Growing Degree Days

Identification

1. Indicator Description

This indicator examines changes in annual growing degree days from 1948 to 2023 at 280 locations across the contiguous 48 states. Growing degree days are calculated using surface air temperature data from meteorological stations overseen by the National Oceanic and Atmospheric Administration (NOAA). Studies have documented a relationship between growing degree days and pollen season length and start date for grass, oak, and birch pollen: as growing degree days increase, grass pollen season lengthens and oak and birch pollen seasons begin earlier (Lo et al., 2019; Zhang et al., 2015). Because allergies are a major public health concern, observed changes in growing degree days, which serve as a proxy for changes in pollen season length and start date, provide insight into ways in which climate change may affect human well-being. More broadly, growing degree days also affect plant growth, agricultural production, and the spread and impact of plant diseases and pests.

2. Revision History

April 2021:	Indicator published.
June 2024:	Indicator updated with data through 2023.

Data Sources

3. Data Sources

Data for this indicator come from NOAA's Global Historical Climatology Network (GHCN) Daily database. This integrated database of land surface stations across the globe provides daily climatological data from numerous sources. Available data include maximum and minimum surface air temperatures from the climate monitoring stations that constitute the U.S. Climate Reference Network. Data availability varies by station; this analysis only used stations that provide minimum and maximum daily temperatures.

4. Data Availability

The GHCN-Daily data employed in the analysis are available for download at: https://doi.org/10.7289/V5D21VHZ. The data employed in the current analysis were downloaded in April 2024 (GHCN-Daily version 3.31); as the GHCN-Daily data set is continuously updated, data downloaded on future dates could differ from the data shown by this indicator.

Individual weather station data are maintained by NOAA's National Centers for Environmental Information (NCEI), and the data are distributed on various computer media (e.g., anonymous FTP sites), with no confidentiality issues limiting accessibility. Specifically, the data for this indicator can be obtained online at: www.ncei.noaa.gov/pub/data/ghcn/daily. Appropriate metadata and "readme" files are also available at this link.

Methodology

5. Data Collection

Systematic collection of weather data in the United States began in the 1800s. Since then, observations have been recorded from 23,000 stations. At any given time, observations are recorded from approximately 8,000 stations. Some of these stations are automated stations operated by NOAA's National Weather Service. The remainder are Cooperative Observer Program (COOP) stations operated by other organizations using trained observers and equipment and procedures prescribed by NOAA. For an inventory of U.S. weather stations and information about data collection methods, see: www.ncei.noaa.gov/products/land-based-station, the technical reports and peer-reviewed papers cited therein, and the National Weather Service technical manuals at: www.weather.gov/coop. Sampling procedures are also described in Kunkel et al. (2005) and in the full metadata for the COOP data set, available at: www.weather.gov/coop. Variables that are relevant to this indicator include observations of daily maximum and minimum temperatures.

The GHCN-Daily database includes the most complete collection of U.S. daily climate summaries available (NOAA, 2024). Its U.S. collection includes a dozen separate data sets archived by NCEI. NCEI explains the variety of databases that feed into the GHCN for U.S.-based stations in online metadata and at: www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily. The GHCN-Daily database contains the earliest observations available for the United States, as well as the latest measurements available from the climate monitoring stations that make up the U.S. Climate Reference Network.

The currently active U.S. stations in GHCN-Daily update data through real-time data feeds. There is continual reprocessing of the data, and all data are subject to change; however, changes to data values for U.S. stations are rare beyond 60 days from the end of a given month.

6. Indicator Derivation

This analysis is based on an approach published by Dr. Yong Zhang of the Environmental and Occupational Health Sciences Institute at Rutgers University. His publication (Zhang et al., 2015) describes the relationship between growing degree days and pollen upon which this indicator is based. Specifically, the authors found that as growing degree days increase, grass pollen season lengthens and oak and birch pollen seasons begin earlier. Drawing on this relationship, this indicator measures changes in growing degree days as a proxy for changes in grass pollen season length and oak and birch pollen season start date. Earlier start dates have also been correlated with longer season length (Anderegg et al., 2021; Lo et al., 2019). Grass, birch, and oak are not the only pollen types collected at NAB stations, but they are collected at a majority of monitoring stations, which is useful context for this national-scale indicator. Data for ragweed, mugwort, and other plant species studied by Zhang et al. (2015) are also measured, but data availability is sparser.

Growing degree days are calculated using daily temperature data from 280 NOAA monitoring sites in the contiguous 48 states for the period 1948–2023. These stations were selected based on the following criteria for data availability:

- 95 percent of the years from 1948 to 2023 must have one day per month with available data for both minimum and maximum temperature. Years with months without any data were removed from the analysis. This eliminates stations that were not operational during part of the period of record or had long periods of incomplete data.

- Each station must have no more than 30 consecutive days of missing data. This capped the number of consecutive days that EPA would interpolate over.
- Each station must have 95 percent completeness overall (i.e., data for 95 percent of all days during the period of record). This ensured that there were no stations with excessive instances of missing data.

EPA selected 1948 as a start date because it enabled inclusion of most stations from the U.S. Historical Climatology Network, which is a key contributing database to the GHCN-Daily. In addition, pre-1948 weather data have limitations as documented in Kunkel et al. (2005). The year 1948 is an established starting point used by other EPA indicators that draw data from GHCN-Daily.

The calculation of growing degree days relies on a widely used averaging method, described in publications such as McMaster and Wilhelm (1997). After downloading the daily temperature data for each of the weather stations employed in the analysis, EPA averaged the maximum and minimum daily temperatures for each day and subtracted a base temperature of 50°F. A negative value is assumed to be zero (i.e., there is no such thing as a negative growing degree day). For stations that had missing days of data, EPA used linear interpolation to estimate the number of growing degree days on those days, based on actual growing degree days calculated for the surrounding dates with available data. As noted in the criteria above, this approach was limited to periods of no more than 30 days, and in practice, most interpolation was conducted over much shorter periods.

For each year at each station, EPA aggregated daily degrees above the base temperature to calculate an annual growing degree day total. EPA then used the series of annual growing degree day totals to calculate a long-term trend for each station, using Sen's slope regression. To provide more context for understanding the magnitude of the observed changes, Figure 1 of this indicator reports trends as percentage increases or decreases, computed from the value for the last year of the regression line relative to the value of the first year of the regression line.

EPA selected 50°F as a baseline temperature for this analysis. Different plant species naturally have different temperature requirements, but for a broad indicator like this one, where multiple species are of interest, it is most useful to set a single baseline. In the absence of using an observation-based model using several inputs, one can use a defined base threshold temperature representative of many places and plants. Two main temperatures—32°F and 50°F—are often used and cited (e.g., by the USA National Phenology Network). EPA chose 50°F to better represent accumulated heat relative to pollen types examined by Zhang et al. (2015) (www.usanpn.org/data/agdd_maps). Crimmins and Crimmins (2019) provide further discussion of how 50°F represents a point of accumulated heat that often aligns with flowering and related activities that are further into the year than simply emergence or initiation of greening.

7. Quality Assurance and Quality Control

The GHCN-Daily data are subject to a strict quality assurance and quality control process, described at www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily (NOAA, 2024). During each reprocessing cycle, the data are checked for formatting inconsistencies such as impossible months or days and invalid characters in data fields. Next, a sequence of fully automated quality assurance procedures identifies daily values that violate one of the quality tests. These tests identify a variety of data problems, including the excessive duplication of data records; exceedance of physical, absolute, and climatological limits; excessive temporal persistence; excessively large gaps in the distributions of values; internal inconsistencies among elements; and inconsistencies with observations at neighboring stations. Data that fail a given quality control check (0.3 percent of all values) are marked with flags, depending on the type of error identified. GHCN-Daily does not contain adjustments for biases resulting from historical changes in instrumentation and observing practices.

Analysis

8. Comparability Over Time and Space

Growing degree days have been calculated using the same methods for all locations and throughout the period of record. The analysis was limited to weather stations that did not move during the period of record. NOAA follows strict protocols to ensure consistent data collection instrumentation over time and across the country.

9. Data Limitations

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

1. This indicator presents information on changes in growing degree days as a proxy for changes in pollen season length and start date for grass, oak, and birch based on work published by Zhang et al. (2015). However, the indicator does not analyze pollen data, and therefore should be viewed as a rough approximation for changes in these pollen season characteristics. Importantly, the length of the pollen season does not necessarily scale linearly with growing degree days, and the relationships demonstrated in the literature cannot be guaranteed to be exactly the same in other locations or under different conditions. That is why this indicator is presented as a screening-level proxy for pollen season.

2. The growing degree day measure reflects cumulative conditions that support plant development, but as a broad indicator, it does not consider plant species-specific temperature thresholds, does not incorporate upper temperature limits into the calculation (as some more sophisticated analyses do), and does not capture potentially important effects in the sequencing of weather conditions for plant development. There are factors other than growing degree days that also affect pollen season duration and start date; some of those factors reflect phenological cycles of plant activity, and some are unrelated to climate such as local plant composition, geographic location (latitudinal position), and proximity to urban areas (Lo et al., 2019). As a result, the link between growing degree days and pollen season timing is not precise.

3. EPA is aware of other analyses that have restricted the calculation of growing degree days to a defined “pollen season” window. However, because this is a broad indicator designed to be relevant to a variety of plant species, which may differ in the timing of their “pollen seasons,” EPA has elected to calculate growing degrees across the entire calendar year for this high-level summary indicator.

4. A change in total growing degree days does not necessarily change the *intensity* of the pollen season—though it may have a relation for some plant species.

10. Sources of Uncertainty

Uncertainty has not been calculated directly for this indicator. However, because growing degree days are based solely on temperature measurements, and because NOAA weather stations measure temperature with precise, well calibrated instruments and protocols in place to minimize error, any uncertainty in growing degree days would be expected to be minimal.

Section 12 discusses the level of statistical confidence in station-specific long-term rates of change calculated via linear regression.

11. Sources of Variability

Inter-annual temperature variability results from normal year-to-year variation in weather patterns, multi-year climate cycles such as the El Niño–Southern Oscillation and Pacific Decadal Oscillation, and other factors. Temperature patterns also vary spatially. This indicator provides information on changes in growing degree days using location-specific trends, as shown in Figure 1.

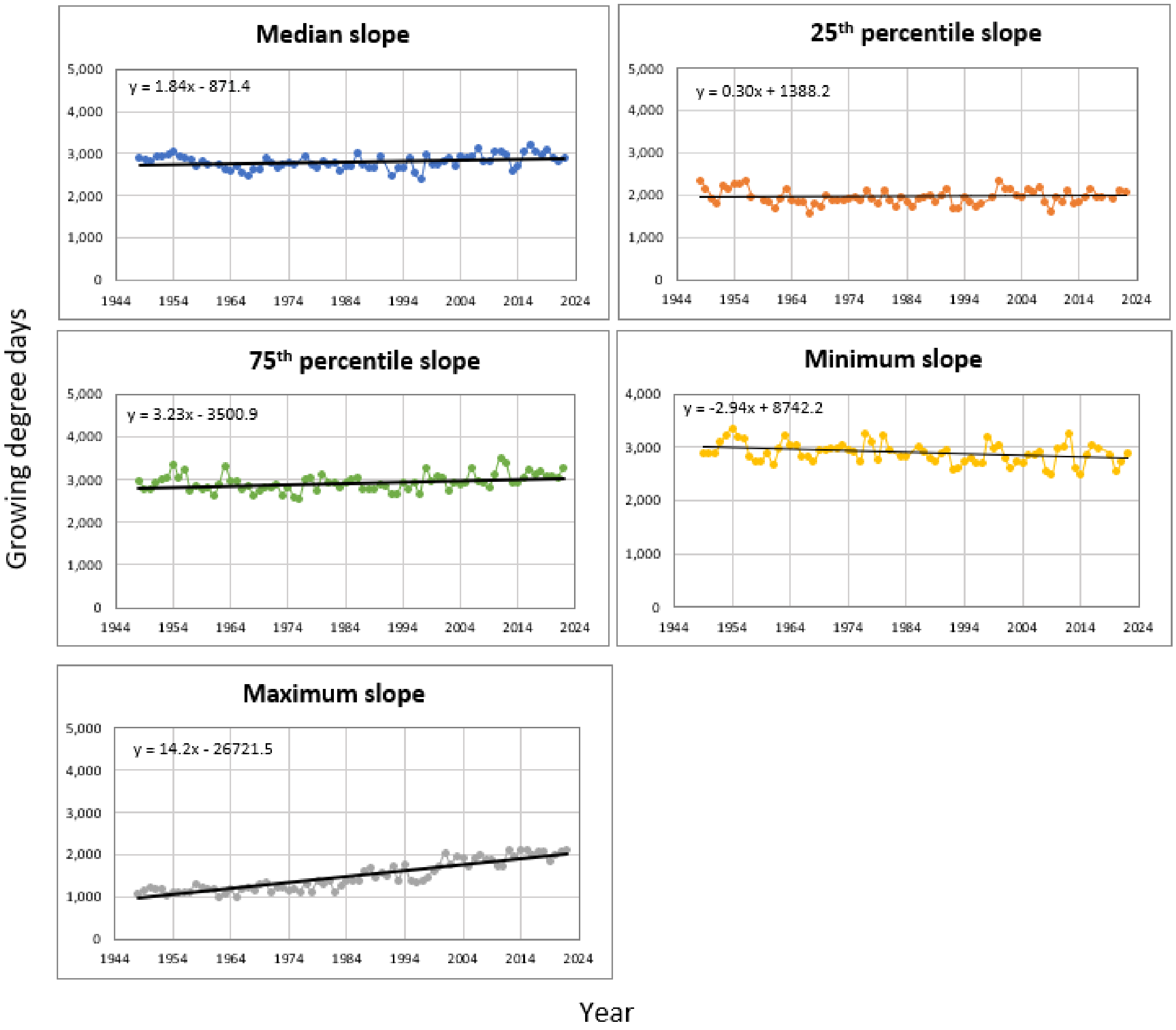
12. Statistical/Trend Analysis

As noted above, Figure 1 of this indicator uses Sen's slope regression to assess the slope of any long-term trend present at each station. This type of regression is useful for a screening-level analysis such as the one presented here. Of the station-specific trends shown in Figure 1, 191 (68.2 percent of stations) are significant to a 95 percent level (Mann-Kendall p-value < 0.05). Higher-magnitude increases in growing degree days—such as those that tend to be prevalent in the western United States—are generally more statistically significant than lower-magnitude trends.

EPA examined these trends further using the Durbin-Watson test for serial correlation (autocorrelation) of the regression residuals. Of the 191 stations that were significant to a 95 percent level ($p < 0.05$) according to the Mann-Kendall test, 119 showed autocorrelation (p-value of the Durbin-Watson test $<$ 0.1, indicating that the test resulted in an extreme value [indicating autocorrelation] and there is a low probability that such an extreme value could have been observed in a non-autocorrelated data set [the null hypothesis]). A block bootstrap (using four blocks) on the Mann-Kendall tau was applied to those 119 sites that had both significant autocorrelation and significant trends. A Mann-Kendall bootstrap block length of four was chosen using the formula $n^{1/3}$, where n is the number of years in the record. The Mann-Kendall test indicated a significant trend in none of the 119 sites after applying the block bootstrap. Thus, when autocorrelation and bootstrapping results are considered, a total of 72 stations (26 percent) had statistically significant trends.

For reference, Figure TD-1 shows the data and Sen's slope trend of annual growing degree days for five stations representing the minimum, maximum, median, 25th percentile, and 75th percentile slopes out of the entire distribution of regression slopes. EPA has included this figure to give a sense of the shape of the data for a representative sample of sites. Visually, Figure TD-1 suggests that a linear regression may be at least a reasonable first-order characterization of the data.

Figure TD-1. Annual Growing Degree Days for Five Sample Sites, 1948–2023



No attempt has been made to aggregate the results of this indicator into overall national or regional trends, as doing so would require consideration of uneven station density and the influence of topography in areas not directly represented by a weather station.

References

Anderegg, W. R. L., Abatzoglou, J. T., Anderegg, L. D. L., Bielory, L., Kinney, P. L., & Ziska, L. (2021). Anthropogenic climate change is worsening North American pollen seasons. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(7), e2013284118. https://doi.org/10.1073/pnas.2013284118

Crimmins, M. A., & Crimmins, T. M. (2019). Does an early spring indicate an early summer? Relationships between intraseasonal growing degree day thresholds. *Journal of Geophysical Research: Biogeosciences*, *124*(8), 2628–2641. https://doi.org/10.1029/2019JG005297

Kunkel, K. E., Easterling, D. R., Hubbard, K., Redmond, K., Andsager, K., Kruk, M. C., & Spinar, M. L. (2005). Quality control of pre-1948 Cooperative Observer Network data. *Journal of Atmospheric and Oceanic Technology*, *22*(11), 1691–1705. https://doi.org/10.1175/JTECH1816.1

Lo, F., Bitz, C. M., Battisti, D. S., & Hess, J. J. (2019). Pollen calendars and maps of allergenic pollen in North America. *Aerobiologia*, *35*(4), 613–633. https://doi.org/10.1007/s10453-019-09601-2

McMaster, G. S., & Wilhelm, W. W. (1997). Growing degree-days: One equation, two interpretations. *Agricultural and Forest Meteorology*, *87*(4), 291–300. https://doi.org/10.1016/S0168-1923(97)00027-0

NOAA (National Oceanic and Atmospheric Administration). (2024). *Global Historical Climatology Network daily (GHCNd)*. Retrieved April 1, 2024, from www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily

Zhang, Y., Bielory, L., Cai, T., Mi, Z., & Georgopoulos, P. (2015). Predicting onset and duration of airborne allergenic pollen season in the United States. *Atmospheric Environment*, *103*, 297–306. https://doi.org/10.1016/j.atmosenv.2014.12.019