U.S. and Global Temperature

Identification

1. Indicator Description

This indicator describes changes in average air temperature for the United States and the world from 1901 to 2021. In this indicator, temperature data are presented as trends in anomalies. Air temperature is an important indicator of climate, and changes in temperature can have wide-ranging direct and indirect effects on the environment and society. Evidence of a warming climate often begins with average surface temperature (USGCRP, 2017).

Components of this indicator include:

- Changes in temperature in the contiguous 48 states over time (Figure 1).
- Changes in temperature worldwide over time (Figure 2).
- A map showing rates of temperature change across the contiguous 48 states and Alaska (Figure 3).

2. Revision History

April 2010:	Indicator published.
December 2012:	Updated indicator with data through 2011.
August 2013:	Updated indicator with data through 2012.
May 2014:	Updated Figures 1 and 2 with data through 2013.
June 2015:	Updated indicator with data through 2014.
August 2016:	Updated indicator with data through 2015.
April 2021:	Updated indicator with data through 2020.
July 2022:	Updated indicator with data through 2021.

Data Sources

3. Data Sources

This indicator is based on temperature anomaly data provided by the National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Information (NCEI), formerly the National Climatic Data Center (NCDC). Specifically, this indicator uses the following NCEI data sets:

- Figure 1, contiguous 48 states surface temperature; Figure 3, surface temperature map: *n*ClimDiv.
- Figure 2, global surface temperature: Global Historical Climatology Network–Monthly (GHCN-M) Version 4.

- Figures 1 and 2, contiguous 48 states and global satellite-based temperature: analyses of satellite data conducted by the Global Hydrology and Climate Center at the University of Alabama in Huntsville (UAH) and Remote Sensing Systems (RSS), maintained by NCEI.

*n*ClimDiv is itself based on data from the daily version of GHCN (GHCN-Daily). These data undergo more extensive processing by NCEI on a monthly basis for inclusion in *n*ClimDiv.

4. Data Availability

All of the underlying data sets can be accessed online, along with descriptions and metadata. Specific data sets were obtained as follows.

Contiguous 48 States Surface Time Series

Surface temperature time series data for the contiguous 48 states (Figure 1) are based on *n*ClimDiv data that were obtained from NCEI's "Climate at a Glance" web interface (www.ncdc.noaa.gov/cag). For access to underlying *n*ClimDiv data and documentation, see: www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php.

Global Surface Time Series

GHCN global surface temperature data (Figure 2) were obtained from NCEI's "Climate at a Glance" web interface (www.ncdc.noaa.gov/cag). For access to underlying GHCN-M Version 4 data and documentation, see: www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-monthly.

Contiguous 48 States and Alaska Map

The map in this indicator (Figure 3) is based on *n*ClimDiv monthly data by climate division, which are publicly available from NCEI's "Climate at a Glance" web interface (www.ncdc.noaa.gov/cag).

Satellite-Based Time Series

EPA obtained the satellite analyses (Figures 1 and 2) from NCEI's public website at: www.ncdc.noaa.gov/temp-and-precip/msu/overview.

Methodology

5. Data Collection

This indicator is based on temperature measurements. The global portion of this indicator presents temperatures measured over land and sea, while the portion for the contiguous 48 states and Alaska shows temperatures measured over land only.

Surface data for this indicator were compiled from thousands of weather stations throughout the United States and worldwide using standard meteorological instruments. Data for the contiguous 48 states and Alaska were compiled in the *n*ClimDiv data set. Data for the rest of the world were taken from GHCN data sets. All of the networks of stations cited here are overseen by NOAA, and their methods of site selection and quality control (QC) have been extensively peer reviewed. As such, they represent the most complete long-term instrumental data sets for analyzing recent climate trends. More information on these networks can be found below.

Contiguous 48 States Surface Time Series; Contiguous 48 States and Alaska Map

The *n*ClimDiv divisional data set incorporates temperature data from GHCN-Daily stations in the contiguous 48 states and Alaska. This data set includes stations that were previously part of the U.S. Historical Climatology Network (USHCN), as well as additional stations that were able to be added to *n*ClimDiv as a result of quality-control adjustments and digitization of paper records. Altogether, *n*ClimDiv incorporates data from more than 10,000 stations. These stations are spread among 357 climate divisions in the contiguous 48 states and Alaska.

In addition to incorporating more stations, the *n*ClimDiv data set differs from the USHCN because it incorporates a grid-based computational approach known as climatologically aided interpolation (Willmott and Robeson, 1995), which helps to address topographic variability. Data from individual stations are combined in a grid that covers the entire contiguous 48 states and Alaska with 5-kilometer resolution. These improvements have led to a new data set that maintains the strengths of its predecessor data sets while providing more robust estimates of area averages and long-term trends. The *n*ClimDiv data set is NOAA's official temperature data set for the contiguous 48 states and Alaska, replacing USHCN.

To learn more about *n*ClimDiv, see: www.ncdc.noaa.gov/news/ncdc-introduces-national-temperature-index-page, www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php, and Vose et al. (2014). Also see Vose et al. (2017) for details of the more recent effort to apply *n*ClimDiv methods to Alaska.

Global Surface Time Series

GHCN-M Version 4 contains monthly temperature data from weather stations worldwide—including stations within the contiguous 48 states and Alaska. Monthly mean temperature data are available for 26,000 stations. Data were obtained from many types of stations. For the global component of this indicator, the GHCN land-based data were merged with an additional set of long-term sea surface temperature data. This merged product is called the extended reconstructed sea surface temperature (ERSST) data set, Version #5 (Huang et al., 2017).

NCEI has published documentation for the GHCN. For more information, including data sources, methods, and recent improvements, see: www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-monthly and the sources listed therein. Additional background on the merged land-sea temperature data set can be found at: www.ncei.noaa.gov/products/land-based-station/noaa-global-temp.

Satellite-Based Time Series

In Figures 1 and 2, surface measurements have been supplemented with satellite-based measurements for the period from 1979 to 2021. These satellite data were collected by NOAA's polar-orbiting satellites, which take measurements across the entire globe. Satellites equipped with the necessary measuring equipment have orbited the Earth continuously since 1978, but 1979 was the first year with complete data. This indicator uses measurements that represent the lower troposphere, which is defined here as the layer of the atmosphere extending from the Earth's surface to an altitude of about 8 kilometers.

NOAA's satellites use the Microwave Sounding Unit (MSU) to measure the intensity of microwave radiation given off by various layers of the Earth's atmosphere. The intensity of radiation is proportional to temperature, which can therefore be determined through correlations and calculations. NOAA uses different MSU channels to characterize different parts of the atmosphere. Note that since 1998, NOAA has used a newer version of the instrument called the Advanced MSU.

For more information about the methods used to collect satellite measurements, see: www.ncdc.noaa.gov/temp-and-precip/msu/overview and the references cited therein.

6. Indicator Derivation

Contiguous 48 States and Global Surface Time Series

NOAA calculated monthly temperature means for each site. In populating the GHCN and *n*ClimDiv, NOAA adjusted the data to remove biases introduced by differences in the time of observation. NOAA also employed a homogenization algorithm to identify and correct for substantial shifts in local-scale data that might reflect changes in instrumentation, station moves, or urbanization effects. These adjustments were performed according to published, peer-reviewed methods. For more information on these quality assurance (QA) and error correction procedures, see Section 7.

In this indicator, temperature data are presented as trends in anomalies. An anomaly represents the difference between an observed value and the corresponding value from a baseline period. This indicator uses a baseline period of 1901 to 2000 for the contiguous 48 states and global data, and a baseline period of 1925 to 2000 for Alaska data due to sparse data prior to 1925. The choice of baseline period *will not* affect the shape or the statistical significance of the overall trend in anomalies. For absolute anomalies in degrees, it only moves the trend up or down on the graph in relation to the point defined as "zero."

To generate the temperature time series, NOAA converted measurements into monthly anomalies in degrees Fahrenheit. The monthly anomalies then were averaged to determine an annual temperature anomaly for each year.

To achieve uniform spatial coverage (i.e., not biased toward areas with a higher concentration of measuring stations), NOAA calculated area-weighted averages of grid-point estimates interpolated from station data. The surface time series for the contiguous 48 states (Figure 1) is based on the *n*ClimDiv gridded data set, which reflects a high-resolution (5-kilometer) interpolated grid that accounts for station density and topography. See: www1.ncdc.noaa.gov/pub/data/cirs/climdiv/divisional-readme.txt for more information. The global graph (Figure 2) comes from an analysis of grid cells measuring 5 degrees by 5 degrees. See: www.ncdc.noaa.gov/temp-and-precip/ghcn-gridded-products for more information.

Figures 1 and 2 show trends from 1901 to 2021, based on NOAA's gridded data sets. Although earlier data are available for some stations, 1901 was selected as a consistent starting point.

Contiguous 48 States and Alaska Map

The map in Figure 3 shows long-term rates of change in temperature over the United States for the period from 1901 to 2021, except for Alaska, for which widespread and reliable data collection did not begin until 1925 (therefore the map shows 1925–2021 for Alaska). Hawaii and U.S. territories are not included in this figure, due to insufficient data completeness or length of the measurement record. This map is based on NOAA's *n*ClimDiv gridded analysis, with results averaged within each climate division. The slope of each temperature trend was calculated from the annual climate division anomalies by ordinary least-squares regression and then multiplied by 100 to obtain a rate of change per century.

Satellite-Based Time Series

NOAA's satellites measure microwave radiation at various frequencies, which must be converted to temperature and adjusted for time-dependent biases using a set of algorithms. Various experts recommend slightly different algorithms. Accordingly, Figure 1 and Figure 2 show globally averaged trends that have been calculated by two different organizations: the Global Hydrology and Climate Center at UAH and RSS. For more information about the methods used to convert satellite measurements to temperature readings for various layers of the atmosphere, see: www.ncdc.noaa.gov/temp-and-precip/msu/overview and the references cited therein. Both the UAH and RSS data sets are based on updated versions of analyses that have been published in the scientific literature. For example, see Christy et al. (2000, 2003), Mears et al. (2003), and Schabel et al. (2002).

NOAA provided data in the form of monthly anomalies. EPA calculated annual anomalies, then shifted the entire curves vertically in order to display the anomalies side-by-side with surface anomalies. Shifting the curves vertically does not change the shape or magnitude of the trends; it simply results in a new baseline. No attempt has been made to portray satellite-based data beyond the time and space in which measurements were made. The satellite data in Figure 1 are restricted to the atmosphere above the contiguous 48 states.

Indicator Development

NOAA released the *n*ClimDiv data set in 2014, which allowed this indicator to use climate divisions in Figure 3 and a high-resolution climate division-based gridded analysis for Figure 1. Previous versions of EPA's indicator presented a contiguous 48 states surface time series and a United States map based on a coarse grid analysis, which was the best analysis available from NOAA at the time.

NOAA is continually refining historical data points in the GHCN and *n*ClimDiv, often as a result of improved methods to reduce bias and exclude erroneous measurements. As EPA updates this indicator to reflect these upgrades, slight changes to some historical data points may become apparent. No attempt has been made to portray data beyond the time and space in which measurements were made.

In June 2017, authors from RSS published a revised analysis of satellite data with new methodological improvements, including a more accurate adjustment for drift in local measurement time (Mears and Wentz, 2017). This improved approach resulted in an estimated rate of global temperature increase that is approximately 30 percent higher than the rate reported in the "RSS" line in Figure 2 of this indicator. Once the new version is adopted as the official RSS data set distributed by NOAA, EPA will incorporate it into this indicator.

7. Quality Assurance and Quality Control

NCEI's databases have undergone extensive QA procedures to identify errors and biases in the data and either remove these stations from the time series or apply correction factors.

Contiguous 48 States Surface Time Series; Contiguous 48 States and Alaska Map

The *n*ClimDiv data set follows the USHCN's methods to detect and correct station biases brought on by changes to the station network over time. The transition to a grid-based calculation did not significantly change national averages and totals, but it has led to improved historical temperature values in certain regions, particularly regions with extensive topography above the average station elevation—topography that is now being more thoroughly accounted for. An assessment of the major impacts of the transition to *n*ClimDiv can be found at: www.ncdc.noaa.gov/news/transitioning-gridded-climate-divisional-dataset.

Global Surface Time Series

QA/QC procedures for GHCN temperature data are described in detail at: www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-monthly and the sources listed therein. GHCN data undergo rigorous QA reviews, which include pre-processing checks on source data; removal of duplicates, isolated values, and suspicious streaks; time series checks to identify spurious changes in the mean and variance via pairwise comparisons; spatial comparisons to verify the accuracy of the climatological mean and the seasonal cycle; and neighbor checks to identify outliers from both a serial and a spatial perspective. NOAA also uses an automated pairwise homogenization algorithm to identify and adjust for cases in which there is an abrupt shift in one station's temperature series relative to many other correlated series from other stations in the region, as such an abrupt shift could indicate an artificial signal from a change in instrumentation or move in station location, etc.

Satellite-Based Time Series

NOAA follows documented procedures for QA/QC of data from the MSU satellite instruments. For example, see NOAA's discussion of MSU calibration at: www.star.nesdis.noaa.gov/smcd/emb/mscat.

Analysis

8. Comparability Over Time and Space

Both *n*ClimDiv and the GHCN have 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. See Section 7 for documentation.

Contiguous 48 States Surface Time Series; Contiguous 48 States and Alaska Map

All GHCN-Daily stations are routinely processed through a suite of logical, serial, and spatial QA reviews to identify erroneous observations. For *n*ClimDiv, all such observations were set to "missing" before computing monthly values, which in turn were subjected to additional serial and spatial checks to eliminate residual outliers. Stations having at least 10 years of valid monthly data since 1950 were used in *n*ClimDiv.

For temperature, bias adjustments were computed to account for historical changes in observation time, station location, temperature instrumentation, and siting conditions. As with USHCN, the method of Karl et al. (1986) was applied to remove the observation time bias from the COOP network, and the pairwise method of Menne and Williams (2009) was used to address changes in station location and instrumentation in all networks. Because the pairwise method also largely accounts for local, unrepresentative trends that arise from changes in siting conditions, *n*ClimDiv contains no separate adjustment in that regard.

For more documentation about *n*ClimDiv, see: www1.ncdc.noaa.gov/pub/data/cirs/climdiv/divisional-readme.txt.

Global Surface Time Series

The GHCN applied stringent criteria for data homogeneity in order to reduce bias. In acquiring data sets, the original observations were sought. See Section 7 for documentation.

For data collected over the ocean, continuous improvement and greater spatial resolution can be expected in the coming years, with corresponding updates to the historical data. For example, there is a known bias during the World War II years (1941–1945), when almost all ocean temperature measurements were collected by U.S. Navy ships that recorded ocean intake temperatures, which can give warmer results than the techniques used in other years. Future efforts will aim to adjust the data more fully to account for this bias.

Satellite-Based Time Series

NOAA's satellites cover the entire Earth with consistent measurement methods. Procedures to calibrate the results and correct for any biases over time are described in the references cited under Section 7.

9. Data Limitations

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

1. Biases in surface measurements may have occurred as a result of changes over time in instrumentation, measuring procedures (e.g., time of day), 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 8. Some scientists believe that the empirical debiasing models used to adjust the data might themselves introduce non-climatic biases (e.g., Pielke et al., 2007).

2. Uncertainties in surface temperature data increase as one goes back in time, as there are fewer stations early in the record. These uncertainties are not sufficient, however, to mislead the user about fundamental trends in the data.

10. Sources of Uncertainty

Surface Time Series and Maps

Uncertainties in temperature data increase as one goes back in time, as there are fewer stations early in the record. These uncertainties are not sufficient, however, to undermine the fundamental trends in the data.

Error estimates are not readily available for U.S. temperature, but they are available for the global temperature time series. See the "total uncertainty" graph at: www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-monthly and additional detail in Menne et al. (2018). In general, Vose and Menne (2004) suggest that the station density in the U.S. climate network is sufficient to produce a robust spatial average.

Satellite-Based Time Series

Methods of inferring tropospheric temperature from satellite data have been developed and refined over time. Several independent analyses have produced largely similar curves, suggesting fairly strong agreement and confidence in the results.

Error estimates for the UAH analysis have previously been published in Christy et al. (2000, 2003). Error estimates for the RSS analysis have previously been published in Schabel et al. (2002) and Mears et al. (2003). Error estimates are not readily available, however, for the updated version of each analysis that EPA obtained in 2022.

11. Sources of Variability

Annual temperature anomalies naturally vary from location to location and from year to year as a result of normal variations 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 presenting a long-term record (more than a century of data) and averaging consistently over time and space.

12. Statistical/Trend Analysis

This indicator uses ordinary least-squares regression to calculate the slope of the observed trends in temperature. A simple t-test indicates that the following observed trends are significant at the 95 percent confidence level:

- Contiguous 48 states temperature, 1901–2021, surface: +0.017°F/year ($p < 0.001$)
- Contiguous 48 states temperature, 1979–2021, surface: +0.050°F/year ($p < 0.001$)
- Contiguous 48 states temperature, 1979–2021, UAH satellite method: +0.032°F/year ($p < 0.001$)
- Contiguous 48 states temperature, 1979–2021, RSS satellite method: +0.055°F/year ($p < 0.001$)
- Global temperature, 1901–2021, surface: +0.017°F/year ($p < 0.001$)
- Global temperature, 1979–2021, surface: +0.031°F/year ($p < 0.001$)
- Global temperature, 1979–2021, UAH satellite method: +0.024°F/year ($p < 0.001$)
- Global temperature, 1979–2021, RSS satellite method: +0.037°F/year ($p < 0.001$)

Among the individual climate divisions shown in Figure 3, 85 percent of divisions have statistically significant temperature trends based on ordinary least-squares linear regression and a 95 percent confidence threshold. All of the divisions with statistically significant temperature trends had positive values; conversely, no temperature trends that showed decreases were shown to be statistically significant.

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