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Organic geochemical records of environmental variability in Lake Malawi during the last 700 years, Part I: The TEX_{86} temperature record

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ABSTRACT

We have applied the TEX_{86} paleothermometer to produce a surface water temperature record for Lake Malawi spanning the past 700 years. Over much of the record temperature fluctuates from ~24–27 °C with a mean of ~25 °C ; however, there has been a substantial increase in temperature of ~2.0 °C during the past ~ 100 years. The TEX_{86} temperature record reveals a strong similarity to the instrumental record; both records demonstrate warming (~0.7–1.4 °C) over the past ~50 years as well as a cooling anomaly around 1959. Comparison of the TEX_{86} temperature record with the proxy records of primary productivity suggests that wind induced upwelling and/or precipitation have a strong influence on the surface temperature of Lake Malawi.

1. Introduction

Although it is well documented that the tropics are the heat engine driving global atmospheric circulation, it is yet unclear how tropical climates respond to many external forcing mechanisms (e.g. changes in sea surface temperature (SST), solar radiation, or atmospheric CO_2 concentrations) (Trenberth et al., 2007). Direct insolation is known to be important in monsoonal dynamics; however, the mechanistic relationship between temperature and changes in hydrologic cycles is not yet fully understood.

As the debate continues regarding the magnitude of recent climate warming in the Northern Hemisphere (McIntyre and McKitrick, 2005; Trenberth et al., 2007), records of tropical lake temperature (O' Reilly et al., 2003; Verburg et al., 2003; Vollmer et al., 2005) have elevated the discussion of the role of the tropics in global climate change, as well as the impact of climatic change on society. Tropical regions support large populations of subsistence-based societies that are highly vulnerable to catastrophic climate events and rapid climate change (Lobell et al., 2008). Changes in climate can have devastating effects in these regions of the world, where technology is scarce and food production and storage is very limited. Recent studies have shown a warming trend in the surface waters of Lake Tanganyika (Plisnier et al., 1999; O'Reilly et al., 2003; Verburg et al., 2003; Tierney et al., 2010) and in the surface and deep waters of Lake Malawi (Vollmer et al., 2005) over the past century. The warming of lakes can have a profound impact on local populations through changes in fishery production and water quality as well as changes in local weather patterns. Documenting the timing and magnitude of climate changes and their relationship to the various forcing mechanisms will improve our ability to prepare for and respond to these events in the future.

Here we present a paleotemperature record for Lake Malawi, the southernmost of the East African rift lakes. The lake extends from 9° to 14° S, and is bordered by the countries of Malawi, Tanzania, and Mozambique (Fig. 1). The lake is very deep (>700 m) and old, as is evidenced by over 4 km of sediments (Scholz and Rosendahl, 1988) accumulated in the basin. Lake Malawi is situated near the Congo Air Boundary where easterly winds from the Indian Ocean converge with the westerly winds of the West African monsoon, and near the southern extent of the seasonal migration of the Intertropical Convergence Zone (ITCZ) (Nicholson, 1996). Sediments accumulate rapidly in the lake's deep basins and are sensitive recorders of climate change. A lack of bioturbation in the lake's anoxic bottom waters makes Lake Malawi an attractive target for high-resolution studies of climate dynamics in the tropics (Finney et al., 1996; Johnson et al., 2001; Brown and Johnson, 2005).

Lake Malawi is meromictic with an anoxic hypolimnion below approximately 200 m (Eccles, 1974). The thermal difference between

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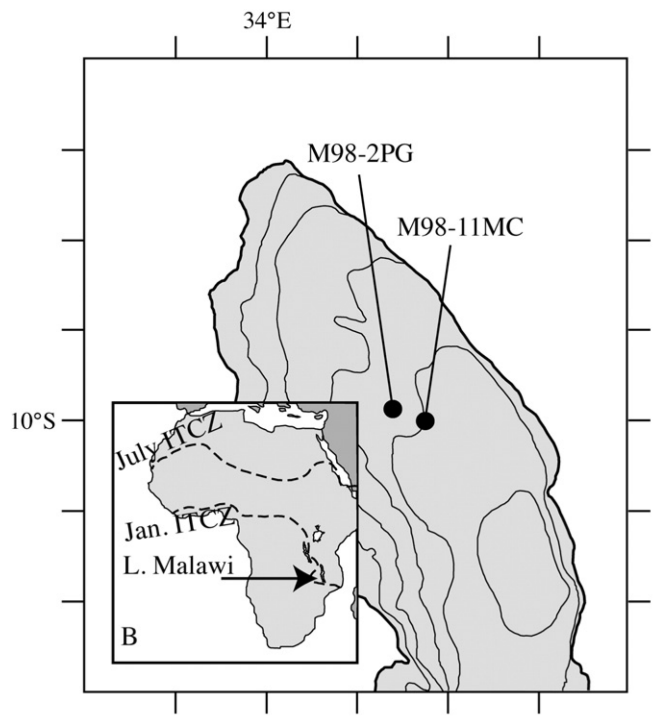

Fig. 1. Coring locations in the northern basin of Lake Malawi. Inset illustrates the extent of the Intertropical Convergence Zone (ITCZ).

the epilimnion and hypolimnion is small (~2–4 °C); however, at these warm temperatures (22–29 °C) the density difference is sufficient to maintain stable stratification. During the austral winter when temperature differences are reduced, stratification is often maintained by the abundance of dissolved solids in the hypolimnion (Wuest et al., 1996). The thermal structure of Lake Malawi is controlled by downward diffusion of heat from the epilimnion and occasional replacement of deep water by winter cooled surface waters (Bootsma and Hecky, 1998; Vollmer et al., 2005). The deep water replacement can be enhanced by a high influx of cool river water to the epilimnion during unusually wet years, which preconditions the surface waters to more intense cooling during the subsequent winter (Vollmer et al., 2005).

During austral winter the predominant winds are from the south, resulting in downwelling and thickening of a warm surface water pool in the northern basin. However, during austral summer the predominant wind direction is from the north as the ITCZ moves over to the south of the lake (Fig. 1). Northerly winds cause upwelling in the northern basin delivering cooler hypolimnetic water and nutrients to the epilimnion (Bootsma and Hecky, 1998). We would therefore expect that prolonged northerly wind events would result in cooling lake surface temperatures and an increase in primary productivity in the northern basin.

Originally developed as an organic geochemical tool for determining past sea surface temperatures from marine sediments (Schouten et al., 2002), the TEX_{86} index is based on the relative abundance of tetraether membrane lipids (glycerol dialkyl glycerol tetraethers, or GDGTs), produced by aquatic Group I *Crenarchaeota* (Domain Archaea). *Crenarchaeota* have been found living throughout the water column in marine and lacustrine systems (Karner et al., 2001; Keough et al., 2003). Unfortunately we do not yet have any measurements of crenarchaeotal abundance in the water column of Lake Malawi. Recent molecular evidence from Lake Challa, Tanzania, demonstrates that *Crenarchaeota* are most abundant in the upper oxygenated water column (Sinninghe Damsté et al., 2009). Crenarchaeotal GDGTs were identified in the guts of decapods from the Atlantic and Mediterranean (Huguet et al., 2006), suggesting that export from surface water by fecal pellets is a likely mechanism for preservation of a surface water signal.

Previous studies have suggested that crenarchaeotal abundance varies seasonally (Wuchter et al., 2005; Herfort et al., 2006; Sinninghe Damsté et al., 2009). A sediment trap study in Lake Challa found highest abundances of crenarchaeotal GDGTs during austral summer just after the period of heaviest rainfall and highest algal productivity (Sinninghe Damsté et al., 2009). This is in agreement with previous studies suggesting that at least some aquatic *Crenarchaeota* are capable of nitrification (Könneke et al., 2005; Leininger et al., 2006; Wuchter et al., 2006) and therefore are likely exploiting the partially mineralized residual ammonium from decaying algae (Wuchter et al., 2006).

Despite the spatial and temporal variability in aquatic crenarchaeotal productivity, the results of the global marine (Schouten et al., 2002; Kim et al., 2008) and lacustrine (Powers et al., 2004, 2010; Blaga et al., 2009) calibrations demonstrate that the TEX_{86} paleothermometer correlates well with mean annual surface water temperature. Further application of TEX_{86} in lacustrine systems has demonstrated its validity as a continental paleothermometer in some systems, particularly in large lakes (Powers et al., 2005; Tierney and Russell, 2009; Blaga et al., 2009; Woltering et al., 2011–this issue). Here we document the thermal history of Lake Malawi spanning the past ~700 years, through the application of the TEX_{86} paleothermometer. We compare the TEX_{86} record to recent instrumental records of Lake Malawi water column and air temperatures spanning the past six decades (Vollmer et al., 2005).

2. Methods

2.1. Chronology

Three cores collected during the 1998 International Decade for East African Lakes (IDEAL) expedition in the north basin of Lake Malawi were used in this study (Fig. 1). Splicing data from multi-cores M98-11MCA and M98-11MCB and gravity trigger core M98-2PG results in a record spanning the past ~700 years (Table 1). All three cores are entirely composed of varved sediments. The age model for multi-core M98-11MCA was established through varve counting and confirmed by ^{210}Pb dating (Johnson et al., 2001; Johnson and McCave, 2008). Core M98-11MCB, taken directly adjacent to M98-11MCA (within the same set of multi-cores), was dated by comparing five distinct marker horizons in both cores and assigning the same age to these horizons. The age model for core M98-2PG is also based on varve counts and stratigraphic correlation of a marker bed that is common to all three cores (Johnson et al., 2001). Repeated varve counts by multiple observers resulted in an error of ± 0.5 varves cm^{-1} establishing the uncertainty in ages of the cores at $\pm 7\%$ (Johnson and McCave, 2008). Therefore the age uncertainty at the bottom of core M98-2PGA is about ± 50 years.

2.2. TEX_{86} analysis

Sediment samples (~1–2 g dry weight) were collected from the cores and analyzed for TEX_{86} as described in Powers et al. (2005). In order to rigorously test reproducibility, 11% of the samples were run in quadruplicate, 22% were run in triplicate and 31% were run in duplicate (Table 1). The records were then combined, by including the mean values of all replicates at their respective ages, to form one continuous record spanning the past 730 years. Standard deviations of replicate analyses were calculated (Table 1).

The results of the global calibration of the TEX_{86} paleothermometer with lake surface temperatures indicate a strong linear relationship with annual lake surface temperatures in primarily large lakes (Powers et al., 2010). We have applied the mean annual lake surface temperature (ALST) calibration equation, $ALST = 55.0^{*}TEX_{86} - 14.0$, with an

Table 1
Results for all Lake Malawi TEX_{86} analyses.

Core	Sample depth (cm)	Age	TEX86 replicate analyses 1	2	3	4	Mean TEX_{86}	Std. dev.	Temperature
M98-11MCA surface		1996	0.771	0.770	0.735	0.737	0.753	0.020	27.43
M98-11MCA	1.5	1992	0.751	0.744	0.738	0.737	0.742	0.007	26.84
M98-11MCA	3	1981	0.755	0.755	0.731	0.732	0.743	0.013	26.87
M98-11MCA	6	1965	0.748		0.738		0.743	0.007	26.85
M98-11MCB	7.5	1959	0.713	0.722	0.710		0.715	0.006	25.33
M98-11MCA	8	1954	0.735	0.738	0.733		0.735	0.003	26.44
M98-11MCA	11	1933	0.750		0.736		0.743	0.010	26.88
M98-11MCB	13.5	1915	0.720	0.723	0.718		0.720	0.003	25.61
M98-11MCB	15.5	1903	0.708				0.708		24.96
M98-11MCA	19	1880	0.704		0.698	0.698	0.700	0.003	24.50
M98-11MCB	23.5	1851	0.713				0.713		25.24
M98-11MCA	28	1806	0.733	0.719	0.717		0.723	0.009	25.76
M98-11MCB	33.5	1765	0.695		0.696		0.696	0.000	24.27
M98-11MCA	37.5	1732	0.706				0.706		24.81
M98-11MCA	40	1726	0.722	0.728			0.725	0.005	25.89
M98-11MCB	41.5	1704	0.714	0.710			0.712	0.003	25.17
M98-11MCB	42.5	1701	0.716	0.706			0.711	0.007	25.10
M98-11MCA	42.75	1698	0.719	0.729	0.713		0.720	0.008	25.61
M98-11MCB	43.5	1691	0.658		0.668	0.666	0.664	0.005	22.50
M98-11MCA	44	1689	0.731	0.716	0.712		0.720	0.010	25.58
M98-11MCB	45.5	1679	0.655		0.673		0.664	0.013	22.52
M98-11MCA	46	1676	0.716				0.716		25.35
M98-2PG	39	1671	0.686		0.678		0.682	0.006	23.51
M98-11MCB	47.75	1665	0.706	0.699	0.705	0.706	0.704	0.003	24.72
M98-11MCB	51.5	1643	0.697	0.692			0.695	0.004	24.20
M98-2PG	45	1630	0.702	0.702	0.692	0.699	0.699	0.005	24.43
M98-2PG	50	1589	0.717				0.717		25.45
M98-2PG	55	1544	0.723				0.723		25.74
M98-2PG	60	1500	0.704				0.704		24.71
M98-2PG	65	1465	0.692		0.682		0.687	0.007	23.79
M98-2PG	70	1425	0.712	0.710			0.711	0.002	25.11
M98-2PG	75	1395	0.703				0.703		24.66
M98-2PG	80	1357	0.700	0.706			0.703	0.004	24.66
M98-2PG	85	1316	0.728	0.725	0.711		0.721	0.009	25.66
M98-2PG	90	1291	0.701				0.701		24.57
M98-2PG	93	1283	0.706				0.706		24.82

$r^2 = 0.86$, corresponding to an error of the calibration of ± 3.7 °C (Powers et al., 2010) to reconstruct mean annual surface temperatures from the north basin of Lake Malawi. While the error of the global calibration is relatively large compared to annual temperature variability in Lake Malawi, the reproducibility of temperature profiles in two cores from the north basin of the lake spanning the past 25,000 years (see Woltering et al., 2010) is excellent, displaying values typically within 0.5 °C of each other.

3. Results and discussion

3.1. Comparison with instrumental record

We compare the TEX_{86} mean annual lake surface temperature record (7 samples) from the past 61 years to the instrumental record of lake surface temperatures (10–50 m) from winter (May–Aug, 15 data points) and summer (Dec–April, 14 data points) and mean annual temperature (calculated by averaging mean winter and mean summer temperatures, 12 data points) of Vollmer et al. (2005). Unfortunately the sampling resolution of the TEX_{86} temperature record is only half the resolution of the instrumental record. Despite the mismatch in resolution of the two records and age uncertainty in the TEX_{86} profile, there are similarities between the two records that validate the use of TEX_{86} as a paleothermometer (Fig. 2).

The TEX_{86} temperature record for this period displays a range of 25.3–27.4 °C, well within the range of the instrumental record with a winter range of 23.3–27.2 °C and a summer range from 26.4–27.4 °C. The close similarity of the absolute temperatures in the TEX_{86} record and the summer instrumental record suggests a higher summer productivity of *Crenarchaeota* in the surface water of Lake Malawi, as was observed in Lake Challa, at the border of Tanzania and Kenya (Sinninghe Damsté et al., 2009), thus resulting in a temperature signal that is warmer than the winter instrumental record. It should be noted that the "winter" season in Malawi is short, and relatively cool temperatures prevail for only 3 months of the year (Eccles, 1974).

The trends in TEX_{86} temperature and winter surface water instrumental records are similar, but given the uncertainty in the derived TEX_{86} temperatures, need to be viewed with reservation. While the TEX_{86} lake surface temperature record for the past 60 years could be viewed as constant, given the size of the error bars, a least-squares linear fit through the TEX_{86} lake surface temperatures indicates an increase of ~0.7 °C ($r^2 = 0.16$). The measured summer surface temperature displays a slight cooling over the same time, while winter surface temperatures rose ~1.4 °C (Vollmer et al., 2005). However, this instrumental average is heavily weighted by a single anomalously cold value from 1939 (if this point is dropped the winter temperature change is only 0.6 °C). Over the entire 61 year instrumental record there has been a mean increase of 0.7 °C both at 100 m and in the hypolimnion (>300 m) in Lake Malawi (Vollmer et al., 2005). Further, there is an increase in air temperature in the basin of 0.6 °C during the same time interval, which is based on interpolated values from direct station observations within the catchment (New et al., 2000). While the TEX_{86} is typically interpreted to reflect mean annual surface water temperatures, in Lake Malawi it is closest to the summer instrumental temperatures in an absolute value, but broadly similar to the trend of winter and annual mean (100 m) temperatures that have been measured over the past six decades. The ecology of *Crenarchaeota* in Lake Malawi needs to be investigated to resolve

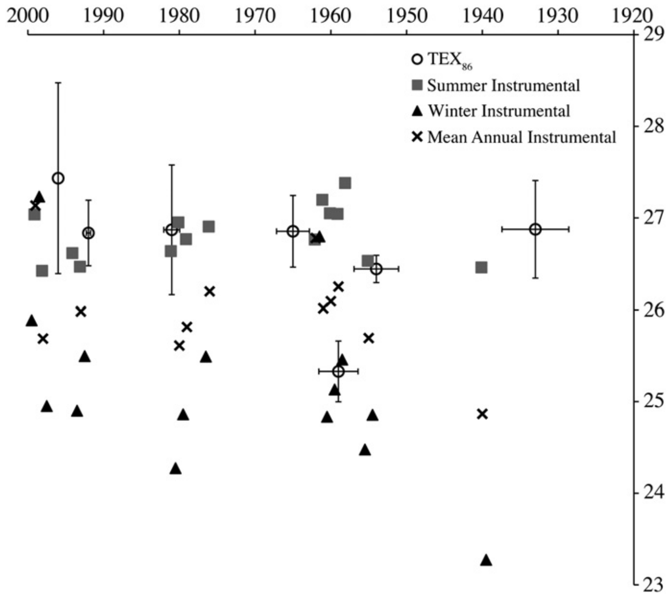

Fig. 2. A comparison of TEX_{86} reconstructed mean annual lake surface temperatures with a compiled instrumental record of summer, annual and winter lake surface temperatures (Vollmer et al., 2005) spanning the past 61 years. Mean annual instrumental temperatures are simply an average of summer and winter instrumental values. There is a pronounced similarity between the TEX_{86} mean annual temperatures and the summer instrumental temperatures likely due to the wet/summer season being the primary growth season for Group I Crenarchaeota in tropical lakes (Sinninghe Damsté et al., 2009). Overall the winter instrumental record shows a warming of 1.4 °C but is weighted by the single point at 1939 without which the warming is closer to 0.6 °C. The TEX_{86} record shows a comparable warming trend of 0.71 °C over the same period. The mean annual instrumental record shows a warming of 0.74 °C. Vertical error bars on the TEX_{86} values represent standard deviations of replicate analyses, horizontal error bars represent the 7% error in age estimates.

more clearly exactly what temperature is actually reflected in the TEX_{86}.

The substantial and abrupt cooling and warming anomaly around 1959 in the TEX_{86} record (within the 7% age error) is also seen in the winter instrumental record though it is of a smaller magnitude (Fig. 2). Overall, the similarities between the TEX_{86} record and the instrumental records support the application of TEX_{86} as a paleothermometer with the potential for reconstruction of records with high temporal resolution.

3.2. Long term thermal history

Results of the TEX_{86} paleotemperature reconstruction demonstrate that Lake Malawi mean annual surface temperatures have risen about 2 °C over the past 700 years, with most of this increase occurring during the last ~100 years (Fig. 3). Throughout much of the record prior to 1900 there is a somewhat regular oscillation around a mean temperature of ~25 °C with a period of approximately 100 years; however, the sampling resolution is not high enough to test the statistical significance of possible cyclicity.

The most dramatic feature of this temperature record is clearly the abrupt warming of Lake Malawi surface waters by about 2 °C since ~1880 AD. This increase coincides with the well-documented rise in global mean temperature over the same interval (e.g., Mann and Jones, 2003; Moberg et al., 2005) (Fig. 3), as well as a similar increase in Lake Tanganyika surface temperatures (Tierney et al., 2010) that are attributed primarily to an increase in atmospheric CO_2, an important greenhouse gas (Crowley, 2000; Etheridge et al., 1996; Hegerl et al., 2003). Lake Malawi temperature and atmospheric CO_2 have risen rapidly since ~1900, when CO_2 levels increased beyond the range of Holocene variability. Surprisingly, the rise in tropical Lake Malawi surface temperature is about 2 °C over the past 100 years, while the rise in global mean temperature has been only about 0.6 °C (Fig. 3), indicating that Lake Malawi is an extremely sensitive recorder of climate variability. The strong coherence with the Lake Tanganyika surface temperature record (Tierney et al., 2010) indicates that Lake Malawi is also indicative of regional climate variability.

A comparison of the Lake Malawi TEX_{86} record with that of global mean temperature further back in time (AD 1200–1900) shows some interesting similarities and differences (Fig. 3). Both records display centennial-scale variability, but the timing of peaks and valleys in the records is not consistently in or out of phase. This inconsistent relationship may be real or it may be an artifact of the sediment age model. Furthermore, the Lake Malawi record does not show any evidence of a so-called “Medieval Warm Period” (MWP), which can be observed in the global mean temperature records of Mann and Jones (2003) and Moberg et al. (2005). However, it should be noted that these two studies define the MWP differently, and also that while there is no warming at the base of the Lake Malawi record, it does not go back far enough to clearly identify a warm period in this interval, particularly as defined by Moberg et al. (2005).

There are two distinct abrupt events of cooling followed by warming, referred to as cooling anomalies, in the TEX_{86} record; one at ~1670–1700 coincident with the Maunder Minimum (1645–1715 AD, Eddy, 1976), and the other at ~1959 (Fig. 1). The Maunder Minimum cooling anomaly was a rapid oscillation of ~3 °C over a 30 year period, whereas the event at ~1959 was ~1 °C and lasted no longer than ~20 years (Fig. 3). Both cooling events are observed in the global mean temperature record as well.

3.3. Long term TEX_{86} record and environmental variables

Solar irradiance certainly plays an important role in the thermal budget of large lakes; however, there are few periods of coherence between the TEX_{86} temperature record and a residual $\delta^{14}C$ curve from INTCAL04 (Reimer et al., 2004) representing terrestrial solar irradiation. The impact of solar variability on tropical climate on this time scale is not clear. While a high-resolution paleoclimate record from Lake Naivasha, Kenya suggests that solar influence is important (Verschuren et al., 2000), an equally high-resolution record from Lake Edward, Uganda, displays no such influence by solar variability (Russell and Johnson, 2007).

Increases in solar radiation in the tropics are expected to increase monsoonal activity through strong convection over the heating landmass, resulting in increased precipitation, at least at orbital amplitudes and time scales (Prell and Kutzbach, 1992). Increased precipitation results in increased nutrient delivery to the lake through runoff, which could promote higher primary productivity in the lake. Indeed we observe similar patterns in the TEX_{86} temperature record and the abundance of total organic carbon (TOC) in the sediment. Because the Lake Malawi bottom waters are anoxic, the TOC record indicates organic carbon inputs to the sediments, which is a combination of algal productivity and terrestrial biomass influx. Therefore, the observed relationship between TEX_{86} and TOC in this system may indicate a relationship between (warmer) temperature and TOC flux to the sediments, as algal production would be increased through precipitation-enhanced nutrient delivery and influxes of terrestrial organic matter could be increased through enhanced surface flux delivering soil-derived organic matter (Fig. 3).

Wind driven mixing can cause episodic cooling events in the surface waters of the north basin of Lake Malawi due to upwelling of cooler, nutrient rich waters, as well as increased evaporation. Vollmer et al. (2005) note that the National Center for Environmental Prediction wind direction data for the period of 1958–1961 reveal a distinct reversal from normal conditions of predominantly southerly winds in the winter to dominantly northerly winds during all seasons. The temperature

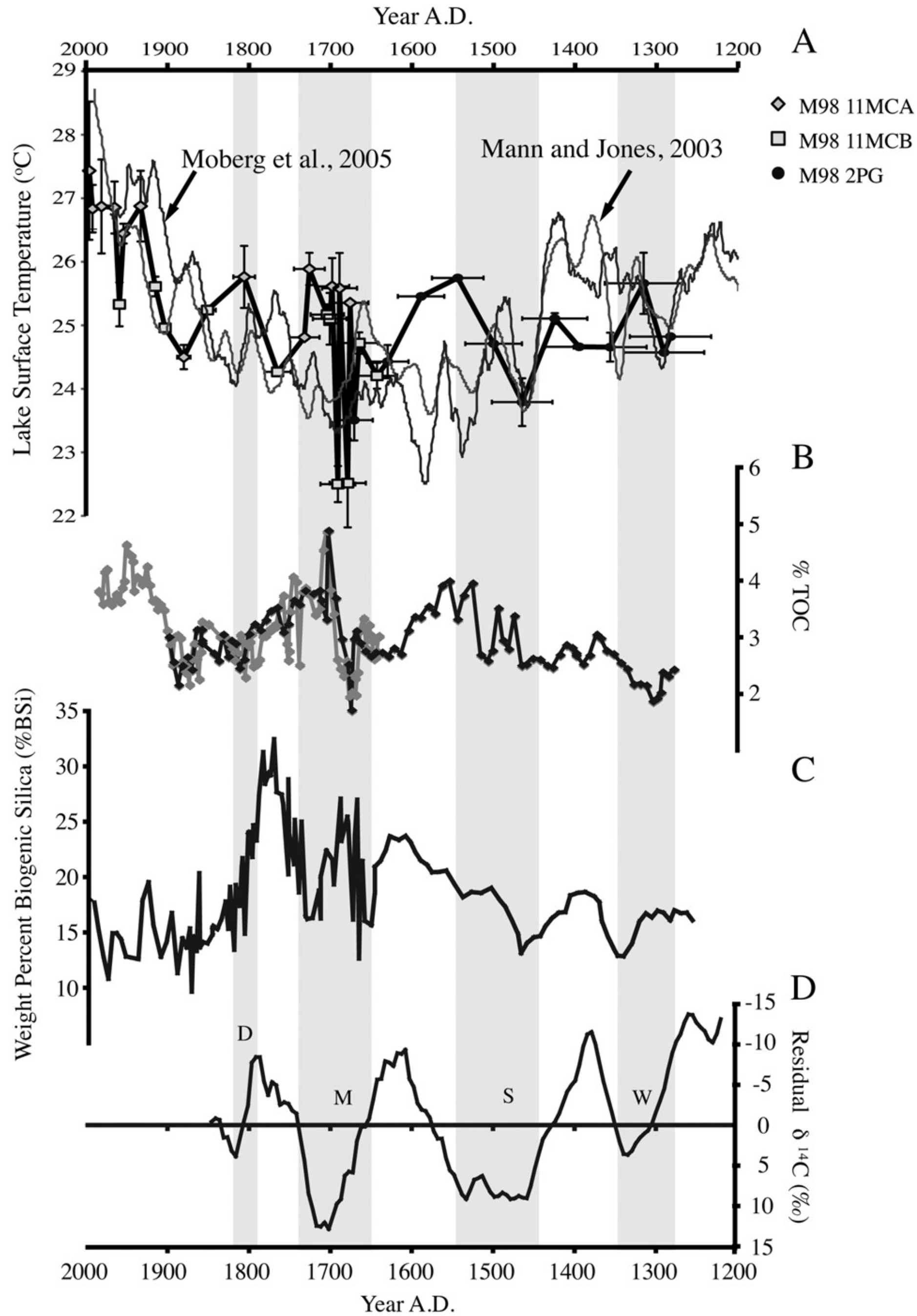

Fig. 3. A) TEX_{86} record of Lake Malawi mean annual surface temperature. The three symbols represent samples taken from each of 3 cores illustrated in the legend above. Additionally, the Mann and Jones (2003) and the Moberg et al. (2005) records of global temperature anomalies (smoothed with a 20-year running mean) are shown. B) Percent total organic carbon from the same cores sampled for TEX86, grey points are from the multi-cores and black points are from M98-2PG (data from Castañeda et al., 2011–this issue). Percent TOC represents a bulk measure of productivity within the lake. C) Weight percent biogenic silica (data from Johnson et al., 2001) representing diatom productivity in the north basin of Lake Malawi. D) Residual δ 14C as a measure of mean solar irradiance at the earth surface. The shaded areas outline periods of solar minima, the Dalton (1790–1820), Maunder (1645–1750), Sporer (1450–1550) and Wolf (1280–1350) respectively.

anomaly in the TEX_{86} record at ~1959 may be due to these prolonged northerly winds over the north basin of the lake resulting in wind driven cooling and extensive upwelling; however, the mean annual air temperature dropped by about 1 °C over the same time interval (Vollmer et al., 2005), so there is likely a component of air-related cooling, as well as upwelling-related cooling, in the TEX_{86} signal.

The abundance of biogenic silica in north basin sediment reflects past diatom productivity, attributed primarily to upwelling induced by northerly winds (Johnson et al., 2002; Brown and Johnson, 2005). The abundance of biogenic silica is roughly anti-phased with the TEX_{86} temperature record over most of the 700-year period (Fig. 3), suggesting that the temperature record is responding at least in part to the intensity of upwelling in the north basin. Whether this variation in upwelling is due primarily to the frequency and intensity of northerly winds or to the strength of summer thermal stratification is not known. However, the substantial warming of the past century is reasonably attributed to greenhouse warming, and related suppression of wind-induced upwelling in the north basin could very well explain the observed persistently low abundance of diatoms over the past ~100 years.

3.4. Societal impacts

Increasing surface water temperatures in Lake Malawi are likely to have a negative impact on fishery production, similar to Lake Tanganyika, through increased stratification and reduced nutrient upwelling to the surface (O'Reilly et al., 2003). Although Lake Malawi has not experienced a decrease in mean wind speed during recent history, the surface waters are warming and deep convective mixing seems to be less frequent than in the past (Vollmer et al., 2005), resulting in reduced nutrient delivery to the epilimnion.

The observed changes in algal community structure include a shift to more dinoflagellates and fewer diatoms in the last ~100 years (Castañeda et al., 2011–this issue), compelling evidence to suggest that primary productivity in Lake Malawi has already been affected by environmental changes associated with global warming. Predicting the magnitude of such changes in the lake ecosystem, and their impact on the people who depend on Lake Malawi for their livelihood, will be facilitated by a better understanding of the complex factors contributing to the thermal state of Lake Malawi.

4. Conclusions

Vollmer et al. (2005) demonstrated that winter surface water temperature in Lake Malawi, as well as deeper water temperature (both in the hypolimnion and at 100 m depth), has risen 0.7 °C over the past 6 decades. Our TEX_{86} data reflect this trend, albeit with some uncertainty. The TEX_{86} record clearly shows a 2 °C warming of the lake since 1880, coincidental with a ~0.6 °C warming in global mean temperature, attributed to anthropogenic CO_2 emissions. The temperature of the lake between the late 13th and late 19th centuries appears to have centennial-scale variability similar to that observed in the global mean temperature record, although age uncertainty in the TEX_{86} record does not allow us to determine whether the records are consistently in phase with each other. The Lake Malawi record shows no evidence for a thermal response to the Medieval Warm Period prior to AD 1500.

The Malawi paleotemperature record is roughly anti-phased with past diatom productivity in the north basin, which responds to upwelling induced by northerly winds when the ITCZ is positioned south of the lake. Upwelling draws cooler, nutrient-rich deep water to the surface and will thereby affect both diatom productivity and surface temperatures. In addition, strengthened summer stratification brought on by warmer surface water temperature such as observed over the past ~100 years will reduce upwelling and diatom productivity.

The significant warming of Lake Malawi in the past century supports building evidence that increased atmospheric CO_2 is affecting tropical ecosystems, including the observed drop in diatom abundance in north basin sediments. The resultant change in climatic state may cause increased stratification in the lake, having lasting impacts on fishery productivity and the welfare of the majority of people in the region who rely on fish as their primary source of protein.

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