Lake surface water temperature

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La Niña—the cool phase of the El Niño–Southern Oscillation (ENSO)—in the Pacific Ocean had a dampening effect on the global temperatures, in comparison to years characterized by El Niño or ENSO-neutral conditions. The year began with La Niña conditions, which first developed in August 2020 and persisted throughout most of 2021 and all of 2022 (see section 4b for details). 2022 was also the warmest La Niña year on record, surpassing the previous record set in 2021.

While it is common, and arguably expected, for each newly completed year to rank as a top 10 warmest year (see Arguez et al. 2020), the global annual temperature for 2022 was lower than we would expect due to the secular warming trend alone, with trend-adjusted anomalies registering between the 20th and 40th percentiles (depending on the dataset) following the Arguez et al. (2020) approach. Trend-adjusted anomalies for 2022 are consistent with the typical slight cooling influence of La Niña and similar to the trend-adjusted anomalies recorded over the relatively cool years from 2011 to 2014, as well as 2021, years that also predominantly exhibited cooler-than-normal ENSO index values.

Above-normal temperatures were observed across much of the world's land and ocean surfaces during 2022 (Plate 2.1a; Appendix Figs. A2.1–A2.4). Notably, record-high annual temperatures were present across Europe, northern Africa, and parts of the Middle East, central Asia, and China, as well as the northern and southwestern Pacific, Atlantic, and Southern Oceans. Below-normal annual temperatures were present across parts of northern North America, South America, Africa, Australia, and the southeastern, central, and eastern tropical Pacific Ocean. The global land-only surface temperature was 0.30°C–0.49°C above normal, the fifth to seventh highest on record, depending on the dataset. The annual global sea-surface temperature was also fifth or sixth highest on record, at 0.19°C–0.26°C above normal.

2. LAKE SURFACE WATER TEMPERATURE

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In 2022, the worldwide averaged satellite-derived lake surface water temperature (LSWT) warm-season anomaly was +0.33°C with respect to the 1995–2020 baseline, the second highest since the record began in 1995. The mean LSWT trend between 1995 and 2022 was 0.20±0.01°C decade^{-1}, broadly consistent with previous analyses (e.g., Carrea et al. 2020, 2021, 2022a; Fig. 2.2a). Warm-season anomalies for each lake are shown in Plate 2.1b. The lake-mean temperature anomalies were positive for 70% and negative for 30% of the 1951 globally distributed lakes. For about 30 other lakes, no anomalies could be computed since no water was found in 2022.

Large regions of coherently high LSWT anomalies were identified in 2022, with 40% of the observed lakes experiencing LSWT

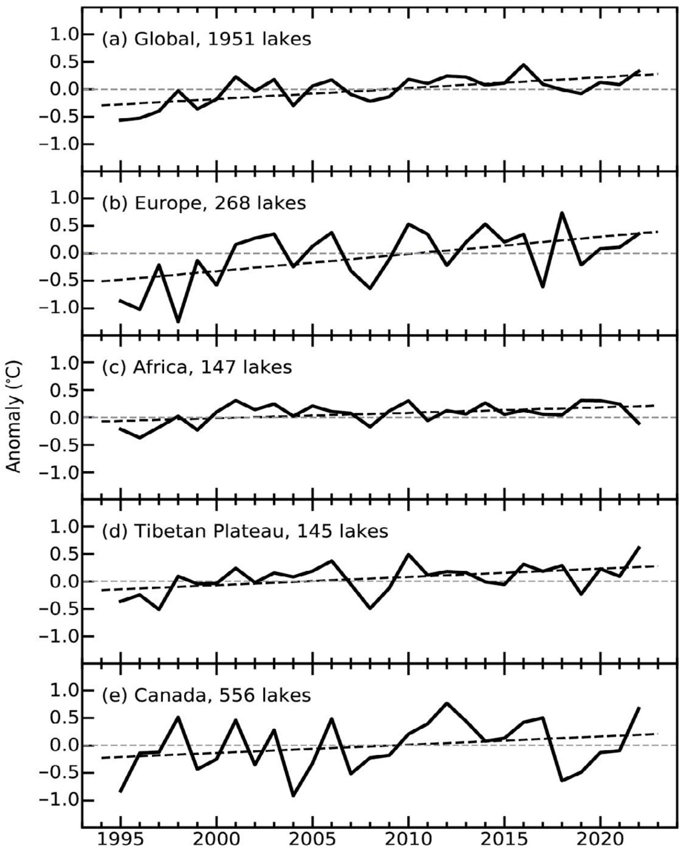

Fig. 2.2. Annual time series of satellite-derived warm-season lake surface water temperature anomalies (°C; 1995–2020 base period) from 1995 to 2022 for lakes distributed (a) globally, and regionally in (b) Europe, (c) Africa, (d) the Tibetan Plateau, and (e) Canada.

anomalies in excess of +0.5°C (Plate 2.1b). The highest anomalies were for lakes situated in the northwestern contiguous United States and Canada. Negative LSWT anomalies were consistently observed throughout most of South America (except Patagonia), parts of Africa, and in Alaska and Greenland.

Four regions of interest were studied in more detail: Canada (number of lakes, n = 556, Figs. 2.2e, 2.3c), Europe (n = 268, Figs. 2.2b, 2.3a), Tibet (n = 145, Figs. 2.2d, 2.3d), and Africa (n = 147, Figs. 2.2c, 2.3b). In these regions, the warm season LSWT anomalies are consistent with the corresponding 2-m air temperature anomalies, as measured by NASA GISS (Hansen et al. 2010; GISS Surface Temperature Analysis [GISTEMP] Team 2022) and show an average warming trend of +0.31±0.03°C decade^{-1} in Europe (Fig. 2.2b) and +0.15±0.03°C decade^{-1} in Canada (Fig. 2.2e). In Africa, long-term change in LSWT is comparatively smaller at +0.10±0.01°C decade^{-1} (Fig. 2.2c), while in Tibet the warming tendency has increased relative to previous reports with the largest positive anomaly in 2022. The warming rate of LSWT in Tibet from 1995 to 2022 was +0.15±0.02°C decade^{-1} (Fig. 2.2d). Moreover, in Tibet, all the observed lakes, except one, experienced positive LSWT anomalies in 2022 with an average of +0.6°C, which is more than double the standard deviation of mean anomalies from 1995 to 2022 and confirmed by high anomalies for the air temperature (Fig. 2.3d). In Europe, below-normal LSWT in northern Europe (80 lakes) was less prevalent than above-normal LSWT (188 lakes), resulting in an average of +0.35°C. In Africa, 60% of the 147 lakes experienced negative LSWT anomalies, and the average anomaly in 2022 was −0.11°C. In Canada, 91% of the observed lakes experienced positive anomalies, with only 9% experiencing negative anomalies for an average of +0.67°C in 2022.

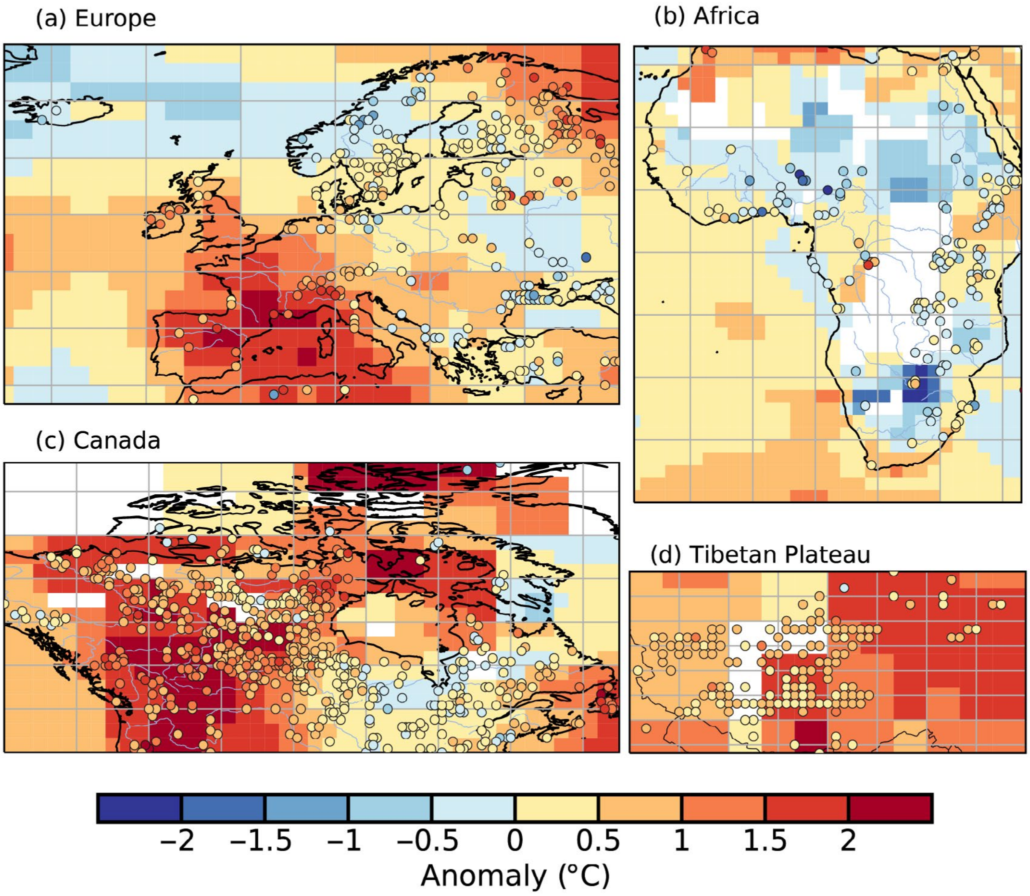

Fig. 2.3. Lake temperature anomalies (°C, colored dots) and 2-m air temperature anomalies (°C) in 2022 for lakes in (a) Europe, (b) Africa, (c) Canada, and (d) the Tibetan Plateau. These values were calculated for the warm season (Jul–Sep in the extratropical Northern Hemisphere; Jan–Mar in the extratropical Southern Hemisphere; Jan–Dec in the tropics) with reference to the 1995–2020 base period.

In situ observations of warm season LSWT anomalies from the 1995–2020 mean for 40 lakes, 18 of which have measurements for the year 2022, are shown in Fig. 2.4 with an average anomaly of −0.03°C. Fourteen lakes experienced positive anomalies (average: +0.70°C) and four lakes negative anomalies (average: −2.60°C) in 2022. At the in situ measurement site on Lake Baikal in Siberia, a temperature anomaly of −6.9°C was recorded, which is very different from the satellite lake-mean anomaly of −0.47°C, suggesting a within-lake variation of the LSWT anomalies (see Carrea et al. 2022a; Toffolon et al. 2020) on Lake Baikal. At the in situ site, such a large negative anomaly suggests a potential intrusion of colder water resembling upwellings in ocean waters; this has been recorded on the lake for more than 20 years at different depths. Overall, the time series of the 18 lakes show clearly that lakes are warming, especially after the year 2000.

In North America, the anomalies recorded from the in situ data for Lakes Superior, Erie, Michigan, and Huron are −2.98°C, +0.67°C, +0.69°C, and +0.55°C, respectively, which are noticeably larger (in absolute terms) than those estimated from satellite measurements (−0.61°C, +0.20°C, +0.28°C, and +0.18°C, respectively). The difference is largely because in situ data are point measurements whereas satellite data represent lake-wide averages, suggesting spatial patterns of the LSWT anomalies (see Carrea et al. 2022a; Toffolon et al. 2020). In Europe, all the lakes with in situ data had positive anomalies, except Lake Balaton (Hungary) which was 0.36°C below its 1995–2020 average (−0.01°C with satellite). Mondsee (Austria) was 1.51°C warmer than average in 2022 and the highest recorded value for the in situ data. In New Zealand, Lake Taupō had a slight negative anomaly of −0.15°C (+0.98°C from satellites) while Rotorua had a positive anomaly of +0.51°C (with reference period 2011–2020) compared to the anomaly from satellite of +0.6°C (with reference period 1995–2020).

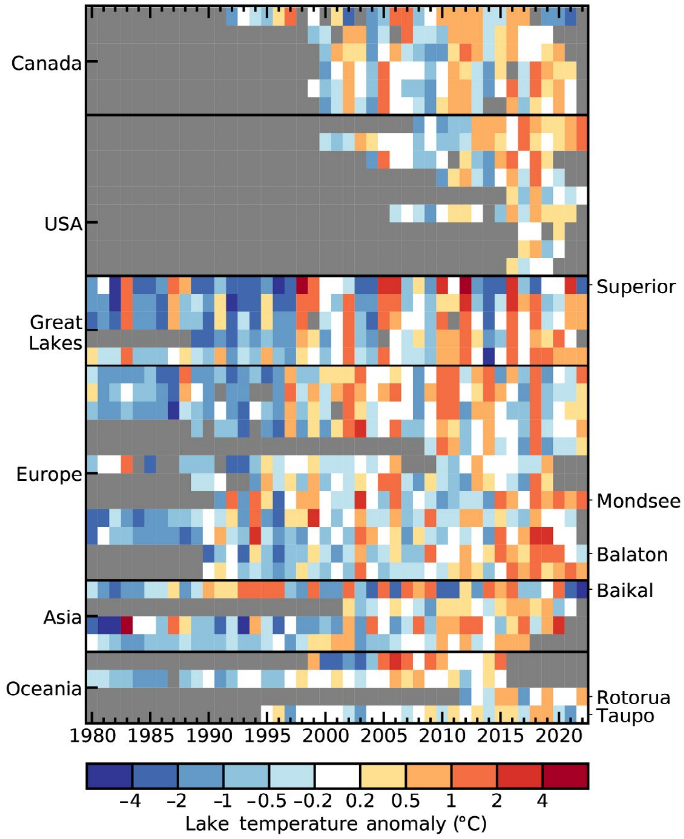

Fig. 2.4. In situ lake surface water temperature (LSWT) observations from 40 globally distributed lakes (the name is reported for the lakes mentioned in the text), showing the annually averaged warm season (Jul–Sep in the Northern Hemisphere; Jan–Mar in the Southern Hemisphere) anomalies (°C; 1995–2020 base period).

The LSWT warm-season averages for midlatitude lakes are computed for summers (July–September in the Northern Hemisphere and January–March in the Southern Hemisphere), and whole-year averages are presented for tropical lakes (within 23.5° of the equator).

LSWT time series were derived from the European Space Agency Climate Change Initiative LAKES/Copernicus C3S climate data record (Carrea et al. 2022b, 2023). For 2022, satellite observation from the Sea and Land Surface Temperature Radiometer on Sentinel3B and MODIS on *Terra* were used. The retrieval method of MacCallum and Merchant (2012) was applied 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 (Carrea et al. 2023).

The satellite-derived LSWT data are spatial averages for each of a total of 1951 lakes. The satellite-derived LSWT data were validated with in situ measurements with an average satellite-minus-in situ temperature difference of less than 0.5°C (Carrea et al. 2023). Lake-wide average surface temperatures have been shown to give a more representative picture of LSWT responses to climate change than single-point measurements (Woolway and Merchant 2018).