Technical Documentation

Seasonality and Climate Change: A Review of Observed Evidence in the United States

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Technical Documentation

This document provides technical documentation for the set of EPA's climate change indicators used in *Seasonality and Climate Change: A Review of Observed Evidence in the United States*, including criteria for their evaluation and selection for inclusion in the report, and information regarding their derivation and underlying datasets. This technical documentation also discusses limitations and sources of uncertainty associated with the indicators.

Contents

Introduction

The Earth's climate is changing, which is driving changes related to seasonality in the United States. The U.S. Environmental Protection Agency (EPA) developed a set of key climate change indicators based on long-term observational datasets to understand these changes. This report uses indicators as well as an extensive review of relevant scientific literature to document historical changes in seasonality and help readers better understand their implications for ecology and human communities. Scientific literature provides support for conclusions drawn from indicators, as well as corresponding consequences and attribution to climate change. For more information on EPA's indicators, see *Climate Change Indicators in the United States* at: https://www.epa.gov/climate-indicators.

The climate change indicators and conclusions drawn from them are illustrative. The selection of indicators in the report is not intended to be comprehensive of all observed changes related to climate; it provides a review of some of the changes that are currently occurring in the United States and around the world. The report is not meant to serve as a comprehensive state of the science related to changes in seasonality, but rather a summary of key historical trends elucidated through indicator datasets and other existing sources of information. While the report aims to highlight examples of the ways in which changes to one seasonal process can drive changes in another (e.g., changes to snowpack affect water availability and therefore agricultural output), the real stories of changes related to seasonality are broader and more complex than what could be captured in this report.

The sections below provide information related to the climate change indicators used in this report, including criteria for their selection, data sources and derivation, and a discussion of limitations and uncertainty.

Evaluation of Indicators

EPA uses a set of 10 criteria to select climate change indicators. These criteria include:

- Indicator data are available to show trends over time.
- Indicator data consist of actual measurements, observations, and derivations thereof.

- Indicator data have broad national coverage or significance.
- Indicator data are peer-reviewed and published.
- Information regarding uncertainty associated with indicator data is available.
- The indicator informs issues of national importance associated with human or natural systems.
- The relationship between the indicator and climate change is supported by published, peer-reviewed science and data.
- Indicator data, methods, and analysis are scientifically objective and transparent.
- Indicator data and analysis are understandable to the public.
- The indicator is feasible to construct within a reasonable timeframe.

To ensure each indicator is fully transparent and peer reviewed, EPA follows an established framework to identify datasets, select indicators, obtain independent expert review, and publish indicators in reports and online. EPA uses the following approach to develop indicators: 1) identify and develop a list of candidate indicators; 2) conduct initial research and screen against a subset of indicator criteria; 3) conduct detailed research and screen against the full set of indicator criteria; 4) select indicators for development; 5) develop draft indicators; 6) facilitate expert review of draft indicators; and 7) periodically re-evaluate indicators. The approach for technical documentation is published online here: https://www.epa.gov/sites/production/files/2016-08/documents/technical-documentation-overview-2016.pdf

All of EPA's climate change indicators address either causes or effects of climate change. While each indicator has a scientifically based relationship to climate change, EPA acknowledges that some indicators more closely correspond to climate than others. Indicators generally consider large space and time scales (e.g., regional observations spanning decades) in order to resolve trends relevant to climate change. In addition, EPA develops a handful of indicators associated with "Community Connection" and "A Closer Look" (e.g., Cherry Blossom Bloom Dates in Washington, DC) in order to address topics of interest specific to particular regions or locations.

Indicator Selection

A subset of EPA's climate change indicators was selected for inclusion in this report. The criteria for choosing which indicators to discuss included whether they exhibited distinct seasonal patterns in the United States, their relevance to the four illustrative themes in the report, and data quality.

The selected indicators are those determined to exhibit important aspects of seasonality such as seasonal processes, shifts in timing or magnitude of seasonal events, or seasonal responses with direct or indirect implications to ecological and social systems or human health. For the indicators featured and for the observational evidence mentioned in the report, the connections to seasonality and climate are consistent with and reference the scientific literature. Some indicators represent seasonality better than others. In all cases, the connection between indicators and other observational evidence to climate change is defined by the referenced scientific literature in the report.

Technical Information

EPA uses a standard format to document the technical information for each climate change indicator. In doing so, EPA complies with the requirements of the Information Quality Act (also referred to as the Data Quality Act) and EPA's *Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by the Environmental Protection Agency*.

Technical documentation accompanies each indicator to record the source(s) of the data, how each indicator was calculated, how accurately each indicator represents the intended environmental condition, and provides documentation of the history of all revisions and updates to the indicator. EPA's technical documentation addresses 13 elements for each indicator:

1. **Indicator description**
2. **Revision history**
3. **Data sources**
4. **Data availability**
5. **Data collection (methods)**
6. **Indicator derivation (calculation steps)**
7. **Quality assurance and quality control (QA/QC)**
8. **Comparability over time and space**
9. **Data limitations**
10. **Sources of uncertainty (and quantitative estimates, if available)**
11. **Sources of variability (and quantitative estimates, if available)**
12. **Statistical/trend analysis (if any has been conducted)**
13. **References**

Table 2 below focuses on the Description, Data Sources, Data Collection, and Indicator Derivation elements for the indicators featured in the main report. These elements are included to provide a foundational understanding of what each indicator represents and how EPA collected and used the data. This appendix does not cover all 13 elements for each indicator. For complete technical documentation, look to EPA's published technical documentation, available here: https://www.epa.gov/climate-indicators/downloads-indicators-technical-documentation.

Table 2. Summarized Technical Documentation for Indicators included in this Report.

Indicator	Description, Scope, Period of Record	Data Sources and Collection	Indicator Derivation	Relationship to Seasonality
Length of Growing Season	Length of the growing season as defined by frost-free days in the contiguous 48 states; 1895 to 2019.	EPA obtained the data for this indicator from NOAA-National Centers for Environmental Information (NCEI). Temperature measurements come from weather	For this indicator, the length of the growing season is defined as the period of time between the last frost of spring and the first frost of	Increasing seasonal temperatures are driving longer growing seasons characterized by changes in days per

		stations in NOAA's Cooperative Observer Program (COOP). Analysis of frost timing and growing season length was provided by Kunkel (2020)[1]	fall, when the air temperature drops below the freezing point of 32°F.	year. The growing season is influenced by air temperatures, frost days, and rainfall, which are associated with climate.[2]
Timing of Last Spring Frost and First Fall Frost	Timing of the last spring frost and the first fall frost in the contiguous 48 states; 1895 to 2016.	EPA obtained the data for this indicator from NOAA-NCEI. Temperature measurements come from weather stations in NOAA's COOP. Analysis of frost timing and growing season length was provided by Kunkel (2020).[1]	For this indicator, minimum daily temperature data from the COOP data set were used to determine the dates of last spring frost and first fall frost using an inclusive threshold of 32°F.	Increasing seasonal temperatures are driving longer growing seasons characterized by changes in days per year. The growing season is influenced by air temperatures, frost days, and rainfall, which are associated with climate.[2]
Snowpack	Changes in springtime mountain snowpack in the western United States; 1955 to 2020.	This indicator is based on data compiled by the U.S. Department of Agriculture's (USDA's) Natural Resources Conservation Service (NRCS). NRCS compiles snowpack measurements collected by USDA staff as well as other agencies and organizations (for example, many measurements in California come from the California Department of Water Resources). The trend analysis was constructed using methods consistent with Mote et al. (2005).[3]	This indicator uses snow water equivalent (SWE) measurements to assess trends in snowpack from 1955 through 2019. SWE is the amount of water contained within the snowpack at a particular location. EPA narrowed the data set to stations with sufficient data, then calculated linear trends in April 1 SWE measurements from 1955 through 2020 for each site. These trends were then converted to percent change since 1955.	Snowpack is a seasonal phenomenon—it exhibits an annual cycle—and is subject to large year-to-year variations. The overall amount and the timing of its onset and duration are strongly associated with changes in seasonal temperature and precipitation patterns.[3-6]
Wildfire Activity: Burned Area	Annual average burned acreage by State; 1984 to 2018.	Burn severity data and state-by-state acreage totals in this map come from a multi-agency project called Monitoring Trends in Burn Severity, which maintains a database of wildfire events across	EPA calculated the average annual acreage burned each month across the United States for each half of the period of record. The date of fire occurrence used in this	The timing, extent, and severity of wildfire in the western United States is strongly influenced by climate. Wildfire activity including onset and

		the United States. These data are publicly available at: https://www.mtbs.gov/direct-download.	analysis corresponds to the ignition date of the fire as defined in the Monitoring Trends in Burn Severity (MTBS) data set. For purposes of this analysis, fires were aggregated by month.	season length are influenced by several climate variables (temperature, precipitation, drought).[7,8]
Wildfire Activity: Season Length	Comparison of monthly burned area due to wildfires in the United States; between 1984 to 2000 and 2001 to 2017.	Wildfire burn acreage was obtained from the MTBS project, sponsored by the Wildland Fire Leadership Council. The project provides data on individual wildfire incidents that meet certain size criteria (≥ 1,000 acres in the western United States or ≥ 500 acres in the eastern United States). These data were available from 1984 to 2017. These data are publicly available at: www.mtbs.gov.	EPA filtered MTBS's database output to remove any fires not meeting MTBS's size criteria and removed fires classified as "prescribed," "wildland fire use," or "unknown." EPA then divided the period of record into two equal halves (1984–2000 and 2001–2017) to support analysis of change over time. EPA calculated the difference in days between the onset of the "historical" wildfire season and the recent onset of the wildfire season. EPA defined the start of the wildfire season as the time of year when 10 percent of the average annual burn acreage was reached, using the cumulative total burned acreage for each of the two timeframes. Changes were characterized using this method rather than measuring a slope over time (e.g., a linear regression) because of the year-to-year variability in the data set.	Wildfire activity is strongly associated with warming and earlier spring snowmelt.[8-10]

Freeze-Thaw Season (formerly Unfrozen Days)	Number of unfrozen days in the contiguous 48 States; 1979 to 2019.	This indicator is based on data collected by National Aeronautics and Space Administration (NASA) satellites and analyzed by the University of Montana. EPA's indicator is an updated version of an analysis originally published in the scientific literature in 2017.[11]	The indicator is based on the freeze-thaw Earth system data record (FT-ESDR) and was developed for land areas where the average number of days with freezing temperatures exceeds five days per year based on surface air temperature (SAT) daily minima over a 36-year record (1979–2014). This indicator is also restricted to land areas with at least some vegetation, as defined from a MODIS land cover map, and limited to areas that are not permanently frozen. Thus, it excludes large water bodies and permanent ice/snow features and focus on areas (covering most of the country) where freeze-thaw cycles influence vegetative growth.	The length of the unfrozen season can be an important factor in determining impacts to surface hydrology, including evapotranspiration and the timing and extent of seasonal snowmelt[77] and the potential growing season for vegetation—for anticipating landscape phenological shifts and important impacts on agriculture and natural resource sectors.[12]
Ragweed Pollen Season	Change in ragweed pollen season; 1995 to 2015.	Data for this indicator come from the National Allergy Bureau, which is part of the American Academy of Allergy, Asthma, and Immunology's Aeroallergen Network. Data were compiled and analyzed by a team of researchers that published a more detailed version of this analysis in a scientific journal with data through 2009.[13]	This indicator established start and end dates for the ragweed pollen season using daily ragweed pollen counts. The start date is the point at which 1 percent of the cumulative pollen count for the season has been observed, meaning 99 percent of all ragweed pollen appears after this day. Similarly, the end date is the point at which 99 percent of the cumulative	Seasonal changes in phenological events from plants such as flowering—especially their timing and relationship to with weather and climate—are among the most sensitive biological responses.[13-15]

			pollen count for the season has been observed.	
Heat Waves: Frequency and Length	Heat wave characteristics in 50 large U.S. cities; 1961 to 2019.	This indicator is based on temperature and humidity measurements from weather stations managed by NOAA's National Weather Service. NOAA calculates daily apparent temperatures for metropolitan areas and publishes the results at www.ncdc.noaa.gov/societal-impacts/heat-stress/data.	For consistency across the country, this indicator defines a heat wave as a period of two or more consecutive days where the daily minimum apparent temperature in a particular city is higher than the 85th percentile of historical July and August temperatures for that city. Historical July and August baseline temperatures are analyzed for a base period of 1981–2010, which was chosen for consistency with other climatology metrics. The analysis is based on the methodology used by Habeeb et al. (2015)[16] to define and analyze heat waves.	Robust evidence that climate change is affecting the frequency, intensity, and duration of heatwaves.[16-19] Heat waves (summer months) show evidence of increasing while cold waves (winter months) appear to be decreasing in frequency and intensity.[20]
Ice Breakup in Three Alaskan Rivers	Ice Breakup Dates for Three Alaskan Rivers, 1896–2020.	Ice breakup dates for the Tanana River at Nenana, the Yukon River at Dawson City, and the Kuskokwim River at Bethel have been recorded and made publicly available as part of three long-running community competitions: the Nenana Ice Classic, the Yukon	This indicator considers annual ice breakup dates for each river. No annual data points were missing in the periods of record for these two rivers, and EPA converted all breakup dates to Julian days.	Lake and river ice phenology are a part of the hydrological cycle, and current trends reflect the shrinkage of the Earth's cryosphere, a widely recognized effect of ongoing

		River Breakup, and the Kuskokwim Ice Classic. The data shown here and other information can be found online at: www.nenanaakiceclassic.com, www.yukonriverbreakup.com/statistics, http://iceclassic.org/historical-data, and additional sources linked from these websites. Ice breakup dates for these rivers are also archived by the National Snow and Ice Data Center at: http://nsidc.org/data/lake_river_ice and the National Weather Service at: www.weather.gov/aprfc/breakupDB.		climate change.[21-23]
Lake Ice Freeze and Thaw Dates	Timing of lake freeze and thaw for a subset of lakes in the northern United States; 1850 to 2015.	This indicator is based mainly on data from the Global Lake and River Ice Phenology Database, which was compiled by the North Temperate Lakes Long Term Ecological Research program at the Center for Limnology at the University of Wisconsin–Madison from data submitted by participants in the Lake Ice Analysis Group. The database is hosted by the National Snow and Ice Data Center (NSIDC) at http://nsidc.org/data/lake_river_ice.	This indicator considered nine-year moving averages for each of the parameters in order to smooth out some of the variability in the annual data and to make it easier to see long-term trends in the display. Long-term trends in thaw date over time were calculated using the Sen slope method. This indicator focuses on thaw dates, not freeze dates, because several of the target lakes have data for only ice-off, not ice-on.	Lake and river ice phenology are a part of the hydrological cycle, and current trends reflect the shrinkage of the Earth's cryosphere, a widely recognized effect of ongoing climate change.[21-23]
Timing of Spring Snowmelt	Magnitude and timing of streamflow in rivers and streams across the United States; 1940 to 2014.	The indicator is based on streamflow data from a set of reference stream gauges specified in the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES-II) database. Daily mean streamflow data are stored in the	The timing of snowmelt runoff is defined using the winter-spring center-of-volume date, which is the date when half of the total streamflow between January 1 and July 31 for sites in the	Warming temperatures promote snowmelt. The timing of snowmelt and subsequent streamflow runoff is significantly tied to seasonal changes.[6,24-26]

		USGS National Water Information System (NWIS) at http://waterdata.usgs.gov/nwis/sw.	western United States, or half of the total streamflow between January 1 and May 31 for sites in the eastern United States, has passed through the gauging station. Rates of change from 1940 to 2014 were computed using the Sen slope, which was then multiplied by the number of years in the study period to estimate total change over time.	
Seasonal Temperatures	Changes in average seasonal air temperature for the United States; 1896 to 2019.	This indicator is based on temperature anomaly data provided by the National Oceanic and Atmospheric Administration's (NOAA's) NCEI, formerly the National Climatic Data Center (NCDC). Specifically, the indicator uses data from NCEI's *n*ClimDiv data set, which is based on data from the daily version of the Global Historical Climatology Network (GHCN-Daily). This dataset is available through NCEI's "Climate at a Glance" web interface (www.ncdc.noaa.gov/cag).	Monthly temperature means were calculated for each station represented in the *n*ClimDiv data set. Data were adjusted to remove biases introduced by differences in the time of observation and shifts in local-scale data that might reflect changes in instrumentation, station moves, or urbanization effects. Area-weighted averages of grid-point estimates were calculated from station data to achieve uniform spatial coverage. Results were initially averaged within each climate division, then aggregated by state and for the contiguous 48 states as a whole based on an area-weighted average of climate divisions. Winter data are nominally assigned to the year in which the winter	Seasonal temperature is an important climatic factor influencing season variation and change. Temperature is an environmental cue for plant and animal processes. From a seasonal perspective in the United States, warming is occurring in all seasons and was greatest and most widespread in winter, with increases of over 1.5°F in most areas.[20]

			ended; for example, "1896" refers to the consecutive three-month period of December 1895, January 1896, and February 1896.	
Snow-to-Precipitation Ratio	Changes in the ratio of snowfall to total winter precipitation in the contiguous 48 states; 1949 to 2016.	The data used for this indicator are based on long-term weather station records compiled by the National Oceanic and Atmospheric Administration's (NOAA's) NCEI following an update published in the scientific literature in 2007.[27]	For this indicator, snow-to-precipitation ratios for each year were calculated by comparing the total snowfall during the months of interest (in terms of liquid-water equivalent) with total precipitation (snow plus rain). Long-term rates of change at each station were determined using a Kendall's tau slope estimator.	Warmer temperatures associated with climate change can influence snowfall by altering weather patterns, causing more precipitation overall, and causing more precipitation to fall in the form of rain instead of snow.[27,28]
Glacier Mass Balance (U.S. and Global)	Balance between snow accumulation and melting in glaciers, and mass change of glaciers in the United States and globally; 1950s to 2015.	Mass balance datasets are available for Gulkana, Wolverine, and South Cascade glaciers on the USGS Benchmark Glacier website at: www2.usgs.gov/climate_landuse/clu_rd/glacierstudies/default.asp. Mass balance data for Lemon Creek Glacier are available on the WGMS Reference Glacier website at: http://wgms.ch/products_ref_glaciers; this site also provides data for the three USGS benchmark glaciers. EPA obtained the most up-to-date data directly from USGS.	For this indicator, glacier surface measurements were used to determine the net change in mass balance from one year to the next, referenced to the previous year's summer surface measurements. The indicator documents changes in mass and volume rather than total mass or volume of each glacier because the latter is more difficult to determine accurately.	Over the last several decades, climate change has led to widespread shrinking of the cryosphere, including seasonal glacier mass loss.[7,29]
Leaf and Bloom Dates	Timing of first leaf dates and flower bloom dates in lilacs and honeysuckle plants in	This indicator is based on leaf and bloom observations that are archived by the USA National Phenology Network (USA-NPN) and climate data that are	This indicator was developed by applying phenological models to nearly 3,000 sites in the contiguous 48 states where	Terrestrial plants time their reproduction based on one or more proximate environmental cues, including

	the contiguous 48 states; 1900 to 2020.	maintained by the National Oceanic and Atmospheric Administration's (NOAA's) NCEI (formerly the National Climatic Data Center). Data for this indicator were analyzed using a method described in Schwartz et al. (2013).[30]	sufficient weather data have been collected. The exact number of sites varies from year to year over the period 1900–2020 depending on data availability.	photoperiod, temperatures, the length of winter (vernalization), and moisture levels or the availability of water.[31] Phenological changes are associated with the seasonal timing of biological events.[30,32,33]
Cherry Blossom Peak Bloom Date	Peak bloom date (PBD) for the most common species of cherry tree planted around the Tidal Basin in Washington, DC; 1921 to 2019	All cherry blossom PBD data, as well as National Cherry Blossom Festival dates, are maintained by the NPS. PBD data back to the 1990s can be found on the National Cherry Blossom Festival and NPS websites at: www.nationalcherryblossomfestival.org/about/bloom-watch and: www.nps.gov/subjects/cherryblossom/bloom-watch.htm. Festival dates for 2012–2019 were provided by the organizers of the festival (contact information at: www.nationalcherryblossomfestival.org).	EPA converted bloom and festival dates into Julian days to support graphing and calculations. By this method, January 1 = day 1, etc. The method also accounts for leap years, such that March 31 = day 90 in a non-leap year and day 91 in a leap year, for example.	Phenological changes are associated with the seasonal timing of biological events.[30,32-34]
Lyme Disease Prevalence	Incidence of Lyme disease in the United States; 1991 to 2018.	This indicator is based on annual numbers of confirmed Lyme disease cases, nationally and by state, compiled by the Centers for Disease Control and Prevention's (CDC's) Division of Vector-Borne Diseases. Incidence was calculated using the most recent mid-year population estimates for each year from the U.S. Census Bureau. The 1996 and 2017 comparison maps also came from CDC.	National incidence of Lyme disease was calculated using the total number of confirmed Lyme disease cases and the national population for each year from 1991 through 2014. EPA calculated incidence by dividing the number of confirmed cases per year by the corresponding population on July 1 in the same calendar year. EPA then multiplied the per-	A warming climate can enhance the risk of vector-borne diseases, such as Lyme disease, by increasing the range of suitable vector habitat.[15,35,36]

			person rate by 100,000 to generate a normalized incidence rate per 100,000 people. This is CDC's standard method of expressing the incidence of Lyme disease.	
Bird Wintering Ranges	Changes in the winter ranges of North American birds from the winter of 1966–1967 to 2013	This indicator is based on data collected by the annual Christmas Bird Count (CBC), managed by the National Audubon Society. Data used in this indicator are collected by citizen scientists who systematically survey certain areas and identify and count widespread bird species. The CBC has been in operation since 1900, but data used in this indicator begin in winter 1966–1967.	This indicator is based on the center of abundance for each species, which is the center of the population distribution at any point in time. This is a common way to characterize the general location of a population. This indicator reports the position of the center of abundance for each year, relative to the position of the center of abundance in 1966 (winter 1966–1967). The change in position is averaged across all 305 species for changes in latitude and across 272 species for changes in distance from the coast.	The timing of seasonal life-cycle events in birds such as migration and bird arrival is driven by temperature, sun angle, and other conditions. As such, shifts in spatial and temporal patterns of bird behavior can indicate changes in seasonal meteorological conditions or changes in the availability of suitable food and habitat.[37,38]
Tropical Cyclone Activity	Aggregate activity of hurricanes and other tropical storms in the Atlantic Ocean, Caribbean, and Gulf of Mexico; 1878 to 2015.	This indicator is based on data maintained by the National Oceanic and Atmospheric Administration's (NOAA's) National Hurricane Center in a database referred to as HURDAT (HURricane DATa). This indicator presents three separate analyses of HURDAT data: a set of hurricane counts compiled by NOAA, NOAA's Accumulated Cyclone Energy (ACE) Index.	All hurricane counts are limited to cyclones in the North Atlantic (i.e., north of the equator) meeting the definition of a hurricane, which requires sustained wind speeds of at least 74 miles per hour. Named storms (including tropical storms > 39mph) are also included in the counts. For all years prior to the onset of complete satellite coverage in 1966, total basin-wide	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, as well as the length of the hurricane season.[20]

			counts have been adjusted upward based on historical records of ship track density. The indicator also uses NOAA's ACE Index to describe the combined frequency, strength, and duration of tropical storms and hurricanes each season, as described in the scientific literature by Bell and Chelliah in 2006.[39]	

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The full report, *Seasonality and Climate Change: A Review of Observed Evidence in the United States*, is available at: https://www.epa.gov/climate-indicators/seasonality-and-climate-change