

## *Lake surface temperature [in “State of the Climate in 2017”]*

Article

Published Version

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enced by a strong La Niña) were considerably cooler than surrounding years and below the overall trend line, whereas 1998 and 2016 were not only considered the warmest years on record when reported, but their values are considerably above the trend line. The year 2014, on the other hand, was considered to be the warmest year on record at the time, even though its value is near the 1975–2017 trend line. The 2017 anomaly is near the trend line for the HadCRUT4 series (~50th percentile) and above the trend in the other in situ datasets (~60th to 80th percentile). While the value of residuals may shift with the addition of each new year of data, the current data suggest that the 2017 annual global temperature and ranking are consistent with the progression of the upward trend since the mid-1970s.

During 2017, much-warmer-than-average conditions were present across most of the world's land and ocean surfaces, with limited areas (parts of the north, central, and eastern Pacific Ocean, the southern Atlantic Ocean, eastern Indian Ocean, and a small area in western North America) experiencing near- to cooler-than-average conditions (Plate 2.1a).

Global average surface air temperatures are also estimated using reanalyses. Reanalysis produces datasets with uniform temporal and spatial coverage of the whole globe, but can suffer from regional model biases and the effects of changes in the observation network during the analysis period. However, surface temperatures from reanalyses should be consistent with observations in regions of good observational coverage. Here we consider three reanalyses: ERA-Interim (Dee et al. 2011a), JRA-55 (Ebita et al. 2011; Kobayashi et al. 2015), and MERRA-2 (Bosilovich et al. 2015; Gelaro et al. 2017). The ERA-Interim 2-m temperature was adjusted by merging analyses over land with short forecasts over ocean and subtracting 0.1°C from the latter before 2002, in order to account for a change in SST provider, following Simmons et al. (2017) and Simmons and Poli (2014). ERA-Interim provides data from 1979, JRA-55 from 1958, and MERRA-2 from 1980.

According to the reanalyses, the annual global 2-m temperature for 2017 was the second highest since their records began and was between 0.39°C and 0.53°C above average, depending on the reanalysis (Table 2.1). The temperatures for the warmest year, 2016, ranged between 0.47°C and 0.62°C above average.

ERA-Interim and MERRA-2 for 2017 also show warmer-than-average conditions over many regions of the world (Online Figs. S2.1–S2.3), particularly over higher northern latitudes. A few regions were

cooler than average, including Antarctica. The 2017 global ocean temperature is the second highest on record in all three reanalyses, whereas over global land the temperature is the second highest in JRA-55 and ERA-Interim but only the fourth highest in MERRA-2, where temperatures were lower than in 2016, 2005, and 2002.

- 2) LAKE SURFACE TEMPERATURE—R. I. Woolway, L. Carrea, C. J. Merchant, M. T. Dokulil, E. de Eyto, C. L. DeGasperi, J. Korhonen, W. Marszelewski, L. May, A. M. Paterson, A. Rimmer, J. A. Rusak, S. G. Schladow, M. Schmid, S. V. Shimaraeva, E. A. Silow, M. A. Timofeyev, P. Verburg, S. Watanabe, and G. A. Weyhenmeyer

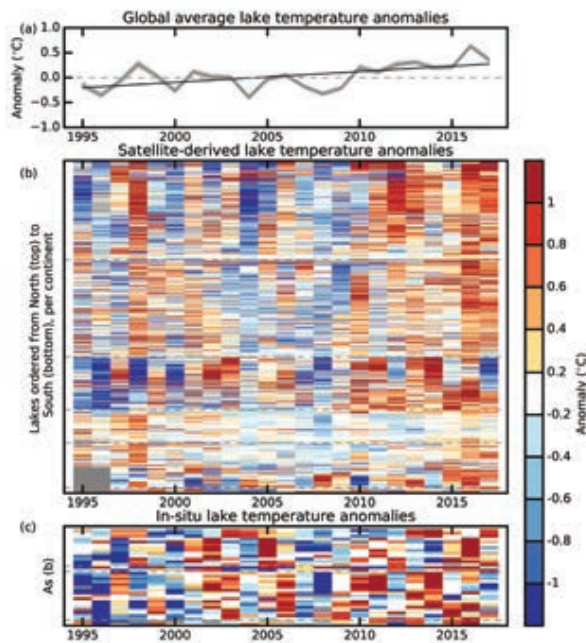
Observed lake surface water temperature anomalies in 2017 are placed in the context of the recent warming observed in global surface air temperature (Section 2b1) by collating long-term in situ lake surface temperature observations from some of the world's best-studied lakes and a satellite-derived global lake surface water temperature dataset. The period 1996–2015, 20 years for which satellite-derived lake temperatures are available, is used as the base period for all lake temperature anomaly calculations. Warm-season averages (i.e., time periods without ice cover: July–September in the Northern Hemisphere above 23.5°N and January–March in the Southern Hemisphere below 23.5°S) are analyzed in line with previous lake surface temperature analyses (Schneider and Hook 2010; O'Reilly et al. 2015; Woolway and Merchant 2017). Temperatures of lakes located within 23.5° of the equator are averaged over the whole year.

Satellite-derived lake surface water temperatures for 688 lakes are used in this analysis to investigate global variations in lake surface water temperature. Satellite-derived surface water temperatures were retrieved during the day using the methods of MacCallum and Merchant (2012) on image pixels filled with water according to both the inland water dataset of Carrea et al. (2015) and a reflectance-based water detection scheme (Xu 2006). The satellite temperatures represent midmorning observations throughout the record (except at the highest latitudes, where observations may be available at other times of day). The observations were generated using data from the ATSR (Along Track Scanning Radiometer) series including ATSR-2 (1995–2003) and the Advanced ATSR (AATSR) (2002–12), extended with *MetOp-A* AVHRR (2007–17). In this study, lake-wide average surface temperatures are used to remove the intralake heterogeneity of surface water temperature responses to climate change (Woolway and Merchant 2018).

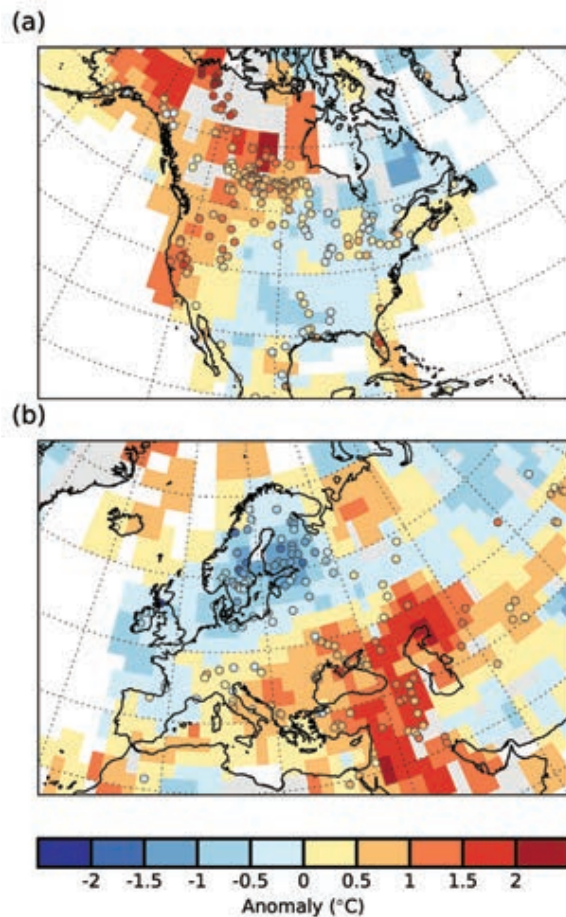
In 2017, satellite-derived lake surface temperatures were lower than observed in 2016 by 0.3°C in the 688-lakes average (Fig. 2.3a), though the mean anomaly for 2017 was still +0.4°C above the baseline, continuing the long-term lake surface warming trend identified in previous analyses (e.g., Woolway et al. 2017) and reflecting the observed increase in global surface air temperature (section 2b1). Lake surface water temperatures in 2017 were the second highest since 1995 (the earliest satellite data used), behind only 2016. Eight of the ten warmest years for lake surface waters in the record have occurred since 2007 (1998 and 2001 rank fifth and ninth, respectively).

Lake surface water temperatures in 2017 were not above average in all regions (Figs 2.3b,c; Plate 2.1b). Below-average lake surface temperatures prevailed throughout north and northwestern Europe (Plate 2.1b; Fig. 2.4) in summer, where lake surface temperatures were up to 1°C cooler than the 20-year base period mean. The satellite data and in situ lake

temperature anomalies agree in this respect. For example, in situ measurements of temperature anomaly in Vättern (Sweden) were  $-0.03^{\circ}\text{C}$  (i.e., below the 20-year base period mean) in summer 2017. There is a clear contrast between Scandinavian lake surface temperature anomalies and those in central Europe, with lake temperature anomalies in the latter region up to 1°C higher than average (Plate 2.1b; Fig. 2.4). This is also confirmed by in situ lake temperature anomalies, for example,  $+0.7^{\circ}\text{C}$  in 2017 for Lake Zurich (Switzerland). Above-average lake surface temperature anomalies are also observed from the satellite data in northwest Canada and the western United States, confirmed by in situ data (e.g.,  $+0.8^{\circ}\text{C}$  in Lake Washington). Lakes in the central and eastern U.S. experienced near-normal lake surface temperatures in 2017, with some regions showing below-average



**FIG. 2.3.** Annual lake surface water temperature anomalies 1995–2017 ( $^{\circ}\text{C}$ ; relative to 1996–2015). (a) Global average (with 95% confidence intervals) satellite-derived lake surface temperature anomalies; (b) satellite-derived lake surface temperature anomalies for 688 lakes; and (c) in situ lake surface temperature anomalies for 34 globally distributed lakes. Annual lake surface water temperatures anomalies are calculated for the warm season (Jul–Sep in NH; Jan–Mar in SH), except within  $23.5^{\circ}$  of the equator, where the averages are taken over the whole year.



**FIG. 2.4.** Comparisons of satellite-derived lake surface water temperature anomalies (colored dots) to air surface temperature anomalies (calculated from the NASA GISS Surface Temperature Analysis) in (a) North America and (b) Europe in 2017. Temperatures anomalies ( $^{\circ}\text{C}$ ; relative to 1996–2015) are calculated for the NH warm season (Jul–Sep).

lake surface temperatures. These regional differences in lake surface temperature anomalies in 2017 reflect the July–September average surface air temperature anomalies (relative to 1996–2015), calculated from the NASA GISS surface temperature analysis (Fig. 2.4; Hansen et al. 2010; GISTEMP Team 2016). In summary, surface air and lake water temperatures in 2017 were generally coherent.

3) LAND SURFACE TEMPERATURE EXTREMES—  
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Changes in temperature extremes are important for climate monitoring due to their sensitivity to relatively small changes in average conditions. Small changes in average temperature can induce much larger changes in the intensity and frequency of corresponding heat extremes. Land surface temperature extremes during 2017 were characterized by overall increased occurrences of warm temperatures and reduced occurrences of cooler temperatures compared to long-term averages. A number of anomalously high temperature events occurred in 2017, in both maximum and minimum daily temperatures. As in previous reports, the GHCNDEX quasi-global gridded dataset (Donat et al. 2013b) is used to monitor global temperature extremes over land. This is quasi-global, as an absence of data over some locations hinders the robust calculation of extremes indices and their trends. A suite of temperature and precipitation extremes indices (Zhang et al. 2011) is first calculated from observed daily station time series in the GHCN-Daily archive (Menne et al. 2012), before interpolating the indices on global grids. Some of the fields of extremes indices have limited spatial coverage, especially across central and eastern Asia, for those derived from minimum temperatures compared to those from maximum temperatures. Therefore, complete coverage derived from the ERA-Interim reanalysis (Dee et al. 2011a) is shown separately in Online Figs. S2.7–S2.9.

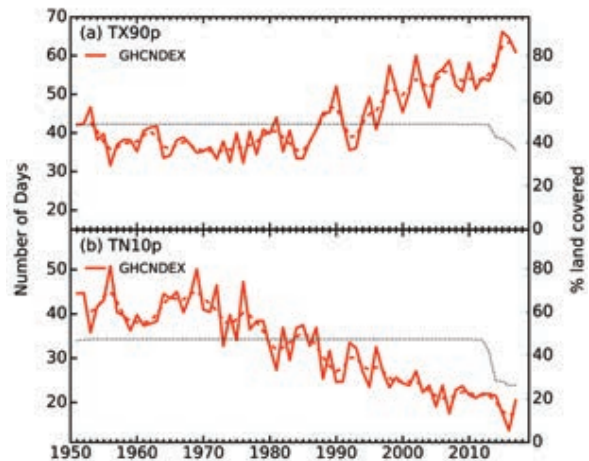
Results are presented for a selection of the temperature indices in GHCNDEX: TX90p (frequency of warm days when daily temperatures exceed the 90th percentile of daily maximum temperatures calculated over the 1961–90 base period), TX10p (cool day frequency, daily temperatures below the 10th percentile), TN90p and TN10p (warm and cool night frequency, respectively), and TXx, TXn, TNx, and TNn (extrema of annual maximum and minimum temperatures, respectively; see online supplement for full definitions). Averaged over areas where there are observations, there were fewer warm days (TX90p) and more cool nights (TN10p) in 2017 compared to 2016. However,

such values are still typically well above and below the climatologically defined threshold of 36.5 days per year, respectively (Fig. 2.5).

Over areas where observations exist, the annual occurrence of warm days (TX90p) and nights (TN90p; Plates 2.1c,d) was typically well above the climatological average. In particular, eastern Asia experienced 20 more warm days than the threshold, whereas southern Europe and eastern Australia experienced more than 40 additional warm days. The frequency of warm nights was less than warm days over Australia and southern Europe but was still 10–30 days and 30–40 days more than the threshold, respectively. Conversely, the U.S. and Canada experienced slightly more warm nights than warm days.

Cool days and nights (TX10p, TN10p; Fig. 2.6) were less frequent than the threshold over some regions, with around 20 fewer cool nights over the U.S. and Canada and 30 fewer nights for Europe. For northern regions with available data, annual minima during both daytime and nighttime (TXn, TNn, Online Figs. S2.4c,d) were very high. The respective annual maxima, however, did not always display similar anomalies (TXx, TNx; Online Figs. S2.4a,b).

The frequency of warm daytime temperatures (TX90p; Online Fig. S2.5) varied across the seasons. During boreal winter (DJF 2016/17), warm day occurrences much higher than the threshold occurred over northern Europe and eastern China, Russia, and Australia. However, western Australia and the



**FIG. 2.5. Global average time series of the number of (a) warm days (TX90p) and (b) cool nights (TN10p) from GHCNDEX relative to 1961–90. (This reference period is used for consistency with other ETCCDI index products.) By construction, these indices have an average of 36.5 days over the reference period. The dotted black line shows the percent of land area with data. Units: days.**