Lake surface temperature [in "State of the Climate in 2016"]

Article

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2.b.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. Silow, M. A. Timofeev, P. Verburg, S. Watanabe, and G. A. Weyhenmeyer*

Observed lake surface water temperature (LSWT) thermal anomalies in 2016 are placed in the context of the recent warming observed in global surface air temperature (section 2b1) by collating long-term in situ LSWT observations from some of the world's best-studied lakes and a satellite-derived global LSWT dataset. The period 1996–2015, 20 years for which satellite-derived LSWTs are available, is used as the base period for all LSWT anomaly calculations. Warm-season averages (July–September in the Northern Hemisphere and January–March in the Southern Hemisphere) are analyzed to avoid ice cover, in line with previous LSWT analyses (Schneider and Hook 2010; Hook et al. 2012; O'Reilly et al. 2015; Torbick et al. 2016; Woolway et al. 2016).

In situ observations from 48 lakes show an average warm-season LSWT anomaly of 1.0°C in 2016 (Fig. 2.b.2.1). The LSWT anomaly in Lake Baikal (Russia), the largest (by volume) and deepest of the world's freshwater lakes, was more than 2.3°C warmer in 2016. Comparable anomalies were observed in the North American Great Lakes, with an average anomaly of +2°C in 2016. Warming is not restricted to the largest lakes. For example, Harp Lake in Dorset, Ontario (Canada; surface area ~1 km^2) was 1.1°C warmer in 2016, compared to its 20-year average. High LSWT anomalies were also observed in central Europe, with LSWT anomalies >+0.5°C, and in Scandinavia, with the second largest lake in Sweden, Lake Vättern, having a LSWT anomaly of +1.3°C. Higher-than-average LSWTs were also evident in the Southern Hemisphere, with Lakes Rotorua and Taupo (New Zealand) showing an average LSWT anomaly exceeding +1°C, and the smaller lakes in the Bay of Plenty region (New Zealand) experiencing an average anomaly of +1°C in 2016.

Satellite-derived warm-season LSWTs generated within the Globolakes project (www.globolakes.ac.uk/) for 681 lakes are used in this analysis to investigate global variations in LSWT. LSWTs were retrieved during the day using the retrieval 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 mid-morning observations throughout the

record. 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 (Advanced Very High Resolution Radiometer) (2007–16).

Globally and regionally averaged warming rates calculated from the satellite data show widespread warming tendencies in recent years (Figs 2.b.2.2), being most evident in the extratropical Northern Hemisphere (>30°N), with a hemispheric average LSWT trend of +0.31°C decade^{-1} ($p = 0.06$). Warming (+0.21°C decade^{-1}, $p = 0.07$) is also found for the Southern Hemisphere (<30°S), but not in the tropics (30°N–30°S; $p = 0.4$). Using all available data, and weighting equally the northern, southern, and tropical regions, we obtain a global LSWT trend of +0.24°C decade^{-1} ($p = 0.01$). Europe is the region showing the largest and most consistent LSWT warming trend (Fig. 2.b.2.2b), inline with previous studies (Hook et al. 2012), with a regional average LSWT trend of +0.55°C decade^{-1}. Other regions such as northeastern North America (+0.43°C decade^{-1}) and southern South America (notably those in southern Chile and Argentina; +0.3°C decade^{-1}) also experience significant regionally averaged warming.

In the year 2016, lakes were particularly warm with a global and equally weighted LSWT anomaly of +0.65°C. LSWT anomalies in the Northern Hemisphere (+0.72°C), Southern Hemisphere (+0.70°C), and the tropics (+0.52°C) were all anomalously high (Figs 2.b.2.2a; Plate 2.1) in 2016. About 83% of satellite-observed LSWT anomalies in 2016 were warmer than their 20-year average.

Global in situ and satellite measurements both point to LSWTs in 2016 being anomalously high, the warmest year in the 21-year record, reflecting the observed warming in global surface air temperature. Rising LSWTs have major implications for lake ecosystems (O'Reilly et al. 2003; Smol et al. 2005; Smol and Douglas 2007) and can, among other things, increase the occurrence of toxic cyanobacterial blooms (Kosten et al. 2012) and subsequently threaten water quality (Huisman et al. 2005). Warming of LSWT has been observed since 1996 and was particularly striking in 2016. If this trend continues, local economies dependent on lakes for drinking water, agricultural irrigation, recreation, and tourism are likely to be increasingly affected.

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List of Figures

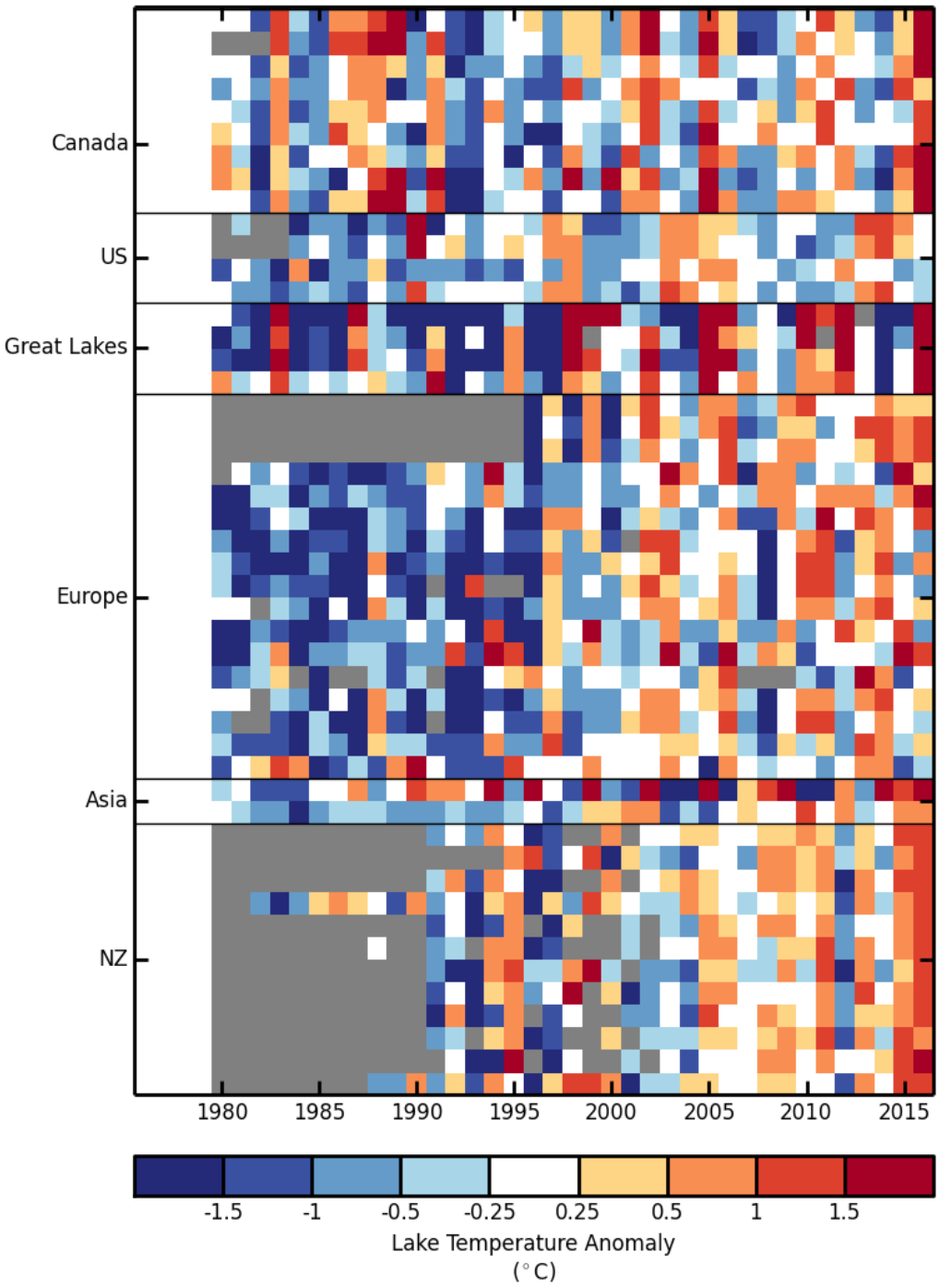


Figure 2.b.2.1. In situ LSWT observations from 48 globally distributed lakes, showing the annually averaged warm season (Jul–Sep in NH; Jan–Mar in SH) anomalies (°C; relative to 1996–2015).

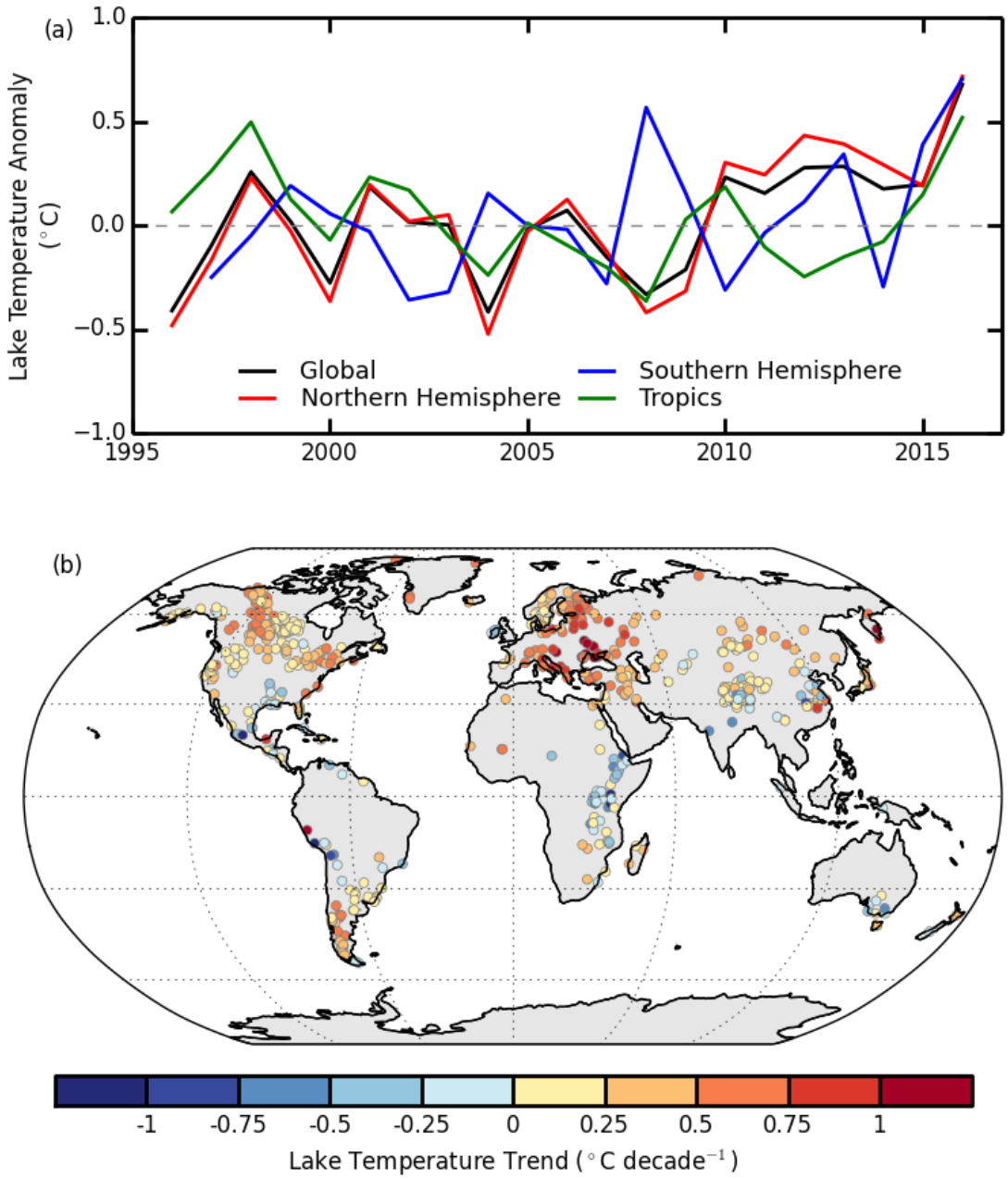
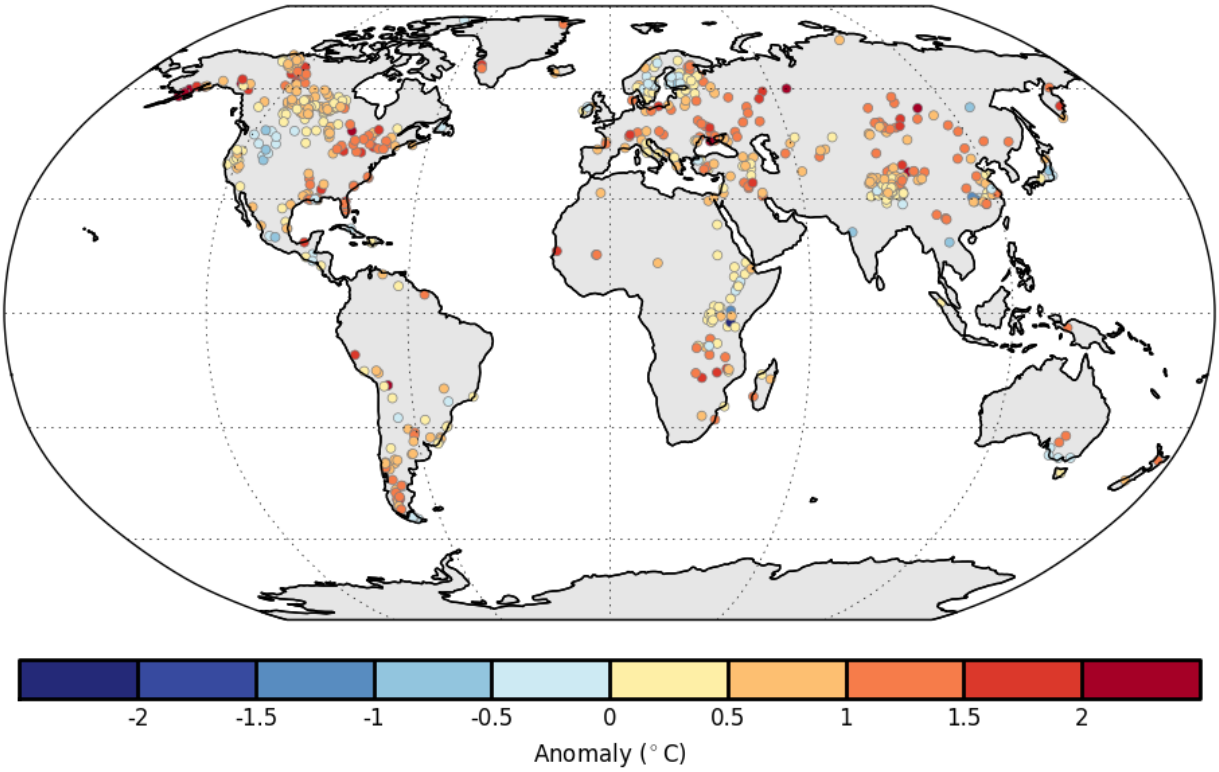


Figure 2.b.2.2. Satellite-derived LSWT measurements from 681 lakes showing (a) global and regional annual average anomalies (°C), and (b) 1996–2016 LSWT trend (°C decade^{-1}). Annual LSWTs are calculated for the warm season (Jul–Sep in NH; Jan–Mar in SH) and LSWT trends are calculated on these anomalies.



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121 **Plate 2.1.** Satellite-derived LSWT anomalies in 2016. Annual LSWTs are calculated for the warm
122 season (Jul–Sep in NH; Jan–Mar in SH).

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