Sea Surface Temperature

Identification

1. Indicator Description

This indicator describes global trends in sea surface temperature (SST) from 1880 to 2023. SST is a key indicator related to climate change because it describes conditions at the boundary between the atmosphere and the oceans, which is where the transfer of energy between the atmosphere and oceans takes place. As the oceans absorb more heat from the atmosphere, SST is expected to increase. Changes in SST can affect circulation patterns and ecosystems in the ocean, and they can also influence global climate through the transfer of energy back to the atmosphere.

Components of this indicator include:

- Global average SST from 1880 to 2023 (Figure 1)
- A global map showing variations in SST change from 1901 to 2022 (Figure 2)

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 Figure 1 with data through 2013. Added Figure 2 to show spatial patterns.
June 2015:	Updated indicator with data through 2014.
August 2016:	Updated indicator with data through 2015.
April 2021:	Updated indicator with data through 2020.
June 2024:	Updated Figure 1 with data through 2023 and Figure 2 with data through 2022.

Data Sources

3. Data Sources

Figure 1 is based on the Extended Reconstructed Sea Surface Temperature (ERSST) analysis developed by the National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Information (NCEI). The reconstruction model used here is ERSST version 5 (ERSST.v5), which covers the years 1880 to 2023 and was described by Huang et al. (2024).

Figure 2 has been adapted from a map in the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (IPPC, 2013). The original map appears in IPCC's Working Group I report as Figure SPM.1 and Figure 2.21, and it shows temperature change over land as well as over the ocean. The data originally come from version 5 of NCEI's NOAA Global Surface Temperature (NOAAGlobalTemp) data set, formerly known as the Merged Land-Ocean Global Surface Temperature Analysis Dataset (MLOST), which combines land-surface air temperature data with SST data from ERSST.v5.

ERSST.v5 is based on a large set of temperature measurements dating back to the 1800s. This data set is called the International Comprehensive Ocean-Atmosphere Data Set (ICOADS), and it is compiled and maintained by NOAA.

4. Data Availability

NCEI and the National Center for Atmospheric Research (NCAR) have historically provided access to monthly and annual SST and error data from the ERSST reconstruction in Figure 1, as well as a mapping utility that allows the user to calculate average anomalies over time and space (www.ncei.noaa.gov/products/extended-reconstructed-sst). EPA uses global data (all latitudes), which can be downloaded from: https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html. Specifically, EPA uses the ASCII text file "aravg.ann.ocean.90S.90N…", which includes annual anomalies and error values for the global ocean. A "readme" file in the same FTP directory explains how to use the ASCII file. At the time of the most recent update for this indicator, NOAA had not posted globally aggregated time series files for ERSST.v5, so EPA obtained the data for Figure 1 from NOAA staff.

Figure 2 is an updated version of a map that was published in IPCC (2013). Underlying gridded data and documentation are available at: www.ncei.noaa.gov/products/land-based-station/noaa-global-temp.

The ERSST reconstruction is based on in situ measurements, which are available online through ICOADS (NOAA, 2021). All underlying ICOADS data are available at: https://icoads.noaa.gov.

Methodology

5. Data Collection

Both components of this indicator—global average SST since 1880 and the map of variations in SST change since 1901—are based on in situ instrumental measurements of water temperature worldwide. When paired with appropriate screening criteria and bias correction algorithms, in situ records provide a reliable long-term record of temperature. The long-term sampling was not based on a scientific sampling design, but was gathered by "ships of opportunity" and other ad hoc records. Records were particularly sparse or problematic before 1900 and during the two World Wars. Since about 1955, in situ sampling has become more systematic and measurement methods have continued to improve. SST observations from drifting and moored buoys were first used in the late 1970s. Buoy observations became more plentiful following the start of the Tropical Ocean Global Atmosphere (TOGA) program in 1985. Locations have been selected to fill in data gaps where ship observations are sparse. The most recent version of ERSST, v5, includes data from the Argo array network of free-drifting floats, which began to be deployed in 2000 and now number close to 4,000 floats throughout the world's oceans. General information on the Argo project can be found at: https://argo.ucsd.edu.

A summary of the relative availability, coverage, accuracy, and biases of the different measurement methods is provided by Reynolds et al. (2002). Sampling and analytical procedures are documented in several publications that can be accessed online. NOAA has documented the measurement, compilation, quality assurance, editing, and analysis of the underlying ICOADS sea surface data set at: https://icoads.noaa.gov/publications.html.

Although SST can also be interpreted from satellite imagery, ERSST.v5 does not include satellite data. In the original update from ERSST.v2 to .v3, satellite data were added to the analysis. However, the latest versions of ERSST do not include satellite data because the addition of satellite data left a residual cold bias, even though the satellite data were corrected with respect to the in situ data. The bias was strongest in the middle and high latitude Southern Hemisphere where in situ data were sparse. The residual bias led to a modest decrease in the global warming trend and modified global annual temperature rankings.

6. Indicator Derivation

Figure 1. Average Global Sea Surface Temperature, 1880–2023

This figure is based on the ERSST, a reconstruction of historical SST using in situ data. The reconstruction methodology has undergone several stages of development and refinement. This figure is based on the most recent data release, version 5 (ERSST.v5). The ERSST.v5 reconstruction adjusts the *in situ* data to represent SST measured at a nominal depth of 0.2 meters, as discussed in Huang et al. (2024).

This reconstruction involves filtering and blending data sets that use alternative measurement methods and include redundancies in space and time. Because of these redundancies, this reconstruction is able to fill spatial and temporal data gaps and correct for biases in the different measurement techniques (e.g., uninsulated canvas buckets, intakes near warm engines, uneven spatial coverage). Locations have been combined to report a single global value, based on scientifically valid techniques for averaging over areas. Specifically, data have been averaged over 2-by-2-degree grid cells. Daily and monthly records have been averaged to find annual anomalies. Thus, the combined set of measurements is stronger than any single set. Fundamental ERSST reconstruction methods are documented in more detail by Smith et al. (2008). Smith and Reynolds (2005) discuss and analyze the similarities and differences between various reconstructions, showing that the results are generally consistent. For example, the long-term average change obtained by this method is very similar to those of the “unanalyzed” measurements and reconstructions discussed by Rayner et al. (2003).

This figure shows the extended reconstructed data as anomalies, or differences, from a baseline “climate normal.” In this case, the climate normal was defined to be the average SST from 1971 to 2000. No attempt was made to project data beyond the period during which measurements were collected.

Additional information on the compilation, data screening, reconstruction, and error analysis of the reconstructed SST data can be found at: www.ncei.noaa.gov/products/extended-reconstructed-sst and in the publications cited therein.

Figure 2. Change in Sea Surface Temperature, 1901–2022

This map is based on gridded data from NOAAGlobalTemp, which in turn draws SST data from ERSST.v5. ERSST’s analytical methods are described above for Figure 1. For this merged product, data have been averaged over 5-by-5-degree grid cells.

EPA replicated and updated the map in IPCC (2013) by calculating trends for each grid cell using an R script that replicates the functions that that the authors of IPCC (2013) used. A long-term trend was calculated for each grid cell using linear regression. Trends have been calculated only for those cells with more than 70 percent complete records and more than 20 percent data availability during the first and last 10 percent of years (i.e., the first and last 12 years). The slope of each grid cell's trend (i.e., the rate of change per year) was multiplied by the number of years in the period to derive an estimate of total change. Parts of the ocean that are blank on the map did not meet these data availability thresholds. Black plus signs (+) indicate grid cells where the long-term trend is significant to a 90 percent confidence level.

EPA displayed only the ocean pixels on the map (no land-based data) because this indicator focuses on SST. EPA also converted the results from Celsius to Fahrenheit.

7. Quality Assurance and Quality Control

Thorough documentation of quality assurance and quality control methods and results is available in the technical references for ERSST.v5 at: www.ncei.noaa.gov/products/extended-reconstructed-sst.

Analysis

8. Comparability Over Time and Space

Presenting the data at a global and annual scale reduces the uncertainty and variability inherent in SST measurements, and therefore the overall reconstruction in Figure 1 is considered to be a good representation of global SST. This data set covers the Earth's oceans with sufficient frequency and resolution to ensure that overall averages are not inappropriately distorted by singular events or missing data due to sparse in situ measurements or cloud cover. The confidence interval shows the degree of accuracy associated with the estimates over time.

Figure 2 is based on several data products that have been carefully assembled to maximize consistency over time and space. Areas with insufficient data for calculating trends have been excluded from the map.

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

Researchers Smith and Reynolds (2005) have compared ERSST with other similar reconstructions using alternative methods. These comparisons yield consistent results, albeit with narrower uncertainty estimates. Hence, the ERSST confidence bands presented in Figure 1 may be more conservative than would be the case had alternative methods been employed.

9. Data Limitations

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

1. The 95 percent confidence interval in Figure 1 is wider than in other methods for long-term reconstructions; in mean SSTs, this interval tends to dampen anomalies.

2. The geographic resolution of Figure 1 is coarse for ecosystem analyses, but reflects long-term and global changes as well as shorter-term variability.

3. The reconstruction methods used to create both components of this indicator removed most random noise in the data; however, the anomalies are also dampened when and where data were too sparse for a reliable reconstruction. The 95 percent confidence interval in Figure 1 reflects this dampening effect and uncertainty caused by possible biases in the observations.

4. Data screening results in loss of multiple observations at latitudes higher than 60 degrees north or south. Effects of screening at high latitudes are minimal in the context of the global average; the main effect is to lessen anomalies and widen confidence intervals. This screening does create gaps in the Figure 2 map, however.

10. Sources of Uncertainty

The ERSST model has largely corrected for measurement error, but some uncertainty still exists. Contributing factors include variations in sampling methodology by era as well as geographic region, and instrument error from buoys and ships.

The ERSST.v5 global reconstruction in Figure 1 includes a confidence interval, which is associated with the biases and errors in the measurements and treatments of the data. For each year, the one-sigma error provided by NOAA was multiplied by 1.96 to approximate a 95 percent confidence interval. The resulting values were added to or subtracted from the reported anomaly to define the upper and lower confidence bounds, respectively.

Processing principles and procedures, including error estimates, for the gridded NOAAGlobalTemp data set (as shown in Figure 2) have been described in Smith et al. (2008). Uncertainty measurements are also available for some of the underlying data. For example, several articles have been published about uncertainties in ICOADS in situ data; see Kennedy (2014) for a summary. See Box 2.1 in IPCC (2013) for additional discussion about the challenge of characterizing uncertainty in long-term climatic data sets.

11. Sources of Variability

SST varies seasonally, but Figure 1 has removed the seasonal signal by calculating annual averages. Temperatures can also vary as a result of inter-annual climate patterns, such as the El Niño-Southern Oscillation. Figure 2 shows how patterns in SST vary regionally.

12. Statistical/Trend Analysis

Analysis by Smith et al. (2008) confirms that the increasing trend apparent from Figure 1 over the 20th century is statistically significant. EPA reached the same conclusion based on least-squares linear regression of the data, finding slopes of +0.010°F/year (1880–2023) and +0.014°F/year (1901–2023), both with $p < 0.0001$ (highly significant). Figure 2 shows long-term linear trends for individual grid cells on the map, and "+" symbols indicate cells where these trends are significant at a 90 percent level based on least-squares linear regression—an approach that is consistent with the original IPCC source map (IPCC, 2013).

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