Length of Growing Season

Identification

1. Indicator Description

This indicator measures the length of the growing season (or frost-free season) in the contiguous 48 states between 1895 and 2015. The growing season often determines which crops can be grown in an area, as some crops require long growing seasons, while others mature rapidly. Growing season length is limited by many different factors. Depending on the region and the climate, the growing season is influenced by air temperatures, frost days, rainfall, or daylight hours. Air temperatures, frost days, and rainfall are all associated with climate, so these drivers of the growing season could change as a result of climate change.

This indicator focuses on the length of the growing season as defined by frost-free days. Components of this indicator include:

- Length of growing season in the contiguous 48 states, nationally (Figure 1), for the eastern and western halves of the country (Figure 2), and by state (Figure 3).
- Timing of the last spring frost and the first fall frost in the contiguous 48 states, both nationally (Figure 4) and by state (Figures 5 and 6).

2. Revision History

April 2010:	Indicator published.
December 2012:	Updated indicator with data through 2011.
August 2013:	Updated indicator on EPA's website with data through 2012.
May 2014:	Updated indicator with data through 2013.
June 2015:	Updated indicator on EPA's website with data through 2014. Added Figures 3, 5, and 6.
August 2016:	Updated indicator with data through 2015.

Data Sources

3. Data Sources

Data were provided by Dr. Kenneth Kunkel of the National Oceanic and Atmospheric Administration's (NOAA's) Cooperative Institute for Climate and Satellites (CICS), who analyzed minimum daily temperature records from weather stations throughout the contiguous 48 states. Temperature measurements come from weather stations in NOAA's Cooperative Observer Program (COOP).

4. Data Availability

EPA obtained the data for this indicator from Dr. Kenneth Kunkel at NOAA CICS. Dr. Kunkel had published an earlier version of this analysis in the peer-reviewed literature (Kunkel et al., 2004), and he provided EPA with an updated file containing growing season data through 2015, aggregated by state, two (east and west) regions, and nationwide.

All raw COOP data are maintained by NOAA's National Centers for Environmental Information (NCEI) (formerly the National Climatic Data Center). Complete COOP data, embedded definitions, and data descriptions can be downloaded from the web at: www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/cooperative-observer-network-coop. There are no confidentiality issues that could limit accessibility, but some portions of the data set might need to be formally requested. Complete metadata for the COOP data set can be found at: www.ncdc.noaa.gov/data-access/land-based-station-data/station-metadata and www.nws.noaa.gov/om/coop.

Methodology

5. Data Collection

This indicator focuses on the timing of frosts, specifically the last frost in spring and the first frost in fall. It was developed by analyzing minimum daily temperature records from COOP weather stations throughout the contiguous 48 states.

COOP stations generally measure temperature at least hourly, and they record the minimum temperature for each 24-hour time span. Cooperative observers include state universities, state and federal agencies, and private individuals whose stations are managed and maintained by NOAA's National Weather Service (NWS). Observers are trained to collect data, and the NWS provides and maintains standard equipment to gather these data. The COOP data set represents the core climate network of the United States (Kunkel et al., 2005). Data collected by COOP sites are referred to as U.S. Daily Surface Data or Summary of the Day data.

The study on which this indicator is based includes data from 750 stations in the contiguous 48 states. These stations were selected because they met criteria for data availability; each station had to have less than 10 percent of temperature data missing over the period from 1895 to 2015. For a map of these station locations, see Kunkel et al. (2004). Pre-1948 COOP data were previously only available in hard copy, but were recently digitized by NCEI, thus allowing analysis of more than 100 years of weather and climate data. The data availability criteria resulted in there being no stations of record within the state of Delaware.

Temperature monitoring procedures are described in the full metadata for the COOP data set available at: www.nws.noaa.gov/om/coop. General information on COOP weather data can be found at: www.nws.noaa.gov/os/coop/what-is-coop.html.

6. Indicator Derivation

For this indicator, the length of the growing season is defined as the period of time between the last frost of spring and the first frost of fall, when the air temperature drops below the freezing point of 32°F. 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. Methods for producing state, regional, and national values by year were designed to weight all areas evenly regardless of station density.

Kunkel et al. (2004) provide a complete description of the analytical procedures used to determine changes in length of growing season. No attempt has been made to represent data outside the contiguous 48 states or to estimate trends before or after the 1895–2015 time period.

Figures 1, 2, and 4. Length of Growing Season, Timing of Last Spring Frost, and Timing of First Fall Frost in the Contiguous 48 States, 1895–2015

Figure 1 provides a time series showing the length of the growing season, which is the number of days between the last spring frost and the first fall frost. Figure 2 shows a time series of the length of growing season for the eastern United States versus the western United States, using 100°W longitude as the dividing line between the two halves of the country. Figure 4 shows the timing of the last spring frost and the first fall frost, also using units of days.

Figures 1, 2, and 4 show the deviation from the 1895–2015 long-term average, which is set at zero for a reference baseline. Thus, if spring frost timing in year *n* is shown as -4, it means the last spring frost arrived four days earlier than usual. Note that the choice of baseline period will not affect the shape or the statistical significance of the overall trend; it merely moves the trend up or down on the graph in relation to the point defined as “zero.”

To smooth out some of the year-to-year variability and make the results easier to understand visually, all three graphs plot 11-year moving averages rather than annual data. EPA chose this averaging period to be consistent with the recommended averaging method used by Kunkel et al. (2004) in an earlier version of this analysis. Each average is plotted at the center of the corresponding 11-year window. For example, the average from 2005 to 2015 is plotted at year 2010. EPA used endpoint padding to extend the 11-year smoothed lines all the way to the ends of the period of record. Per the data provider’s recommendation, EPA calculated smoothed values centered at 2011, 2012, 2013, 2014, and 2015 by inserting the 2010–2015 average into the equation in place of the as-yet unreported annual data points for 2016 and beyond. EPA used an equivalent approach at the beginning of the time series.

Figures 3, 5, and 6. Change in Length of Growing Season, Timing of Last Spring Frost, and Timing of First Fall Frost by State, 1895–2015

Figure 3 shows a map of long-term trends in the length of growing season for each of the contiguous 48 states. Figures 5 and 6 show state-level trends in the timing of the last spring frost date and first fall frost date for the contiguous 48 states, respectively.

Each state-level trend was calculated using the Sen slope method, which is a widely accepted method of estimating linear trends by finding the median of the slopes between all pairs of years and values. The median slope for each state was then multiplied by the length of the period of record to estimate the total change over time.

Due to a lack of stations meeting the data availability criteria throughout the period of record, no state trend could be calculated for Delaware. Several other states—Connecticut, Maryland, Nevada, Rhode Island, West Virginia, and Wyoming—had occasional years in which data were not available.

7. Quality Assurance and Quality Control

NOAA follows extensive quality assurance and quality control (QA/QC) procedures for collecting and compiling COOP weather station data. For documentation of COOP methods, including training manuals and maintenance of equipment, see: www.nws.noaa.gov/os/coop/training.htm. These training materials also discuss QC of the underlying data set. Pre-1948 COOP data were recently digitized from hard copy. Kunkel et al. (2005) discuss QC steps associated with digitization and other factors that might introduce error into the growing season analysis.

The data used in this indicator were carefully analyzed in order to identify and eliminate outlying observations. A value was identified as an outlier if a climatologist judged the value to be physically impossible based on the surrounding values, or if the value of a data point was more than five standard deviations from the station's monthly mean. Readers can find more details on QC analysis for this indicator in Kunkel et al. (2004) and Kunkel et al. (2005).

Analysis

8. Comparability Over Time and Space

Data from individual weather stations were averaged to determine national, regional, and state-level annual values in the length of growing season and the timing of spring and fall frosts. To provide spatial representativeness, national, regional, and state-level values were computed using a spatially weighted average, and as a result, stations in low-station-density areas make a larger contribution to the national, regional, or state average than stations in high-density areas.

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this indicator are as follows:

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

2. The urban heat island effect can influence growing season data; however, these data were carefully quality-controlled and outlying data points were not included in the calculation of trends.

10. Sources of Uncertainty

Kunkel et al. (2004) present uncertainty measurements for an earlier (but mostly similar) version of the national and regional analyses. To test worst-case conditions, Kunkel et al. (2004) computed growing season trends for a thinned-out subset of stations across the country, attempting to simulate the density of the portions of the country with the lowest overall station density. The 95 percent confidence intervals for the resulting trend in length of growing season were ±2 days. Thus, there is very high likelihood that observed changes in growing season are real and not an artifact of sampling error.

11. Sources of Variability

At any given location, the timing of spring and fall frosts naturally varies from year to year as a result of normal variation in weather patterns, multi-year climate cycles such as the El Niño–Southern Oscillation and Pacific Decadal Oscillation, and other factors. This indicator accounts for these factors by applying an 11-year smoothing filter for Figures 1, 2, and 4 and by presenting a long-term record (more than a century of data). In addition, the Sen slope analysis used in calculating trends in Figures 3, 5, and 6 minimizes the impact of outliers and statistical noise by using the median slope over the period of record. Overall, variability should not impact the conclusions that can be inferred from the trends shown in this indicator.

12. Statistical/Trend Analysis

EPA calculated long-term trends in Figures 1, 2, and 4 by ordinary least-squares regression to support statements in the "Key Points" text, as shown in Table TD-1. All of these trends were statistically significant at a 95 percent confidence level ($p < 0.05$). These results corroborate earlier findings by Kunkel et al. (2004), who determined that the overall increase in growing season was statistically significant at a 95 percent confidence level in both the East and the West. For confirmation, EPA ran several of the same analyses using Sen slope linear regression, which yielded nearly identical results.

Table TD-1. Linear Regression Results, 1895–2015

Parameter	Slope (days/year)	P-value
National average	0.118	< 0.0001
West	0.218	< 0.0001
East	0.083	< 0.0001
Spring	-0.0622	< 0.0001
Fall	0.0554	< 0.0001

The maps in Figures 3, 5, and 6 all show trends over time that have been calculated using a Sen slope analysis based on a weighted annual average of stations in each state. All three sets of state-level trends were evaluated for statistical significance at a 95 percent confidence interval. Overall, 37, 27, and 32 states had statistically significant trends for Figures 3, 5, and 6, respectively.

References

Kunkel, K.E., D.R. Easterling, K. Hubbard, and K. Redmond. 2004. Temporal variations in frost-free season in the United States: 1895–2000. Geophys. Res. Lett. 31:L03201.

Kunkel, K.E., D.R. Easterling, K. Hubbard, K. Redmond, K. Andsager, M.C. Kruk, and M.L. Spinar. 2005. Quality control of pre-1948 Cooperative Observer Network data. J. Atmos. Ocean. Tech. 22:1691–1705.