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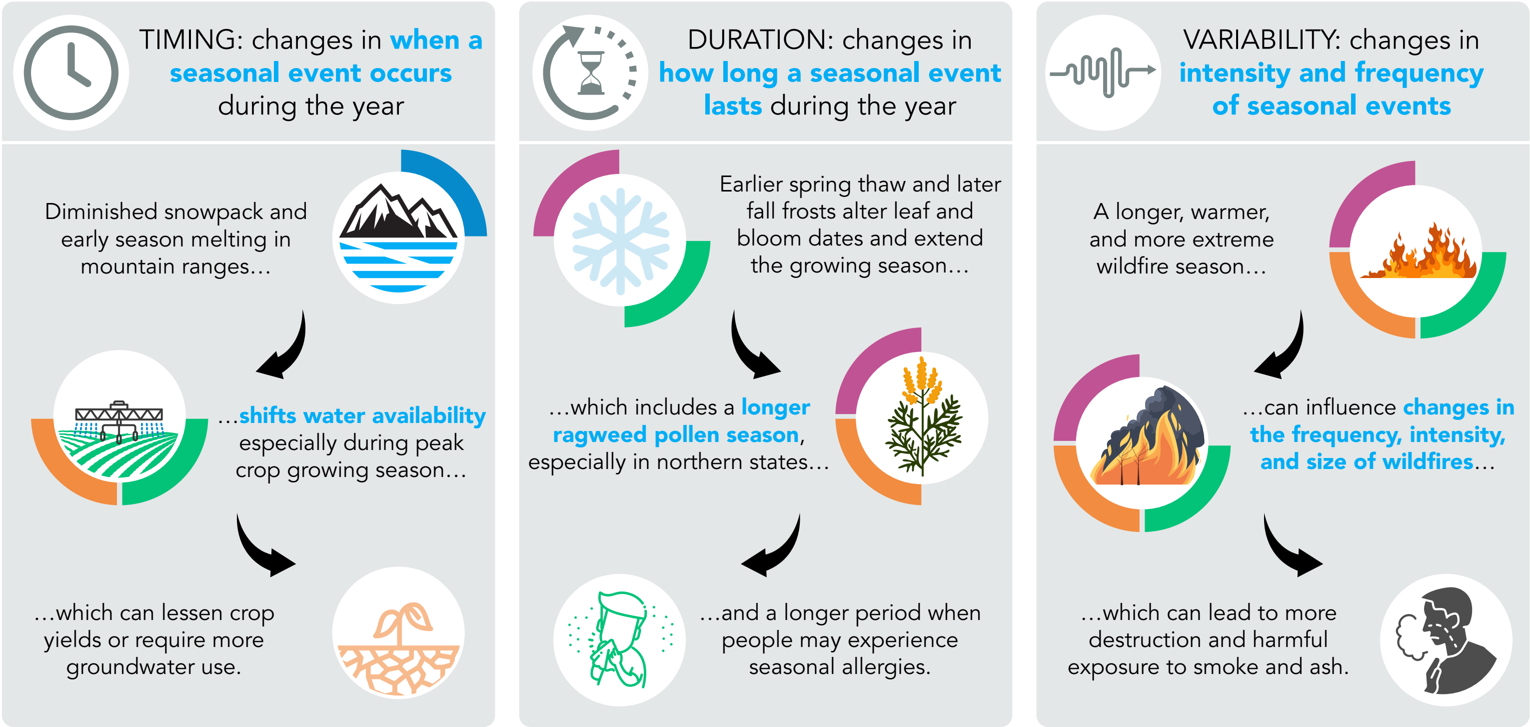
SEASONALITY AND CLIMATE CHANGE

A REVIEW OF OBSERVED EVIDENCE IN THE UNITED STATES

EPA U.S. Environmental Protection Agency

The concept of ***seasonality*** refers to ***recurring events or processes that are correlated with seasons***, such as rising temperatures at the end of winter, the blooming of wildflowers in spring, the onset of allergies during ragweed season, and leaf-fall in autumn.

Three aspects of seasonality that are impacted by climate change are:



EPA'S CLIMATE CHANGE INDICATORS

In addition to support from the scientific literature, this report draws on data and findings from EPA's Climate Change Indicators. EPA works in partnership with more than 50 data contributors from various government agencies, academic institutions, and other organizations to compile a key set of indicators related to the causes and effects of climate change. These indicators also provide important input to the National Climate Assessment and other efforts to understand and track the science and impacts of climate change. Learn more about EPA's indicators at https://www.epa.gov/climate-indicators.

FRONT MATTER

The Earth's climate is changing. Multiple lines of evidence show changes in our weather, oceans, ecosystems, and seasonal events. This technical report summarizes the current state of the science on observed changes related to seasonality in the United States and discusses how climate change affects the timing and nature of seasonal events. The report uses several key indicators sensitive to and related to seasonality as a framework for understanding the implications of a changing climate over time. The indicators are based on long-term observations and reveal the many dimensions of seasonal events, including critical connections between physical changes and biological responses. The report provides examples of how changes in seasonality affect ecological and human systems, as well as our everyday lives

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PEER REVIEW

The primary indicators compiled and used in this report have been independently peer reviewed as part of EPA's Climate Change Indicators effort. In addition, this Technical Report, including the technical supporting documentation, was peer reviewed by three external experts in a process independently coordinated by Abt Associates and an EPA peer-review coordinator. EPA gratefully acknowledges the following peer reviewers for their useful comments and suggestions: Kathy Jacobs, Holly R. Prendeville, and Scott Steinschneider. 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 Appendix to this report provides more information about the peer review.

RECOMMENDED CITATION

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INTRODUCTION

This technical report summarizes observed changes related to seasonality in the United States, discusses how climate change affects the timing and nature of seasonal events, and describes some of the related implications of those changes. To accomplish this, the report uses a subset of indicators based on long-term observations to explore the interconnectedness of seasonal changes, including the cascading effect of physical climatic changes and downstream biological, ecological, and social responses.

The report aims to summarize the current state of the science related to historical changes in seasonality and provide tangible examples of the ways in which climate change is altering the nature of seasonal events—and how these changes affect ecological and societal systems. Examining indicators of seasonal processes and systems sensitive to seasonality provides a framework for better understanding the implications of a changing climate through time.

WHAT IS SEASONALITY?

The concept of seasonality refers to recurring events or processes that are correlated with seasons, such as rising temperatures at the end of winter, the blooming of wildflowers in spring, the onset of allergies during ragweed season, and leaf-fall in autumn.

This report considers three aspects of seasonality: 1) **shifts in the timing of seasonal events** (e.g., the timing of animal migrations); 2) **changes in the duration of seasonal events** (e.g., the length of the wildfire season); and 3) **changes in the variability of events and processes that occur during certain times of the year** (e.g., the number of major hurricanes during the hurricane season, the extent and severity of wildfires, or the prevalence and spread of Lyme disease).

WHY FOCUS ON CLIMATE CHANGE AND SEASONALITY?

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.[1] At the core of these changes are increases in temperature. These changes in physical climate lead to wide-ranging impacts such as warmer winters; precipitation patterns shifting from snow to rain; species shifting the timing or location of their seasonal activities, such as migration and reproduction; geographic expansion and outbreaks of pests; and increases in the likelihood or duration of extreme events such as heat waves, hurricanes, and wildfires.[1] Some of these impacts may be beneficial, such as longer growing seasons for crops or reductions in winter heating fuel costs. An understanding of how seasonality is changing will inform efforts to monitor, communicate, and prepare for these climate impacts.

Key takeaways:

- **Climate-related changes in seasonality are evident and happening now in most regions of the United States.** Changes in seasonality are well documented in indicators and the scientific literature and can be found across the United States at different scales.
- **Changes to seasonality have wide-ranging impacts—both positive and negative—across physical, ecological, and societal systems.** For example, increases in temperature can reduce seasonal snowpack and lead to early snowmelt in mountain regions that provide water to downstream agricultural areas,[2] ultimately affecting crops and produce.[3] Warmer and shorter winters may reduce the length of the ski season, but could extend the season for other recreational activities such as boating. Understanding how seasonal events are linked across sectors can help us plan for and address risks associated with the effects of climate change at seasonal and longer time scales.[4]
- **Some of the changes underway can lead to harmful impacts on human health.** Summer heat waves, which are becoming more intense and frequent, can cause heat stroke, respiratory problems, and other health conditions. Prolonged wildfire and pollen seasons can lead to unhealthy air quality and pose risks for people with allergies and asthma.
- **Climate indicators are important in framing and documenting changes in seasonality.** Long-term observational records, such as from weather stations or streamflow gauges, are necessary to develop indicators that summarize changes in seasonality. Indicators help us see how variations in the timing of seasonal events are tied to long-term changes in physical drivers such as temperature and precipitation.[5] Regular data collection and monitoring must be in place in order to continually to track these trends.

CHANGES IN SEASONALITY SERVE AS A BAROMETER FOR CLIMATE CHANGE

Seasonality is dynamic, and characteristics and events associated with the seasons can vary naturally from year to year. For example, some years have hotter summers and snowier winters, and some hurricane seasons have stronger and more destructive storms. Human-induced climate change has a strong influence over this variability and is fundamentally changing seasonality in the United States.[6, 108]

WHAT IS AN INDICATOR?

An indicator is a convenient, useful analytical expression of data that represents the state or trend of certain environmental or societal conditions over a given area and a specified period of time. Indicators of seasonality can illustrate such changes as increases or decreases, rates of change, and the magnitude, timing, duration, peak, severity, and frequency of seasonal events.

Climate change drives shifts in the *timing* of seasonal events, such as the formation of lake ice in winter, as well as the *increased variability* of seasonal events, such as the severity of heat waves in summer. Climate change also alters the *duration* and *frequency* of seasonal events, potentially affecting societal risk and prolonging exposure to more extreme events within a season.[6] For example, the wildfire season in the western United States now starts earlier, extends later into fall, and includes more frequent and destructive wildfires than in the past.[7] In turn, all of these changes in seasonality drive impacts and consequences across environmental and societal systems.

Climate change is often difficult to contextualize and address because it manifests over long timescales. However, changes in seasonality provide tangible evidence of climate change occurring over relatively short timescales—including within human lifetimes. Because we understand seasonal responses and relationships to climate, analyzing changes in seasonality can aid our understanding of how the impacts of climate change may unfold over longer timescales.

Observational records of seasonality are increasingly used to monitor and analyze climate change and its many consequences. Because climate can fluctuate naturally over the short term, scientists require long records of observations to detect influences of climate change on seasonality. For example, weather and year-to-year natural climate variations, such as El Niño and La Niña events, can significantly affect seasonal conditions, at least over periods of a decade or less.[8] Therefore, it is important to collect and study long observational records to detect climate-related shifts in seasonality that are separate from natural variability. The indicators described in this report have been chosen because of their ability to demonstrate these long-term changes.

A number of recent studies attribute observed changes in seasonality to human-caused climate change. For instance, studies show that recent record summer temperatures and heat waves in the United States, such as those in 2014 and 2016, were likely to occur in the presence of human-caused greenhouse warming and extremely unlikely to occur in its absence.[9,10] Similarly, climate change has reduced the probability of cold weather extremes in many parts of the world,[10] and the number of seasonal cold snaps in the United States has decreased significantly since the early 1900s.[6] These findings underscore the impact that climate change has already had in reshaping seasonal phenomena in the United States.

Moreover, studies have long documented the interface between climate change, seasonality, and ecosystems.[5] Across ecosystems worldwide, climate change has impacted the timing of seasonal life history transitions—such as juvenile development and reproduction—for a range of organisms, including plants, birds, mammals, fish, and others.[11-14] The majority of observations and evidence for these changes are drawn from terrestrial systems, but evidence from marine systems is growing.[15]

> Changes in seasonality provide tangible evidence of climate change occurring over relatively short timescales and within human lifetimes. Climate change impacts the timing, duration, frequency, and severity of seasonal events in ways that are important to human society.

This report summarizes current knowledge related to the implications and relevance of observed changes in seasonality. While observed changes in seasonality are linked to human-caused climate change, this report does not explore attribution of changes in seasonality to climate change, nor does it try to quantify cause and effect beyond relationships that have already been published in peer-reviewed literature.

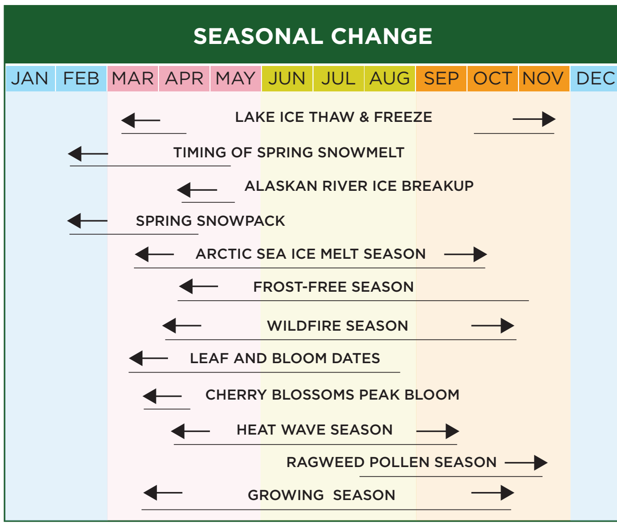
OBSERVED SEASONALITY CHANGES IN THE UNITED STATES

This report summarizes a variety of observational evidence and indicators across geographies to build a composite, data-rich view of changes in seasonality in the United States and their relation to climate change. EPA tracks and compiles indicators using the best available monitoring data, prioritizing datasets that represent regional to national geographies and long time periods. EPA's Climate Change Indicators in the United States are available online: https://www.epa.gov/climate-indicators.

Figure 1 illustrates examples of indicators and key evidence of changes in the timing of seasonal events that have been observed in the United States across various geographies and time scales. These indicators provide multiple lines of evidence for shifts in the timing of seasonal conditions and events.

Indicators reveal that warming temperatures have shortened frost seasons, led snowmelt to occur earlier in the year, and contributed to a decline in snowpack. Similarly, wildfire and heat wave seasons have increased in duration and severity, impacting ecosystems, human health, and economies. Leaf and bloom dates are occurring earlier than before, and the growing season has extended to cover a greater portion of the year. Subsequent sections of this report explore how changes in one season cascade across and impact events in other seasons (e.g., winter conditions affect harvests in the following fall).

Observed Evidence of Changes in Seasonality Related to Timing



KEY EVIDENCE
Lake ice is thawing earlier by 24 days; **Lake ice is freezing** later by 10 days since 1973.[a]
Spring snow is melting 8 days earlier on average since 1940.[b]
River ice is breaking up 3 days earlier on average since 1924.[c]
Spring snowpack is declining; snowpack peaks 9 days earlier on average since 1955.[d]
Arctic sea ice melt season has increased by 38 days since 1979.[c]
Frost-free season is growing longer by 4 days per decade since 1979.[c, e]
Wildfire season is occurring earlier, based on wildfire activity since the 1980s.[d]
Leaf and bloom dates are occurring earlier since 1981.[e]
Cherry blossom peak bloom date is 6 days earlier since 1921.[f]
Heat wave season is 47 days longer than in 1961.[g]
Ragweed pollen season is from 6 days to 3 weeks longer since 1995.[h]
Growing season is 2 weeks longer overall since 1985 (last spring frost earlier; first fall frost later).[e]

[a] Northeast, Northern Midwest
[b] West, Northeast
[c] Alaska
[d] West
[e] Contiguous U.S.
[f] Washington, DC
[g] 50 large cities across the U.S.
[h] Central U.S.

Figure 1. *Summary of illustrative examples of changes in seasonality across the United States. Solid bars represent the approximate time of year over which the indicators typically occur, and arrows denote earlier (⟵) and later (⟶) shifts in the season as shown by indicator datasets. Note that some of these examples are limited to specific geographic regions (e.g., cherry blossom peak bloom in Washington, DC). All indicators and data were sourced from the EPA Climate Change Indicators, available at: https://www.epa.gov/climate-indicators.*

SEASONAL CHANGES HAVE ASSOCIATED DOWNSTREAM EFFECTS

Changes in seasonality are not isolated, but rather linked across time, space, and systems. Physical changes in seasonality (e.g., changes in average winter temperatures or changes in the length of the snow season) can affect a wide range of ecological and societal processes.[16] For example, warmer winters make it easier for agricultural pests to survive between growing seasons and create adverse conditions for crops that require winter chill hours to bear fruit the following season.[17-19] Figure 2 provides an example of how seasonal processes are connected, from physical climatological changes to ecological and societal responses. In this example, warmer winters can reduce mountain snowpack and the volume of runoff-fed streams and reservoirs that are used for crop irrigation. These impacts can converge and compound to affect the agricultural sector.[20]

Seasonal changes and downstream relationships

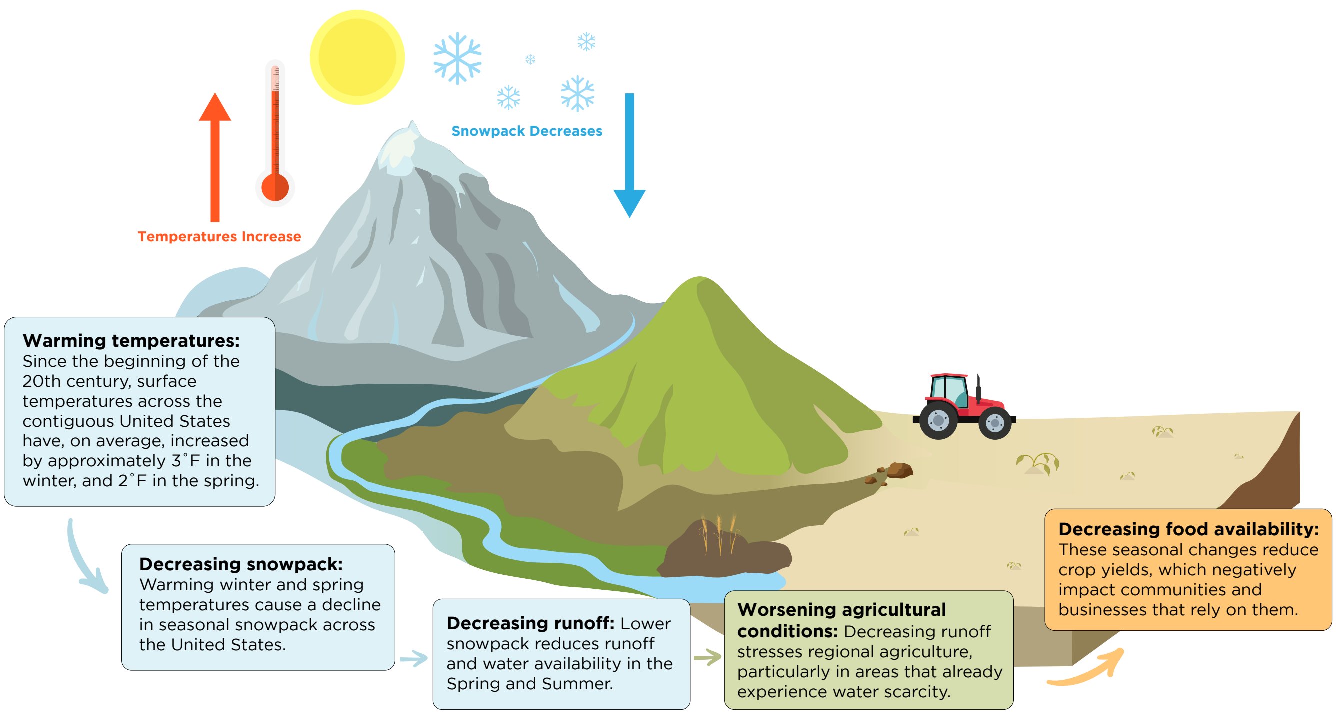


Figure 2. *Seasonal processes are interlinked and changes in seasonality can have cascading impacts across physical, ecological, and societal systems. Note that this example focuses on decreasing snowpack leading to decreased water supplies, which is a regional issue for the western United States.*

SEASONALITY AND CLIMATE CHANGE: A HEALTH FOCUS

Through its influence on the timing, duration, and variability of seasonal events, climate change can affect people's potential exposure to new and existing hazards that pose risks to public health. For example:

Extreme Heat: As global temperatures continue to rise, summers are becoming hotter and the heat wave season is lengthening. Summertime temperatures in many parts of the United States have already increased to thresholds that are challenging for groups at higher risk for heat-related illness and mortality.[1,90] Warmer winters are expected to reduce the number of illnesses and premature deaths from exposure to cold, although several studies suggest that this reduction will be smaller than the increase in illnesses and deaths from extreme heat.[90]

Wildfire: Wildfires in the western United States have become increasingly severe and cover broader areas. In some areas of the West, the wildfire season is also becoming longer. These changes can increase people's exposure to the health hazards of wildfires, including poor air quality that can contribute to respiratory illness.[1,90]

Vector-borne diseases: Climate change—especially changes to temperature extremes and precipitation patterns—can expand the geographic range, affect the abundance, and lengthen the activity period of disease-transmitting ticks, mosquitoes, and other vectors that spread illnesses such as Lyme disease and West Nile virus infection.[1,90]

Pollen Season: Allergy seasons are becoming longer and more intense in some parts of the country due to expanded pollen seasons and higher pollen counts for common allergen species such as ragweed, grass, oak, and birch, leading to respiratory health impacts.[1,90]

Water-borne illnesses: Warmer fresh and marine waters can affect the range and growing season of harmful algae and bacteria, viruses, and parasites, increasing the risk of exposure to toxins and waterborne pathogens.[1,90]

SYNTHESIS OF OBSERVED CHANGES IN SEASONALITY

The sections below present a synthesis of the observed changes in seasonality in the United States as highlighted in four illustrative themes, or discussion topics. These topics explore changes in seasonality as well as the ways in which these changes are interconnected across time and space and between systems. This synthesis relies on many indicator datasets developed by EPA, along with supporting scientific evidence and insights from peer-reviewed literature to provide a fuller understanding of changes and associated impacts.

THEME 1
SEASONAL CHANGES IN TEMPERATURE AND PRECIPITATION

Seasonal temperatures and seasonal precipitation patterns in much of the United States have changed since the early 20th century, driving many downstream ecological and societal impacts. Observed changes in seasonal temperature include both increases in average temperatures and more frequent and severe extremes, such as heat waves. Changing precipitation patterns include long-term changes in average seasonal conditions as well as increased seasonal variability, which drives more intense periods of drought and flooding.

Annual mean surface temperatures across the contiguous 48 states has been increasing by an average of 0.16°F per decade since 1901, with a greater rate of increase since 1980.[1,21] Warming has occurred in each season (Figure 3), with winters warming the most and experiencing temperature increases of nearly 3°F over this same period (1896–2019).[22]

Seasonal temperature in the West and upper Midwest states have warmed the most, while states in the Southeast have warmed the least or cooled slightly (Figure 3). Examining long-term temperature records, researchers found that the length of the four individual seasons is changing in terms of start and end dates. In the Northern Hemisphere, summers grew longer between 1952 and 2011, whereas winter, autumn, and spring grew shorter.[108]

Additionally, the coldest part of the temperature distribution is warming: the annual number of days with extreme cold temperatures (colder than the 5th percentile) has declined since the 1950s (see here), and upward trends in winter temperature minima have amplified the effects of warming average winter temperatures.

Although experiencing a less frigid winter may seem good to some people, warming winters have far-reaching consequences, including decreased snowpack,[23,24] fewer chilling hours for cold-dependent crops,[18,25] and a longer mosquito season.[26] The section below on early season warming and downstream impacts discusses these and other consequences in more detail.

Change in Temperature by Season in the contiguous 48 States, 1896–2020

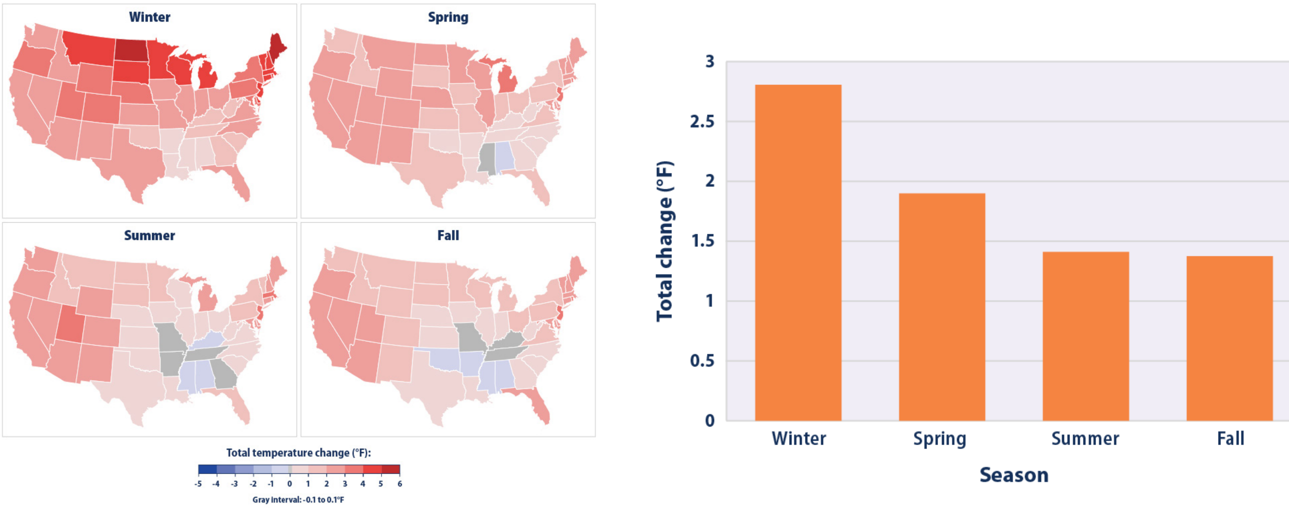


Figure 3. *Map showing total seasonal temperature change, by state, across the contiguous United States from 1896 to 2020. Right: Bar chart indicating average annual temperature change, by season, across the contiguous United States from 1896 to 2020. Seasons are defined as winter (December (from the previous year), January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November). Source: EPA (2020).*[22]

Other seasons have also warmed. Summer heat waves have increased in frequency, intensity, and duration and, in the 2010s, increasingly occurred during spring and fall compared to the 1960s, lengthening the heat wave season.[27] Climate change also increases high-humidity events, which combine with extreme heat to compound human health impacts.[28] Extreme heat events can have large, immediate impacts on animals, ecosystems, and human communities.[29,30] Theme 4 below on seasonality and extreme events discusses these issues in more detail.

Similar to temperature, precipitation patterns in the United States have changed with respect to both seasonal averages and extremes. Annual average precipitation increased at a rate of 0.17 inches per decade between 1901 and 2015, due mostly to large increases during the fall season.[31] Changes in annual precipitation differ across regions, with increases in the Northeast, Midwest, and Great Plains, and decreases in the West, Southwest, and Southeast.[1]

Changes in seasonal temperatures and precipitation patterns can alter hydrologic systems, seasonal biology, and extreme events, as well as the downstream impacts associated with these changes. The following sections focus on these important seasonal connections in more detail.

THEME 2

EFFECTS OF WARMER, SHORTER WINTERS

Although temperatures in all seasons have been increasing in the United States, winter temperatures have increased at the highest rate. A warmer winter can have several implications, including some that manifest in other seasons, such as spring and summer water availability and the length of the agricultural growing season. This section explores how physical changes such as warming and shorter winters can influence a range of impacts, including to ecosystems and human society. The box on page 16 describes how glaciers and the seasonality of lake and river ice—including dates of ice freeze and breakup—are responding to climate change and variability.

The warming climate affects precipitation and other hydrologic processes, which has driven pronounced changes to snowfall and snowpack in the United States. With respect to snowfall, the proportion of winter precipitation that falls as rain rather than snow has been increasing. Observations across the contiguous 48 states show that nearly 80 percent of weather stations experienced a general decrease in the proportion of precipitation falling as snow from 1949 to 2020.[32]

Seasonal snowpack—the amount of snow that accumulates and compresses on the ground—has also decreased over time (see Figure 4).[33] Recent snowpack declines are almost unprecedented in the last millennium, largely a result of springtime warming.[34] The western United States, especially, has experienced widespread temperature-related reductions in snowpack, with annual peak snowpack depth decreasing by approximately 4 inches from 1982 to 2018. In addition, long-term measurements indicate the annual timing of peak snowpack has shifted earlier at most locations. This earlier seasonal trend is especially pronounced in southwestern states such as Colorado, New Mexico, and Utah. Across all stations, peak snowpack has shifted earlier by an average of nearly eight days since 1982.[24] Furthermore, observations suggest the annual cycle of snowpack is narrowing, corresponding to a shrinking of the length of the winter season.[35]

Snowpack provides two-thirds of the inflow to the major reservoirs in the western United States.[24] As snowpack decreases and snowmelt occurs earlier in spring, western water availability becomes increasingly stressed, which can contribute to drought conditions.[36,37] For example, the historic California drought from 2011 to 2017 was exacerbated by record low snowpack in the Sierra Nevada mountains caused by limited precipitation and high winter temperatures.[38,39] Loss of snowpack has also led to decreasing water resources in other areas. Reduced snowpack decreases the albedo effect (i.e., reflectivity: snow has a high albedo and so reflects a large proportion of incoming solar radiation) and increases evapotranspiration, which have combined to decrease mean annual discharge in the Colorado River.[40] In parts of the country where streamflow is strongly influenced by snowmelt, winter-spring runoff is happening at least five days earlier than in the mid-20th century at most streamflow gauges (Figure 4). Trends are based on the winter-spring center of volume, which is the date when half of the total streamflow has passed by each streamflow gauge. The trends observed in these data are consistent with observations of changes in seasonal snowmelt and streamflow in different regions of the country.[41-44]

Water deficits due to reductions in snowpack and snowmelt have critical consequences for human populations, as snowmelt-derived water is used for hydropower, agriculture, and drinking water supply.[24] California invested $2.7 billion in 2018 in new water projects, in part to deal with increasingly persistent drought conditions and the need for greater water security.[45] Additionally, western U.S. wildfire activity has been shown to strongly correspond with warming and earlier snowmelt.[7] In Alaska, the timing of snowmelt is one of the key factors that determines the onset of the fire season in the boreal forest.[46]

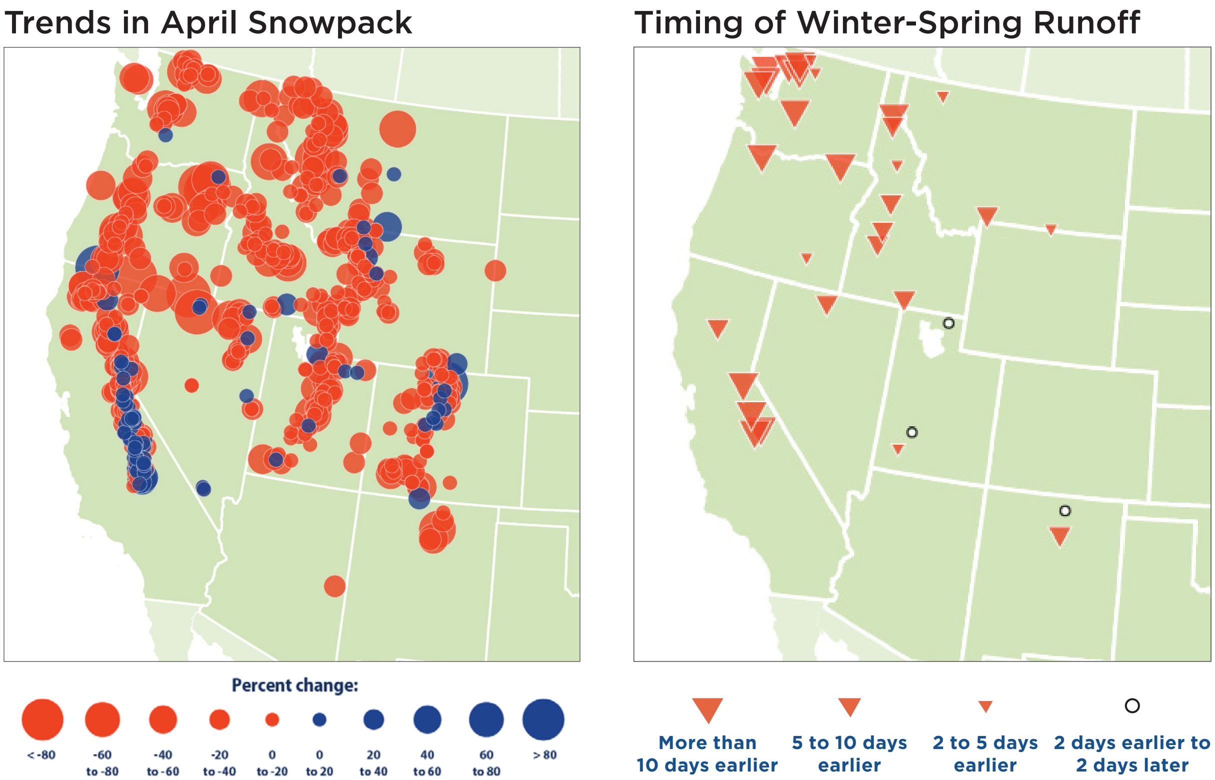


Figure 4. *Warming winters are driving declines in snowpack and earlier snowmelt and runoff. Trends in April snowpack in the western United States from 1955 to 2020 (left); timing of winter-spring runoff in the western United States from 1940 to 2018 (right). Source: EPA (2020).*[24, 109]

Winter outdoor recreation—particularly in the Northwest, Northern Great Plains, and Northeast regions of the United States—is impacted by warming winters. As a greater portion of precipitation falls as rain rather than snow, snowpack decreases, spring thaws occur earlier, and fall frosts occur later, activities such as skiing are limited to a shorter period in the winter and a smaller geographic range.[1] This can have serious economic consequences: in the Northeast alone, the winter recreation industry supports nearly 45,000 jobs and brings in $2.6–$2.7 billion in revenue annually.[1] Projections indicate that activities that rely on natural snow and ice cover may not be economically viable by 2100 except in the northernmost latitudes of the United States unless global greenhouse gas emissions are severely curtailed.[1]

INDICATORS OF MELTING AND THAWING LANDSCAPES

Northern regions are warming faster than the rest of the world.[47] The melting and thawing of frozen, ice-covered landscapes, such as the near-global retreat of glaciers, widespread loss of lake ice around the Northern Hemisphere, and disappearing Arctic sea ice, provide some of the most iconic imagery for documenting the impact of climate change.[47] Many of these changes occur over long timescales, corresponding to warmer seasonal temperatures and changes in the amount, timing, and type of seasonal precipitation.

Arctic Sea Ice

Over the past several decades, Arctic sea ice has declined rapidly, with the largest decreases occurring in the summer and fall. Arctic sea ice decline is, in large part, driven by rising temperatures and a longer ice melt season. Figure 5 shows this lengthening trend in the Arctic sea ice melt season, with the blue lines indicating the start and end of each year's season, and the shaded band delineating season length. Other factors that affect Arctic sea ice extent include fluctuations in oceanic and atmospheric circulation and natural annual and decadal variability. Declining sea ice negatively impacts Arctic ecosystems, and Arctic wildlife are already threatened by declining birth rates and restricted access to food sources because of reduced sea ice coverage and thickness.[33] These ecological impacts, as well as the loss of the ice itself, are also restricting the traditional subsistence hunting lifestyle of indigenous Arctic populations such as the Yup'ik, Iñupiat, and Inuit.

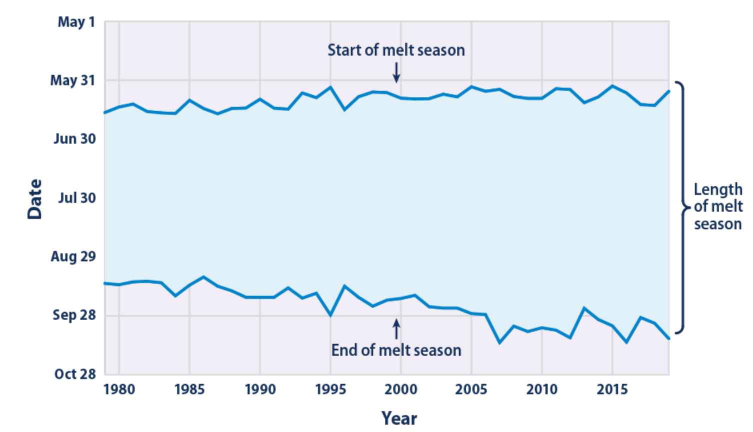


Figure 5. *Timing of each year's Arctic sea ice melt season. The shaded band spans from the date when ice begins to melt consistently until the date when it begins to refreeze. Source: EPA (2020).[110]*

Lake ice cover

Across 14 northern U.S. lakes, freeze dates are occurring later than they did historically, by about 0.5 to 1.5 days per decade. Additionally, lakes are, for the most part, thawing earlier in the spring, with ice breakup dates occurring up to 24 days earlier than they did

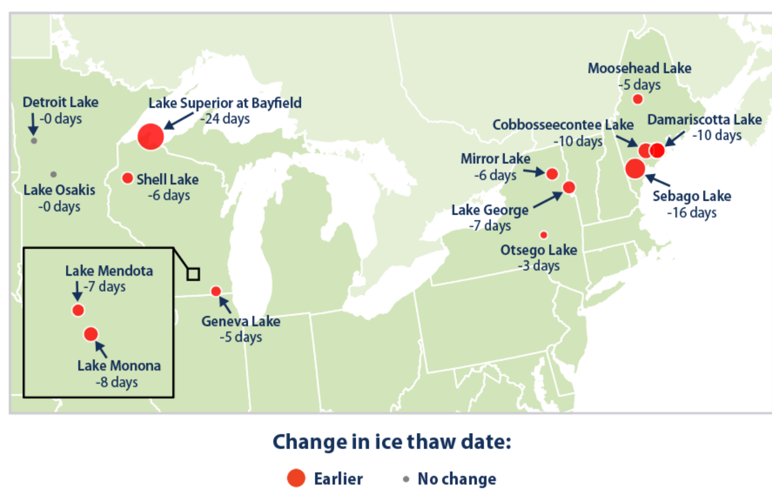


Figure 6. *Change in the "ice-off" date, or date of ice thawing and breakup, for 14 U.S. lakes during the period from 1905 to 2019. All of the lakes have red circles with negative numbers, which represent earlier thaw dates. Larger circles indicate larger changes. Source: EPA (2020).[111]*

110 years ago (Figure 6).[48] Later freeze dates and earlier thaw dates are a product of warming temperatures, as well as other climate factors such as cloud cover, heavy precipitation, and wind. This is consistent with observations of declines in seasonal ice cover duration and concentration in the Great Lakes region and throughout the Northern Hemisphere.[47,49] Early ice-out or thaw in the spring can impair water quality in lakes, contributing to anoxic conditions (low oxygen levels) or higher-than-average phosphorus and chlorophyll levels later in the summer months. The loss of lake ice has cultural significance for Native Americans, including limiting spiritual ceremonies, fish harvest, travel, recreation, and other activities.[50] The cultural importance of lake ice is evident in long-term records of lake ice that have been maintained for centuries.[47,49,51]

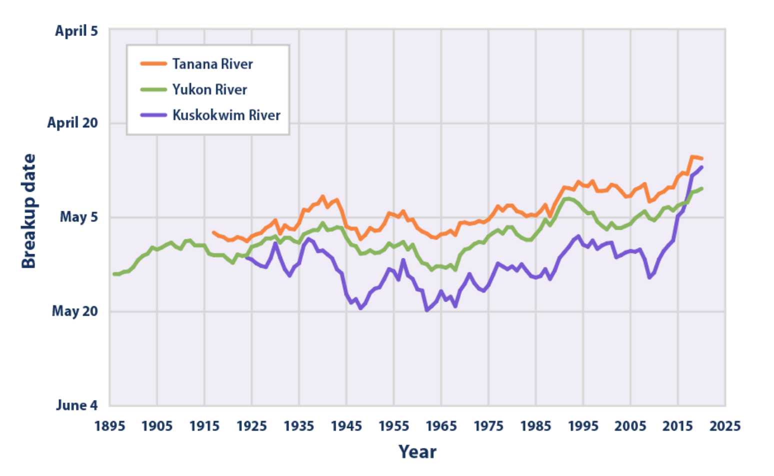


Figure 7. *Ice breakup dates at three Alaskan rivers: the Tanana, Kuskokwim, and Yukon. Source: EPA (2020).*[52]

Ice breakup in three Alaskan rivers Rising air temperatures are in part contributing to earlier spring ice breakup in the Tanana, Kuskokwim, and Yukon rivers in Alaska,[52] with nine of the 10 earliest ice breakup dates of the Tanana occurring between 1990 and present day and the earliest spring ice breakup in recorded history occurring in 2019.[53] At all three locations, the earliest breakup dates on record have occurred within the last two years. Earlier spring ice breakup has important implications for the communities that live along the Tanana and Yukon, as these rivers serve as centers for transportation, fishing, and hunting, and fulfill basic needs of surrounding wildlife communities. Furthermore, early thawing as well as thawing of permafrost has the potential to damage surrounding/overlying infrastructure and ecosystems through destructive ice movement, extreme flooding, and soil instability.[48]

THEME 3

BIOLOGICAL RESPONSES AND PHENOLOGY IN A WARMING WORLD

Many plants and animals are sensitive to and respond to changes in seasonal events (i.e., environmental drivers and cues such as temperature thresholds or snowmelt), and thus their responses make for good indicators. This section examines the ways in which plant and animal species are responding to ongoing climatological changes, such as shifts in temperature, frost, snowmelt, and wet and dry seasons. Observations reveal in rich detail the many ways in which ecosystems and the agriculture sector are affected by shifts in these seasonal patterns.

One such set of observations pertains to *phenology*. Phenology is the study of plant and animal life-cycle events in relation to environmental drivers such as weather and climate, and phenological data make quite useful indicators.[54] Ecological plant studies often report phenological events as occurring on an annual date that is tied to local environmental cues such as temperature or the length of winter (also referred to as vernalization). Recent observations have linked climate-induced changes in phenology to human health impacts, including changes in the duration of the pollen allergy season; cultural and outdoor recreational events, such as the National Cherry Blossom Festival; wildfire activity; and agricultural yield.[4,5] The text box at the end of this section further explores the implications of phenological changes in response to climate.

This report includes evidence of temperature increases and warmer winters leading to earlier snowmelt and longer frost-free seasons. For example, the duration of the freeze-thaw season has increased steadily in recent years (Figure 8). This indicator uses satellite measurements to track the number of days per year in the contiguous 48 states and Alaska in which the ground is unfrozen. Changes in unfrozen days and the seasonal freeze-thaw cycle are important ecologically, as a reduction in frozen land surfaces can lead to greater vegetation growth and productivity.[55]

Freeze-Thaw Conditions: Frost-Free Season, 1979–2019

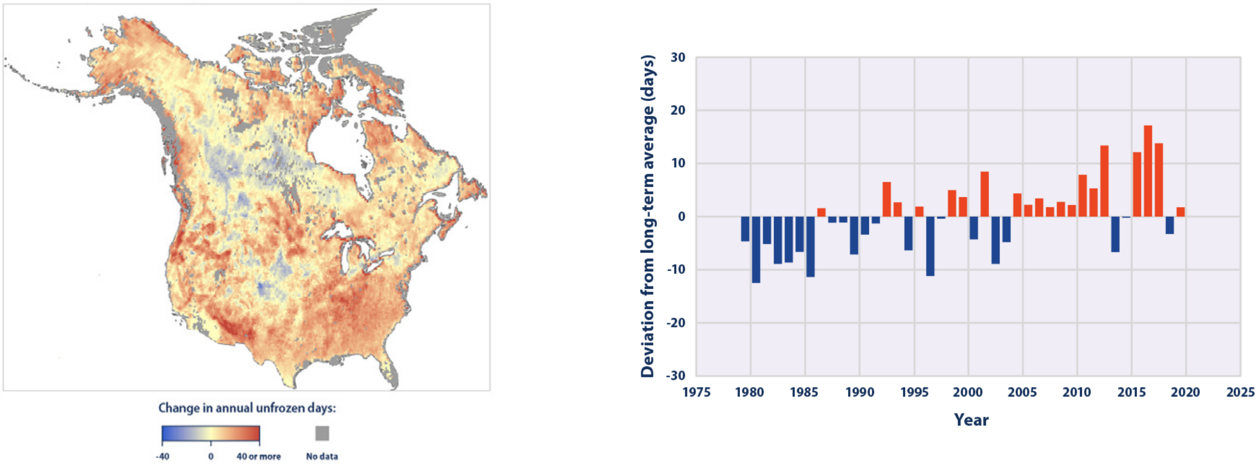


Figure 8. *Left: Change in annual frost-free season in North America. Right: Length of the frost-free season in the contiguous 48 states compared with the historical average (1979–2019). For each year, the bar represents the number of days shorter or longer than average. Positive numbers represent years with more frost-free days than average (red bars). Negative numbers represent years with fewer frost-free days than average (blue bars). Source: EPA (2020).[56]*

In addition to an overall increase in the number of annual unfrozen days, the United States is experiencing a longer growing season. Since 1980, the last spring frost has occurred an average of three-and-a-half days earlier than the long-term average, and the first fall frost has occurred about three days later (Figure 8).[56] Correspondingly, the average length of the growing season has increased by more than two weeks in the contiguous 48 states since 1895, with a more rapid expansion since the 1970s (Figure 9).[57]

Length of the Growing Season in the Contiguous 48 States, 1895–2020

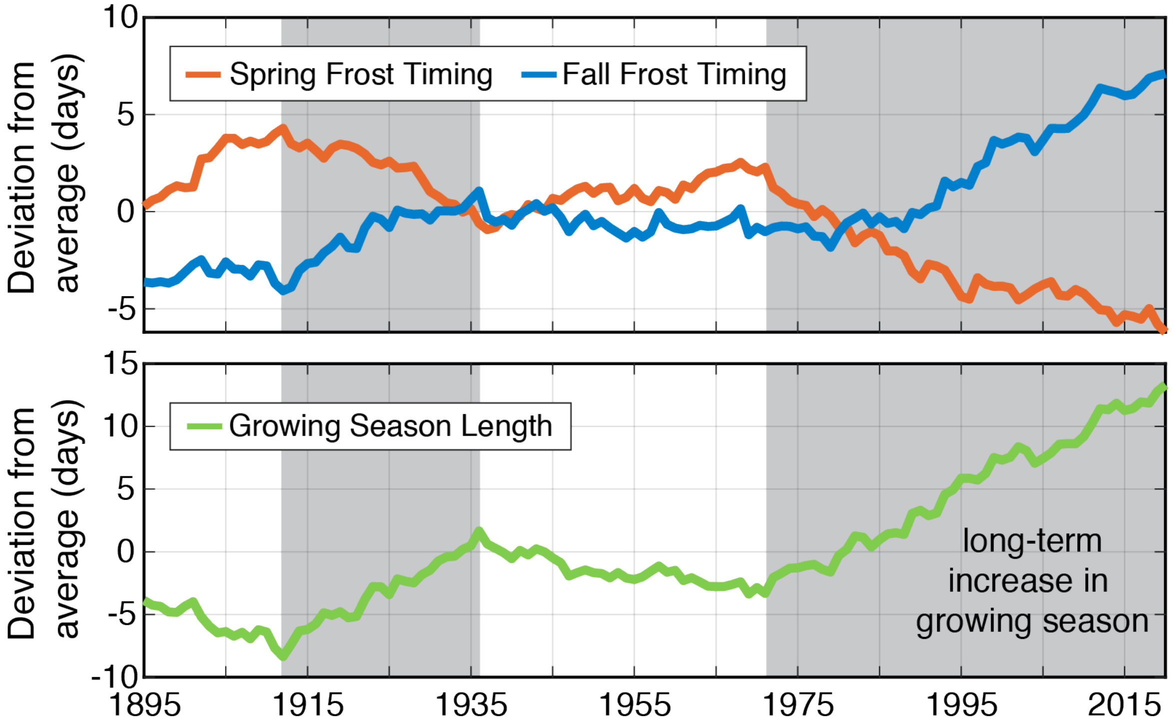


Figure 9. *Deviation in the timing of spring and fall frost dates from 1895–2020 relative to the long-term average (1895–2020). Bottom: Deviation in growing season length from 1895–2020 relative to the long-term average (1895–2020). Grey shading denotes periods in which the length of the growing season is increasing over multiple decades, largely in correspondence to earlier cessation of spring frost and later onset of fall frost. Source: EPA (2020).*[57]

Regionally, the largest increases in the length of the growing season have occurred in the Southwest, in areas sensitive to warming and where exposure to frost is historically low (Figure 10). For example, both Arizona and California experienced nearly 50 more growing days in 2020 than in 1895.[58]

Extended growing seasons result in both positive and negative impacts on plant species and agriculture. Studies show that longer growing seasons extend forage production into late fall and early spring, which benefits farmers

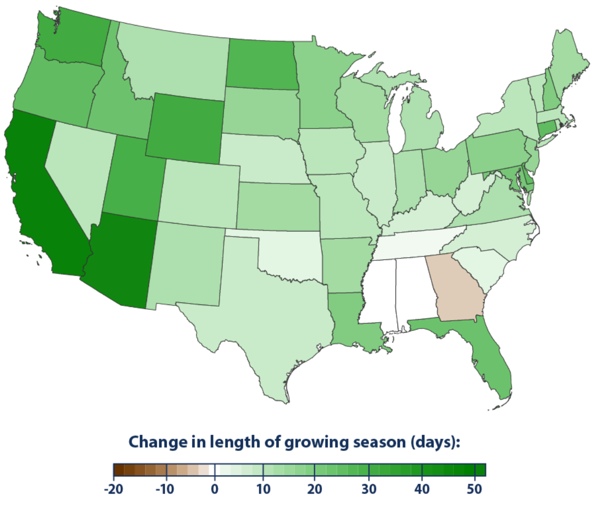


Figure 10. *Change in the length of the growing season for each state in the contiguous 48 states from 1895 to 2020. Source: EPA (2020).*[57]

by lessening their need to produce reserves to support livestock in winter.[59] At the same time, warming is expected to diminish forage quality, which requires farmers to produce more forage for their livestock.[59] In addition, warmer winters have increased survival rates for insect pests, which further stress crops and increase the need and costs for pesticides during the growing season.

The agricultural sector relies heavily on predictable seasonal patterns in temperature, precipitation, and corresponding animal and crop life cycles. In western regions fed by snowmelt, such as off the Sierras, Cascades, and Rockies, earlier snowmelt or rainy seasons shifts runoff and water availability away from the peak of the growing season when it is needed most. Surface water shortages are particularly damaging to crop yields and increase the need for supplementary groundwater pumping and irrigation.[60] Water shortages are increasingly compounded by extreme heat events and drought.[61,62]

Warming-induced stress on vegetation and crops can carry a hefty price tag. Many tree and vine crops require a certain number of "chill hours" during the winter to properly flower and fruit; climate change-induced warming has begun and is expected to continue to reduce the number of winter chill hours, which can negatively impact crops.[63] For example, in the winter of 2016–2017, warmer weather contributed to an 80-percent loss in Georgia's peach industry the following summer, with roughly two-thirds of those losses attributed to a lack of chill hours necessary for the fruit development.[25]

In addition to impacting agricultural yields, increases in the number of growing and flowering days have direct implications for human health. For example, the season for ragweed pollen, one of the most common environmental allergens in the United States, grew longer at 10 of 11 study locations in the Midwest from 1995 to 2015 (Figure 11). These trends are strongly related to changes in the length of the frost-free season and the timing of the first fall frost.[64,65] The trend in a longer ragweed season is more pronounced within northern states, which is consistent with warming trends showing that higher latitudes are experiencing more rapid and intense warming.[66] Higher temperatures throughout ragweed pollen season also enable ragweed plants to produce larger quantities of more allergenic pollen.[64,67]

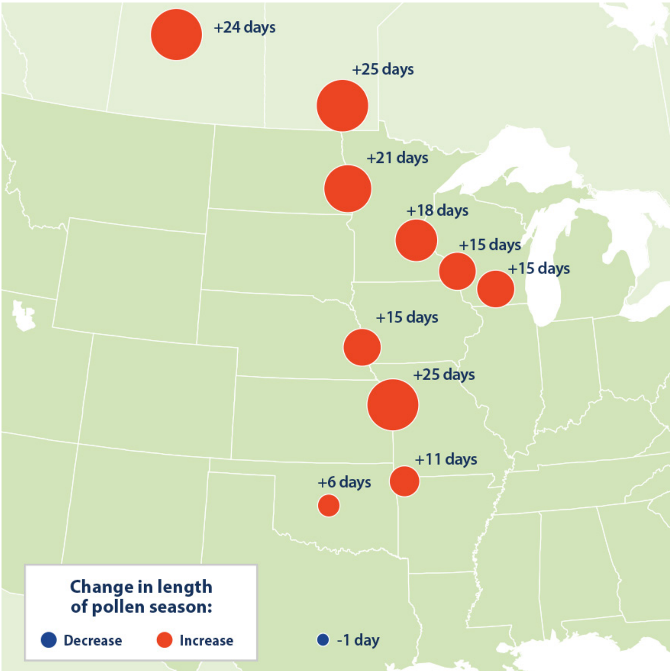


Figure 11. Change in the length in the ragweed pollen season at 11 sites in the Midwest between 1995 and 2015. Source: EPA (2020).[64]

Observed increases in growing degree days also correspond with a longer grass pollen season and an earlier start date for oak and birch pollen seasons.[68] Together, these factors contribute to longer allergy seasons and higher pollen counts. The health effects of a longer and more intense allergy season have already been observed, such as with increased sales of over-the-counter allergy medicine, more emergency department visits for asthma attacks, and an increase in hay fever cases.[69] A recent study of pollen observations found that advances in the initiation of the pollen season and increases in spring pollen integrals strongly support a phenological seasonal shift to earlier in the year.[70]

Additionally, a warming climate can enhance the risk of vector-borne diseases, such as Lyme disease and West Nile virus, by increasing the range of suitable vector habitat. The incidence of Lyme disease in the United States has been increasing due to many factors. Increased temperatures can create a longer seasonal period of deer tick activity and expanded habitat (see the section on Supplementary Indicators of Seasonal Changes).[71] In 2010, Lyme disease ticks were confirmed in the upper Great Lakes region at Isle Royale and nearby Grand Portage National Monument (just below the U.S.-Canadian border) for the first time.[72]

A welcome sign of spring occurs when certain flowering trees and plants blossom—a phenological event. Changes in the timing of these events has significance to society and tourism. The National Cherry Blossom Festival draws more than 1.5 million visitors annually to Washington, DC, to enjoy blooms from the city's 3,000 cherry trees. Each year, the National Park Service determines the dates of the festival by estimating when the trees will be in peak bloom based on local temperatures during the winter and early spring. The average peak bloom date has been April 4 since recordkeeping began in 1921. However, the peak bloom date has occurred before April 4 in 14 of the past 20 years, and peak bloom dates shifted earlier by nearly six days between 1921 and 2019 (see Supplementary Indicators of Seasonal Changes).[73]

Animals also respond to seasonal changes. For example, changes in seasonality influence migration patterns and behavior for many animals. Bird migration patterns are influenced by many environmental cues, including seasonal temperatures, and long-term observations show that many bird species have change their wintering ranges. The average winter center of abundance of 305 North American bird species shifted northward by at least 40 miles between 1966 and 2013 (Figure 12),[74] with nearly 50 bird species shifting northward by more than 200 miles. Similarly, observations show that the average center of biomass for 140 marine fish and invertebrate species shifted an average of 20 miles northward and 21 feet deeper from 1982 to 2018.[75] Other species shifts are explored in the text box below on phenological mismatch.

Change in Latitude of the Average Winter Bird Center of Abundance, 1966–2013

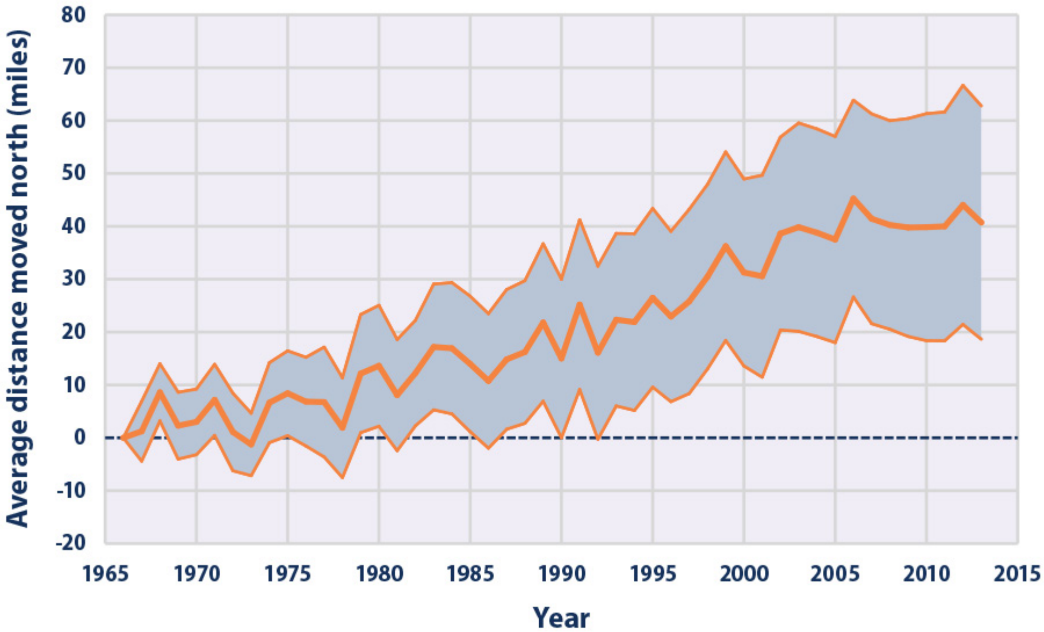


Figure 12. *Change in latitude of the average winter center of abundance among 305 North American bird species, 1966–2013. The shaded band shows the upper and lower confidence intervals or range of values around the average, based on the number of measurements collected and the precision of the methods used. Source: EPA (2020).[74]*

Some species are benefiting from climate change, although this can come at a cost to others. One such example is the southern pine beetle. These beetles are freeze-intolerant, and their range has historically been restricted to areas south of New Jersey. However, warmer winters have allowed southern pine beetles to expand their range into New York, Connecticut, Massachusetts, and Rhode Island, with recent northern outbreaks partially attributed to a winter warming trend.[76,77] Models estimate that by midcentury, southern pine beetles could expand their range throughout the northeastern United States and even into Canada.[78] The expansion of this beetle into new areas is an ecological and economic concern, as they can cause extensive mortality in pine forests, disrupting ecosystems services, shifting forest structure, and threatening native biodiversity.[76,78]

Similarly, mountain pine beetles pose a threat to pine forests in the western United States. Since 2000, these beetles have impacted roughly 10.3 million hectares in this region and are ranked as the most damaging forest insect on the National Insect and Disease Forest Risk Assessment.[79] When mountain pine beetle infestations lead to tree mortality, they also increase the amount of fuel available for wildfires. Moreover, climate change is expected to lead to higher temperatures and more frequent and severe droughts—conditions that increase the frequency and severity of both beetle outbreaks and wildfires.[80] Ultimately, mountain pine beetle outbreaks and wildfires result in compounding impacts, creating conditions in the western United States conducive to both increased forest mortality and more frequent wildfires, but also downstream impacts such as reduced air quality, river pollution, and erosion.

TIMING MATTERS: INDICATORS OF PHENOLOGICAL MISMATCH

The science of phenology studies periodic events in the life cycles of plants and animals that are influenced by variations in climate. Due to climate change, seasonal interactions among species that have historically been synchronized—such as the timing of caterpillar eggs hatching to match budbreak of their host trees for food—may become un-synchronized (i.e., occurring at different times from each other) as species respond differently to changes in seasonality.[81] This phenomenon is referred to as phenological mismatch (or trophic asynchrony) and can disrupt population dynamics, ecosystems, and ecosystem services.[82]

Phenological mismatch has been observed with Pacific black brant (a type of goose) and sedge (plants that are a food source for the geese) in Alaska. Due to warmer winters and earlier springs, these migratory geese have been arriving in Alaska earlier each year. Their earlier arrival means they feed on sedge earlier in the plant's life cycle, leading to reduced biomass, reproduction, and genetic diversity in the plant population. In turn, these changes have implications for a shift in the sedge system from being a summer-season carbon sink to a carbon source.[83]

Because it can be difficult to quantify and attribute phenological mismatch in observational studies, experimental approaches have also been undertaken to explore whether certain biotic interactions would experience mismatch and what the consequences might be. Several studies have shown that phenological mismatch between insect hatches and budbreak or leaf availability of their host plant can be caused by higher temperatures, and that this may constrain the insect populations.[84]

Generally, either one or both species in the mismatched interaction will experience negative consequences based on the nature of their relationship (e.g., antagonistic predator-prey interactions may see an increase in abundance of the prey if they become mismatched from their predator, whereas in a mutualistic interaction—such as with pollinators and flowers—both species may suffer from decreased nutrition and reproductive success, respectively).[85] Although it can be difficult to predict how interspecies interactions and ecosystem communities will shift under climate change, we can look to current examples as illustrations of the types of changes that could occur more frequently in the future.

Phenological mismatches can also occur at the societal level, posing particular challenges for Tribal and Alaska Native communities. For example, shifts in the timing of plant flowering or fruit production, or in the timing of bird, mammal, or fish migration, can reduce the availability of culturally significant foods and medicinal plants, make them available outside of legal harvest windows, or create mismatches with traditional time-specific ceremonies or other events. In Alaska, thinning sea ice in springtime creates dangerous conditions for seal and walrus hunters.[113]

THEME 4
SEASONALITY AND EXTREME EVENTS

In addition to its impact on long-term average changes in seasonality, climate change can affect the frequency and/or severity of shorter-term acute or extreme events with disproportionately large-scale impacts. Extreme climatological events that are closely linked to seasons include heat waves, wildfires, and tropical cyclone activity. In many cases, climate change is increasing the frequency and severity of these seasonal extremes, as well as lengthening the period of the year during which they occur.

Summer heat waves are becoming more intense and frequent, and the duration of the period of the year experiencing heat waves has increased as a result of climate change.[86,87] In this report, heat waves are defined as a period of two or more consecutive days where the daily minimum apparent temperature (actual temperature adjusted for humidity) exceeds the 85th percentile of historical July and August temperatures (1981–2010) for that location. In the last half century, the United States has seen marked increases in extreme high temperatures, with heat waves occurring almost three times more frequently in recent years compared with the long-term average.[27] An analysis of urban temperature shows 46 of 50 major cities in the United States experienced a statistically significant increase in heat wave frequency between the 1960s and 2010s (Figure 13). The average heat wave season (the number of days between the first heat wave of the year and the last) increased by 47 days across the 50 cities over the same time period.[27]

Changes in Heat Wave Frequency and Season, 1961–2019

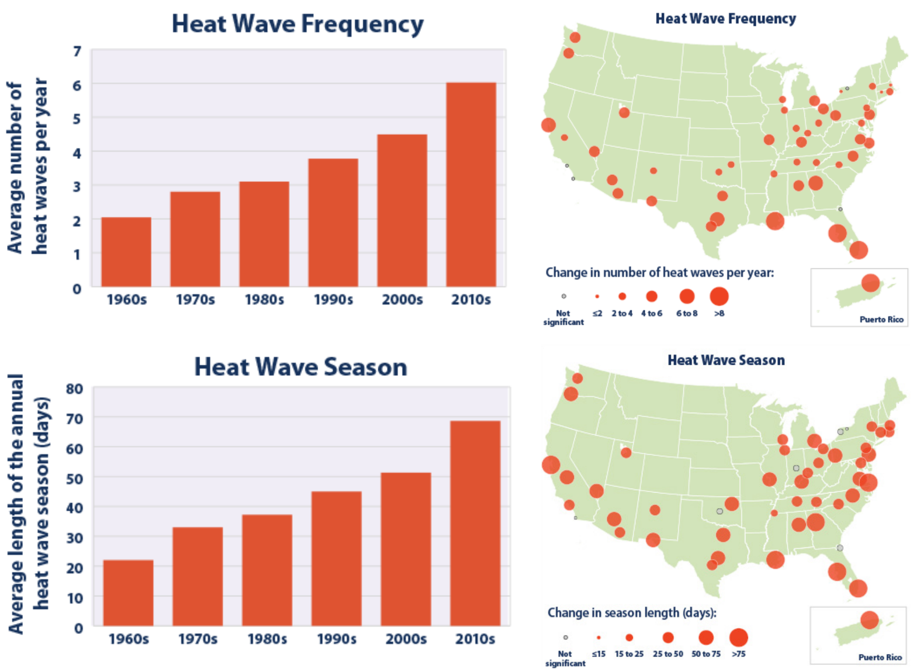


Figure 13. *Changes in the number of heat waves per year (frequency) and the number of days between the first and last heat wave of the year (season length). A heat wave is defined as a period of two or more consecutive days where the daily minimum apparent temperature exceeds the 85th percentile of historical July and August temperatures (1981–2010) for that location. These data were analyzed from 1961 to 2019 for 50 large U.S. metropolitan areas. The graphs show averages across all 50 metropolitan areas by decade. The size/color of each circle in the maps indicates the rate of change per decade. Hatching represents cities where the trend is not statistically significant. Source: EPA (2020).[27]*

Heat waves, especially when coupled with periods of high humidity, have consequences for animals, ecosystems, and human communities.[30,31] Extreme heat events can induce a range of dangerous—and sometimes fatal—human health conditions, including heat stroke, and have been linked to respiratory problems as a result of harmful air pollutant build-up.[88] In the United States, extreme heat events cause more deaths annually than any other form of extreme weather.[89] Vulnerable populations, including elderly people and people living in poverty, often experience particularly negative impacts from extreme heat.[90]

Warmer conditions also contribute to more intense and prolonged wildfire seasons in the United States. Changes in wildfire seasons are connected to rising temperatures through a range of processes in conjunction with other human-induced factors.[91,92] For example, human activities and land management practices also affect wildfire activity, and preferred practices in wildfire management have evolved over time, from older policies that favored complete wildfire prevention to more recent policies of wildfire suppression and controlled burns. Resources available to fight and manage wildfires can also influence the amount of area burned over time. Warmer springs and summers increase atmospheric aridity and generate more dry fuel and flammable forests that feed large wildfires. In California, warming increases the likelihood that dry fuels persist into fall when strong wind events, such as the Santa Ana winds, fan and spread wildfires over large areas.[93] Compounding matters, heat waves can amplify these processes to precondition landscapes for large wildfires. Declines in summer precipitation and wetting rain days (widespread rain that over an extended period of time significantly reduces fire danger[94]) are also a key driver in the increased extent of wildfires in many areas of the western United States.[95]

Since the late 20th century, the length of the wildfire season—the period between the first and last large wildfire of the year—has increased in step with temperature increases. On average, fire seasons from 2003–2012 were almost three months longer than those from 1973–1982.[7] Wildfire seasons have also become more severe, with more frequent and larger fires burning larger areas. Notably, the five years with the greatest wildfire acreage burned since 1960 all occurred in the last 15 years, with burn extents during the 2015, 2017, and 2020 seasons exceeding 10 million acres nationally.[96] The increase in burn area has been most significant in western states (Figure 14), where the area burned has more than doubled over the past 40 years in many states. While most increases have occurred in the summer months during the height of the wildfire season, additional increases have occurred in the spring and fall, signaling an extension of the wildfire season through time. Meteorological observations used to estimate the length of fire weather season show increases over a similar period.[97]

Wildfire Activity: Burned Acres and Seasonality in the United States, 1984–2017

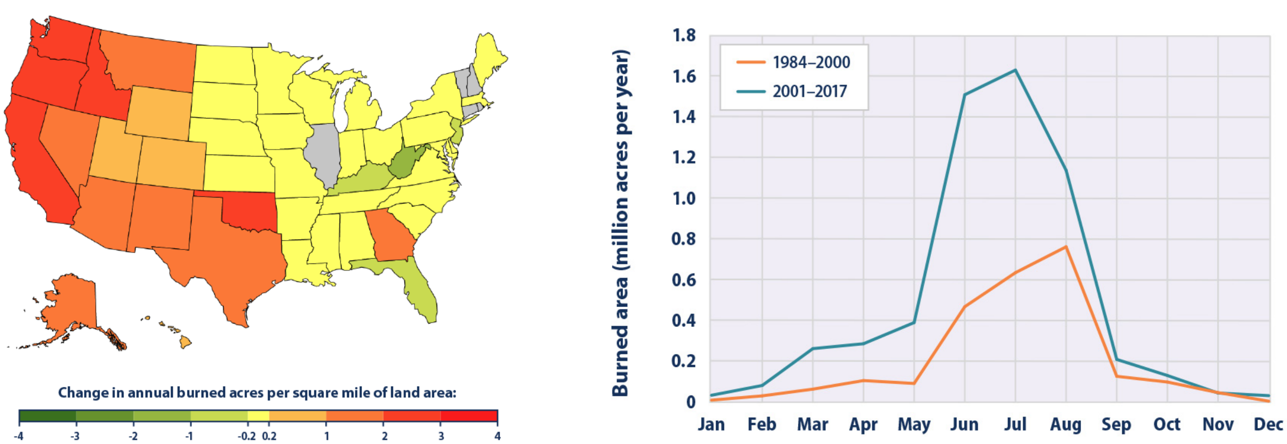


Figure 14. *Left: Change over time in the number of acres burned in each state as a proportion of that state's total land area, based on a comparison between 1984–1999 and 2000–2014. Right: Comparison in the monthly distribution of burned area due to wildfires in the United States between the periods 1984–2000 and 2001–2017. Source: EPA (2020).[112]*

Increasingly prolonged and more severe wildfire seasons have had devastating impacts on human communities and ecological systems across the western United States. Tangible impacts, such as the destruction of residences and city infrastructure, are often represented in dollar loss statistics that indicate the “price” of wildfire burn in a given year. The total U.S. wildfire dollar loss nearly doubled between 2010 and 2018, rising from $13.4 billion to $25.6 billion.[98] The National Oceanic and Atmospheric Administration tracks the number and cost of billion-dollar weather and climate disasters (individual events where the cost of damages meets or exceeds $1 billion).1 Between 1980 and 2020, there were 18 billion-dollar wildfire seasons in the United States; 15 of those had occurred since 2000.[99] Eight of these billion-dollar wildfire seasons occurred between 2010 and 2020, with the estimated total costs for these eight seasons totaling over $58 billion.[99] Some of these damages were influenced by increased development and land use changes during this time period.

The consequences of worsening wildfire seasons far exceed those represented by a dollar statistic. For example, smoke from wildfires has significant air quality impacts: in 2020 alone, more than 50 million—or one in seven—Americans experienced “unhealthy” air from smoke during wildfire season.[100] In addition, wildfire smoke can significantly decrease photosynthetic activity, negatively impacting plant communities far beyond immediate burn areas.[101] Severe wildfires also have detrimental impacts on local water quality. Post-burn soils are hydrophobic, meaning that they repel water and increase surface runoff during storms. These factors increase the risk of mudslides as well as the likelihood of debris and elevated levels of nitrogen and phosphorus entering water systems and causing algal blooms.[102]

The degree to which climate change has impacted hurricanes and tropical storms, collectively referred to as tropical cyclones, is a topic of intense interest given that their extreme rains, high winds, and storm surge can cause severe property damage, soil erosion, flooding, and loss of life. Tropical cyclones most commonly occur during the “hurricane season” running from June through November and draw their energy from warm tropical oceans. Changes in sea surface temperatures can alter the intensity of wind and rain associated with tropical cyclones.

Observations show an upward, non-significant trend in the frequency of hurricanes occurring in the North Atlantic since the 1970s,[103] which has been driven, in part, by reductions in aerosols from human activity.[104] The intensity and duration of tropical cyclones also increased during that period as measured using the Accumulated Cyclone Energy (ACE) Index, which considers maximum wind speeds throughout the lifetime of each observed storm.[103] A recent study found that observed increases in the intensification of hurricanes between 1982 and 2009 are highly unusual compared to modeled internal climate variability and are consistent with a positive contribution from human-caused climate change.[105] However, it is premature to conclude with high confidence that climate change has imparted a broadscale detectable impact on hurricane activity, because the quality of the observed record is limited prior to 1970 and natural variability plays such a large role.

Researchers have also investigated whether the Atlantic hurricane season is lengthening. One study found that the dates between the earliest and latest tropical cyclone formations in the Atlantic were widening by about one day per year, potentially as a result of increasing sea surface temperatures.[106] Figure 15 shows the number of days between the first and last tropical cyclone, hurricane, and major hurricane within the Atlantic basin for each calendar year since 1979. Similar to other studies, this analysis shows that the length of the season has grown by about 1–2 days per year over the recent period. However, the attribution of these trends to any single driving factor is difficult and other studies have found conflicting results meaning that the uncertainty in these trends is high.[107]

Change in the Number of Days in the Atlantic Hurricane Season, 1970–2020

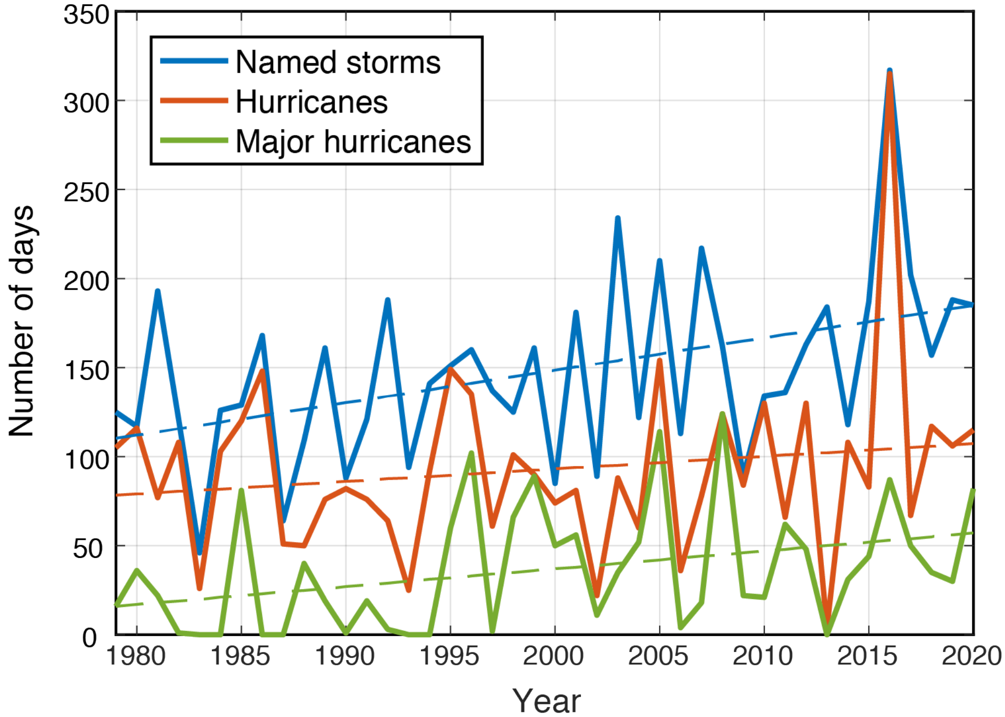


Figure 15. *Number of days between first and last occurrence of named storms, hurricanes, and major hurricanes in the Atlantic and linear trends for the period 1970–2020. Data source: National Hurricane Center HURDAT2 archive.*

SUMMARY AND RELATED RESEARCH

The systems and relationships described above provide multiple lines of evidence showing that many changes in seasonality are consistent with a warming world. Tracking these observed changes through indicators is one way in which we can better communicate and understand the broader implications of a changing climate. Together, the indicators and other observational evidence related to seasonality discussed in this report clearly demonstrate that such changes are occurring now across all regions of the United States, and have far-reaching associated consequences to ecosystems, human health and well-being, and the economy.

This report leverages several readily available data sources; however, additional monitoring, data, and indicators are needed to improve our ability to characterize these changes and address gaps in knowledge. For example, only limited data are available to understand and develop indicators on changes in seasonality and phenology in marine and coastal environments. Several biological and life-cycle processes are seasonal and based on environmental cues (e.g., fish migration, phytoplankton blooms, spawning). Similarly, more comprehensive and widespread sampling data on pollen in the United States are needed to better characterize seasonal changes in pollen and allergies for the purposes of protecting public health.

The climate research community is increasingly interested in research at seasonal-to-sub-seasonal scales and climate-sensitive processes relevant to such areas as public health and national security. Predictive models are often used to estimate the severity of extreme heat in the upcoming summer, the spread of infectious diseases in winter, or how mosquito populations will respond to precipitation and temperatures in spring. Indicators provide insights into the historical behavior of these seasonal processes, which can be assimilated into predictive models or used to benchmark the severity of forecasted outcomes. Changes in the timing and nature of seasonal processes will require adjusting policies and management practices to adapt to new conditions. Thus, combining historically based data and indicators with predictive modeling will improve our ability to understand and plan for these changes.

SUPPLEMENTARY INDICATORS OF SEASONAL CHANGES

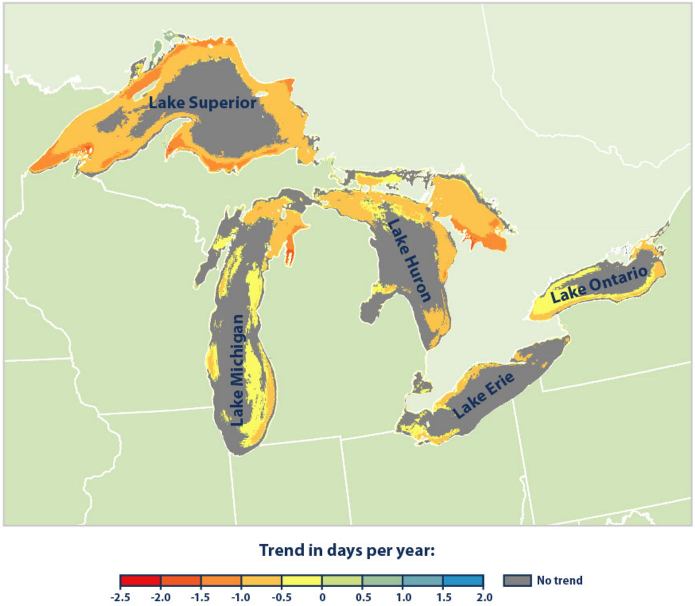
This section presents an expanded set of EPA's climate change indicators relevant to seasonality to supplement the indicators and figures presented in the main report and to demonstrate the breadth and depth of seasonality changes occurring in the United States and around the world. The following pages show figures and key points for each supplementary indicator. The indicators include a range of temporal and spatial scales, and it is best to interpret these changes individually.

The summary table below summarizes all of EPA's climate change indicators features in the main report and this supplementary section. For reference, the indicators are grouped into the general dimensions of seasonality discussed in the report, including seasonal timing, length, and variability. For background information and additional figure details for all of these indicators, see the EPA Climate Change Indicators webpage.

Table 1: Summary of EPA's Climate Change Indicators Related to Seasonality.
***Bolded** indicators are those that appear in the supplementary section below.*

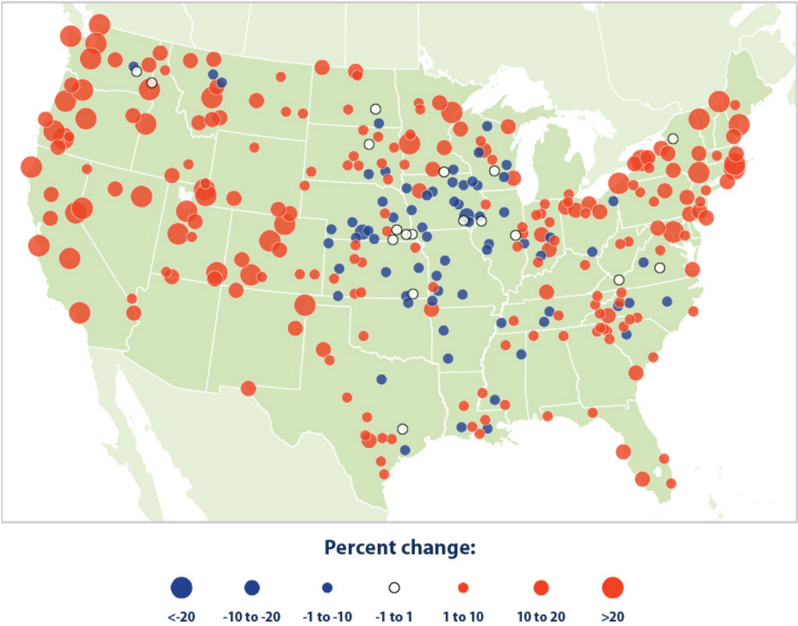
SEASON LENGTH	SEASON TIMING	SEASONAL VARIABILITY
1. Great Lakes Ice Cover	**1. Peak Snowpack Date**	**1. Heating and Cooling Degree Days**
2. Arctic Sea Ice Melt Season	**2. High Winter-Spring Flow Carried by Rivers and Streams**	**2. Snowfall**
3. Hurricane Season	3. Alaskan River Ice Breakup	3. Seasonal Temperatures
4. Freeze-Thaw Season (Unfrozen Days)	**4. Lake Ice (Freeze-thaw Dates)**	**4. Glacier Mass Balance**
5. Growing Season	5. Timing of Spring Snowmelt	**5. Residential Energy Use (summer and winter)**
6. Growing Degree Days	**6. Leaf and Bloom Dates**	**6. Lyme Disease Prevalence**
7. Heat Wave Season	**7. Cherry Blossom Bloom Dates**	**7. Snow-to-Precipitation Ratio**
8. Ragweed Pollen Season		8. Wildfire Activity: Extent
9. Wildfire Activity: Season		

SEASON LENGTH



Key Point: Since 1973, ice cover on Lakes Huron, Michigan, Ontario, and Superior has decreased at rates ranging from approximately one-quarter of a day to more than half a day per year.

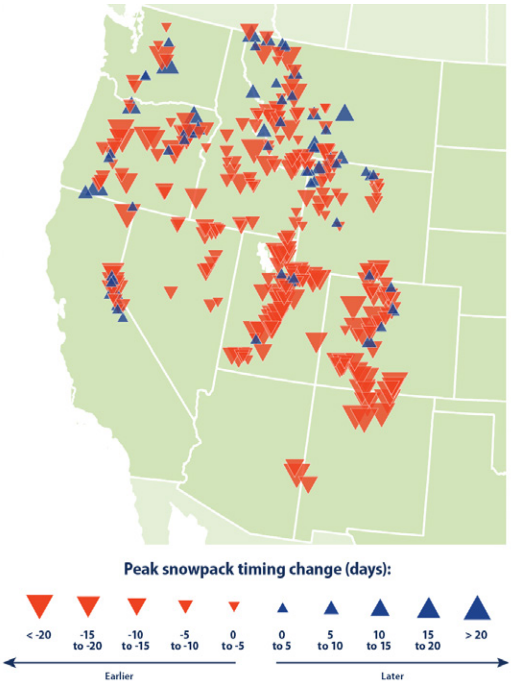
Average annual rate of change in the duration of ice cover in the Great Lakes from 1973–2019. Duration is measured as the number of days in which each pixel has an ice cover concentration of at least 10 percent.



Key Point: Between 1994 and 2018, the number of growing degree days increased in all regions of the contiguous 48 states. The largest increases occurred in the Southeast (354 days), Southern Great Plains (331 days), and Southwest (331 days). The smallest increases in days occurred in the Northern Great Plains (198 days) and Midwest (199 days).

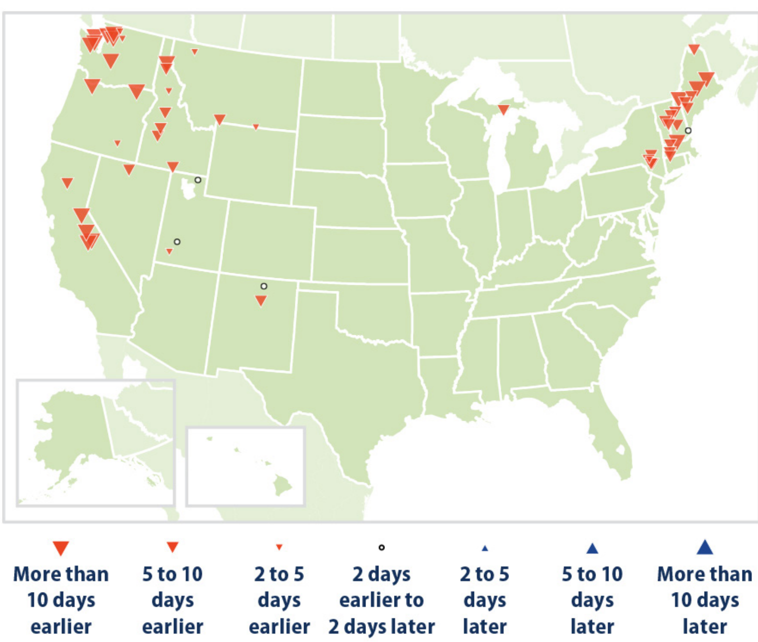
Change in number of growing degree days in the contiguous 48 states from 1948–2020.

SEASON TIMING



Key Point: The timing of peak snowpack shifted earlier by an average of 9 days from 1982–2020 in the West.

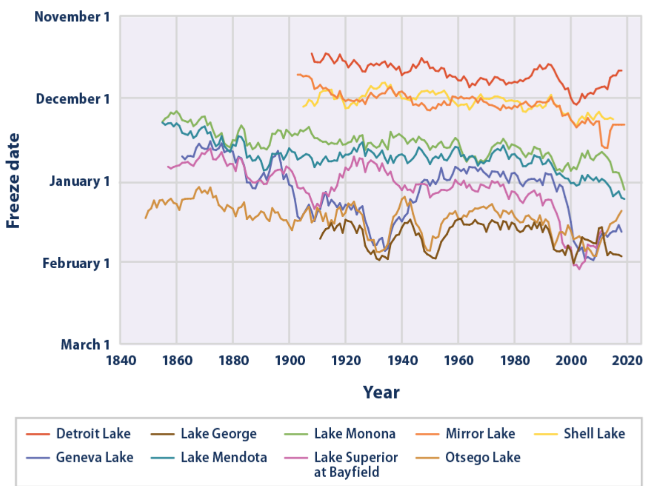
Trends in the date when snowpack reaches its deepest level across the western United States. Blue circles represent a shift to later timing; red circles represent a shift to earlier timing.

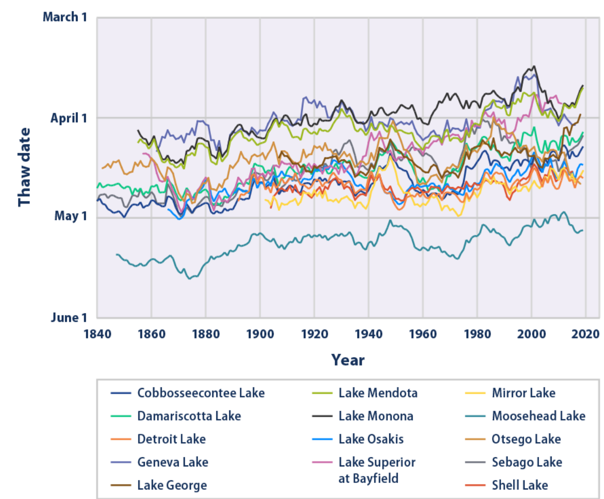


Key Point: In parts of the country with substantial snowmelt, winter-spring runoff is happening at least five days earlier than in the mid-20th century at most gauges. The largest changes have occurred in the Pacific Northwest and Northeast.

Changes in the timing of annual high winter-spring flow carried by rivers and streams from 1940–2018. 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.

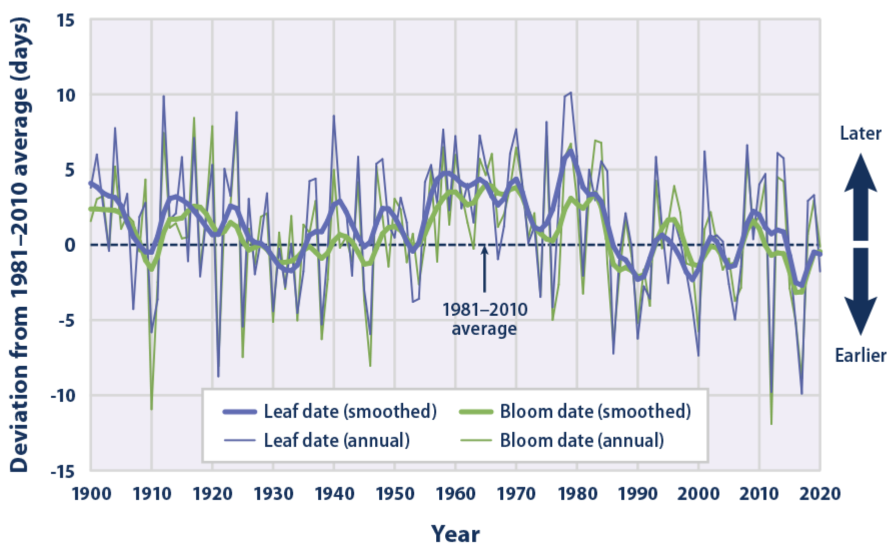
SEASON TIMING





Date of first freeze for nine U.S. lakes and date of ice thawing and breakup for 14 U.S. lakes. The data are available from as early as 1840 to 2016, depending on the lake, and have been smoothed using a nine-year moving average.

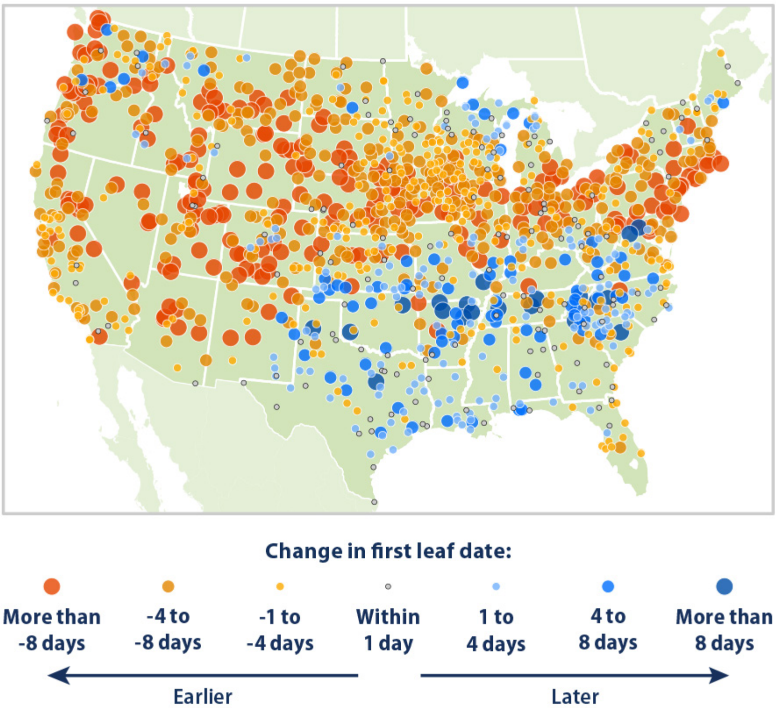
Key Point: Freeze dates have shifted later at a rate of roughly half a day to one-and-a-half days per decade. Thaw dates for most of these lakes show a trend toward earlier ice breakup in the spring. Spring thaw dates have grown earlier by up to 24 days in the past 111 years.



Key Point: First leaf and bloom dates in lilacs and honeysuckles in the contiguous 48 states show a great deal of year-to-year variability.

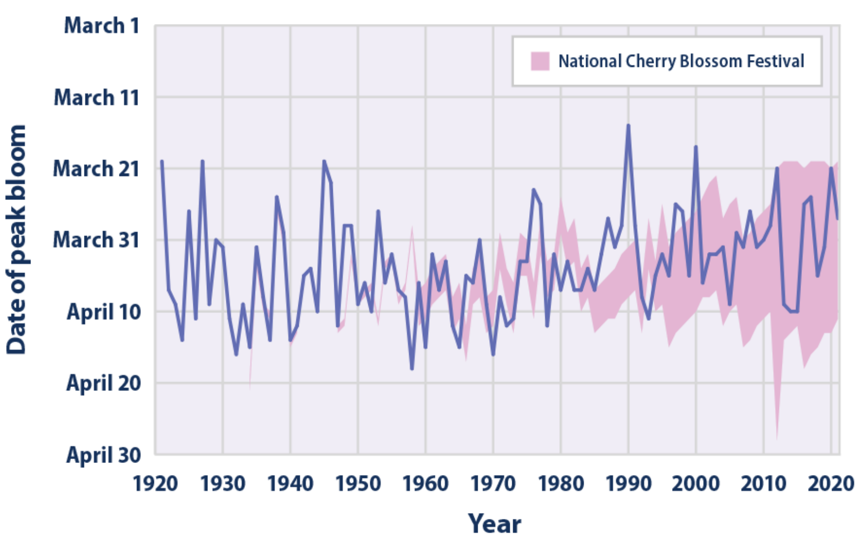
Trends in lilac and honeysuckle first leaf dates and first bloom dates across the contiguous 48 states, using the 1981–2010 average as a baseline. Positive values indicate that leaf growth and blooming began later in the year, and negative values indicate that leafing and blooming occurred earlier.

SEASON TIMING



Key Point: Leaf and bloom events are happening earlier throughout the North and West but later in much of the South. This observation is generally consistent with regional differences in temperature change.

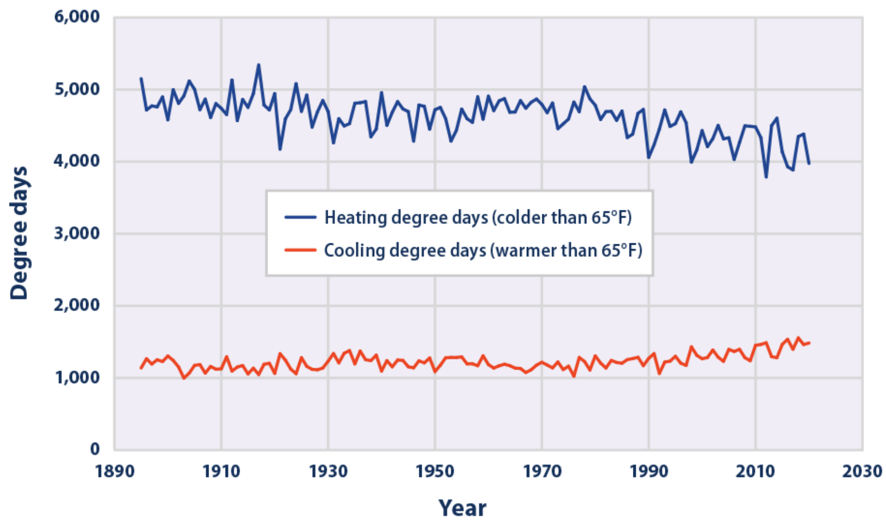
First leaf date trends in lilac and honeysuckle at weather stations across the contiguous 48 states. This map compares the average first leaf date for two 10-year periods (1951–1960 and 2011–2020).



Key Point: Peak bloom date for the cherry trees is occurring earlier than it did in the past. Since 1921, peak bloom dates have shifted earlier by approximately six days. The average peak bloom date is April 4th.

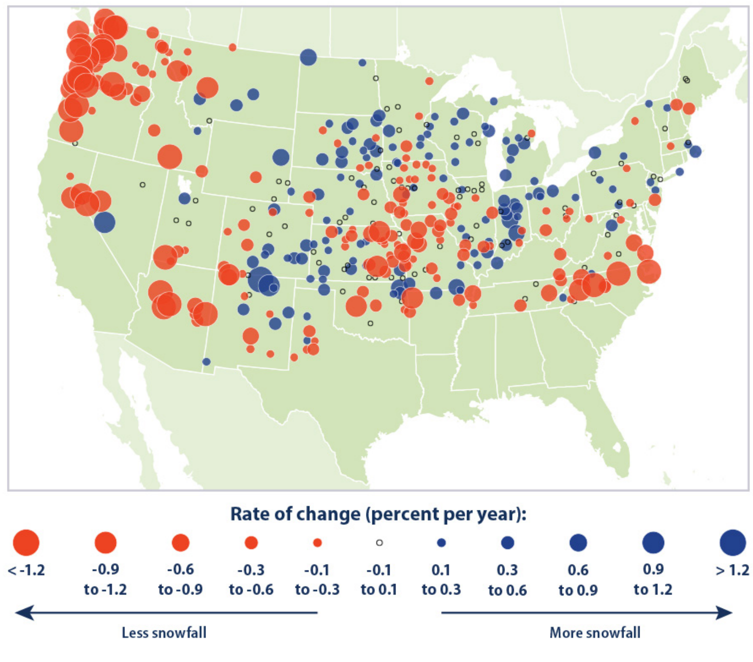
Peak bloom date each year for the main type of cherry tree around the Tidal Basin in Washington, DC. The peak bloom date occurs when 70 percent of the blossoms are in full bloom. The shaded band shows the timing of the annual National Cherry Blossom Festival.

SEASONAL VARIABILITY



Key Point: Since around 1980, the number of heating degree days has decreased and the number of cooling degree days has increased relative to the 20th century average. The recent increase in cooling days is driven by more frequent days above 65°F and more frequent extreme high temperatures.

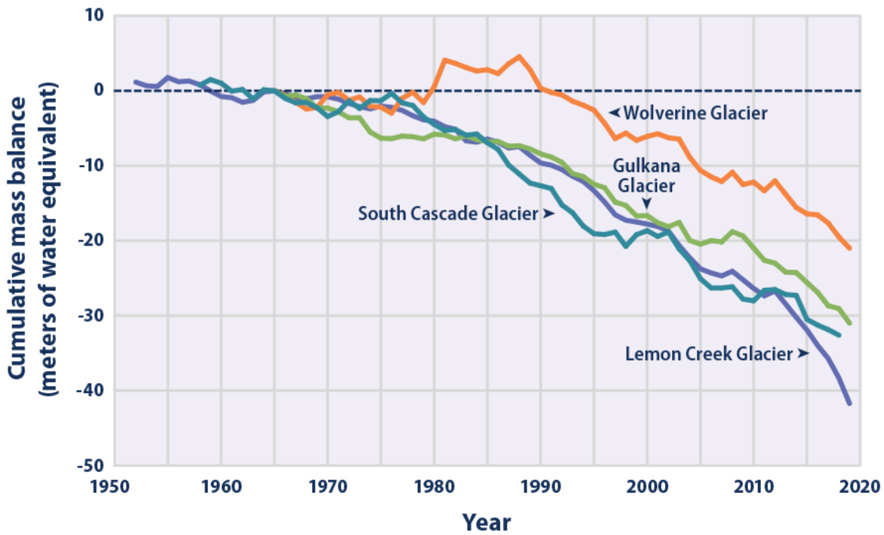
Heating and cooling degree days in the United States from 1895 to 2020.



Key Point: Total snowfall has decreased in many parts of the country since widespread observations became available in 1930, with 57 percent of stations showing a decline. Among all of the stations shown, the average change is a decrease of 0.19 percent per year.

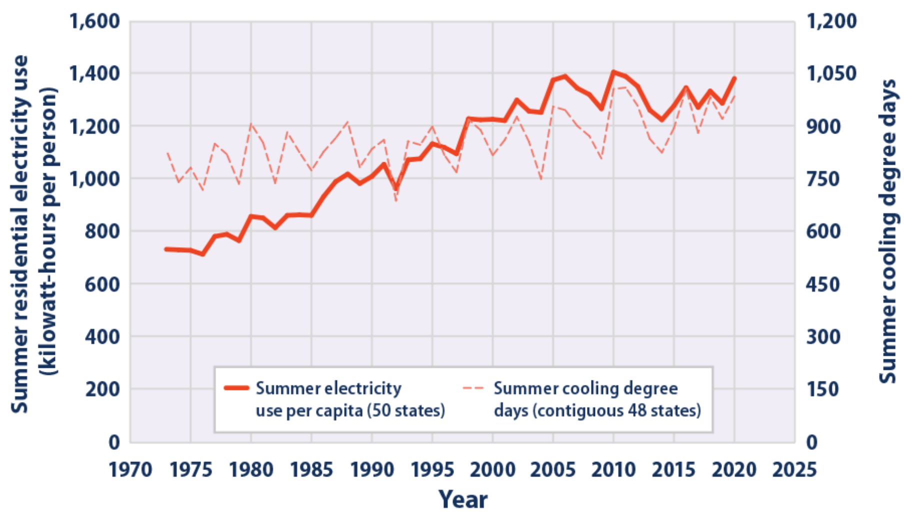
Average rate of change in total snowfall from 1930 to 2007 at 419 weather stations in the contiguous 48 states. Blue circles represent increased snowfall; red circles represent a decrease.

SEASONAL VARIABILITY



Key Point: The four U.S. reference glaciers have shown an overall decline in mass balance since the 1950s and an acerated rate of decline in recent years

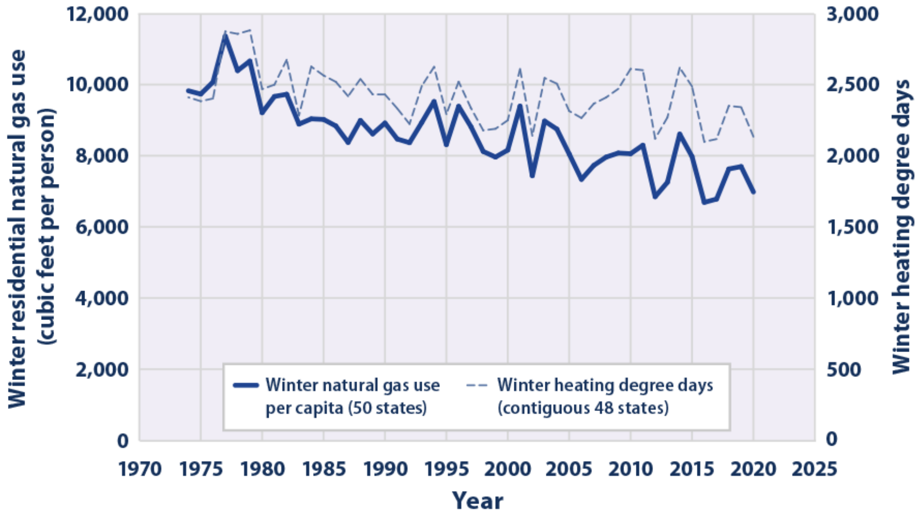
Cumulative change in mass balance of four reference glaciers in the United States beginning in the 1950s. Each glacier's mass balance is set to zero for the base year of 1965. For consistency, measurements are in meters of water equivalent, which represent changes in the average thickness of a glacier.



Key Point: The amount of electricity used by the average American at home during the summer has nearly doubled since 1973.

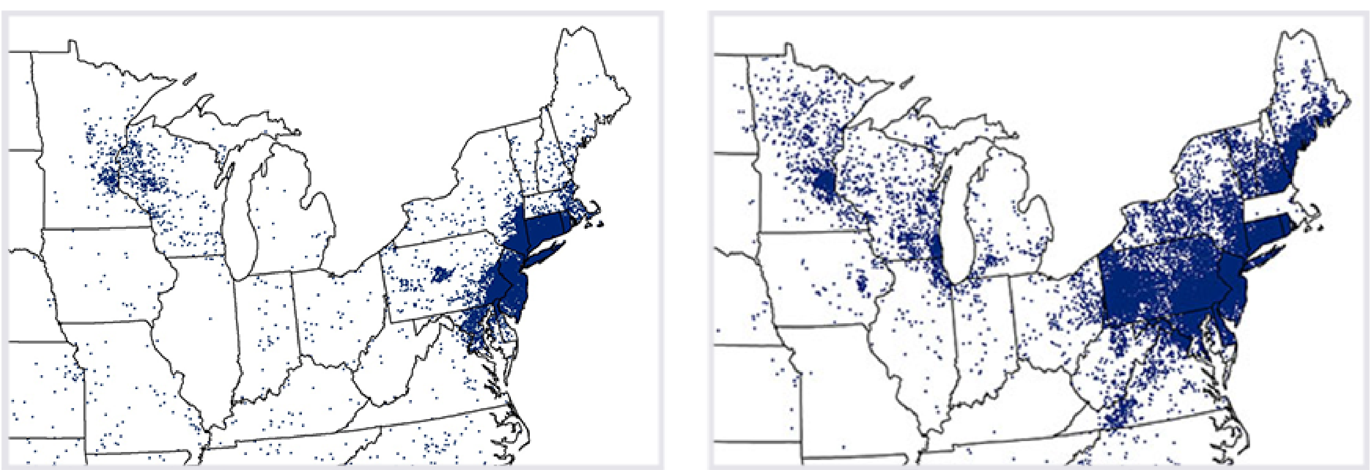
Residential summer electricity use per capita and summer cooling degree days in the United States, 1973–2020. The black line shows average summer electricity use per capita, and it represents all 50 states plus Washington, DC. For reference, the orange line shows the average number of cooling degree days for the same months across the contiguous 48 states plus DC.

SEASONAL VARIABILITY



Key Point: The amount of natural gas used by the average American at home during the winter has decreased since 1973.

Residential winter natural gas use per capita and winter heating degree days in the United States, 1974–2020. The black line shows average winter natural gas use per capita, and it represents all 50 states plus Washington, DC. For reference, the blue line shows the average number of heating degree days for the same months across the contiguous 48 states plus DC.

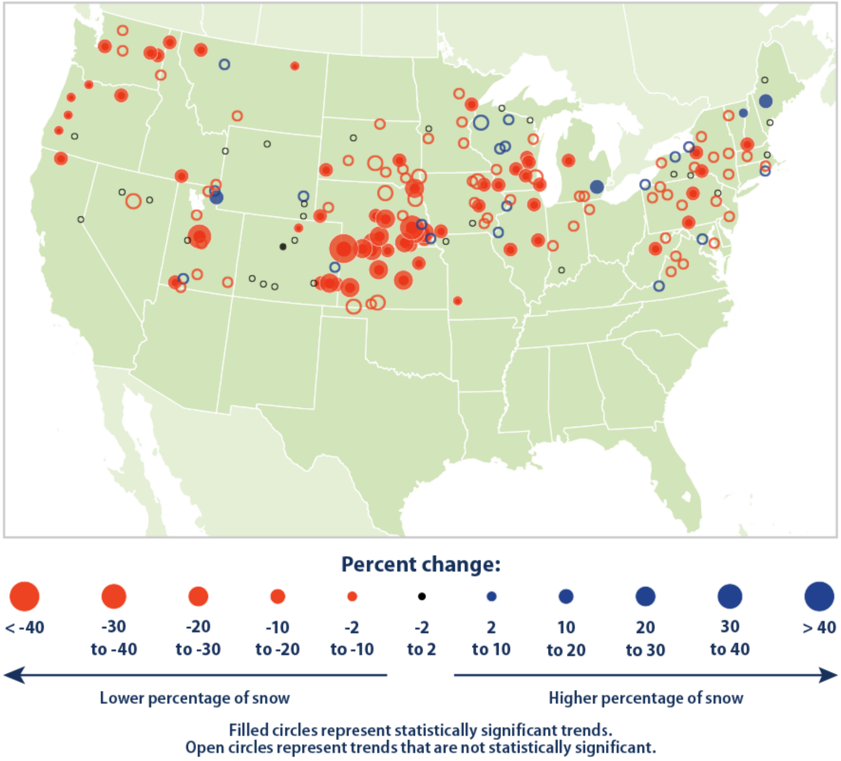


1996 **2018**

The distribution of Lyme disease cases in the United States, which is reported to CDC in 1996 and 2018. Each dot represents an individual case placed according to the patients' county of residence, which may be different from the county of exposure. These maps focus on the parts of the U.S. where Lyme disease is most common.

Key Point: The incidence of Lyme disease has approximately doubled since 1991.Driven by multiple factors, the number and distribution of reported cases of Lyme disease have increased over time. Note that because these data only include diagnosed cases of Lyme disease, the actual incidence is likely higher.

SEASONAL VARIABILITY



Key Point: Nearly 80 percent of the stations across the contiguous 48 states have experienced a decrease in the proportion of precipitation falling as snow.

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.

APPENDIX

FIGURES AND METADATA

Underlying datasets, metadata, and figures associated with EPA's climate change indicators are available at www.epa.gov/climate-indicators or the Global Change Information System (https://data.globalchange.gov).

LIMITATIONS AND UNCERTAINTY

This section discusses limitations and sources of uncertainty associated with climate change indicators featured in this report. This discussion does not intend to be comprehensive, but rather presents a synthesis of the types of limitations and uncertainties common across climate change indicators. For more detailed information, EPA provides documentation of these elements in the technical documentation for each climate change indicator: https://www.epa.gov/climate-indicators/downloads-indicators-technical-documentation.

Each of the climate change indicators featured in this report is associated with underlying limitations. First, methodologies used to obtain observations may change through time in ways that affect the calculation of indicators. For example, indicators of tropical cyclones are temporally constrained to the modern satellite era, because modern satellite observations provide a more accurate record of tropical cyclone activity. Data collection may also differ regionally: for example, indicators of bird wintering ranges depend on observations from citizens who may employ slightly different data collection methods. Finally, time series trends drawn from indicator datasets are largely dependent on the length of the observational record. Together, these factors may impact the confidence, application, or conclusions drawn from indicators contained in this report.

Uncertainty associated with climate change indicators may correspond to the period of the observational record, measurement uncertainty, or other factors. While long, multi-decadal observational datasets better resolve long-term trends that exceed the "noise" produced by interannual variability, some indicators have larger uncertainties based on the shortness of their observational records. Uncertainties may also propagate from measurement uncertainty: for example, measurements of glacier mass balance may suffer from obstructed instrumentation or factors not related to climate change. Sources of uncertainty are discussed more completely in the technical documentation corresponding to each climate change indicator.

INFORMATION QUALITY

EPA follows an established framework to identify data, select indicators, obtain independent expert review, and publish indicators. EPA uses a set of 10 criteria to evaluate and select data for indicator development. This screening process is conducted in two stages, described at https://www.epa.gov/climate-indicators/frequent-questions-about-climate-change-indicators#q16.

The development of this report, including technical documentation, was conducted in accordance with EPA's Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by the Environmental Protection Agency.

When evaluating the quality, objectivity, and relevance of scientific and technical information, the considerations that EPA takes into account can be characterized by five general assessment factors, as found in A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information. These general assessment factors and how EPA considers them in development of climate change indicators are: soundness, Applicability and Utility, Clarity and Completeness, Uncertainty and Variability, and Evaluation and Review.

PEER REVIEW

The primary indicators compiled and used in this report have been independently peer reviewed as part of EPA's Climate Change Indicators effort. In addition, this Technical Report, including the technical supporting documentation, was peer reviewed by three external experts in a process independently coordinated by Abt Associates and an EPA peer-review coordinator.

EPA gratefully acknowledges the following peer reviewers for their useful comments and suggestions: Kathy Jacobs, Holly R. Prendeville, and Scott Steinschneider. 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. Details describing this review can be found below.

Peer review of this report followed the procedures in EPA's Peer Review Handbook, 4th Edition (EPA/100/B-15/001) for reports that do not provide influential scientific information.[a] The review was managed by a contractor under the direction of a designated EPA peer review leader, who coordinated the preparation of a peer review plan, the scope of work for the review contract, and the charge for the reviewers. The peer review leader played no role in producing the draft report. Each reviewer was charged with reviewing the entire report and technical documentation, providing substantive comments, and making an overall assessment about whether the report sections reviewed should be published with little or no revision, or require a major rewrite. Peer reviewers were charged with making specific comments and edits as well as providing written response to a set of six charge questions. The EPA author team then responded to and addressed all comments from the peer reviewers in a written summary and revised the report accordingly.

This report contains several already published EPA climate indicators. These indicators, including the graphics, summary text, and technical documentation, undergo internal review, data provider/collaborator review, and an independent external peer review consistent with the procedure described at U.S. Environmental Protection Agency. Climate Change Indicators in the United States. www.epa.gov/climate-indicators.[b]

[a] U.S. EPA. 2015. EPA's peer review handbook. Fourth edition. EPA 100/B-15/001. www.epa.gov/osa/peerreview-handbook-4th-edition-2015.

[b] https://www.epa.gov/climate-indicators/frequent-questions-about-climate-change-indicators#q18

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