Lake Temperature

Identification

1. Indicator Description

This indicator describes how surface water temperatures in North American lakes have changed since 1985, based on satellite data. Surface water temperature affects ecosystems and human uses of lakes, as it influences species ranges and distribution, recreational uses, water levels, and the presence and growth of algae and bacteria that can harm human health. Water temperature is a useful indicator of climate change because it can be affected by air temperatures.

2. Revision History

April 2021: Indicator published.

Data Sources

3. Data Sources

This indicator is based on surface water temperature data from satellite imagery collected and processed by the National Oceanic and Atmospheric Administration (NOAA) and the European Space Agency (ESA). These data have been further analyzed, compiled, and published by a group of researchers from multiple organizations who work together as a group called the Global Lake Temperature Collaboration (GLTC).

4. Data Availability

Data for this indicator were obtained from the Long Term Ecological Research Network Data Portal at: https://portal.edirepository.org/nis/mapbrowse?scope=knb-lter-ntl&identifier=10001&revision=3 (doi:10.6073/pasta/379a6cebee50119df2575c469aba19c5). Underlying satellite data are available from NOAA at: www.nesdis.noaa.gov/content/imagery-data-0 and from ESA at: https://earth.esa.int/eogateway.

Methodology

5. Data Collection

This indicator is based on a combination of data from two sets of satellite instruments: the Advanced Very High Resolution Radiometer (AVHRR) series operated on NOAA satellites and the Along Track Scanning Radiometer series (ATSR-1, ATSR-2, Advanced ATSR [AATSR]) operated by ESA. All of these instruments measure thermal infrared radiation, which can be converted to surface water temperature. These instruments have been the authoritative source of remotely sensed surface water temperature data for decades; their methods have been carefully refined and the resulting data have been used widely and featured in numerous peer-reviewed publications.

The AVHRR has been deployed on a succession of satellites since the late 1970s, and the ATSR series has been in use since 1991. The satellites that carry these instruments are polar-orbiting, which allows them to map the entire surface of the Earth with multiple passes per day. AVHRR pixel resolution for this indicator is 4 kilometers (km); ATSR/AATSR pixel resolution ranges from 1 to 2 km. This indicator starts at 1985 based on the availability of a particular processed data set, the AVHRR Pathfinder collection version 5. For more information about data collection, see Sharma et al. (2015), AVHRR instrument details at: www.avl.class.noaa.gov/release/data_available/avhrr/index.htm, and ATSR/AATSR instrument details at: https://earth.esa.int/web/sppa/mission-performance/esa-missions/ers-1/atsr-1/sensor-description, https://earth.esa.int/web/sppa/mission-performance/esa-missions/ers-2/atsr-2/sensor-description, and https://earth.esa.int/web/sppa/mission-performance/esa-missions/envisat/aatsr/sensor-description.

6. Indicator Derivation

Sharma et al. (2015) and the references cited therein describe steps that were taken to convert thermal infrared measurements into temperatures and select appropriate lake pixels and appropriate timestamps for long-term analysis. Additional calculations for this indicator are described below.

As part of the AVHRR Pathfinder analysis, NOAA and the National Aeronautics and Space Administration (NASA) jointly processed AVHRR data to provide two temperature measurements per day of large inland water bodies. This indicator uses version 5 of the Pathfinder analysis. For more information about Pathfinder processing methods, see NOAA's website at: www.nodc.noaa.gov/SatelliteData/pathfinder4km. GLTC employed similar methods to process ATSR/AATSR data, as described by Sharma et al. (2015).

This indicator focuses on nighttime measurements to capture data at a time when the lake surface temperature remains mostly constant and is not affected by ephemeral daytime heating. Using measurements from a consistent time of day also improves comparability over time (see Section 8). This indicator uses AVHRR data from between 10:00 p.m. and 5:00 a.m. local time, with most measurements taken between 1:00 and 4:00 a.m. ATSR data are from approximately 10:30 p.m. local time.

This indicator focuses on summer temperatures, which represent an average of daily temperatures from July, August, and September. These months were chosen to provide a consistent measurement period that is free from the influence of freezing. Not every day had valid data during this period, for a variety of reasons, such as cloud cover. Thus, a simple arithmetic mean of the days with available data could be biased. To account for uneven temporal coverage during the period of interest, GLTC used a locally weighted regression smoothing (LOWESS) approach to derive a temperature curve for each year at each site. A three-month average was computed from this curve, but only if at least 20 valid days of cloud-free data were available within the three-month window.

GLTC limited its analysis to lakes that were large enough to have at least a 10 km by 10 km area of water surface with no islands or shorelines. This criterion eliminated small lakes where satellite image pixels could reflect a combination of land and water surface temperatures, and where human activities along the shore could have a sizable influence on measured water temperatures. Next, GLTC selected a single location in each lake for analysis—a single spot that is as far as possible from any shorelines or islands—

with the exception of the Salton Sea and Lake Tahoe, where GLTC analyzed two and four sites, respectively. The analyses in this indicator are based on a single AVHRR data pixel and a 3-by-3 array of (higher-resolution) ATSR/AATSR data pixels that correspond to each selected location.

GLTC calculated an average summer temperature for each location for each year using the methods described above. EPA then used these annual data points to calculate a long-term temperature trend for each lake in the data set. EPA's analysis was restricted to lakes that had at least 13 years of available data within the 1985–2009 period, including at least one year of data during the first five years of the period (1985–1989) and at least one year of data during the last five years (2004–2009). These endpoint criteria were put in place to ensure that the indicator does not make assumptions about trends for periods of time that are not actually represented in the data. "Available data" means a valid summer average in the GLTC data set, which required at least 20 days of valid cloud-free data in a given year.

EPA calculated each long-term trend by performing a Sen slope regression, which determines the median of all possible pair-wise slopes in a temporal data set. This regression approach is consistent with other studies such as O'Reilly et al. (2015), who performed a similar analysis on lake temperature trends at a global scale. EPA then calculated the total change between the 1985 and 2009 data points along the regression line (i.e., the line of best fit). This approach is analogous to multiplying the regression slope (degrees per year) by the number of years in the period—in this case, the difference between 1985 and 2009, which is an interval of 24 years.

A total of 34 lakes met the criteria described above in that they were large enough and had sufficient years of data for analysis. These 34 lakes are listed in Table TD-1 and labeled on the locator map in Figure TD-1. They are all natural lakes, not impoundments created by humans, although one of these lakes (Lac Saint-Jean in Canada) now has a hydroelectric dam at its outlet. This dam predates the start of data collection for this indicator, so its presence is consistent for all years of this analysis.

Table TD-1. Lakes Analyzed in This Indicator

United States	United States/Canada	Canada	Mexico
Great Salt Lake Iliamna Lake Lake Michigan Lake Okeechobee Pyramid Lake Salton Sea (two sites) Selawik Lake Lake Tahoe (four sites) Lake Winnebago	Lake Erie Lake Huron Lake of the Woods Lake Ontario Lake St. Clair Lake Superior	Lake Athabasca Bras d'Or Lake Lake Claire Lake Doré Dubawnt Lake Great Bear Lake Great Slave Lake Kasba Lake Lake Manitoba Lac La Martre Lake Nipigon Peter Pond Lake Reindeer Lake Lake Simcoe Lac Saint-Jean Lake Tulemalu Lake Winnipeg Lake Winnipegosis	Lago de Chapala

Figure TD-1. Lakes Analyzed in This Indicator

All temperatures were converted from Celsius to Fahrenheit to make them consistent with all of EPA's other temperature-related indicators. For the Salton Sea and Lake Tahoe, EPA calculated the total temperature change for each individual site with data, then calculated an unweighted arithmetic mean across multiple sites to arrive at the values that are displayed in Figure 1 of this indicator.

Indicator Development

In addition to remotely sensed data, Sharma et al. (2015) also provide an analysis of *in situ* data for many of the same lakes. Because of the many differences in timeframes, methods, frequency, and measurement time-of-day across the various *in situ* measurement programs that contributed data, EPA elected to base this indicator solely on satellite data, which reflect more consistent methods over time and space. A remotely sensed indicator should also be more feasible to maintain with new data in the future: continued satellite data depend on one or two data collection programs, as opposed to dozens of local monitoring networks with varying degrees of permanence.

7. Quality Assurance and Quality Control

Satellite observations of surface temperature are subject to several quality assurance and quality control (QA/QC) measures prior to publication. For example, all AVHRR data are validated by NOAA personnel.

Following this step, an automated algorithm flags and excludes temperatures not within the normal range of expected temperatures, correcting for processing errors in the original satellite data. Finally, multiple cloud masks are applied to satellite imagery so that the final product includes only completely cloud-free data.

Sharma et al. (2015) describe several steps that were taken to validate AVHRR and ATSR/AATSR satellite data using *in situ* measurements from buoys and other sampling programs. This indicator uses data from two series of satellite instruments to provide more accurate estimates of average lake surface temperature. Section 6 describes additional steps that were taken to weed out lakes and years with insufficient days of valid cloud-free data, minimize local anthropogenic influences, and avoid using data from pixels that contain any land surface.

Analysis

8. Comparability Over Time and Space

The satellite temperature observations that underlie this indicator have been collected and processed systematically since at least 1985, allowing for comparability over time and space. Routine processing of these satellite measurements includes adjustments for known differences in instruments over time, based on extensive calibration with measurements collected at the surface. For example, see AVHRR calibration documentation linked from: www.avl.class.noaa.gov/release/data_available/avhrr/index.htm and: www.ncdc.noaa.gov/cdr/fundamental/avhrr-radiances-nasa. As described in Section 6, the analytical methods for this indicator include using a consistent target location within each lake over the entire period of record, using a consistent seasonal window (July–September) and time of day (nighttime) for all measurements used in the analysis, and using a LOWESS temperature curve to eliminate the bias that could result from certain parts of a given summer having more cloud-free days than others.

9. Data Limitations

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

1. Besides climate change, natural year-to-year variability in air temperatures and other factors can influence water temperatures. This indicator accounts for these types of variations by focusing on long-term trends over 25 years of data.

2. Water temperature can be influenced by wastewater discharges and other human activities. To minimize the influence of human activities, this indicator focuses on 34 relatively large natural lakes and uses data from a specific point in each lake that is as far as possible from any shoreline, including islands. Nonetheless, some of the selected lakes still have substantial shoreline development, controlled inflows and outflows, and other modifications.

3. The selected measurement location in each lake may be representative of the lake as a whole, but it is also possible that other parts of the lake have warmed or cooled at different rates.

4. This indicator only examines summer water temperatures, and it is not appropriate to infer that other seasons have experienced comparable changes. It is more difficult to generate a consistent long-term analysis of temperature for other seasons, at least in certain lakes, because ice cover distorts the temperature signal.

5. This indicator uses nighttime measurements to avoid being overly influenced by short-term daytime heating. It does not provide information about temperatures at other times of day.

10. Sources of Uncertainty

Surface water temperature observations from satellites are subject to navigation, timing, and calibration errors. However, the AVHRR and ATSR/AATSR data sets are mature products that have undergone extensive review and adjustment to minimize uncertainty. For more information on the steps taken to minimize uncertainty in each data set, visit the AVHRR and ATSR/AATSR project pages documented in Section 5, "Data Collection."

In an earlier analysis, Schneider and Hook (2010) validated the surface water temperatures from the AVHRR and ATSR/AATSR data sets against *in situ* measurements from nine buoys in the Great Lakes. Their analysis indicated a bias of 0.09°C, 0.02°C, and −0.04°C in the ATSR-1, ATSR-2, and AATSR data sets, respectively, with standard deviations of 0.55°C, 0.33°C, and 0.44°C. Validation of the three-month summer means from the AVHRR data set against the *in situ* data indicated a bias of 0.15°C, with a standard deviation of 0.31°C and root mean square error of 0.53°C. Schneider and Hook (2010) also determined that there was no significant trend in the time series of annual biases from either data set, indicating that satellite calibration drift has not influenced this indicator's results.

11. Sources of Variability

Surface water temperature is sensitive to many natural environmental factors, including natural fluctuations in air temperature, precipitation, and water movement. In addition to climate, water temperature is also affected by human water use. For example, industries, agricultural operations, and water treatment systems have outflows into several of the lakes in this indicator, which could affect water temperatures in specific areas of the lake. This analysis attempts to minimize human influence by focusing on relatively large lakes and analyzing specific locations as far as possible from any shoreline.

12. Statistical/Trend Analysis

Each long-term trend shown in Figure 1 is based on a Sen slope linear regression of the available annual data points. The map symbology also indicates whether each trend is significant to a 95 percent level ($p<0.05$). Of the 34 lakes analyzed, nine had statistically significant changes—all increases.

In a comparison with trends from the *in situ* data, Schneider and Hook (2010) determined that seasonal averages generated from a combined AVHRR and ATSR/AATSR data set could reliably ($p<0.05$) be used to identify non-zero trends in excess of 0.023°C/year.

References

O'Reilly, C.M., et al. 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophys. Res. Lett. 42:10773–10781. doi:10.1002/2015GL066235

Schneider, P., and S.J. Hook. 2010. Space observations of inland water bodies show rapid surface warming since 1985. Geophys. Res. Lett. 37:22405–22409. doi:10.1029/2010GL045059

Sharma, S., et al. 2015. A global database of lake surface temperatures collected by *in situ* and satellite methods from 1985–2009. Sci. Data 2:150008. doi:10.1038/sdata.2015.8