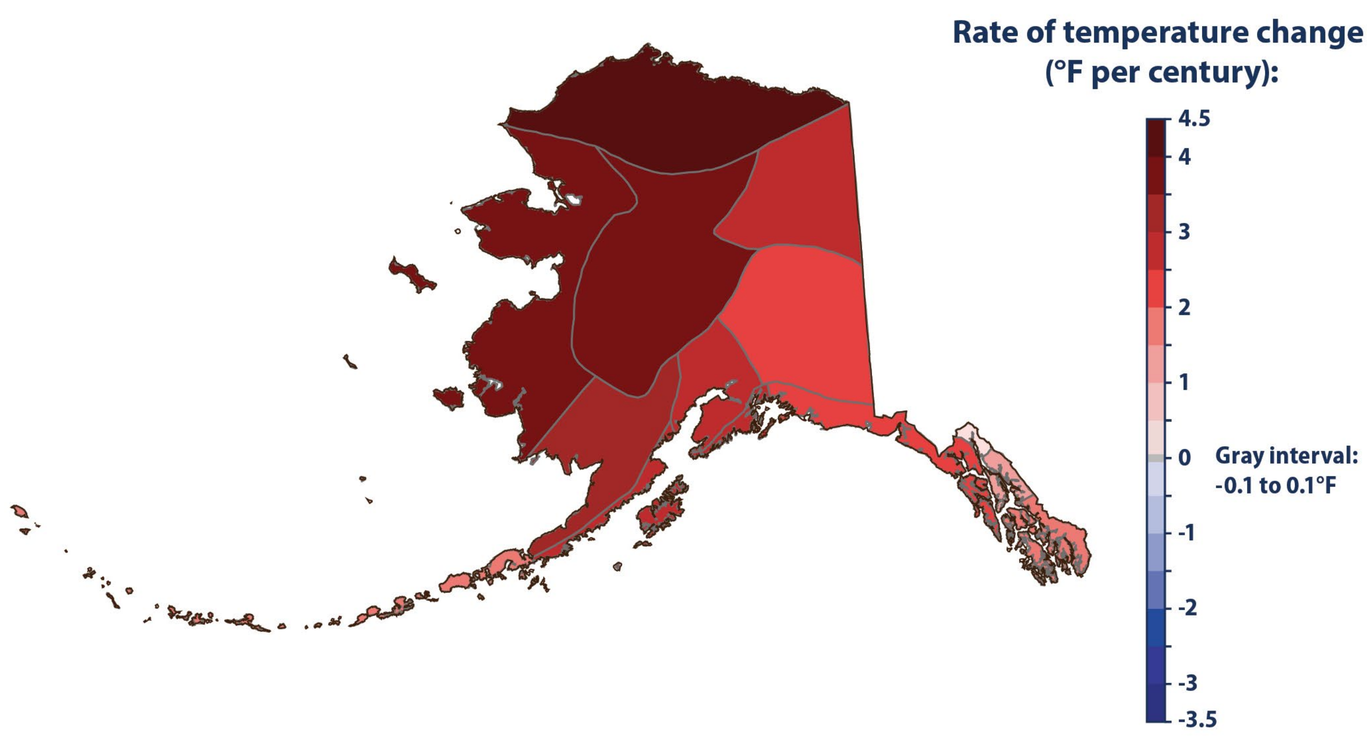


Figure 49. Rate of Temperature Change in Alaska, 1925–2023

This map shows how annual average air temperatures have changed in Alaska since 1925. The data are shown for climate divisions, as defined by the National Oceanic and Atmospheric Administration. Data source: NOAA, 2024.[1]

As temperatures rise, Arctic sea ice is decreasing.

Why it matters

Alaska's northern coast lies along the Arctic Ocean, where sea ice is an integral part of life. Arctic mammals such as polar bears and walruses rely on sea ice for hunting, breeding, and migrating. These animals face the threat of declining birth rates and restricted access to food sources because of reduced sea ice coverage and thickness. These changes matter to people, too. Impacts on Arctic wildlife, as well as the loss of ice itself, are already restricting the traditional subsistence hunting lifestyles of Indigenous Peoples such as the Yup'ik, Iñupiat, and Inuit.

What's happening

During the dark winter months, sea ice, which is sea water that freezes from the ocean surface down to several feet below, covers almost the entire Arctic Ocean. In summer, some of this ice melts because of warmer temperatures and long hours of sunlight. Sea ice typically reaches its minimum thickness and extent in mid-September, when the area covered by ice is roughly half as large as it is at the end of winter. The ice then begins to expand again during fall and winter when temperatures fall and sunlight is limited. However, warmer air and water temperatures are reducing the amount of sea ice present.

Because sea ice is light-colored, it reflects more sunlight (solar energy) back to space than liquid water, thereby playing an important role in maintaining the Earth's energy balance and helping to keep polar regions cool. As the amount of sea ice in the Arctic region decreases, the cooling effect is reduced. This can magnify the original warming due to more absorption of solar energy by the oceans, leading to even more loss of sea ice.

- EPA's Arctic Sea Ice indicator shows a long-term decrease in the extent of sea ice during all months over the past several decades. The largest year-to-year decreases have occurred in the summer and fall months.[2,3]
- The September 2023 sea ice extent was the fifth smallest on record. It was about 789,000 square miles less than the historical 1981–2010 average for that month (Figures 50 and 51)—a difference almost three times the size of Texas. September 2012 had the lowest sea ice extent ever recorded. For March, the lowest sea ice extent on record was in 2017 (Figure 51).
- Evidence suggests that fewer patches of older, thicker sea ice are surviving through one or more melt seasons and persisting through multiple years. A growing percentage of Arctic sea ice is only one or two years old. Young, multi-year ice implies that the ice cover is thinning, which makes it more vulnerable to further melting.
- The length of the melting season for Arctic sea ice has grown by 37 days since 1979. On average, Arctic sea ice now starts melting seven days earlier and starts refreezing 30 days later than it has historically.

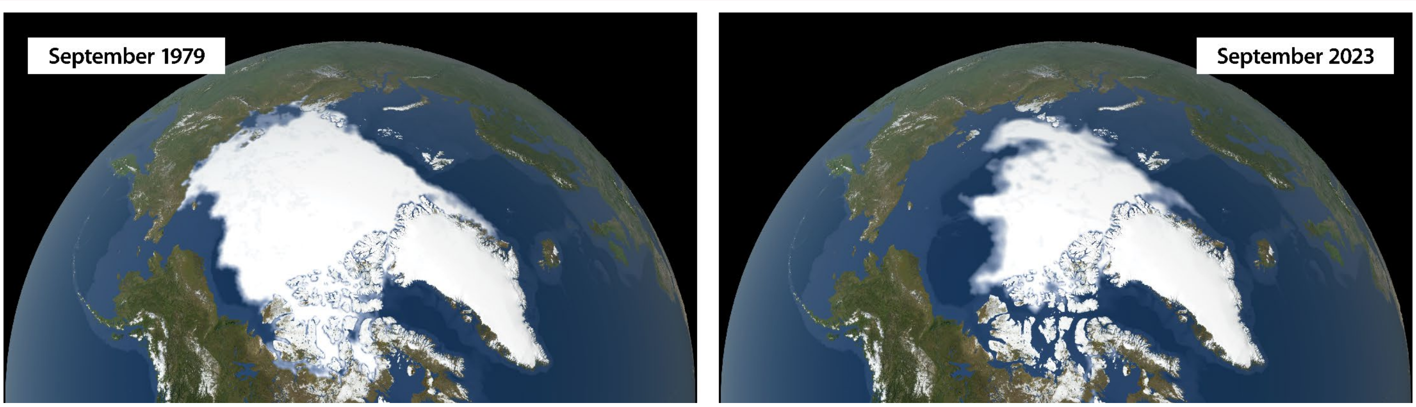


Figure 50. Dwindling Arctic Sea Ice, September 1979 vs. September 2023

Source: NASA, 2023.[4]

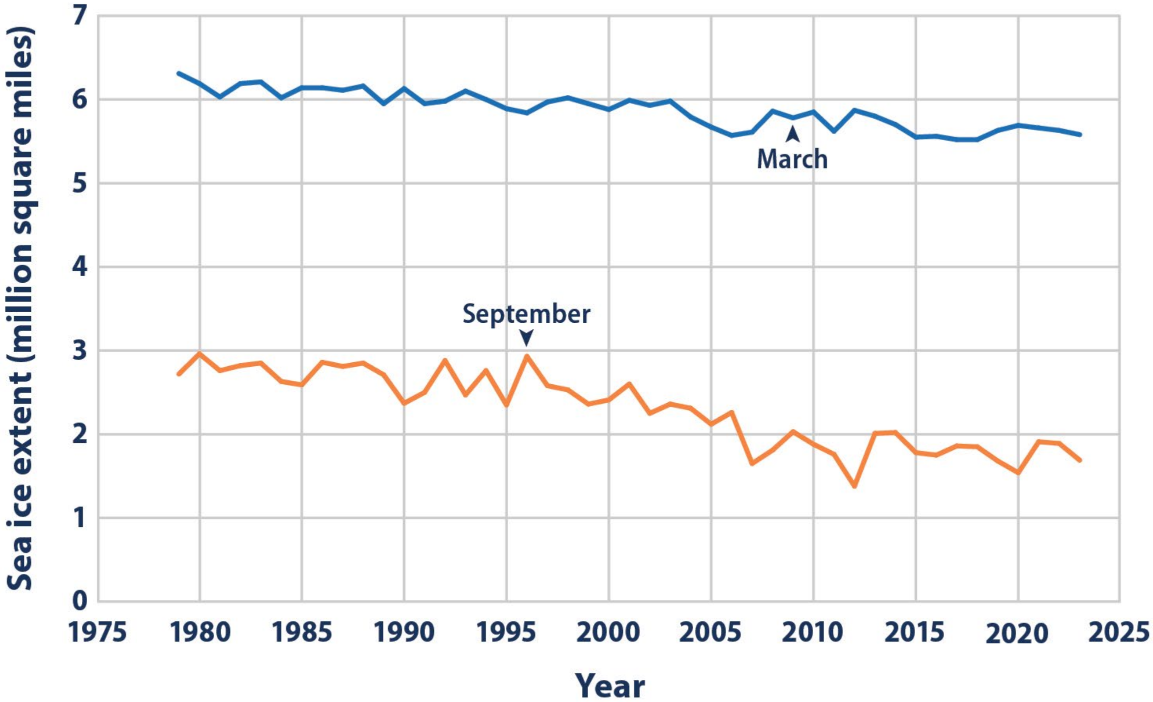


Figure 51. March and September Monthly Average Arctic Sea Ice Extent, 1979–2023

This graph shows Arctic sea ice extent for the months of September and March of each year from 1979 through 2023. September and March are when the minimum and maximum extents typically occur each year. Data source: NSIDC, 2023.[5]

Shrinking sea ice threatens Arctic species like the black guillemot

Decreasing sea ice has major impacts on Arctic species and ecosystems. One example of this is a bird called the black guillemot. A colony of black guillemots have made Cooper Island near Utqiagvik (formerly Barrow), Alaska, home for at least 50 years. The area's unique landscape and sea ice are integral components of this bird's habitat. The black guillemot spends the winter on Arctic sea ice, and it breeds on land near the edge of the ice in summer.[6] One of the main food sources for the birds' chicks is the Arctic cod, which thrives in cold, ice-covered waters.

Warming temperatures and reduced sea ice have contributed to population declines of these birds and the Arctic cod that serves as their preferred food source. EPA's [A Closer Look: The Black Guillemots of Cooper Island] explores changes in the population of black guillemot.

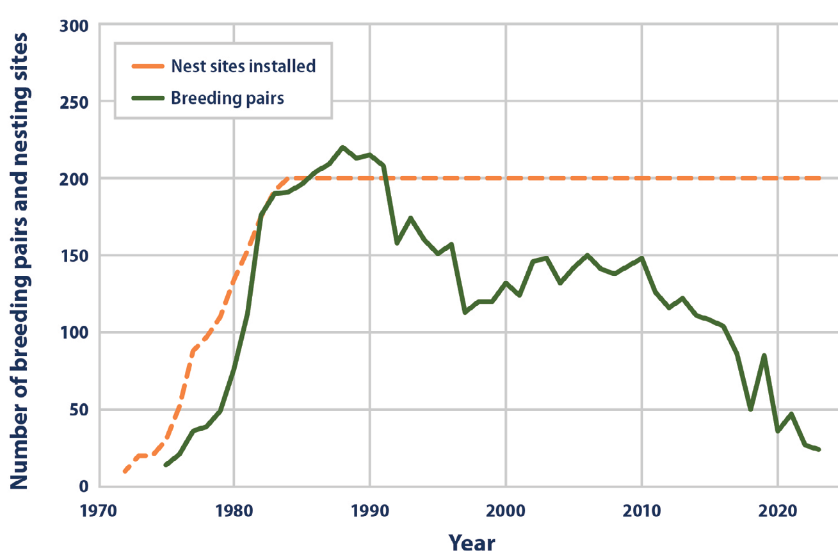
- While the black guillemot population on Cooper Island reached a peak of more than 200 pairs in the late 1980s, the number has decreased by more than 80 percent since then. In 2023, scientists observed only 24 breeding pairs (Figure 52).
- The decline over the last three decades has coincided with reduced breeding success,[7] earlier egg laying,[8] and a decrease in the presence of sea ice in the region.[9,10]

Cooper Island lies off Alaska's northern coast.

The black guillemot is just one species, but its story illustrates a broader trend. Shrinking sea ice has wider implications for animals in the Arctic that depend on marine prey, such as polar bears, and for people who depend on Arctic animals for food and other resources.

Figure 52. Cooper Island Black Guillemot Breeding Pairs, 1972–2023

This figure shows the number of breeding pairs in the black guillemot colony that inhabits Cooper Island off the north coast of Alaska, measured at the peak of breeding season (blue line). The dashed orange line indicates the number of installed nest site structures available to black guillemots on Cooper Island each year. Data source: Divoky, 2024.[11]



Rising temperatures are causing permafrost to thaw.

Why it matters

In addition to snow and ice, frozen ground—called permafrost—is a crucial feature of the Alaskan landscape. A thawing permafrost layer can lead to severe impacts on people and the environment. For instance, as permafrost thaws, it can turn into a muddy slurry that cannot support the weight of the soil and vegetation above it. That instability also risks damaging the infrastructure on top of it, such as roads, buildings, and pipes. Infrastructure damage and erosion, due in part to permafrost thaw, has already caused some communities in western and southern Alaska to have to relocate. Additionally, organic matter (like the remains of plants) currently frozen in the permafrost will start to decompose when the ground thaws, resulting in the emission of methane and carbon dioxide into the atmosphere. These emissions further contribute to climate change.

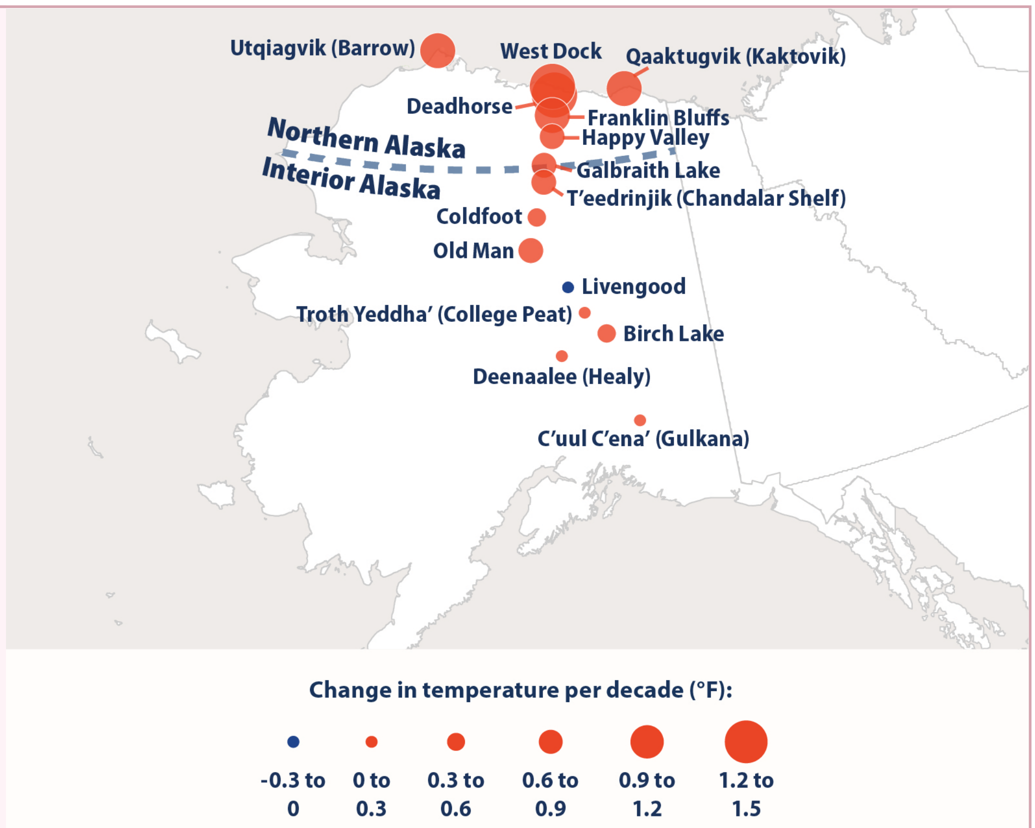
What's happening

Permafrost is defined as ground that remains at or below the freezing point of 32°F for two or more years. It often contains ice. Permafrost usually lies below an "active layer" of ground that freezes and thaws every year with seasonal changes in temperature. In Alaska, about 80 percent of the ground has permafrost underneath it. A warming climate has brought higher temperatures to Alaska and other areas with permafrost, causing some of the permafrost to thaw.

- EPA's Permafrost indicator shows that between 1978 and 2022, permafrost temperatures increased at 14 out of 15 locations measured across Alaska (Figure 53).
- In general, permafrost has warmed more quickly in northern Alaska than interior Alaska. This is consistent with changes in air temperatures, which have increased more quickly in northern Alaska than in other parts of the state (Figure 53).[12]

Figure 53. Change in Permafrost Temperatures in Alaska, 1978–2022

This map shows the change in permafrost temperature per decade for 15 long-term borehole sites in Alaska. Larger circles correspond to greater rates of warming per decade. The blue circle represents one site with a cooling trend. Borehole measurement depths range from 49 to 85 feet. Data source: University of Alaska Fairbanks, 2023.[13]



Thawing permafrost forces a move to more solid ground

The community of Niugtaq, located in western Alaska, faces big threats from thawing permafrost and erosion. Because of the risks these changes pose to structures and critical infrastructure, the community is being relocated to a new site—a large but necessary undertaking.

As a result of the degraded permafrost, buildings are sinking into the tundra, and the drinking water system no longer works. The community also faces severe storm surge from the Ninglick River during times of high water, leading to loss of land along the river bank. As the climate warms, these threats to the community's health and safety have grown.

Niugtaq's residents have been working with the state of Alaska, federal agencies, and private funders since the 1990s to move to safer ground in Mertarvik, 9 miles across the river. Such a move required extensive site assessments and planning. Creating a new community also takes significant funding for infrastructure, buildings and housing, power, transportation, and more. Some Niugtaq residents have moved into new homes, but many steps remain to relocate the entire community.[14]

River ice is breaking up earlier in Alaska.

Why it matters

River ice breakup is an important time of transition for communities in Alaska that rely on relatively remote and free-flowing wild rivers for transportation, subsistence hunting and fishing, and other needs. Early thawing can lead to severe ice movement, jamming, damage to infrastructure, and destructive floods.[15]

What's happening

Regions in the far north, including Alaska, are warming more quickly than other parts of the world, and this pattern is expected to continue.[16,17] The Tanana, Yukon, and Kuskokwim rivers in Alaska provide a particularly noteworthy record of northern climate.

Some towns have annual competitions to guess when ice breakup will occur. Since 1917, the Nenana Ice Classic competition on the Tanana River in central Alaska has paid several million dollars in winnings to the people who come closest to guessing the exact date and time when the river ice will break up. Similar traditions exist on the Kuskokwim River in Bethel, where breakup dates have been recorded since 1924, and in Dawson City on the Yukon River, just across the border in Canada, where breakup dates have been recorded since 1896. The data collected by these communities highlight how river ice breakup dates have changed over time.

- EPA's Community Connection: Ice Breakup in Three Alaskan Rivers shows that all three of these rivers demonstrate long-term trends toward earlier ice breakup in the spring. Looking at the average change over all years of data, the ice breakup dates for all three rivers have shifted earlier by eight to nine days (Figure 54).
- At all three locations, the earliest breakup dates ever recorded have occurred within the past four years (Figure 54).

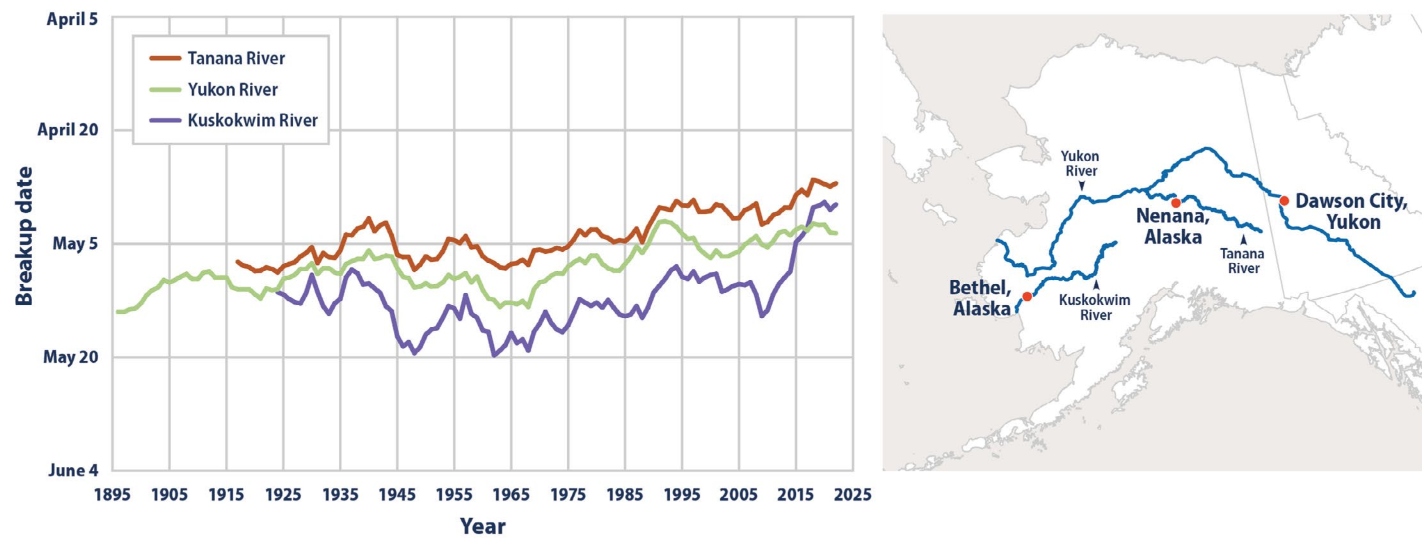


Figure 54. Ice Breakup Dates for Three Alaskan Rivers, 1896–2022

This graph shows the date each year when ice breaks up at three locations: the town of Nenana on the Tanana River, Dawson City on the Yukon River, and Bethel on the Kuskokwim River. The annual data for each river have been plotted using a nine-year moving average. Data sources: Nenana Ice Classic, 2022;[18] Yukon River Breakup, 2022;[19] Kuskokwim Ice Classic, 2022;[20] National Weather Service, 2022.[21]

Spring events are arriving earlier in Alaska.

Why it matters

The earlier arrival of spring can have a variety of impacts on ecosystems and human society. For example, as the Changing Seasons chapter explains, an earlier spring might lead to longer growing seasons, more abundant invasive species and pests, and earlier and longer allergy seasons. Changes in timing of warmup, and the way different animals and plants respond to them, can also cause important events in animals' life cycles to become out of sync with the food sources they depend on. This timing is especially critical in Alaska and for Alaska Native communities, where many economically and culturally significant ecological events are precisely matched to the state's dramatic temperature differences and short growing seasons. These events include salmon runs, caribou migration and calving, and the arrival of hundreds of species of birds that breed in Alaska every year.

What's happening

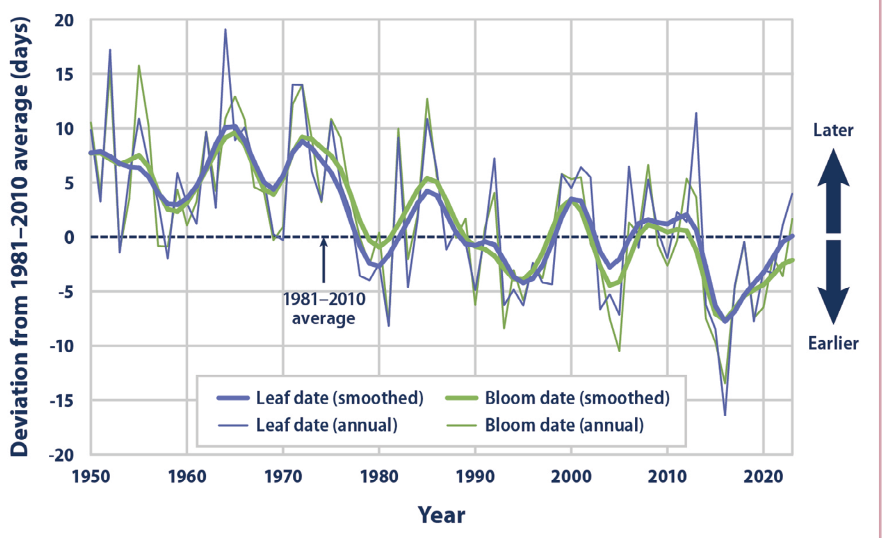
As Alaska's physical environment warms earlier each spring, that change can cause certain biological events to happen earlier too. Plant growth, flower blooms, animal migration, and animal breeding activities are all examples of seasonal events that can be influenced by changes in climate. Different plant and animal species respond to different environmental cues, such as temperature, light, rainfall, and humidity.

An earlier section of this report introduced the Leaf and Bloom Dates indicator, which tracks the first leaf dates and the first bloom dates of lilacs and honeysuckles. These flowering plants grow throughout most of the United States, and local observers across the country have carefully recorded their "first leaf" and "first bloom" dates for many decades—making lilac and honeysuckle leaf and bloom dates a useful general indicator of the timing of spring events. While there are fewer direct historical observations from Alaska, and these plants only grow in certain parts of the state, the data that are available have helped scientists understand how lilac and honeysuckle leaf and bloom dates typically correspond to local air temperatures. This allows scientists to use local temperature data to "fill the gap" where needed.

The results in EPA's Leaf and Bloom Dates indicator show that spring events in Alaskan plants are shifting earlier, especially over the last few decades (Figure 55). This shift has been much more dramatic in Alaska than in other parts of the country.

Figure 55. First Leaf and Bloom Dates in Alaska, 1950–2023

This figure shows modeled trends in lilac and honeysuckle first leaf dates and first bloom dates across Alaska, using the 1981 to 2010 average as a baseline. Positive values indicate that leaf growth and blooming began later in the year, and negative values indicate that leafing and blooming occurred earlier. The thicker lines were smoothed using a nine-year weighted average. Choosing a different long-term average for comparison would not change the shape of the data over time. Data source: 2024 update by M. Schwartz to data from Schwartz et al., 2013.[22]



Taking action: engaging communities on climate change in the Arctic

Arctic communities have been affected greatly by climate change. The Local Environmental Observer (LEO) Network provides a way for the Tribal health system and local observers to document and share knowledge about environmental conditions and climate change in the region.

Launched at the Center for Climate and Health at the Alaska Native Tribal Health Consortium in 2012, the LEO Network helps engage the local community and technical experts on climate and environmental events. Using the LEO Network, local observers and experts can collect and share observations, as well as connect with other community members and experts from many different organizations. By combining traditional knowledge, conventional science, and modern technology, LEO Network members help raise awareness about environmental conditions that affect Arctic communities.

Conclusion

The indicators in this report present compelling evidence that the composition of the atmosphere and many fundamental aspects of our climate in the United States are changing. These changes include rising air and water temperatures, more heavy precipitation, more frequent heat waves, and more intense Atlantic hurricanes. Many observed climate changes are linked to rising levels of greenhouse gases in our atmosphere, caused by human activities.

Climate change is affecting the environment in ways that have significant impacts on the health and well-being of people and ecosystems. For example, as temperatures increase, the frequency of extreme heat days and heat waves also increases, which puts people at greater risk for heat-related illnesses and deaths. Less snowpack and increased glacier melt affect water resources for both ecosystems and human use. Changes in the timing and character of seasons affect the number of days suitable for growing crops and increase pollen that triggers seasonal allergies. These changes will not be experienced equally, as some communities have faced and will continue to face disproportionate impacts of climate change due to existing vulnerabilities, including socioeconomic disparities, historical patterns of inequity, and systemic environmental injustices.

The indicators highlighted in this report do not represent all possible measures of the causes and effects of climate change. The report does not present all of the climate change indicators found in the scientific assessment literature, not does it present all of the indicators EPA itself maintains. The full suite of EPA's climate change indicators is available on EPA's Climate Change Indicators in the United States website. The collection covers a broad range of topics, including greenhouse gases, weather and climate, oceans, snow and ice, health and society, and ecosystems.

Looking ahead, EPA will continue to work in partnership with other agencies, organizations, and individuals to maintain and improve the climate change indicators resource. As new indicator data become available, EPA plans to continue to update the indicators online and explore additional indicators that can more comprehensively document climate change and its effects, including its disproportionate impacts. Identifying and analyzing indicators improves our understanding of climate change, validates projections of future change, and, importantly, assists EPA in its efforts to slow climate change and adapt to its impacts.

Climate Change Resources

To learn more about climate change and what EPA is doing to protect human health and the environment, please visit EPA's Climate Change website. On this site you can explore resources about climate change science, impacts, and actions.

Climate Science and Greenhouse Gases

- View the latest information about EPA's climate change indicators and download figures as well as accompanying technical documentation.
- Learn more about greenhouse gases and the science of climate change.
- Read about sources of greenhouse gas emissions and learn about the Inventory of U.S. Greenhouse Gas Emissions and Sinks.
- Search EPA's database of frequently asked questions about climate change.
- Find climate change resources for educators and students.

Climate Impacts

- Discover the varied impacts of climate change on society and ecosystems.
- Explore the many ways that climate change threatens human health.
- Learn about climate equity, environmental justice, and the disproportionate impacts of climate change.

Actions to Address Climate Change

- Learn about EPA's climate change regulatory actions and initiatives as well as its partnership programs.
- Read about EPA's climate adaptation efforts.
- Explore what you can do to help reduce greenhouse gas emissions.

Other Resources

For more information, explore these websites with authoritative scientific information about climate change:

- The Intergovernmental Panel on Climate Change (IPCC) is the international authority on climate change science. The IPCC website summarizes the current state of scientific knowledge about climate change.
- The U.S. Global Change Research Program (USGCRP) is a multi-agency effort focused on improving our understanding of the science of climate change and its potential impacts on the United States through reports such as the *National Climate Assessment*.
- NOAA's Climate.gov site provides scientific data and information about climate science, adaptation, and mitigation.

Endnotes

Introduction

1. Jay, A. K., Crimmins, A. R., Avery, C. W., Dahl, T. A., Dodder, R. S., Hamlington, B. D., Lustig, A., Marvel, K., Méndez-Lazaro, P. A., Osler, M. S., Terando, A., Weeks, E. S., & Zycherman, A. (2023). Chapter 1: Overview: Understanding risks, impacts, and responses. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH1

2. IPCC (Intergovernmental Panel on Climate Change). (2021). *Climate change 2021—The physical science basis: Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896

Greenhouse Gases

1. Climate Watch. (2023). *Climate Watch historical GHG emissions.* Retrieved September 27, 2023, from www.climatewatchdata.org/ghg-emissions

2. The World Bank. (2024). *World Development Indicators. Population Total.* Retrieved May 29, 2024, from https://data.worldbank.org/indicator/SP.POP.TOTL

3. U.S. EPA (Environmental Protection Agency). (2024). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022* (EPA 430-R-24-004). www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022

4. Marvel, K., Su, W., Delgado, R., Aarons, S., Chatterjee, A., Garcia, M. E., Hausfather, Z., Hayhoe, K., Hence, D. A., Jewett, E. B., Robel, A., Singh, D., Tripati, A., & Vose, R. S. (2023). Chapter 2: Climate trends. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH2

5. *Antarctic Ice Cores: approximately 805,669 BCE to 2001 CE*
Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T. F., Fischer, H., Kipfstuhl, S., & Chappellaz, J. (2015). Revision of the EPICA Dome C CO2 record from 800 to 600 kyr before present. *Geophysical Research Letters*, *42*(2), 542–549. https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2014GL061957

Mauna Loa, Hawai'i: 1959 CE to 2023 CE
NOAA (National Oceanic and Atmospheric Administration). (2024). *Annual mean carbon dioxide concentrations for Mauna Loa, Hawai'i (updated March 5, 2024)* [Data set]. Retrieved March 5, 2024, from https://gml.noaa.gov/ccgg/trends/data.html

Barrow, Alaska: 1974 CE to 2023 CE
Cape Matatula, American Samoa: 1976 CE to 2023 CE
South Pole, Antarctica: 1976 CE to 2023 CE
NOAA (National Oceanic and Atmospheric Administration). (2024). *Monthly mean carbon dioxide concentrations for Barrow, Alaska; Cape Matatula, American Samoa; and the South Pole (updated February 12, 2024)* [Data set]. Retrieved March 5, 2024, from https://gml.noaa.gov/aftp/data/trace_gases/co2/in-situ/surface

Cape Grim, Australia: 1977 CE to 2023 CE
CSIRO (Commonwealth Scientific and Industrial Research Organisation). (2024). *Monthly mean baseline (background) carbon dioxide concentrations measured at the Cape Grim Baseline Air Pollution Station, Tasmania, Australia (updated January 2024)* [Data set]. Retrieved March 4, 2024, from http://capegrim.csiro.au/GreenhouseGas/data/CapeGrim_CO2_data_download.csv

Shetland Islands, Scotland: 1993 CE to 2002 CE
Steele, L. P., Krummel, P. B., & Langenfelds, R. L. (2007). *Atmospheric CO2 concentrations (ppmv) derived from flask air samples collected at Cape Grim, Australia, and Shetland Islands, Scotland* [Data set]. Commonwealth Scientific and Industrial Research Organisation. Retrieved January 20, 2009, from https://cdiac.ess-dive.lbl.gov/trends/co2/csiro

Lampedusa Island, Italy: 1993 CE to 2000 CE
Chamard, P., Ciattaglia, L., di Sarra, A., & Monteleone, F. (2001). Atmospheric carbon dioxide record from flask measurements at Lampedusa Island. In *Trends: A compendium of data on global change.* U.S. Department of Energy. https://cdiac.ess-dive.lbl.gov/trends/co2/lampis.html

Heat on the Rise

1. NOAA (National Oceanic and Atmospheric Administration). (2024). *Climate at a glance.* Retrieved March 25, 2024, from www.ncei.noaa.gov/access/monitoring/climate-at-a-glance
2. NOAA (National Oceanic and Atmospheric Administration). (2024). *Climate at a glance.* Retrieved March 25, 2024, from www.ncei.noaa.gov/access/monitoring/climate-at-a-glance
3. Marvel, K., Su, W., Delgado, R., Aarons, S., Chatterjee, A., Garcia, M. E., Hausfather, Z., Hayhoe, K., Hence, D. A., Jewett, E. B., Robel, A., Singh, D., Tripati, A., & Vose, R. S. (2023). Chapter 2: Climate trends. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH2
4. NOAA (National Oceanic and Atmospheric Administration). (2024). *U.S. Climate Extremes Index.* Retrieved April 18, 2024, from www.ncei.noaa.gov/access/monitoring/cei
5. NOAA (National Oceanic and Atmospheric Administration). (2024). *U.S. Climate Extremes Index.* Retrieved April 18, 2024, from www.ncei.noaa.gov/access/monitoring/cei
6. Hayden, M. H., Schramm, P. J., Beard, C. B., Bell, J. E., Bernstein, A. S., Bieniek-Tobasco, A., Cooley, N., Diuk-Wasser, M., Dorsey, M. K., Ebi, K., Ernst, K. C., Gorris, M. E., Howe, P. D., Khan, A. S., Lefthand-Begay, C., Maldonado, J., Saha, S., Shafiei, F., Vaidyanathan, A., & Wilhelmi, O. V. (2023). Chapter 15: Human health. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH15
7. Hayden, M. H., Schramm, P. J., Beard, C. B., Bell, J. E., Bernstein, A. S., Bieniek-Tobasco, A., Cooley, N., Diuk-Wasser, M., Dorsey, M. K., Ebi, K., Ernst, K. C., Gorris, M. E., Howe, P. D., Khan, A. S., Lefthand-Begay, C., Maldonado, J., Saha, S., Shafiei, F., Vaidyanathan, A., & Wilhelmi, O. V. (2023). Chapter 15: Human health. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH15
8. Hayden, M. H., Schramm, P. J., Beard, C. B., Bell, J. E., Bernstein, A. S., Bieniek-Tobasco, A., Cooley, N., Diuk-Wasser, M., Dorsey, M. K., Ebi, K., Ernst, K. C., Gorris, M. E., Howe, P. D., Khan, A. S., Lefthand-Begay, C., Maldonado, J., Saha, S., Shafiei, F., Vaidyanathan, A., & Wilhelmi, O. V. (2023). Chapter 15: Human health. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH15
9. Hayden, M. H., Schramm, P. J., Beard, C. B., Bell, J. E., Bernstein, A. S., Bieniek-Tobasco, A., Cooley, N., Diuk-Wasser, M., Dorsey, M. K., Ebi, K., Ernst, K. C., Gorris, M. E., Howe, P. D., Khan, A. S., Lefthand-Begay, C., Maldonado, J., Saha, S., Shafiei, F., Vaidyanathan, A., & Wilhelmi, O. V. (2023). Chapter 15: Human health. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH15
10. Heat Injury and Illness Prevention in Outdoor and Indoor Work Settings, 86 F.R. 59309 (proposed October 27, 2021) (to be codified at 29 C.F.R. §§ 1910, 1915, 1917, 1918, 1926, and 1928). www.govinfo.gov/content/pkg/FR-2021-10-27/pdf/2021-23250.pdf
11. NOAA (National Oceanic and Atmospheric Administration). (2024). *Heat stress datasets and documentation* (provided to EPA by NOAA in April 2024) [Data set].
12. U.S. EPA (Environmental Protection Agency). (2023). *Heat islands and equity.* www.epa.gov/heatislands/heat-islands-and-equity
13. NOAA (National Oceanic and Atmospheric Administration). (2023). *Weather related fatality and injury statistics.* Retrieved August 15, 2024, from www.weather.gov/hazstat
14. Sarofim, M. C., Saha, S., Hawkins, M. D., Mills, D. M., Hess, J., Horton, R., Kinney, P., Schwartz, J., & St. Juliana, A. (2016). Chapter 2: Temperature-related death and illness. In USGCRP (U.S. Global Change Research Program), *The impacts of climate change on human health in the United States: A scientific assessment* (pp. 43–69). http://doi.org/10.7930/J0MG7MDX
15. CDC (U.S. Centers for Disease Control and Prevention). (2024). *CDC WONDER database: All ages deaths by underlying cause* [Data set]. Retrieved May 22, 2024, from https://wonder.cdc.gov/Deaths-by-Underlying-Cause.html
16. CDC (U.S. Centers for Disease Control and Prevention). (2024). *Indicator: Heat-related mortality* (Annual national totals provided by National Center for Environmental Health staff in June 2024) [Data set]. National Center for Health Statistics. https://ephtracking.cdc.gov
17. Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K. L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S. I., Thomas, A., Warren, R., & Zhou, G. (2018). Chapter 3: Impacts of 1.5°C global warming on natural and human systems. In IPCC (Intergovernmental Panel on Climate Change), *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable*

development, and efforts to eradicate poverty (pp. 175–312). Cambridge University Press. www.ipcc.ch/sr15/chapter/chapter-3

18. BLS (U.S. Bureau of Labor Statistics). (2024). *Census of Fatal Occupational Injuries (CFOI)*. Retrieved April 29, 2024, from www.bls.gov/iif/oshcfoi1.htm
19. NOAA (National Oceanic and Atmospheric Administration). (2024). *NOAA Monthly U.S. Climate Divisional Database (nClimDiv).* Retrieved March 1, 2024, from www1.ncdc.noaa.gov/pub/data/cirs/climdiv
20. Zamuda, C. D., Bilello, D. E., Carmack, J., Davis, X. J., Efroymson, R. A., Goff, K. M., Hong, T., Karimjee, A., Loughlin, D. H., Upchurch, S., & Voisin, N. (2023). Chapter 5: Energy supply, delivery, and demand. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH5
21. EIA (U.S. Energy Information Administration). (2022). *Electricity retail sales to the residential sector, monthly.* Retrieved January 13, 2023, from www.eia.gov/opendata
22. BEA (U.S. Bureau of Economic Analysis). (2022). *Population (POPTHM).* FRED, Federal Reserve Bank of St. Louis. Retrieved January 13, 2023, from https://fred.stlouisfed.org/series/POPTHM
23. NOAA (National Oceanic and Atmospheric Administration). (2022). *National Centers for Environmental Information.* Retrieved January 13, 2023, from www.ncei.noaa.gov

Extreme Events

1. Bell, J. E., Herring, S. C., Jantarasami, L., Adrianopoli, C., Benedict, K., Conlon, K., Escobar, V., Hess, J., Luvall, J., Garcia-Pando, C. P., Quattrochi, D., Runkle, J., & Schreck, C. J., III. (2016). Chapter 4: Impacts of extreme events on human health. In USGCRP (U.S. Global Change Research Program), *The impacts of climate change on human health in the United States: A scientific assessment* (pp. 99–128). https://health2016.globalchange.gov/extreme-events
2. Marvel, K., Su, W., Delgado, R., Aarons, S., Chatterjee, A., Garcia, M. E., Hausfather, Z., Hayhoe, K., Hence, D. A., Jewett, E. B., Robel, A., Singh, D., Tripati, A., & Vose, R. S. (2023). Chapter 2: Climate trends. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH2
3. Leung, L. R., Terando, A., Joseph, R., Tselioudis, G., Bruhwiler, L. M., Cook, B., Deser, C., Hall, A., Hamlington, B. D., Hoell, A., Hoffman, F. M., Klein, S., Naik, V., Pendergrass, A. G., Tebaldi, C., Ullrich, P. A., & Wehner, M. F. (2023). Chapter 3: Earth systems processes. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH3
4. NOAA (National Oceanic and Atmospheric Administration). (2024). *U.S. Climate Extremes Index*. Retrieved April 18, 2024, from www.ncei.noaa.gov/access/monitoring/cei
5. Abatzoglou, J. T., McEvoy, D. J., & Redmond, K. T. (2017). The West Wide Drought Tracker: Drought monitoring at fine spatial scales. *Bulletin of the American Meteorological Society, 98*(9), 1815–1820. https://doi.org/10.1175/BAMS-D-16-0193.1
6. Western Regional Climate Center. (2024). *WestWide Drought Tracker*. Retrieved January 1, 2024, from https://wrcc.dri.edu/wwdt
7. Navajo Nation Department of Fish and Wildlife. (2018). *Climate adaptation plan for the Navajo Nation*. www.navajoclimatechange.org/adaptation-plan
8. Emanuel, K. A. (2023). Update to data originally published in Emanuel, K. (2007). Environmental factors affecting tropical cyclone power dissipation. *Journal of Climate, 20*(22), 5497–5509. https://doi.org/10.1175/2007JCLI1571.1
9. National Association of State Foresters. (2009). *Quadrennial fire review*. www.forestsandrangelands.gov/documents/strategy/foundational/qfr2009final.pdf
10. NOAA (National Oceanic and Atmospheric Administration). (2022). *Billion-dollar weather and climate disasters*. Retrieved June 1, 2022, from www.ncei.noaa.gov/access/billions
11. NIFC (National Interagency Fire Center). (2022). *Historical wildland fire information: Federal firefighting costs: Suppression only (1985–2020)* [Data set]. Retrieved June 1, 2022, from www.nifc.gov/fire-information/statistics/suppression-costs
12. NWCG (National Wildfire Coordinating Group). (2017). *NWCG report on wildland firefighter fatalities in the United States: 2007–2016*. www.nwcg.gov/sites/default/files/publications/pms841.pdf
13. West, J. J., Nolte, C. G., Bell, M. L., Fiore, A. M., Georgopoulos, P. G., Hess, J. J., Mickley, L. J., O'Neill, S. M., Pierce, J. R., Pusede, S., Shindell, D. T., & Wilson, S. M. (2023). Chapter 14: Air quality. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH14
14. Ostoja, S. M., Crimmins, A. R., Byron, R. G., East, A. E., Méndez, M., O'Neill, S. M., Peterson, D. L., Pierce, J. R., Raymond, C., Tripati, A., & Vaidyanathan, A. (2023). Focus on western wildfires. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.F2
15. Westerling, A. L. (2016). Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*(1696), 20150178. https://doi.org/10.1098/rstb.2015.0178
16. Ostoja, S. M., Crimmins, A. R., Byron, R. G., East, A. E., Méndez, M., O'Neill, S. M., Peterson, D. L., Pierce, J. R., Raymond, C., Tripati, A., & Vaidyanathan, A. (2023). Focus on western wildfires. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.F2
17. NIFC (National Interagency Fire Center). (2024). *Total wildland fires and acres (1983–2023)* [Data set]. Retrieved February 21, 2024, from www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html

18. Short, K. C. (2015). Sources and implications of bias and uncertainty in a century of US wildfire activity data. *International Journal of Wildland Fire, 24*(7), 883–891. https://doi.org/10.1071/WF14190

Water Resources at Risk

1. NOAA (National Oceanic and Atmospheric Administration). (2024). Extended version of GPCC data set originally published in Blunden, J., Boyer, T., & Bartow-Gillies, E. (2023). State of the climate in 2022. *Bulletin of the American Meteorological Society, 104*(9), S1–S516. https://doi.org/10.1175/2023BAMSStateoftheClimate.1
2. NOAA (National Oceanic and Atmospheric Administration). (2024). *Climate at a glance*. Retrieved March 25, 2024, from www.ncei.noaa.gov/access/monitoring/climate-at-a-glance
3. NOAA (National Oceanic and Atmospheric Administration). (2024). *Fast facts: Great Lakes*. Retrieved May 29, 2024, from https://coast.noaa.gov/states/fast-facts/great-lakes.html
4. U.S. EPA (Environmental Protection Agency). (2023). *Lake Erie*. Retrieved May 29, 2024, from www.epa.gov/greatlakes/lake-erie
5. USDA (U.S. Department of Agriculture) Natural Resources Conservation Service. (2024). *Snow telemetry (SNOTEL) and snow course data and products*. Retrieved January 2, 2024, from www.drought.gov/data-maps-tools/nrcs-snotel-and-snow-course-data
6. USDA (U.S. Department of Agriculture) Natural Resources Conservation Service. (2023). *Snow telemetry (SNOTEL) and snow course data and products*. Retrieved October 1, 2023, from www.drought.gov/data-maps-tools/nrcs-snotel-and-snow-course-data
7. USGS (U.S. Geological Survey). (2023). Analysis of data from the National Water Information System. Retrieved September 2023.
8. National Drought Mitigation Center. (2021). *Data tables*. Retrieved March 1, 2021, from https://droughtmonitor.unl.edu/DmData/DataTables.aspx

Changing Seasons

1. Marvel, K., Su, W., Delgado, R., Aarons, S., Chatterjee, A., Garcia, M. E., Hausfather, Z., Hayhoe, K., Hence, D. A., Jewett, E. B., Robel, A., Singh, D., Tripati, A., & Vose, R. S. (2023). Chapter 2: Climate trends. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH2
2. Marvel, K., Su, W., Delgado, R., Aarons, S., Chatterjee, A., Garcia, M. E., Hausfather, Z., Hayhoe, K., Hence, D. A., Jewett, E. B., Robel, A., Singh, D., Tripati, A., & Vose, R. S. (2023). Chapter 2: Climate trends. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH2
3. NOAA (National Oceanic and Atmospheric Administration). (2024). *National Centers for Environmental Information*. Retrieved February 1, 2024, from www.ncei.noaa.gov
4. NOAA (National Oceanic and Atmospheric Administration). (2024). *National Centers for Environmental Information*. Retrieved February 1, 2024, from www.ncei.noaa.gov
5. NOAA (National Oceanic and Atmospheric Administration). (2021). *National Centers for Environmental Information*. Retrieved February 1, 2021, from www.ncei.noaa.gov
6. *Cobbosseecontee Lake, Damariscotta Lake, Moosehead Lake, and Sebago Lake, Maine, 1800s–2008*
   Hodgkins, G. A. (2010). *Historical ice-out dates for 29 Lakes in New England, 1807–2008 (Open-File Report 2010–1214)*. U.S. Geological Survey. https://pubs.usgs.gov/of/2010/1214

   Cobbosseecontee Lake, Damariscotta Lake, Moosehead Lake, and Sebago Lake, Maine, 2009–2019
   USGS (U.S. Geological Survey). (2021). Personal communication.
   Detroit Lake, Minnesota, 2006–2019
   Minnesota Department of Natural Resources. Retrieved October 2020 from www.dnr.state.mn.us/lakefind/ice.html?id=03038100

   Lake Osakis, Minnesota, 2013–2019
   Minnesota Department of Natural Resources. Retrieved October 2020 from www.dnr.state.mn.us/lakefind/ice.html?id=77021500

   Geneva Lake, Wisconsin, 2005–2015
   Geneva Lake Environmental Agency. *Geneva Waters*. Retrieved June 2016 from www.gleawi.org/geneva-waters-newsletter

   Geneva Lake, Wisconsin, 2016
   Lake Geneva Regional News. Retrieved August 2017 from https://lakegeorgeassociation.org

   Lake George, New York, 2005–2018
   Lake George Association. Retrieved October 2020 from https://lakegeorgeassociation.org

   Lake Mendota and Lake Monona, Wisconsin, 2013–2019
   Wisconsin State Climatology Office. Retrieved October 2020 from https://climatology.nelson.wisc.edu

   Mirror Lake, New York, 2005–2019
   Ausable River Association. Retrieved October 2020 from www.ausableriver.org/watershed/lakes/mirror-lake/mirror-lake-ice-record

   Otsego Lake, New York, 2005–2018
   State University of New York Oneonta Biological Field Station. Annual reports. Retrieved October 2020 from https://suny.oneonta.edu/biological-field-station/publications

   Shell Lake, Wisconsin, 2005–2015
   Washburn County Clerk. (2016). Personal communication.

All other data
Benson, B., Magnuson, J., & Sharma, S. (2020). *Global Lake and River Ice Phenology Database (Version 1)* [Data set]. National Snow and Ice Data Center. Retrieved March 1, 2021, from https://nsidc.org/data/g01377/versions/1

7. Schwartz, M. D., Ahas, R., & Aasa, A. (2006). Onset of spring starting earlier across the Northern Hemisphere. *Global Change Biology, 12*(2), 343–351. https://doi.org/10.1111/j.1365-2486.2005.01097.x
8. Schwartz, M. D., Ault, T. R., & Betancourt, J. L. (2013). Spring onset variations and trends in the continental United States: Past and regional assessment using temperature-based indices. *International Journal of Climatology, 33*(13), 2917–2922. https://doi.org/10.1002/joc.3625
9. National Cherry Blossom Festival. (2024). *Bloom watch*. Retrieved March 21, 2024, from https://nationalcherryblossomfestival.org/bloom-watch
10. National Park Service. (2024). *Bloom watch*. Retrieved March 21, 2024, from www.nps.gov/subjects/cherryblossom/bloom-watch.htm
11. Kunkel, K. E. (2024). Expanded analysis of data originally published in Kunkel, K. E., Easterling, D. R., Hubbard, K., & Redmond, K. (2004). Temporal variations in frost-free season in the United States: 1895–2000. *Geophysical Research Letters, 31*(3), L03201. https://doi.org/10.1029/2003GL018624
12. Salo, P. M., Arbes, S. J., Jaramillo, R., Calatroni, A., Weir, C. H., Sever, M. L., Hoppin, J. A., Rose, K. M., Liu, A. H., Gergen, P. J., Mitchell, H. E., & Zeldin, D. C. (2014). Prevalence of allergic sensitization in the United States: Results from the National Health and Nutrition Examination Survey (NHANES) 2005–2006. *Journal of Allergy and Clinical Immunology, 134*(2), 350–359 (See online data repository). https://doi.org/10.1016/j.jaci.2013.12.1071
13. Fann, N., Brennan, T., Dolwick, P., Gamble, J. L., Ilacqua, V., Kolb, L., Nolte, C. G., Spero, T. L., & Ziska, L. (2016). Chapter 3: Air quality impacts. In USGCRP (U.S. Global Change Research Program), *The impacts of climate change on human health in the United States: A scientific assessment* (pp. 69–98). https://doi.org/10.7930/J0GQ6Vp6
14. Burbank, A. J., Hernandez, M. L., Jefferson, A., Perry, T. T., Phipatanakul, W., Poole, J., & Matsui, E. C. (2023). Environmental justice and allergic disease: A work group report of the AAAAI Environmental Exposure and Respiratory Health Committee and the Diversity, Equity and Inclusion Committee. *Journal of Allergy and Clinical Immunology, 151*(3), 656–670. https://doi.org/10.1016/j.jaci.2022.11.025
15. NOAA (National Oceanic and Atmospheric Administration). (2024). *Global Historical Climatology Network daily (GHCNd)*. Retrieved April 1, 2024, from www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily
16. West, J. J., Nolte, C. G., Bell, M. L., Fiore, A. M., Georgopoulos, P. G., Hess, J. J., Mickley, L. J., O'Neill, S. M., Pierce, J. R., Pusede, S., Shindell, D. T., & Wilson, S. M. (2023). Chapter 14: Air quality. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH14
17. IPCC (Intergovernmental Panel on Climate Change). (2021). *Climate change 2021—The physical science basis: Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896
18. Ziska, L., Knowlton, K., Rogers, C., Dalan, D., Tierney, N., Elder, M. A., Filley, W., Shropshire, J., Ford, L. B., Hedberg, C., Fleetwood, P., Hovanky, K. T., Kavanaugh, T., Fulford, G., Vrtis, R. F., Patz, J. A., Portnoy, J., Coates, F., Bielory, L., & Frenz, D. (2011). Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *Proceedings of the National Academy of Sciences, 108*(10), 4248–4251. https://doi.org/10.1073/pnas.1014107108
19. Ziska, L., Knowlton, K., & Rogers, C. (2016). Update to data originally published in Ziska, L., Knowlton, K., Rogers, C., Dalan, D., Tierney, N., Elder, M. A., Filley, W., Shropshire, J., Ford, L. B., Hedberg, C., Fleetwood, P., Hovanky, K. T., Kavanaugh, T., Fulford, G., Vrtis, R. F., Patz, J. A., Portnoy, J., Coates, F., Bielory, L., & Frenz, D. (2011). Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *Proceedings of the National Academy of Sciences, 108*(10), 4248–4251. https://doi.org/10.1073/pnas.1014107108

Ocean Impacts

1. IEA (International Energy Agency). (2021). *Key world energy statistics 2021.* www.iea.org/reports/key-world-energy-statistics-2021
2. CSIRO (Commonwealth Scientific and Industrial Research Organization) (2024). Update to data originally published in Domingues, C. M., Church, J. A., White, N. J., Gleckler, P. J., Wijffels, S. E., Barker, P. M., & Dunn, J. R. (2008). Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature, 453*(7198), 1090–1093. https://doi.org/10.1038/nature07080
3. IAP (Institute of Atmospheric Physics). (2024). Update to data originally published in Cheng, L., Trenberth, K. E., Fasullo, J., Boyer, T., Abraham, J., & Zhu, J. (2017). Improved estimates of ocean heat content from 1960 to 2015. *Science Advances, 3*(3), e1601545. https://doi.org/10.1126/sciadv.1601545
4. MRI/JMA (Meteorological Research Institute/Japan Meteorological Agency). (2024). *Global ocean heat content.* Retrieved March 1, 2024, from www.data.jma.go.jp/gmd/kaiyou/english/ohc/ohc_global_en.html

5. NOAA (National Oceanic and Atmospheric Administration). (2024). *Global ocean heat and salt content: Seasonal, yearly, and pentadal fields.* Retrieved March 1, 2024, from www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT
6. Pratchett, M. S., Wilson, S. K., Berumen, M. L., & McCormick, M. I. (2004). Sublethal effects of coral bleaching on an obligate coral feeding butterflyfish. *Coral Reefs, 23*(3), 352–356. https://doi.org/10.1007/s00338-004-0394-x
7. Pershing, A., Griffis, R., Jewett, E. B., Armstrong, C. T., Bruno, J. F., Busch, S., Haynie, A. C., Siedlecki, S., & Tommasi, D. (2018). Chapter 9: Oceans and marine resources. In USGCRP (U.S. Global Change Research Program), *Impacts, risks, and adaptation in the United States: The Fourth National Climate Assessment, volume II.* https://doi.org/10.7930/NCA4.2018.CH9
8. Mills, K. E., Osborne, E. B., Bell, R. J., Colgan, C. S., Cooley, S. R., Goldstein, M. C., Griffis, R. B., Holsman, K., Jacox, M., & Micheli, F. (2023). Chapter 10: Ocean ecosystems and marine resources. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH10
9. Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., Menne, M. J., Smith, T. M., Vose, R. S., & Zhang, H.-M. (2017). *NOAA Extended Reconstructed Sea Surface Temperature (ERSST), version 5* [Data set]. Retrieved February 1, 2024, from https://doi.org/10.7289/V5T72FNM
10. Mills, K. E., Osborne, E. B., Bell, R. J., Colgan, C. S., Cooley, S. R., Goldstein, M. C., Griffis, R. B., Holsman, K., Jacox, M., & Micheli, F. (2023). Chapter 10: Ocean ecosystems and marine resources. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH10
11. Mills, K. E., Osborne, E. B., Bell, R. J., Colgan, C. S., Cooley, S. R., Goldstein, M. C., Griffis, R. B., Holsman, K., Jacox, M., & Micheli, F. (2023). Chapter 10: Ocean ecosystems and marine resources. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH10
12. Mills, K. E., Osborne, E. B., Bell, R. J., Colgan, C. S., Cooley, S. R., Goldstein, M. C., Griffis, R. B., Holsman, K., Jacox, M., & Micheli, F. (2023). Chapter 10: Ocean ecosystems and marine resources. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH10
13. NOAA (National Oceanic and Atmospheric Administration). (2024). *DisMAP data records.* Distribution Mapping and Analysis Portal. Retrieved May 6, 2024, from https://apps-st.fisheries.noaa.gov/dismap/DisMAP.html
14. NOAA (National Oceanic and Atmospheric Administration). (2024). *DisMAP data records.* Distribution Mapping and Analysis Portal. Retrieved May 6, 2024, from https://apps-st.fisheries.noaa.gov/dismap/DisMAP.html
15. NOAA (National Oceanic and Atmospheric Administration). (2024). *DisMAP data records.* Distribution Mapping and Analysis Portal. Retrieved May 6, 2024, from https://apps-st.fisheries.noaa.gov/dismap/DisMAP.html
16. NOAA (National Oceanic and Atmospheric Administration). (2024). *DisMAP data records.* Distribution Mapping and Analysis Portal. Retrieved May 6, 2024, from https://apps-st.fisheries.noaa.gov/dismap/DisMAP.html
17. Mills, K. E., Osborne, E. B., Bell, R. J., Colgan, C. S., Cooley, S. R., Goldstein, M. C., Griffis, R. B., Holsman, K., Jacox, M., & Micheli, F. (2023). Chapter 10: Ocean ecosystems and marine resources. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment.* https://doi.org/10.7930/NCA5.2023.CH10
18. NOAA (National Oceanic and Atmospheric Administration). (2024). *Optimum interpolation SST.* Retrieved March 1, 2024, from www.ncei.noaa.gov/products/optimum-interpolation-sst
19. NOAA (National Oceanic and Atmospheric Administration). (2023). *What a marine heatwave means for south Florida.* www.aoml.noaa.gov/what-a-marine-heatwave-means-for-south-florida
20. NOAA (National Oceanic and Atmospheric Administration). (2023). *Extreme ocean temperatures are affecting Florida's Coral Reef.* www.nesdis.noaa.gov/news/extreme-ocean-temperatures-are-affecting-floridas-coral-reef
21. NOAA (National Oceanic and Atmospheric Administration). (2023). *NOAA scientists return to Cheeca Rocks, find reef completely bleached.* www.aoml.noaa.gov/cheeca-rocks-reef-completely-bleached
22. NOAA (National Oceanic and Atmospheric Administration). (2023). *What a marine heatwave means for south Florida.* www.aoml.noaa.gov/what-a-marine-heatwave-means-for-south-florida
23. Bednaršek, N., Tarling, G. A., Bakker, D. C. E., Fielding, S., Jones, E. M., Venables, H. J., Ward, P., Kuzirian, A., Lézé, B., Feely, R. A., & Murphy, E. J. (2012). Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience, 5*(12), 881–885. https://doi.org/10.1038/ngeo1635
24. Calculated from numbers in the IPCC Sixth Assessment Report. From 1750 to 2019: total human emissions of 685 petagrams of carbon and ocean uptake of 170 petagrams. Source: Canadell, J. G., Monteiro, P. M. S., Costa, M. H., Cotrim da Cunha, L., Cox, P. M., Eliseev, A. V., Henson, S., Ishii, M., Jaccard, S., Koven, C., Lohila, A., Patra, P. K., Piao, S., Rogelj, J., Syampungani, S., Zaehle, S., & Zickfeld, K. (2021). Chapter 5: Global carbon and other biogeochemical cycles and feedbacks. In IPCC (Intergovernmental Panel on Climate Change), *Climate change 2021—The physical science basis: Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press. https://doi.org/10.1017/9781009157896.007
25. Bates, N.R. (2016). Update to data originally published in Bates, N. R., Best, M. H. P., Neely, K., Garley, R., Dickson, A. G., & Johnson, R. J. (2012). Detecting anthropogenic carbon dioxide uptake and ocean acidification in the North Atlantic Ocean. *Biogeosciences, 9*(7), 2509–2522. https://doi.org/10.5194/bg-9-2509-2012

26. González-Dávila, M. (2012). Update to data originally published in González-Dávila, M., Santana-Casiano, J. M., Rueda, M. J., & Llinás, O. (2010). The water column distribution of carbonate system variables at the ESTOC site from 1995 to 2004. *Biogeosciences, 7*(10), 3067–3081. https://doi.org/10.5194/bg-7-3067-2010

27. University of South Florida. (2021). *Carbon Retention in a Colored Ocean (CARIACO) Ocean Time-Series Program* [Data set]. https://erddap.bco-dmo.org/erddap/tabledap/bcodmo_dataset_3093.htmlTable

28. University of Hawai'i. (2023). *Hawaii Ocean Time-series (HOT)* [Data set]. https://hahana.soest.hawaii.edu/hot/hotco2/HOT_surface_CO2.txt

Rising Seas

1. IPCC (Intergovernmental Panel on Climate Change). (2021). *Climate change 2021—The physical science basis: Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896

2. WGMS (World Glacier Monitoring Service). (2024). *Fluctuations of Glaciers Database* [Data set]. https://doi.org/10.5904/WGMS-FOG-2024-01

3. Marvel, K., Su, W., Delgado, R., Aarons, S., Chatterjee, A., Garcia, M. E., Hausfather, Z., Hayhoe, K., Hence, D. A., Jewett, E. B., Robel, A., Singh, D., Tripati, A., & Vose, R. S. (2023). Chapter 2: Climate trends. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH2

4. IPCC (Intergovernmental Panel on Climate Change). (2021). *Climate change 2021—The physical science basis: Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896

5. USGS (U.S. Geological Survey). (2024). *Glacier-wide mass balance and compiled data inputs* (8.1) [Data set]. https://doi.org/10.5066/F7HD7SRF

6. Otosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N.-J., Amory, C., Van Den Broeke, M. R., Horwath, M., Joughin, I., King, M. D., Krinner, G., Nowicki, S., Payne, A. J., Rignot, E., Scambos, T., Simon, K. M., Smith, B. E., Sørensen, L. S., Velicogna, I., Whitehouse, P. L., ... Wouters, B. (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. *Earth System Science Data, 15*(4), 1597–1616. https://doi.org/10.5194/essd-15-1597-2023

7. IPCC (Intergovernmental Panel on Climate Change). (2013). *Climate change 2013—The physical science basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, A. Boschung, A. Nauels, Y. Xia, V. Bex, & Midgley, Eds.). Cambridge University Press. www.ipcc.ch/report/ar5/wg1

8. Otosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N.-J., Amory, C., Van Den Broeke, M. R., Horwath, M., Joughin, I., King, M. D., Krinner, G., Nowicki, S., Payne, A. J., Rignot, E., Scambos, T., Simon, K. M., Smith, B. E., Sørensen, L. S., Velicogna, I., Whitehouse, P. L., Wouters, B. (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. *Earth System Science Data, 15*(4), 1597–1616. https://doi.org/10.5194/essd-15-1597-2023

9. NASA (National Aeronautics and Space Administration). (2024). *Vital signs: Ice sheets*. Retrieved February 29, 2024, from https://climate.nasa.gov/vital-signs/ice-sheets

10. Sweet, W. V., Horton, R., Kopp, R. E., LeGrande, A. N., & Romanou, A. (2017). Chapter 12: Sea level rise. In USGCRP (U.S. Global Change Research Program), *Climate science special report: Fourth National Climate Assessment, volume I* (pp. 333–363). https://doi.org/10.7930/J0VM49F2

11. Sea Level Research Group. (2024). *Trend map*. Retrieved May 17, 2024, from https://sealevel.colorado.edu/trend-map

12. CSIRO (Commonwealth Scientific and Industrial Research Organisation). (2017). Update to data originally published in Church, J. A., & White, N. J. (2011). Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics, 32*, 585–602. www.cmar.csiro.au/sealevel/sl_data_cmar.html

13. NOAA (National Oceanic and Atmospheric Administration). (2024). *Laboratory for Satellite Altimetry: Sea level rise*. Retrieved March 1, 2024, from www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/LSA_SLR_timeseries_global.php

14. NOAA (National Oceanic and Atmospheric Administration). (2024). Update to data originally published in NOAA. (2009). *Sea level variations of the United States 1854–2006* (NOAA Technical Report NOS CO-OPS 053). www.tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf

15. NOAA (National Oceanic and Atmospheric Administration). (2024). *Tides and currents: CO-OPS derived product API* [Data set]. https://api.tidesandcurrents.noaa.gov/dpapi/prod

16. NOAA (National Oceanic and Atmospheric Administration). (2024). *Personal communication: Alaskan site data, 1950–2023.*

17. NOAA (National Oceanic and Atmospheric Administration). (2024). *Tides and currents: CO-OPS derived product API* [Data set]. https://api.tidesandcurrents.noaa.gov/dpapi/prod

18. NOAA (National Oceanic and Atmospheric Administration). (2024). *Personal communication: Alaskan site data, 1950–2023.*

Alaska's Warming Climate

1. NOAA (National Oceanic and Atmospheric Administration). (2024). *Climate at a glance*. Retrieved March 25, 2024, from www.ncei.noaa.gov/access/monitoring/climate-at-a-glance
2. NSIDC (National Snow and Ice Data Center). (2023). *Sea ice: Why it matters*. https://nsidc.org/learn/parts-cryosphere/sea-ice/why-sea-ice-matters
3. Comiso, J. C. (2012). Large decadal decline of the Arctic multiyear ice cover. *Journal of Climate, 25*(4), 1176–1193. https://doi.org/10.1175/JCLI-D-11-00113.1
4. NASA (National Aeronautics and Space Administration). (2023). *Scientific Visualization Studio*. https://svs.gsfc.nasa.gov
5. NSIDC (National Snow and Ice Data Center). (2023). *Data and image archive*. Retrieved October 1, 2023, from https://nsidc.org/data/seaice_index/data-and-image-archive
6. Divoky, G. J., Douglas, D. C., & Stenhouse, I. J. (2016). Arctic sea ice a major determinant in Mandt's black guillemot movement and distribution during non-breeding season. *Biology Letters, 12*(9), 20160275. https://doi.org/10.1098/rsbl.2016.0275
7. Divoky, G. J., Lukacs, P. M., & Druckenmiller, M. L. (2015). Effects of recent decreases in arctic sea ice on an ice-associated marine bird. *Progress in Oceanography, 136*, 151–161. https://doi.org/10.1016/j.pocean.2015.05.010
8. Cox, C. J., Stone, R. S., Douglas, D. C., Stanitski, D. M., Divoky, G. J., Dutton, G. S., Sweeney, C., George, J. C., & Longenecker, D. U. (2017). Drivers and environmental responses to the changing annual snow cycle of northern Alaska. *Bulletin of the American Meteorological Society, 98*(12), 2559–2577. https://doi.org/10.1175/BAMS-D-16-0201.1
9. Divoky, G. J., Lukacs, P. M., & Druckenmiller, M. L. (2015). Effects of recent decreases in arctic sea ice on an ice-associated marine bird. *Progress in Oceanography, 136*, 151–161. https://doi.org/10.1016/j.pocean.2015.05.010
10. USGCRP (U.S. Global Change Research Program). (2017). *Climate science special report: Fourth National Climate Assessment (NCA4), volume I* (D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, & T. K. Maycock, Eds.). https://doi.org/10.7930/J0J964J6
11. Divoky, G. J. (2024). Update to data originally published in Divoky, G. J., Lukacs, P. M., & Druckenmiller, M. L. (2015). Effects of recent decreases in arctic sea ice on an ice-associated marine bird. *Progress in Oceanography, 136*, 151–161. https://doi.org/10.1016/j.pocean.2015.05.010
12. Huntington, H. P., Strawhacker, C., Falke, J., Ward, E. M., Behnken, L., Curry, T. N., Herrmann, A. C., Itchuaqiyaq, C. U., Littell, J. S., Logerwell, E. A., Meeker, D., Overbeck, J. R., Peter, D. L., Pincus, R., Quintyne, A. A., Trainor, S. F., & Yoder, S. A. (2023). Chapter 29: Alaska. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH29
13. University of Alaska Fairbanks. (2023). *Sites map*. Retrieved November 1, 2023, from https://permafrost.gi.alaska.edu/sites_map
14. Alaska Department of Commerce, Community, and Economic Development. (2023). *Newtok Planning Group: Working together for the safe and healthy future of Newtok at Mertarvik*. Retrieved May 7, 2024, from www.commerce.alaska.gov/web/dcra/PlanningLandManagement/NewtokPlanningGroup.aspx
15. Beltaos, S., & Burrell, B. C. (2003). Climatic change and river ice breakup. *Canadian Journal of Civil Engineering, 30*(1), 145–155. https://doi.org/10.1139/l02-042
16. Marvel, K., Su, W., Delgado, R., Aarons, S., Chatterjee, A., Garcia, M. E., Hausfather, Z., Hayhoe, K., Hence, D. A., Jewett, E. B., Robel, A., Singh, D., Tripati, A., & Vose, R. S. (2023). Chapter 2: Climate trends. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH2
17. IPCC (Intergovernmental Panel on Climate Change). (2021). *Climate change 2021—The physical science basis: Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896
18. Nenana Ice Classic. (2022). *The Nenana Ice Classic*. Retrieved May 1, 2022, from www.nenanaakiceclassic.com
19. Yukon River Breakup. (2022). *Yukon River breakup*. Retrieved May 1, 2022, from https://yukonriverbreakup.com
20. Kuskokwim Ice Classic. (2022). *Kuskokwim Ice Classic*. Retrieved May 1, 2022, from http://iceclassic.org
21. National Weather Service. (2022). *Alaska-Pacific River Forecast Center: Break up database*. Retrieved May 1, 2022, from www.weather.gov/aprfc/breakupDB
22. Schwartz, M. D., Ault, T. R., & Betancourt, J. L. (2013). Spring onset variations and trends in the continental United States: Past and regional assessment using temperature-based indices. *International Journal of Climatology, 33*(13), 2917–2922. https://doi.org/10.1002/joc.3625

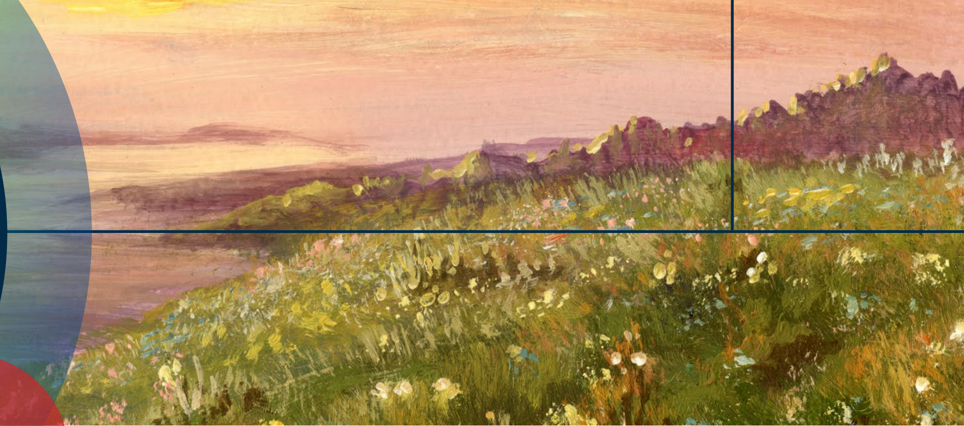


Image Credits

- Cover artwork by Jill Pelto: “Landscape of Change” and “Replanting Resilience.”
- p. 1: Artwork by Jill Pelto: “Replanting Resilience.”
- p. 2: Artwork for “Ocean Impacts” chapter by Jill Pelto: “Gulf of Maine Temperature Variability.”
- p. 2: Artwork for “Rising Seas” chapter by Jill Pelto: “Climate Change Data.”
- p. 8: Illustration from EPA’s “Climate Change Science” site (https://www.epa.gov/climatechange-science).
- p. 31: Forest fire photo by Mike Lewelling, National Park Service.
- p. 32: Screenshot from the AirNow Fire and Smoke Map (https://fire.airnow.gov).
- p. 35: Lake photo by Zachary Haslick, Aerial Associates Photography, Inc.
- p. 52: Artwork by Jill Pelto: “Gulf of Maine Temperature Variability.”
- p. 59: Image from NOAA’s Coral Reef Watch (https://coralreefwatch.noaa.gov).
- p. 62: Artwork by Jill Pelto: “Climate Change Data.”
- p. 66: GRACE satellite rendering by NASA Jet Propulsion Laboratory.
- p. 71: Oyster-planting photo by Patrick Bloodgood, U.S. Army.
- p. 75: Satellite images of Arctic sea ice from NASA’s Scientific Visualization Studio (https://svs.gsfc.nasa.gov).
- p. 78: House construction photo from the Office of Senator Lisa Murkowski.

United States Environmental Protection Agency

EPA 430-R-24-003

July 2024
www.epa.gov/climate-indicators