High and Low Temperatures

Identification

1. Indicator Description

This indicator describes trends in unusually hot and cold temperatures across the United States over approximately the last 100 years. Extreme temperature events like summer heat waves and winter cold spells can have profound effects on society.

Components of this indicator include:

- An index reflecting the frequency of extreme heat events (Figure 1)
- The percentage of land area experiencing unusually hot summer temperatures or unusually cold winter temperatures (Figures 2 and 3, respectively)
- The proportion of record-setting high temperatures to record low temperatures over time (Figure 4)

2. Revision History

April 2010: Indicator posted
December 2011: Updated Figure 1 with data through 2010; combined Figures 2 and 3 into a new Figure 2, and updated data through 2011; added new Figures 3 and 4; and expanded the indicator from "Heat Waves" to "High and Low Temperatures"
February 2012: Updated Figure 1 with data through 2011
March 2012: Updated Figure 3 with data through 2012
October 2012: Updated Figure 2 with data through 2012
August 2013: Updated Figure 1 on EPA's website with data through 2012; updated Figure 3 on EPA's website with data through 2013

Data Sources

3. Data Sources

Index values for Figure 1 were provided by Dr. Kenneth Kunkel of the National Oceanic and Atmospheric Administration's (NOAA's) Cooperative Institute for Climate and Satellites (CICS), who updated an analysis that was previously published in U.S. Climate Change Science Program (2008). Data for Figures 2 and 3 come from NOAA's U.S. Climate Extremes Index (CEI). Data for Figure 4 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 NCDC.

4. Data Availability

Figure 1. U.S. Annual Heat Wave Index, 1895–2012

Data for this figure were provided by Dr. Kenneth Kunkel of NOAA CICS, who performed the analysis based on data from NCDC's publicly available databases.

Figures 2 and 3. Area of the Contiguous 48 States with Unusually Hot Summer Temperatures (1910–2012) or Unusually Cold Winter Temperatures (1911–2013)

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) can be downloaded from: ftp://ftp.ncdc.noaa.gov/pub/data/cei/dk-step1-hi.06-08.results and: ftp://ftp.ncdc.noaa.gov/pub/data/cei/dk-step2-hi.06-08.results, respectively. The data for unusually cold winter maximum and minimum temperatures (CEI steps 1a and 2a) can be downloaded from: ftp://ftp.ncdc.noaa.gov/pub/data/cei/dk-step1-lo.12-02.results and: ftp://ftp.ncdc.noaa.gov/pub/data/cei/dk-step2-lo.12-02.results, respectively. A "readme" file (ftp://ftp.ncdc.noaa.gov/pub/data/cei) explains the contents of the data files. NOAA's CEI website (http://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.

Figure 4. 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 press release that accompanied the publication of that peer-reviewed study (http://www2.ucar.edu/news/1036/record-high-temperatures-far-outpace-record-lows-across-us). 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) paper.

Underlying Data

NCDC 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 and accompanying metadata, visit NCDC's website at: http://www.ncdc.noaa.gov/oa/ncdc.html.

Many of the weather stations are part of NOAA's Cooperative Observer Program (COOP). Complete data, embedded definitions, and data descriptions for these stations can be found online at: www.ncdc.noaa.gov/doclib/. State-specific data can be found at: www7.ncdc.noaa.gov/IPS/coop/coop.html;jsessionid=312EC0892FFC2FBB78F63D0E3ACF6CBC. There are no confidentiality issues that may limit accessibility. Additional metadata can be found at: www.nws.noaa.gov/om/coop/.

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. Observations are made on an hourly basis, and the maximum and minimum temperatures are recorded for each 24-hour time span.

NOAA's National Weather Service (NWS) operates some stations (called first-order stations), but the vast majority of U.S. weather stations are part of NWS's Cooperative Observer Program (COOP). The COOP data set represents the core climate network of the United States (Kunkel et al., 2005). Cooperative observers include state universities, state and federal agencies, and private individuals. Observers are trained to collect data following NWS protocols, and equipment to gather these data is provided and maintained by the NWS.

Data collected by COOP are referred to as U.S. Daily Surface Data or Summary of the Day data. Variables that are relevant to this indicator include observations of daily maximum and minimum temperatures. General information about the NWS COOP data set is available at: www.nws.noaa.gov/os/coop/what-is-coop.html. Sampling procedures are described in Kunkel et al. (2005) and in the full metadata for the COOP data set available at: www.nws.noaa.gov/om/coop/.

NCDC also maintains a database called the U.S. Historical Climatology Network (USHCN), which contains data from a subset of COOP and first-order weather stations that meet certain selection criteria and undergo additional levels of quality control. USHCN contains monthly averaged maximum, minimum, and mean temperature data from approximately 1,200 stations within the contiguous 48 states. The period of record varies for each station but generally includes most of the 20th century. One of the objectives in establishing the USHCN was to detect secular changes of regional rather than local climate. Therefore, stations included in this network are only those believed to not be influenced to any substantial degree by artificial changes of local environments. To be included in the USHCN, a station had to meet certain criteria for record longevity, data availability (percentage of available values), spatial coverage, and consistency of location (i.e., experiencing few station changes). An additional criterion, which sometimes compromised the preceding criteria, was the desire to have a uniform distribution of stations across the United States. Included with the data set are metadata files that contain information about station moves, instrumentation, observing times, and elevation. NOAA's website (www.ncdc.noaa.gov/oa/climate/research/ushcn) provides more information about USHCN data collection.

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

- Figure 1 is based on stations from the COOP data set that had sufficient data during the period of record (1895–2012).
- Figures 2 and 3 are based on the narrower set of stations contained within the USHCN, which is the source of all data for NOAA's CEI. 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.
- In Figure 4, 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 4, 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 4) is considered.

6. Indicator Derivation

Figure 1. U.S. Annual Heat Wave Index, 1895–2012

Data from the COOP data set have been used to calculate annual values for a U.S. Annual Heat Wave Index. In this indicator, heat waves are defined as warm periods of at least four days with an average temperature (that is, averaged over all four days) exceeding the threshold for a one-in-10-year occurrence (Kunkel et al., 1999). The Annual U.S. Heat Wave Index is a frequency measure of the number of heat waves that occur each year. A complete explanation of trend analysis in the annual average heat wave index values, especially trends occurring since 1960, can be found in Appendix A, Example 2, of U.S. Climate Change Science Program (2008). Analytical procedures are described in Kunkel et al. (1999).

Figures 2 and 3. Area of the Contiguous 48 States with Unusually Hot Summer Temperatures (1910–2012) or Unusually Cold Winter Temperatures (1911–2013)

Figure 2 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 3 displays the percentage of land area that experienced unusually cold maximum and minimum winter temperatures.

Figures 2 and 3 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 2 displays data for summer, which the CEI defines as June, July, and August. Figure 3 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 2012 to February 2013 is plotted at year 2013. This explains why Figures 2 and 3 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 2005 to 2013 is plotted at year 2009. NOAA NCDC 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 NCDC, EPA calculated smoothed values as follows: If 2013 was the most recent year with data available, EPA calculated smoothed values to be centered at 2010, 2011, 2012, and 2013 by inserting the 2013 data point into the equation in place of the as-yet-unreported annual data points for 2014 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).

Figure 4. Record Daily High and Low Temperatures in the Contiguous 48 States, 1950–2009

Figure 4 displays the proportion of daily record high and daily record low temperatures reported at a subset of quality-controlled NCDC 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.nws.noaa.gov/os/coop/training.htm. 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 copy. Quality control procedures associated with digitization and other potential sources of error are discussed in Kunkel et al. (2005).

Quality control procedures for the USHCN are summarized at: www.ncdc.noaa.gov/oa/climate/research/ushcn/#processing. Homogeneity testing and data correction methods are described in numerous peer-reviewed scientific papers by NCDC. 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. 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)

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 U.S. Annual Heat Wave Index and 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 at 1950 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 NCDC. 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). Balling and Idso (2002) compare the USHCN data with several surface and upper-air data sets and show that the effects of the various USHCN adjustments produce a significantly more positive, and likely spurious, trend in the USHCN data. In contrast, a subsequent analysis by Vose et al. (2003) found that USHCN station history information is reasonably complete and that the bias adjustment models have low residual errors.

Further analysis by Menne et al. (2009) suggests that:

> …the collective impact of changes in observation practice at USHCN stations is systematic and of the same order of magnitude as the background climate signal. For this reason, bias adjustments are essential to reducing the uncertainty in U.S. climate trends. The largest biases in the HCN are shown to be associated with changes to the time of observation and with the widespread changeover from liquid-in-glass thermometers to the maximum minimum temperature sensor (MMTS). With respect to [USHCN] Version 1, Version 2 trends in maximum temperatures are similar while

> minimum temperature trends are somewhat smaller because of an apparent overcorrection in Version 1 for the MMTS instrument change, and because of the systematic impact of undocumented station changes, which were not addressed [in] Version 1.

USHCN Version 2 represents an improvement in this regard.

Some observers have expressed concerns about other aspects of station location and technology. For example, Watts (2009) expresses concern that many U.S. weather stations are sited near artificial heat sources such as buildings and paved areas, potentially biasing temperature trends over time. In response to these concerns, NOAA analyzed trends for a subset of stations that Watts had determined to be "good or best," and found the temperature trend over time to be very similar to the trend across the full set of USHCN stations (www.ncdc.noaa.gov/oa/about/response-v2.pdf). While it is true that many stations are not optimally located, NOAA's findings support the results of an earlier analysis by Peterson (2006) that found no significant bias in long-term trends associated with station siting once NOAA's homogeneity adjustments have been applied.

9. Sources of Uncertainty

Uncertainty may be introduced into this data set when hard copies of historical data are digitized. As a result of these and other reasons, uncertainties in the temperature data increase as one goes back in time, particularly given that there are fewer stations early in the record. However, NOAA does not believe 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. Uncertainty measurements are not included with the publication of the U.S. Annual Heat Wave Index or the CEI seasonal temperature data. Error measurements for the pre-1948 COOP data set are discussed in detail in Kunkel et al. (2005).

10. 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, 2, and 3) and decadal averages (Figure 4) to reduce the year-to-year "noise" inherent in the data.

11. Statistical/Trend Analysis

Heat wave trends are somewhat difficult to analyze because of the presence of several outlying values in the 1930s. Statistical methods used to analyze trends in the U.S. Annual Heat Wave Index are presented in Appendix A, Example 2, of U.S. Climate Change Science Program (2008). Despite the presence of inter-annual variability and several outlying values in the 1930s, standard statistical treatments can be applied to assess a highly statistically significant linear trend from 1960 to 2011. However, the trend over the full period of record is not statistically significant.

This indicator does not report on the slope of the apparent trends in Figures 2, 3, and 4, nor does it calculate the statistical significance of these trends.

12. 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.
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 reasons, uncertainties in the temperature data increase as one goes back in time, particularly given that there are fewer stations early in the record. However, NOAA does not believe these uncertainties are sufficient to undermine the fundamental trends in the data. More information about limitations of early weather data can be found in Kunkel et al. (2005).

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