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Late-twentieth-century warming in Lake Tanganyika unprecedented since AD 500

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Instrumental observations suggest that Lake Tanganyika, the largest rift lake in East Africa, has become warmer, increasingly stratified and less productive over the past 90 years (refs 1,2). These trends have been attributed to anthropogenic climate change. However, it remains unclear whether the decrease in productivity is linked to the temperature rise[3,4], and whether the twentieth-century trends are anomalous within the context of longer-term variability. Here, we use the TEX_{86} temperature proxy, the weight per cent of biogenic silica and charcoal abundance from Lake Tanganyika sediment cores to reconstruct lake-surface temperature, productivity and regional wildfire frequency, respectively, for the past 1,500 years. We detect a negative correlation between lake-surface temperature and primary productivity, and our estimates of fire frequency, and hence humidity, preclude decreased nutrient input through runoff as a cause for observed periods of low productivity. We suggest that, throughout the past 1,500 years, rising lake-surface temperatures increased the stratification of the lake water column, preventing nutrient recharge from below and limiting primary productivity. Our records indicate that changes in the temperature of Lake Tanganyika in the past few decades exceed previous natural variability. We conclude that these unprecedented temperatures and a corresponding decrease in productivity can be attributed to anthropogenic global warming, with potentially important implications for the Lake Tanganyika fishery.

Lake Tanganyika is one of the world's great ancient rift lakes—it is the second largest (by volume) and second deepest lake in the world (Fig. 1). Four countries border Tanganyika (Burundi, Tanzania, Zambia and the Democratic Republic of the Congo) and the lake supports a prodigious pelagic clupeid (sardine) fishery (~200,000 tons per year), which provides a major source of animal protein for people in the region[5] as well as employment for approximately 1 million people[6]. As the sardine fishery depends on high algal productivity in the open-water food web and an efficient carbon transfer from algae to fish[7], it is sensitive to variations in primary productivity in the lake that occur in response to changes in nutrient flux. As a result of Tanganyika's great size and depth, more than 95% of the major nutrients assimilated in primary production are recycled or generated in-lake[8]. However, the majority of these nutrients reside in the hypolimnion, and Lake Tanganyika is permanently stratified. Thus nutrient flux to the photic zone is dependent on seasonal wind-driven mixing[9], which is less effective given warmer surface waters.

Observational lake-temperature data from the past 90 years suggest that Lake Tanganyika has warmed significantly in response to global climate change, and that this warming has promoted an increase in stratification and a subsequent reduction in primary productivity[1,2]. Specifically, from AD 1913 to 2000 the lower metalimnion (~110 m depth, just below the thermocline) of the lake warmed by 0.9 °C, the hypolimnion (below ~300 m depth) warmed by 0.2 °C and phytoplankton biomass between 1975 and 2000 decreased by 70% (ref. 2). The late-twentieth-century drop in primary production in Tanganyika may have contributed[1] to declines in catch per unit effort during the late twentieth century (absolute catch increased between the 1950s and 1990s; refs 4, 6), although most of this short-term change is probably the result of changing fishing intensity and technologies[4]. Furthermore, given that the instrumental temperature and productivity records in Lake Tanganyika are short, some have questioned whether the trends seen in the instrumental data are truly related to global warming[3,4]. Here, we resolve the issue by reconstructing primary productivity, lake-surface-water temperature (LST) and fire frequency (an indicator of aridity) in the Lake Tanganyika basin for the past 1,500 years. This continuous, high-resolution coupled productivity/LST/aridity record in the East African region overlaps with the instrumental record, allowing for direct comparison between the proxy record and the modern instrumental data.

Our record is based on analysis of two lake-sediment cores, piston core NP04-KH1 and an overlapping multicore MC1 (Fig. 1). These core sites are located near the remote and sparsely settled Mahale Mountains, thus are not heavily influenced by local anthropogenic impacts (for example, deforestation, human-induced fire or nutrient loading from agriculture; compare ref. 10). Sediment core chronologies are based on unsupported ^{210}Pb and radiocarbon dating (Supplementary Information). To reconstruct LST, we used the TEX_{86} proxy, which relates the degree of cyclization of aquatic archaeal glycerol dialkyl glycerol tetraethers to temperature. This proxy is well validated in oceans as a method of reconstructing sea-surface temperature[11], and can also be used in some large lakes including Lake Tanganyika[12,13]. For this study, we improved the large-lake calibration[14] by adding additional tropical lake sites (Supplementary Information).

To reconstruct primary productivity, we measured the percentage of biogenic silica (BSi) in the sediment. On the basis of wet biomass, diatoms are one of the dominant phytoplankton groups in Lake Tanganyika[2]. Thus changes in diatom abundance through time, inferred from biogenic silica in the sediment, give a reasonable

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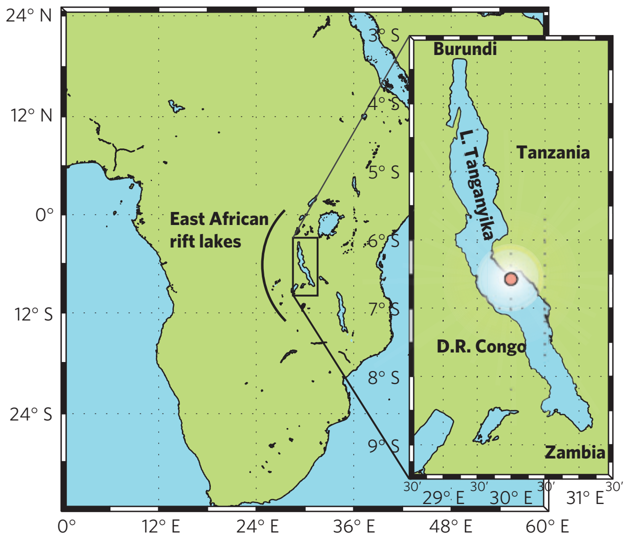

Figure 1 | The location of Lake Tanganyika, East Africa and the sediment cores KH1 and MC1 analysed in this study. Cores were collected from the Kalya Platform area, 6° 33.147′ S 29° 58.480′ E, 309 m water depth; pink dot in inset.

estimate of primary productivity in the lake. To reconstruct fire frequency and aridity in the Tanganyika basin, we measured the abundance of charcoal particles in the sediment. Though fire frequency can be controlled by the amount of biomass available for burning, charcoal has been previously shown to be a reliable indicator of Tanganyika basin aridity in areas of low population density such as our coring site[10]. Furthermore, our charcoal results from MC1 show a systematic decrease (wetter conditions) from the late 1800s to the present, similar to the instrumental trend for the greater East African region[15]. BSi and charcoal data are shown here in units of normalized abundance (Supplementary Information).

Figure 2 summarizes our results. Before the twentieth century, LST varied between 22.5 °C and 24.3 °C (Fig. 2a). LSTs were relatively warm between AD 500 and 700, followed by an interval of cool LSTs that lasted until AD 1100. Lake Tanganyika then experienced a period of extended warmth between 1100 and 1400, followed by a return to cooler LSTs between 1400 and 1500 and more variable temperatures until 1900. Beginning around 1900, LSTs trend upwards, rising about 2 °C in 100 years (see Fig. 2 inset). Our uppermost sample from core MC1 (identified using ^{210}Pb dating as about AD 1996), calibrates to 25.7 °C. This is within the range of 2003 measurements of seasonal LST for the Kalya Slope area (25.5–26.3 °C; see Fig. 2 inset) and is also similar to the annual average LST measured near Mpulungu, at the southern end of the lake (26.1 °C; ref. 16).

Our inferred surface warming is more than twice the magnitude of the warming that has occurred below the thermocline at 110 m (Fig. 2 inset), verifying the supposition made from deep-water measurements alone[1,2] that Lake Tanganyika developed an increasingly greater temperature gradient between the epilimnion and hypolimnion during the twentieth century. Our inference that LSTs increased by 2 °C since 1900 is higher than the instrumental estimate of LST warming (1.3 °C since AD 1913; ref. 17), but this discrepancy may be a consequence of the limited number of LST measurements in the historical dataset vis à vis the seasonal and spatial variability in Tanganyika LST. Furthermore, the increase in LST between the mid-1960s and 1990 inferred from our proxy data (1 °C) is similar to the observed 0.8 °C rise in Tanganyika-basin air temperatures during the same time interval[17], demonstrating that Tanganyika LSTs are keeping pace with rising air temperatures. In a warming climate, it might be expected that in a deep lake such as Tanganyika the LST would increase more slowly than air

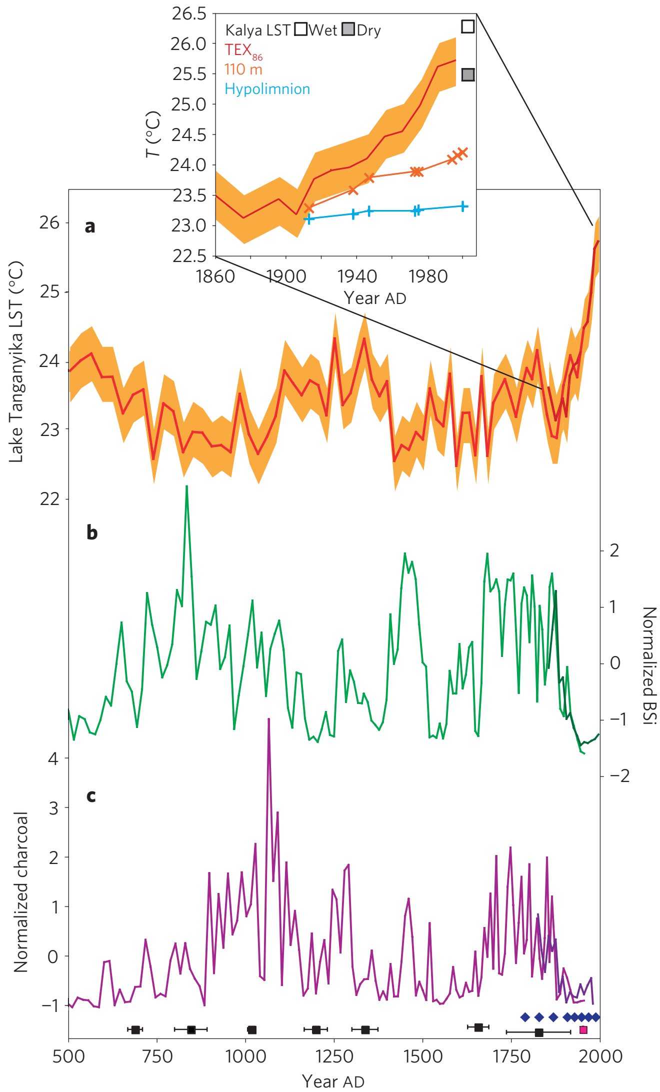

Figure 2 | The Lake Tanganyika palaeorecord for the past 1,500 years. **a**, TEX_{86}-inferred LST measured in core KH1 (red line) and MC1 (dark red line), orange shading is 95% error bars, which include analytical error and a leave-one-out estimate of calibration error (Supplementary Information). **b**, Normalized biogenic silica abundance in core KH1 (green line) and MC1 (dark-green line). **c**, Normalized charcoal abundance in core KH1 (purple line) and MC1 (dark-purple line). Plotted below the charcoal data are ^{14}C dates (with 1σ errors), unsupported ^{210}Pb dates (blue) and a stratigraphic tie point between MC1 and KH1 (pink). The inset shows TEX_{86} LST data from multicore MC1 alongside instrumental 110 m temperatures[2] (dark orange) and hypolimnion temperatures[2] (light blue) and instrumental LST in the Kalya Slope area for the wet (stratified) season (white square) and dry (upwelling) season (grey square) in 2003 (ref. 16).

temperature owing to the transfer of heat to the deep hypolimnion through mixing (much like the ocean). In fact, it seems that the increasingly severe stratification in Tanganyika slows the transfer of heat to deeper waters and enables Tanganyika to behave like a shallower water body, where increases in LSTs keep pace, or even exceed, increases in air temperatures[17]. Our data thus support the argument that the estimated 0.4 W m^{-2} net heat absorption by Lake Tanganyika since 1913, which is about twice the rate in the global ocean, is largely a reflection of stronger climate forcing in the East African region[17]. The correlation, both visual and statistical, between LST and BSi highlights the relationship between LST, wind mixing and related changes in primary productivity (Fig. 2). Over our entire record, LST and BSi are significantly negatively correlated ($r = -0.576, p = 0.001, n = 75$). Excluding the twentieth-century data, which have a strong antiphased trend, LST and BSi are still significantly correlated above the 99% confidence level ($r = -0.524, p = 0.003, n = 70$). This demonstrates that low LSTs are generally associated with higher diatom productivity before strong anthropogenic forcing of global climate. In the past 150 years, BSi values plummeted from relatively high levels during the early 1800s to some of the lowest sustained values during the past 1,500 years. This abrupt drop occurred in concert with the rapid rise in LST, implying that warm LSTs had a negative impact on lake primary productivity throughout the twentieth century through an increase in water-column stratification.

It is also possible that, on multidecadal and longer timescales, higher rates of precipitation may have increased nutrient recharge and availability, and hence primary productivity[18]. However, our charcoal data (Fig. 2c) show that humid conditions (low charcoal) were associated with low productivity from AD 1500 to 1650 and from the mid-nineteenth century onwards, and arid conditions (high charcoal) accompanied high productivity from 1650 to 1800. In addition, BSi and charcoal have a very weak positive correlation ($r = 0.348$, $n = 149$, $p = 0.074$). Alternatively, given the size of Lake Tanganyika, there could be a significant lag time between nutrient recharge and utilization by surface production. Given estimates of nutrient residence times in Lake Tanganyika (nitrogen, 4.6 years; phosphorus, 140 years; silica, 6,800 years; ref. 8), only phosphorus has a residence time compatible with the timescale of productivity variations observed in our record. Calculation of the lagged cross-correlation function between the BSi and charcoal time series reveals that the highest (negative) correlation value (high productivity as a consequence of wet conditions) occurs at a timelag of 260 years ($r = -0.387$, $n = 149$, $p < 0.05$). This could support the nutrient recharge hypothesis, but the correlation coefficient is nearly equal in magnitude to the zero-lag value, and is largely driven by movement of the arid period from 1650 to 1800 forward into the modern (low-BSi) interval. As the relationship between LST and BSi is more robust, we conclude that, in the recent past and on these timescales, it is temperature and its effect on stratification, and not rainfall, that is largely controlling primary productivity.

Our LST reconstruction is qualitatively similar to Northern Hemisphere temperature reconstructions[19] (Fig. 3a), implying that Tanganyika LST largely followed global trends in temperature during the past 1,500 years, much as it has in the past half-century[17]. As LST closely tracks air temperatures over the instrumental period, we can also infer that air temperatures in this region of East Africa varied in concert with the global average and thus were controlled primarily by the major forcings influencing temperatures over this timescale, both natural (solar radiation, volcanism) and anthropogenic (greenhouse-gas emissions; refs 19, 20). The temporal resolution of our dataset precludes comparison between Tanganyika LST and volcanic events of the past, but we can compare our record with changes in solar irradiance (total solar irradiance (TSI) anomaly, estimated from ^{10}Be in ice cores[21]; Fig. 3b). TSI and Tanganyika LST share some similar centennial-scale features, including maxima near 1350 and minima at 1450, 1250 and 1000. However, TSI variability clearly does not explain the dramatic twentieth-century increase in LST, which, as with global temperatures, is probably a response to greenhouse-gas forcing.

Our palaeorecords show that the LST increase in Lake Tanganyika during the past 90 years is uncharacteristic of the preceding natural variability and unprecedented in the past 1,500 years, suggesting that the recent anomalous trend in Tanganyika LST is a response to anthropogenic greenhouse-gas forcing. Furthermore, our data demonstrate that LST and primary productivity are closely related in both the pre-anthropogenic and anthropogenic eras, confirming that warm surface temperatures increase the degree of stratification within Lake Tanganyika and reduce primary productivity. Apart from fishing intensity, the present decline in primary productivity is likely to further impact the clupeid fishery, with potentially dire implications for the communities and the regional economy that depend on it.

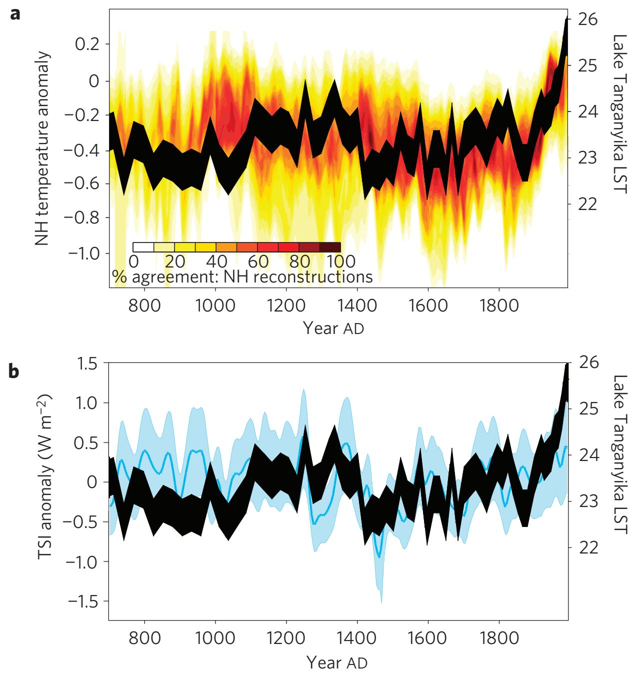

Figure 3 | A comparison between Lake Tanganyika LST and global temperature trends and forcings. a, Lake Tanganyika LST (black, including 95% error) plotted next to composite Northern Hemisphere temperature anomaly reconstructions[19]; colours represent the percentage agreement between the reconstructions. **b**, Lake Tanganyika LST and TSI anomaly (blue shading indicates 1σ error; ref. 21).

Methods

Charred particles (charcoal) were analysed by disaggregating and wet sieving weighed samples in deionized water using a 125 μm stainless-steel sieve. Wet weights were determined for a separate aliquot from each sample, which was oven-dried and reweighed to determine water content and to calculate original dry weights for sieved samples. Samples were counted using an Olympus SZX12 Stereomicroscope. Remaining sediment was freeze-dried and homogenized. ∼30–50 mg of sediment was analysed for biogenic silica content (%BSi) by dissolving the sediment in a hot 0.5 N NaOH solution for 90 min exactly, removing a 0.5 ml aliquot, diluting the solution 9× with distilled water and then following the method of ref. 22 to analyse %BSi by a colorimetric method. %BSi 2σ standard error, on the basis of duplicate measurements (and corrected for $n = 2$), was ±1.5%. The rest of the sediment was extracted for TEX_{86} analysis by accelerated solvent extraction (DIONEX) with CH_2Cl_2:MeOH (9:1). The resulting extract was purified and then analysed for TEX_{86} determination by high-performance liquid chromatography/positive-ion atmospheric pressure chemical ionization mass spectrometry on an Agilent 1200 HPLC/MS system according to the methods in ref. 23. Analytical 2σ standard error, on the basis of duplicate measurements (and corrected for $n = 2$), was ±0.1 °C. This error is compounded with the leave-one-out calibration error 0.4 °C (Supplementary Information) to give a total 95% error of ±0.4 °C.

To estimate correlation coefficients and significance (p value), time series were resampled at a constant time interval (10 years for %BSi and charcoal, and 20 years for TEX_{86}), and then linearly regressed to determine correlation. p values were calculated by a Monte Carlo method using 10,000 phase-randomized simulations in the manner described in ref. 24.

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Author contributions

J.E.T. designed the experiment, assisted with the laboratory analyses, analysed the results and wrote the paper. M.T.M. produced the majority of the biogenic silica and TEX_{86} data and assisted in writing the manuscript. N.M. produced the remaining biogenic silica and TEX_{86} data. C.J. and A.S.C. produced the charcoal data. P.W.S. was responsible for the ^{210}Pb analyses and multicore age model. J.M.R. and A.S.C. helped design the experiment and supervised the project.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to J.E.T.