High and Low Temperatures

Identification

1. Indicator Description

This indicator examines metrics related to trends in unusually hot and cold temperatures across the United States over the last several decades. Changes in many extreme weather and climate events have been observed, and further changes, such as fewer cold days and nights and more frequent hot days and nights, are likely to continue this century (IPCC, 2013). Extreme temperature events like summer heat waves and winter cold spells can have profound effects on human health and society.

Components of this indicator include:

- The percentage of land area experiencing unusually hot summer temperatures or unusually cold winter temperatures (Figures 1 and 2, respectively).
- Changes in the prevalence of unusually hot and unusually cold temperatures throughout the year at individual weather stations (Figures 3 and 4).
- The proportion of record-setting high temperatures to record low temperatures over time (Figure 5).

2. Revision History

April 2010:	Indicator published.
December 2012:	Combined original Figures 2 and 3 into new Figure 2. Updated Figure 1 with data through 2011, and updated Figure 2 with data through 2012. Added Figure 3 and Figure 4 to show to show unusually cold winter temperatures and record daily highs and lows, respectively.
August 2013:	Updated Figure 1 with data through 2012; updated Figure 3 with data through 2013.
May 2014:	Added Figures 4 and 5 and renumbered “Record Daily Highs and Record Daily Lows” to Figure 6. Updated Figures 1 and 2 with data through 2013; updated Figure 3 with data through 2014.
June 2015:	Updated Figures 1, 2, 4, and 5 with data through 2014; updated Figure 3 with data through 2015.
August 2016:	Updated Figures 1, 2, 4, and 5 with data through 2015; updated Figure 3 with data through 2016.
April 2021:	Moved Figure 1 to new “Heat Waves” indicator; renumbered the remaining figures. Updated the newly numbered Figures 1–4 with data through 2020.

3. Data Sources

Data for Figures 1 and 2 come from the National Oceanic and Atmospheric Administration's (NOAA's) U.S. Climate Extremes Index (CEI), which is maintained by NOAA's National Centers for Environmental Information (NCEI) and based on a specific quality-controlled subset of long-term stations that NCEI has designated as its U.S. Historical Climatology Network (USHCN) data set (www.ncdc.noaa.gov/extremes/cei/data-used). Data for Figures 3 and 4 come from U.S. weather stations within NCEI's Global Historical Climatology Network, Daily edition (GHCN-Daily). Data for Figure 5 come from an analysis published by Meehl et al. (2009).

All components of this indicator are based on temperature measurements from weather stations overseen by NOAA's National Weather Service (NWS). These underlying data are maintained by NCEI.

4. Data Availability

Figures 1 and 2. Area of the Contiguous 48 States with Unusually Hot Summer Temperatures (1910–2020) or Unusually Cold Winter Temperatures (1911–2020)

NOAA has calculated each of the components of the CEI and has made these data files publicly available. The data for unusually hot summer maximum and minimum temperatures (CEI steps 1b and 2b) and for unusually cold winter maximum and minimum temperatures (CEI steps 1a and 2a) can be downloaded from: www.ncdc.noaa.gov/extremes/cei/graph. NOAA's CEI website (www.ncdc.noaa.gov/extremes/cei) provides additional descriptions and links, along with a portal to download or graph various components of the CEI, including the data sets listed above.

Figures 3 and 4. Changes in Unusually Hot and Cold Temperatures in the Contiguous 48 States, 1948–2020

Data for these maps came from Version 3.28 of NCEI's GHCN-Daily data set, which provided the optimal format for processing. Within the contiguous 48 states, the GHCN pulls data directly from a dozen separate data sets maintained at NCEI. NCEI explains the variety of databases that feed into the GHCN for U.S.-based stations in online metadata and at: www.ncdc.noaa.gov/ghcn-daily-methods. The data for this indicator can be obtained online via FTP at: ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/daily. Appropriate metadata and "readme" files are also available at this link.

Figure 5. Record Daily High and Low Temperatures in the Contiguous 48 States, 1950–2009

Ratios of record highs to lows were taken from Meehl et al. (2009) and a supplemental release that accompanied the publication of that peer-reviewed study (www.eurekalert.org/pub_releases/2009-11/ncfa-rht111209.php). Meehl et al. (2009) covered the period from 1950 to 2006, so the "2000s" bar in Figure 5 is based on a subsequent analysis of data through 2009 that was conducted by the authors of the paper and presented in the aforementioned press release. For confirmation, EPA obtained the actual counts of highs and lows by decade from Claudia Tebaldi, a co-author of the Meehl et al. (2009) study.

Underlying Data

NCEI maintains a set of databases that provide public access to daily and monthly temperature records from thousands of weather stations across the country. For access to these data, see NCEI's website at: www.ncdc.noaa.gov. There are no confidentiality issues that may limit accessibility. For an inventory of stations and station metadata, see: www.ncdc.noaa.gov/data-access/land-based-station-data.

Methodology

5. Data Collection

Since systematic collection of weather data in the United States began in the 1800s, observations have been recorded from 23,000 stations. At any given time, approximately 8,000 stations are recording observations on an hourly basis, along with the maximum and minimum temperatures for each day. 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.ncdc.noaa.gov/data-access/land-based-station-data, 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.

All five figures use data from the contiguous 48 states. Original sources and selection criteria are as follows:

- Figures 1 and 2 are based on a narrower set of stations that NOAA has designated as part of the USHCN. The USHCN is a subset of COOP and automated weather stations that meet certain selection criteria for record longevity, data availability, spatial coverage, and consistency of location. They also undergo additional levels of quality control. The period of record varies for each station, but generally includes most of the 20th century. Additional selection criteria were applied to these data prior to inclusion in CEI calculations, as described by Gleason et al. (2008). In compiling the temperature components of the CEI, NOAA selected only those stations with monthly temperature data at least 90-percent complete within a given period (e.g., annual, seasonal) as well as 90-percent complete for the full period of record.

- Figures 3 and 4 use daily maximum and minimum temperature data from GHCN-Daily Version 3.28. GHCN-Daily contains historical daily weather data from thousands of monitoring stations across the United States. This analysis is limited to the period from 1948 to 2020 because it enabled inclusion of most stations from the USHCN, which is a key contributing database to the GHCN-Daily. Station data are included only for years in which data are reported (one or more days) in six or more months. If a station reported data from fewer than six months, data from the entire year are removed. After filtering for individual years (above), stations are removed from further consideration if fewer than 75 percent of the years of data are included. Years need not be consecutive. As a result, Figures 3 and 4 show trends for 1,066 stations.

- In Figure 5, data for the 1950s through 1990s are based on a subset of 2,000 COOP stations that have collected data since 1950 and had no more than 10 percent missing values during the period from 1950 to 2006. These selection criteria are further described in Meehl et al. (2009).

- In Figure 5, data for the 2000s are based on the complete set of COOP records available from 2000 through September 2009. These numbers were published in Meehl et al. (2009) and the accompanying press release, but they do not follow the same selection criteria as the previous decades (as described above). Counts of record highs and lows using the Meehl et al. (2009) selection criteria were available, but only through 2006. Thus, to make this indicator as current as possible, EPA chose to use data from the broader set that extends through September 2009. Using the 2000–2006 data would result in a high:low ratio of 1.86, compared with a ratio of 2.04 when the full-decade data set (shown in Figure 5) is considered.

6. Indicator Derivation

Figures 1 and 2. Area of the Contiguous 48 States with Unusually Hot Summer Temperatures (1910–2020) or Unusually Cold Winter Temperatures (1911–2020)

Figure 1 of this indicator shows the percentage of the area of the contiguous 48 states in any given year that experienced unusually warm maximum and minimum summer temperatures. Figure 2 displays the percentage of land area that experienced unusually cold maximum and minimum winter temperatures.

Figures 1 and 2 were developed as subsets of NOAA's CEI, an index that uses six variables to examine trends in extreme weather and climate. These figures are based on components of NOAA's CEI (labeled as Steps 1a, 1b, 2a, and 2b) that look at the percentage of land area within the contiguous 48 states that experienced maximum (Step 1) or minimum (Step 2) temperatures much below (a) or above (b) normal.

NOAA computed the data for the CEI and calculated the percentage of land area for each year by dividing the contiguous 48 states into a 1-degree by 1-degree grid and using data from one station per grid box. This was done to eliminate many of the artificial extremes that resulted from a changing number of available stations over time.

NOAA began by averaging all daily highs at a given station over the course of a month to derive a monthly average high, then performing the same step with daily lows. Next, period (monthly) averages were sorted and ranked, and values were identified as "unusually warm" if they fell in the highest 10th percentile in the period of record for each station or grid cell, and "unusually cold" if they fell in the lowest 10th percentile. Thus, the CEI has been constructed to have an expected value of 10 percent for each of these components, based on the historical record—or a value of 20 percent if the two extreme ends of the distribution are added together.

The CEI can be calculated for individual months, seasons, or an entire year. Figure 1 displays data for summer, which the CEI defines as June, July, and August. Figure 2 displays data for winter, which the CEI defines as December, January, and February. Winter values are plotted at the year in which the season ended; for example, the winter from December 2017 to February 2018 is plotted at year 2018. This explains why Figures 1 and 2 appear to have a different starting year, as data were not available from December 1909 to calculate a winter value for 1910. To smooth out some of the year-to-year variability, EPA applied a nine-point binomial filter, which is plotted at the center of each nine-year window. For example, the smoothed value from 2010 to 2018 is plotted at year 2014. NOAA NCEI recommends this approach and has used it in the official online reporting tool for the CEI.

EPA used endpoint padding to extend the nine-year smoothed lines all the way to the ends of the period of record. As recommended by NCEI, EPA calculated smoothed values as follows: if 2020 was the most recent year with data available, EPA calculated smoothed values to be centered at 2017, 2018, 2019, and 2020 by inserting the 2020 data point into the equation in place of the as-yet-unreported annual data points for 2020 and beyond. EPA used an equivalent approach at the beginning of the time series.

The CEI has been extensively documented and refined over time to provide the best possible representation of trends in extreme weather and climate. For an overview of how NOAA constructed Steps 1 and 2 of the CEI, see: www.ncdc.noaa.gov/extremes/cei. This page provides a list of references that describe analytical methods in greater detail. In particular, see Gleason et al. (2008).

Figures 3 and 4. Changes in Unusually Hot and Cold Temperatures in the Contiguous 48 States, 1948–2020

For Figure 3, the change in the number of days per year on which the daily maximum temperature exceeded the 95th percentile temperature was determined through the following steps:

1. At each monitoring station, the 95th percentile daily maximum temperature was determined for the full period of record (1948–2020).

2. For each station, the number of days in each calendar year on which the maximum daily temperature exceeded the station-specific 95th percentile temperature was determined.

3. The average rate of change over time in the number of >95th percentile days was estimated from the annual number of >95th percentile days using ordinary least-squares linear regression.

4. Regression coefficients (the average change per year in >95th percentile days) for regressions significant at the 90-percent level ($p \leq 0.1$) were multiplied by the number of years in the analysis (1948–2020 is 72 years) to estimate the total change in the number of annual >95th percentile days over the full period of record. Where $p > 0.1$, coefficients were set to zero. These values (including “zero” values for stations with insignificant trends) were mapped to show trends at each climate station.

Figure 4 was constructed using a similar procedure with daily minimum temperatures and the 5th percentile.

Figure 5. Record Daily High and Low Temperatures in the Contiguous 48 States, 1950–2009

Figure 5 displays the proportion of daily record high and daily record low temperatures reported at a subset of quality-controlled NCEI COOP network stations (except for the most recent decade, which is based on the entire COOP network, as described in Section 5). As described in Meehl et al. (2009), steps were taken to fill missing data points with simple averages from neighboring days with reported values when there are no more than two consecutive days missing, or otherwise by interpolating values at the closest surrounding stations.

Based on the total number of record highs and the total number of record lows set in each decade, Meehl et al. (2009) calculated each decade's ratio of record highs to record lows. EPA converted these values to percentages to make the results easier to communicate.

Although it might be interesting to look at trends in the absolute number of record highs and record lows over time, these values are recorded in a way that would make a trend analysis misleading. A daily high or low is registered as a "record" if it broke a record *at the time*—even if that record has since been surpassed. Statistics dictate that as more years go by, it becomes less likely that a record will be broken. In contrast, if a station has only been measuring temperature for 5 years (for example), every day has a much greater chance of breaking a previous record. Thus, a decreasing trend in absolute counts does not indicate that the climate is actually becoming less extreme, as one might initially guess. Meehl et al. (2009) show that actual counts indeed fit a decreasing pattern over time, as expected statistically.

7. Quality Assurance and Quality Control

The NWS has documented COOP methods, including training manuals and maintenance of equipment, at: www.weather.gov/coop. These training materials also discuss quality control of the underlying data set. Additionally, pre-1948 data in the COOP data set have recently been digitized from hard copies. Quality control procedures associated with digitization and other potential sources of error are discussed in Kunkel et al. (2005).

Data from weather stations go through a variety of additional quality assurance and quality control procedures before they can be added to historical data sets such as the USHCN and GHCN. Procedures that were used to address specific potential problems in trend estimation in the most recent version of the USHCN are summarized at: www.ncdc.noaa.gov/ushcn/introduction. Homogeneity testing and data correction methods are described in numerous peer-reviewed scientific papers by NCEI. A series of data corrections was developed to specifically address potential problems in trend estimation of the rates of warming or cooling in USHCN Version 2 and beyond. They include:

- Removal of duplicate records.
- Procedures to deal with missing data.
- Adjusting for changes in observing practices, such as changes in observation time.
- Testing and correcting for artificial discontinuities in a local station record, which might reflect station relocation, instrumentation changes, or urbanization (e.g., heat island effects).

Quality control procedures for GHCN-Daily data are described at: www.ncdc.noaa.gov/ghcn-daily-methods. GHCN-Daily data undergo rigorous quality assurance reviews, starting with pre-screening for data and station appropriateness. GCHN-Daily's "Methods" page also provides a detailed description of the data integration process. Further quality assurance procedures for individual data points include removal of duplicates, isolated values, suspicious streaks, and excessive or unnatural values; spatial comparisons that verify the accuracy of the climatological mean and the seasonal cycle; and neighbor checks that identify outliers from both a serial and a spatial perspective. 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.

Analysis

8. Comparability Over Time and Space

Long-term weather stations have been carefully selected from the full set of all COOP stations to provide an accurate representation of the United States for the proportion of record daily highs to record daily lows (Kunkel et al., 1999; Meehl et al., 2009). Some bias may have occurred as a result of changes over time in instrumentation, measuring procedures, and the exposure and location of the instruments. The record high/low analysis begins with 1950 data, in an effort to reduce disparity in station record lengths.

The USHCN has undergone extensive testing to identify errors and biases in the data and either remove these stations from the time series or apply scientifically appropriate correction factors to improve the utility of the data. In particular, these corrections address changes in the time-of-day of observation, advances in instrumentation, and station location changes. Homogeneity testing and data correction methods are described in more than a dozen peer-reviewed scientific papers by NCEI. Data corrections were developed to specifically address potential problems in trend estimation of the rates of warming or cooling in the USHCN (see Section 7 for documentation).

NOAA's Climate Reference Network (www.ncdc.noaa.gov/crn), a set of optimally-sited stations completed in 2008, can be used to test the accuracy of recent trends. While it is true that some stations are not optimally located, NOAA's findings support the results of an earlier analysis by Peterson (2006), who found no significant bias in long-term trends associated with station siting once NOAA's homogeneity adjustments were applied. An independent analysis by the Berkeley Earth Surface Temperature (BEST) project (http://berkeleyearth.org/summary-of-findings) used more stations and a different statistical methodology, yet found similar results.

As documented in Section 7, GHCN-Daily stations are extensively filtered and quality-controlled to maximize comparability across stations and across time.

9. Data Limitations

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

1. Biases may have occurred as a result of changes over time in instrumentation, measuring procedures, and the exposure and location of the instruments. Where possible, data have been adjusted to account for changes in these variables. For more information on these corrections, see Section 7. Some scientists believe that the empirical de-biasing models used to adjust the data might themselves introduce non-climatic biases (e.g., Pielke et al., 2007).

2. Observer errors, such as errors in reading instruments or writing observations on the form, are present in the earlier part of this data set. Additionally, uncertainty may be introduced into this data set when hard copies of data are digitized. As a result of these and other factors, uncertainties in the temperature data increase as one goes back in time, particularly because there were fewer stations early in the record. NOAA does not believe, however, that these uncertainties are sufficient to undermine the fundamental trends in the data. More information about limitations of pre-1948 weather data can be found in Kunkel et al. (2005).

10. Sources of Uncertainty

Uncertainty may be introduced into this data set when hard copies of historical data are digitized. For this and other reasons, uncertainties in the temperature data increase as one goes back in time, particularly because there are fewer stations early in the record. NOAA does not believe, however, that these uncertainties are sufficient to undermine the fundamental trends in the data. Vose and Menne (2004) suggest that the station density in the U.S. climate network is sufficient to produce robust spatial averages.

Error estimates have been developed for certain segments of the data set, but do not appear to be available for the data set as a whole.

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. This indicator presents nine-year smoothed curves (Figures 1 and 2), long-term rates of change (Figures 3 and 4), and decadal averages (Figure 5) to reduce the year-to-year “noise” inherent in the data. Temperature patterns also vary spatially. This indicator provides information on geographic differences using location-specific trends in Figures 3 and 4.

12. Statistical/Trend Analysis

Figures 3 and 4 use ordinary least-squares linear regression to calculate the slope of observed trends in the annual number of 95^{th} and 5^{th} percentile days at each monitoring station. Trends that are not statistically significant at the 90 percent level ($p \leq 0.1$) are displayed as zero (i.e., they are grouped into the “-5 to 5” class). Of all the stations grouped into the “-5 to 5” class, only one (a station in Figure 4) has a trend that is statistically significant at the 90-percent level ($p \leq 0.1$).

This indicator does not report on the slope of the apparent trends in Figures 1, 2, and 5, nor does it calculate the statistical significance of these trends.

References

Gleason, K.L., J.H. Lawrimore, D.H. Levinson, T.R. Karl, and D.J. Karoly. 2008. A revised U.S. climate extremes index. J. Climate 21:2124–2137.

IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013: The physical science basis. Summary for policymakers. Working Group I contribution to the IPCC Fifth Assessment Report. Cambridge, United Kingdom: Cambridge University Press. www.ipcc.ch/report/ar5/wg1.

Kunkel, K.E., R.A. Pielke Jr., and S. A. Changnon. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. B. Am. Meteorol. Soc. 80:1077–1098.

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.

Meehl, G.A., C. Tebaldi, G. Walton, D. Easterling, and L. McDaniel. 2009. Relative increase of record high maximum temperatures compared to record low minimum temperatures in the U.S. Geophys. Res. Lett. 36:L23701.

Peterson, T.C. 2006. Examination of potential biases in air temperature caused by poor station locations. B. Am. Meteorol. Soc. 87:1073–1080. https://journals.ametsoc.org/view/journals/bams/87/8/bams-87-8-1073.xml.

Pielke, R., J. Nielsen-Gammon, C. Davey, J. Angel, O. Bliss, N. Doesken, M. Cai, S. Fall, D. Niyogi, K. Gallo, R. Hale, K.G. Hubbard, X. Lin, H. Li, and S. Raman. 2007. Documentation of uncertainties and biases associated with surface temperature measurement sites for climate change assessment. B. Am. Meteorol. Soc. 88:913–928.

Vose, R.S., and M.J. Menne. 2004. A method to determine station density requirements for climate observing networks. J. Climate 17(15):2961–2971.