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A TEX$_{86}$ lake record suggests simultaneous shifts in temperature in Central Europe and Greenland during the last deglaciation

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[1] High-resolution quantitative temperature records from continents covering glacial to interglacial transitions are scarce but important for understanding the climate system. We present the first decadal resolution record of continental temperatures in Central Europe during the last deglaciation (~14,600–10,600 cal. yr B.P.) based on the organic geochemical palaeothermometer TEX$_{86}$. The TEX$_{86}$-inferred temperature record from Lake Lucerne (Vierwaldstättersee, Switzerland) reveals typical oscillations during the Late Glacial Interstadial, followed by an abrupt cooling of 2°C at the onset of Younger Dryas and a rapid warming of 4°C at the onset of the Holocene, within less than 350 years. The remarkable resemblance with the Greenland and regional stable oxygen isotope records suggests that temperature changes in continental Europe were dominated by large-scale reorganizations in the northern hemispheric climate system. **Citation:** Blaga, C. I., G.-J. Reichart, A. F. Lotter, F. S. Anselmetti, and J. S. Sinninghe Damsté (2013), A TEX$_{86}$ lake record suggests simultaneous shifts in temperature in Central Europe and Greenland during the last deglaciation, *Geophys. Res. Lett.*, *40*, 948–953, doi:10.1002/grl.50181.

1. Introduction

[2] The Late Glacial period was characterized by large and rapid changes in temperature and precipitation [e.g., *Taylor et al*., 1997; *Birks and Ammann*, 2000; *Denton et al*. 2005; *EPICA*, 2006], marking the transition from the Last Glacial Maximum (LGM) to the Early Holocene. Most reconstructions of past temperatures focused on the Greenland and Antarctic ice cores and on marine records but less is known on how temperatures of the continental interiors fluctuated. Palaeoclimatic studies focusing on the last deglaciation showed unstable climatic conditions in Central Europe, based on correlations of isotope records, pollen, cladoceran, and chironomids from lake deposits in Germany and Switzerland with the Greenland isotope records [e.g., *von Grafenstein et al*., 1999; *Ammann et al*, 2000; *Lotter et al*., 1992, 2000, 2012; *Schwander et al*., 2000; *Heiri and Lotter*, 2005]. The reconstructed amplitude of the changes in July/summer temperature in Central Europe during the shifts from the Oldest Dryas to the Interstadial (i.e., Bølling/Allerød), from the Interstadial to the Younger Dryas (YD), and finally from the YD to the early Holocene are believed to range between 3°C and 6°C [e.g., *Coope et al*. 1998; *Lotter et al*., 2000, 2012]. Ostracod oxygen-stable isotope signatures from perialpine lake sediments indicate that the annual mean air temperature at the onset of the YD decreased by 5°C, while the transition to the Holocene is marked by a rapid increase of 7°C [*Schwalb*, 2003]. Although regional high-resolution stable oxygen isotope records show changes that appear to be synchronous with those observed in Greenland [e.g., *Lotter et al*. 1992; *von Grafenstein et al*., 1999; *Schwander et al*., 2000; *Genty et al*., 2006], it remained unclear to what extent the observed changes in these proxy records are related to temperature or other climate variables (e.g., precipitation).

[3] The TetraEther index of archaeal isoprenoid Glycerol Diakyl Glycerol Tetraethers (GDGTs) membrane lipids with 86 carbons (TEX$_{86}$) [*Schouten et al*., 2002] has been shown to record temperature changes not only in the marine but also in the lacustrine realm [*Powers et al*., 2005, 2010; *Tierney et al*., 2008]. For marine and lacustrine settings, the TEX$_{86}$ relationships are nearly identical, probably because of the underlying physiological mechanism of adaptation of membrane fluidity by the Archaea present in marine and freshwater settings that are producing these lipids.

[4] We have recently performed a seasonal study of GDGTs in Lake Lucerne by determining concentrations of GDGTs in suspended particulate matter, fluxes of GDGTs in descending particles, and GDGT distributions in surface sediments [*Blaga et al*., 2011]. This revealed that the isoprenoid GDGTs in surface sediments are predominantly derived from Thaumarchaeota living in the deeper waters and that the TEX$_{86}$ temperature signal reflects the annual mean temperature of the lake water at approximately 50 m below the surface. Here we apply the TEX$_{86}$ palaeothermometry to a core obtained from Lake Lucerne (Vierwaldstättersee), Switzerland, to study in high-resolution temperature changes in Central Europe during the deglaciation and compare them with the ice-core oxygen isotope record from Greenland.

2. Materials and Methods

[5] Lake Lucerne is a perialpine lake of glacial origin (434 m above sea level) located in Central Switzerland (47°01′N, 8°24′E) with a total surface area of 116 km^2. It consists of seven sub-basins, separated by subaqueous sills. Five of these basins form a chain from the main inflow to the outflow: Lake Uri, Treib Basin, Gersau Basin, Vitznau

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All Supporting Information may be found in the online version of this article.

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Basin, and Chrüztrichter Basin (Figure 1). The basins of Lake Lucerne are fed by four major Alpine rivers (Reuss, Muota, Engelberger Aa, and Sarner Aa) that drain a large part of the catchment (2124 km^2) and provide ~80% of the lake's total water supply (109 m^3/s). All but one basin are characterized by elongated shapes, relatively steep slopes, and flat intermediate basin plains.

[6] A series of long piston cores located along seismic profiles has been previously retrieved from Lake Lucerne [*Schnellmann et al*., 2002], allowing to select a site with a continuous sedimentary record. Sediment core 4WS00-4P (825 cm length) was collected at a water depth of 95 m using a Kullenberg-type gravity piston corer from the sill separating the Chrüztrichter from the Vitznau Basin (Figure 1), the two last basins in the chain and most distant to the major river inflows. The core was split in 1 m long sections and measured regarding the petrophysical properties of the sediments, photographed, and described macroscopically. The basal part of the studied section (625–825 cm) consists of very thinly laminated, light-gray to yellowish mud, changing gradually into laminated, medium to light-gray mud with low organic carbon content. The lowermost section (625–825 cm) of core 4WS00-4P was subsampled in contiguous 1 cm thick slices, generating 200 individual samples for GDGT analysis.

[7] Freeze-dried and ground samples (3–9 g) were extracted using an Accelerated Solvent Extractor 200 (ASE 200, DIONEX) with a mixture of dichloromethane (DCM) and methanol (MeOH) (9:1, vol/vol) at 100°C and 7.6×10^6 Pa. The total extract was concentrated using rotary vacuum evaporation. The extract was subsequently dried under a gentle flow of nitrogen. The dried extract was redissolved in a mixture of hexane/DCM 9:1 (vol/vol) and applied over a column filled with activated alumina, where the apolar and polar compounds were sequentially eluted with hexane/DCM 9:1 (vol/vol) and DCM/MeOH 1:1 (vol/vol). The polar fraction was dried under a N_2 flow, ultrasonically dissolved in a hexane/2-propanol 99:1 (vol/vol) mixture at a concentration of 2 mg/mL and filtered through a 0.45 μm polytetrafluoroethylene filter (ø 4 mm) prior to analysis.

[8] GDGTs were analyzed with an HP 1100 series liquid chromatography–mass spectrometer (LC-MS) equipped with an autoinjector and ChemStation chromatography manager software. Separation was achieved on an Alltech Prevail Cyano column (2.1 × 150 mm; 3 μm) maintained at 30°C. For the first 5 min, elution was isocratic with 90% A (hexane) and 10% B (hexane/isopropanol 9:1 vol/vol), followed by a linear gradient to 16% B for 34 min. The injection volume of the sample was 10 μL. To detect the different GDGTs, single ion monitoring of $[\text{M}+\text{H}]^+$ was used. TEX_{86} and isoprenoid tetraether (BIT) indices were calculated according to the following equations:

$$\text{TEX}_{86} = \frac{\text{GDGT II} + \text{GDGT III} + \text{GDGT IV'}}{\text{GDGT } I + \text{GDGT II} + \text{GDGT III} + \text{GDGT IV'}} \quad (1)$$

$$\text{BIT} = \frac{\text{GDGT } V + \text{GDGT VI} + \text{GDGT VII}}{\text{GDGT IV} + \text{GDGT } V + \text{GDGT VI} + \text{GDGT VII}} \quad (2)$$

where I–VII refer to the different GDGTs [*Blaga et al*., 2009]. The lake calibration established by *Powers et al*. [2010] was used to convert TEX_{86} values into absolute temperatures:

$$T = 55.2 * \text{TEX}_{86} - 14.0 \quad (3)$$

3. Results and Discussion

3.1. TEX_{86} and BIT Records and Their Correlation to the NGRIP δ^{18}O Record

[9] We studied the distribution of isoprenoid and branched GDGTs in 200 contiguous sediment horizons encompassing the glacial-interglacial transition as well as the Late Glacial Interstadial in a core from Lake Lucerne (Figure 1). The input of archaeal GDGTs from soil may affect the TEX_{86} palaeothermometry, and this may be assessed by using the Branched and Isoprenoid Tetraether (BIT) index [*Blaga et al*., 2009]. The BIT index reflects the relative input of aquatically produced versus soil-derived GDGTs and may indicate the input of soil-derived organic matter into the lake [*Verschuren et al*., 2009]. BIT data from various sites in

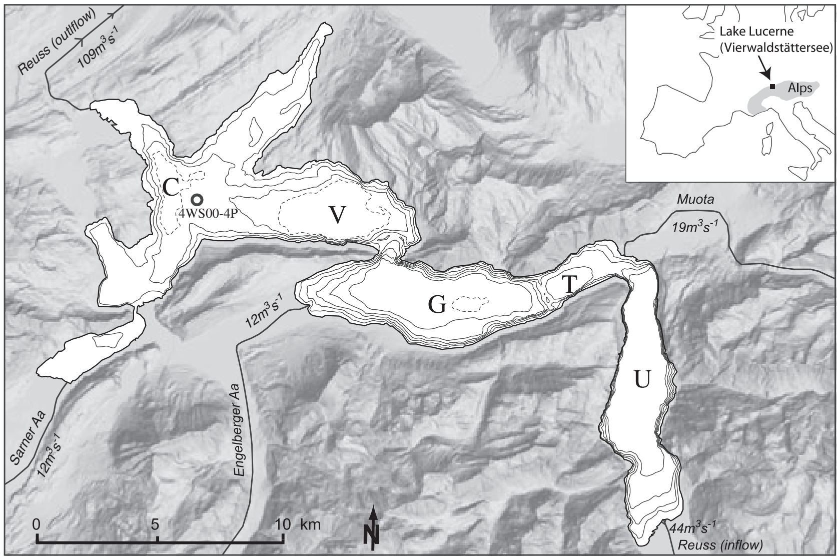

Figure 1. Map of Lake Lucerne with the location of the coring site. Capital letters indicate names of sub-basins: C = Chrüztrichter, V = Vitznau, G = Gersau, T = Treib, and U = Uri Basins.

Lake Lucerne showed that the input of soil organic matter is limited at the coring site [*Blaga et al.*, 2009], which was one of the reasons to select this core for study.

[10] The high-resolution TEX_{86} record shows TEX_{86} values between 0.33 and 0.42 (Figure 2c). At the base of the record, TEX_{86} is low (0.33), rapidly increasing to values of 0.37 and higher. The subsequent plateau of relatively high TEX_{86} values shows several distinct low-amplitude fluctuations and is followed by a decrease in TEX_{86} to the lowest values (0.34–0.35) within ~20 cm. TEX_{86} remains low over the following ~50 cm with no systematic trend. The subsequent sharp increase in TEX_{86}, reaching values as high as 0.42, occurs within 20 cm.

[11] Comparison of our TEX_{86} record with the North Greenland Ice Core Project (NGRIP) oxygen isotope record [*North Greenland Ice Core Project Members*, 2004] (Figure 2b; see also supplemental information) reveals a close resemblance, which suggests that the major climate oscillations recorded in the Greenland ice core are also reflected in the TEX_{86} record from Central Europe. Comparing smaller-scale features of the two records critically depends on the age models used. According to the four dated horizons of core 4WS00-4P (Figure 2), the section studied (624–824 cm) encompasses the time from ~14,500 to ~10,500 cal. yr B.P.; that is, the studied sediments cover the transition from late Glacial conditions (Oldest Dryas) to the Late Glacial Interstadial (i.e., Bølling/Allerød), the YD cold phase, and the early Holocene (Preboreal). In more detail, a comparison of the records shows that the NGRIP and other regional $\delta^{18}O$ records [see *Lotter et al.*, 1992; *von Grafenstein et al.*, 1999; *Schwander et al.*, 2000; *Genty et al.*, 2006] (e.g., Figure 2a] and our TEX_{86} record show also a good correspondence on a shorter time scale (cf. Figures 2a–c). The short-term interstadial fluctuations (such as the Aegelsee and Gerzensee oscillations; see *Lotter et al.* [1992] and *van Raden et al.* [2013] for a discussion of classical terminology

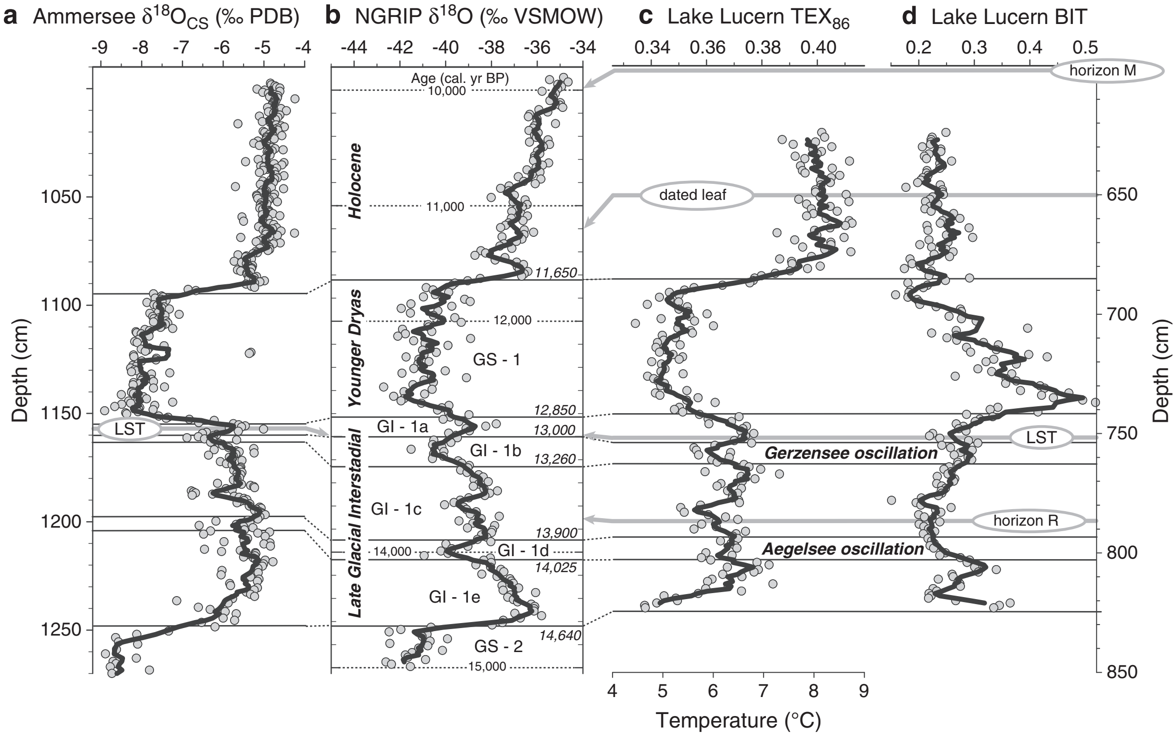

Figure 2. Comparison of the high-resolution TEX_{86} and BIT records (c and d) from sediments of Lake Lucerne (plotted against depth) with the $\delta^{18}O$ record of the NGRIP ice core [*Rasmussen et al.*, 2006] plotted versus age (cal. yr B.P.) (b) and the record of $\delta^{18}O$ of ostracods shells ($\delta^{18}O_{CS}$) from the Ammersee (southern Germany) [*von Grafenstein et al.*, 1999] plotted versus depth (a) across the Late Glacial Interstadial, YD and onset of the Holocene. TEX_{86} values were converted into temperature (lower scale) using the lake calibration of *Powers et al.* [2010]. The thick black lines in the records represent the 5-point (and 9-point for the Ammersee record) moving average, which typically gives the average of approximately 100 years for both records. Horizontal black lines in Figure 2b depict the boundaries between the various isotope stages [*Rasmussen et al.*, 2006], and these boundaries were visually correlated to the Ammersee $\delta^{18}O_{CS}$ record [*von Grafenstein et al.*, 1999] and the Lake Lucern TEX_{86} temperature and BIT records. Note that the boundary between GS-2 and GI-1e for the Lake Lucern data is uncertain because TEX_{86} values still decline at the base of the core. Four horizons in the Lake Lucern core provided independent confirmation of these correlations. Marker horizons M and R are basin-wide recognized well-dated events occurring at 596 and 787 cm, and dated at 9965 and 13,720 cal yr B.P., respectively [see *Schnellmann et al.*, 2006]. The Laacher See Tephra (LST) was identified in the magnetic susceptibility record at 752 cm [*Schnellmann et al.*, 2006] dated to 12,972 cal. Yr B.P. measured on different wood remains by *Friedrich et al.* [1999] and corresponding well with the reported varve date of the LST of 12,880 cal. yr B.P. by *Brauer et al.* [2000]. A radiocarbon date of a fossil leaf of 11,205 (10,764–11,546) cal. Yr B.P. at 650 cm depth [*Schnellmann et al.*, 2006] provides a fourth chronological tie point. The LST has also been recognized in the Ammersee core.

of events used in the study of Swiss lakes) match with the corresponding Greenland $\delta^{18}O$ fluctuations (i.e., GI-1d and GI-1b, respectively). Given the uncertainties of the estimated ages of the marker horizons in our core (see supplementary information) and counting errors of the NGRIP core (resulting in a 100 year uncertainty at the onset of the Holocene; ~190 years at the onset of Interstadial) [*Rasmussen et al.*, 2006], the variations revealed in the TEX_{86} and NGRIP $\delta^{18}O$ records are considered to show synchronous climatic fluctuations.

[12] The BIT values for the studied section vary between 0.15 and 0.55 (Figure 2d). The base of the studied interval shows relatively high BIT values around 0.35, followed by a decrease to values around 0.2. At 815 cm (~14,200 cal. yr B.P.); BIT values increase during a short peak, with values reaching 0.35. A longer plateau, with average BIT values around 0.25 follows, which sharply ends at 750 cm (~13,000 cal yr B.P.). Highest BIT indices (0.55) are observed shortly after the onset of the YD, when the saw-tooth pattern in the BIT index shows a rapid increase in abundances of branched GDGTs relative to crenarchaeol (Figure 2d). The onset of the YD is also characterized by high absolute concentrations of branched GDGTs (unpublished data), indicating that the enhanced influx of branched GDGTs from soils caused the higher BIT values. This suggests that soils, which developed during the Late Glacial Interstadial, eroded as a consequence of the climate-induced opening of the forest cover [*Ammann et al.*, 2000] during the YD cold phase. BIT values subsequently decrease toward the Holocene, indicating a gradual reduction in delivery of branched GDGTs. This reduction during the second half of the YD can be explained by either exhaustion of the topsoil layers or an overall dryer local climate during the second part of the YD [*Lotter et al.*, 1992]. The YD/Holocene transition and the early Holocene are marked by continuing low BIT values (Figure 2), probably as a consequence of increased Holocene vegetation cover [*Lotter*, 1999]. The BIT record clearly reflects changes in landscape openness and soil erosion in the hydrological catchment.

[13] Although BIT values are relatively high for application of the TEX_{86} palaeothermometer [*Blaga et al.*, 2009] at the onset of the YD, the more or less constant TEX_{86} values but rapidly declining BIT values during the YD (Figure 2) clearly show that the delivery of soil-derived isoprenoid GDGTs did not influence TEX_{86} during this interval, indicating no impact on TEX_{86} palaeothermometry.

3.2. TEX_{86} Palaeothermometry and Climatic Implications

[14] In order to reconstruct absolute temperature changes based on the TEX_{86} temperature proxy, first a temperature calibration has to be applied to the Lake Lucerne record. In recent years the application of GDGTs as temperature indicators for marine and freshwater environments has led to different TEX_{86}-to-temperature calibrations [*Schouten et al.*, 2002; *Powers et al.*, 2010; *Kim et al.*, 2010]. Application of these different calibrations results in different reconstructed absolute temperatures; however, the amplitude of the reconstructed temperature offsets between Oldest Dryas, Interstadial, YD, and Holocene temperatures is insensitive to the calibration used. All calibrations consistently indicate a maximum offset of about 4°C between YD and Holocene, the most pronounced event in the TEX_{86} record.

[15] Our recent process study of the present-day Lake Lucerne indicated that the dominant production of isoprenoid GDGTs occurs at the base of the thermocline, resulting in relatively low TEX_{86} values of around 0.30 [*Blaga et al.*, 2011], which are lower than the values reported here. However, the GDGT composition of surface sediments (top 100 cm) revealed that the recent eutrophication of the lake seemed to have had a significant effect on the niche of the Thaumarchaeota since TEX_{86} values in sediments deposited before ~1970 are approximately 0.35, higher than in the surface sediments, while temperatures of the lake in the last century have not substantially changed. Clearly, there remain some questions about the influences of seasonality and water depth on TEX_{86} reflects exactly in this system, but the relatively low TEX_{86} values indicate that it does not reflect summer surface (0–20 m) water temperatures. It rather mainly records temperatures of deeper water masses that are much more constant over the annual cycle [*Blaga et al.*, 2011] and therefore likely reflect mean annual temperatures.

[16] TEX_{86}-inferred temperatures rapidly increase at the base of the Lake Lucerne record. (Figure 2). This warming likely corresponds to the major shift in the NGRIP and Ammersee $\delta^{18}O$ record at ~14,600 cal. yr B.P. at the transition from GS-2 to GI-1e (cf. Figures 2b, c), although it is not clear if our core has penetrated into GS-2. Therefore, it remains unclear whether the observed warming (~2.5°C) of the temperature of Lake Lucerne reflects the maximum warming during this transition. The warming at the onset of the Interstadial on the Swiss Plateau is reflected in an increase in $\delta^{18}O$ values measured in many carbonate-rich lake sediments (e.g., see Figure 2a for the Ammersee record) that coincide with the onset of reforestation with juniper and birch [*Lotter et al.*, 1992; 2012].

[17] The section corresponding to the Late Glacial interstadial has relatively constant high TEX_{86}-inferred water temperatures of ~6.5°C but reveals three relatively short periods of cooling (Figure 2c) that show a strong similarity with the NGRIP $\delta^{18}O$ record (i.e., GI-1b, 1d, and the cooling event within GI-1c). Around 14,000 cal. yr B.P. (Aegelsee oscillation) [*Lotter et al.*, 2000], lower TEX_{86} temperatures correspond to low $\delta^{18}O$ values (GI-1d) from 14,025 to 13,900 cal. yr B.P. in the NGRIP record. This oscillation is known to have had a short duration (~100 years) and occurred during times characterized by a highly unstable environment. Despite its short duration, it is reflected in the TEX_{86} data, pointing to a high sensitivity of Lake Lucerne to short-lived climate fluctuations. The two other short cooling events [GI-1b (Gerzenzee oscillation) and the cooling event within GI-1c] are observed as water temperature decreases of about 1°C in the Lake Lucerne TEX_{86} record (Figure 2c) and are actually more pronounced than the Aegelsee oscillation. Comparison of the three temperature records (Figures 2a–c) reveals that these short-lived cooling events are more clearly revealed in the TEX_{86} record than in the $\delta^{18}O$ record from the nearby Ammersee. A high-resolution record of Gerzensee sediments from 15,500 to 13,000 cal yr. B.P. showed that these short-lived cooling events were not evident in chironomid-inferred July air temperatures, whereas pollen-inferred July temperatures did reveal the Aegelsee and Gerzensee oscillation, and perhaps also the cooling event during GI-1c (*Lotter et al.*, 2012).

[18] The transition to the YD is characterized by a TEX_{86}-inferred water temperature drop from 7°C during the late Interstadial to 5°C during the YD. When comparing this cooling to the one evident from the NGRIP and Ammersee

δ^{18}O records, it seems to last longer (cf. Figures 2a–c), although this may be caused by temporarily increased accumulation rates related to the increased soil erosion during the early YD as inferred from the BIT record (Figure 2d). The TEX_{86} temperatures remain stable between 4.5°C and 5.5°C throughout the YD. At the onset of the Holocene, a sharp increase in TEX_{86}-inferred water temperature from an average of 5°C to as high as 9°C over a transitional phase of ~350 years is observed. Again, this temperature shift seems slower than that observed for the NGRIP and Ammersee δ^{18}O records. The TEX_{86}-inferred temperature change indicates a shift that is similar to the one estimated from the δ^{18}O record of Lake Neuchatel [*Schwalb*, 2003] (3°C–4.5°C between the YD and the Holocene). Other nearby small lakes indicated a temperature increase of 4°C –7°C [*Eicher and Siegenthaler*, 1976; *Eicher et al*., 1981] at the onset of the Holocene. The early Holocene is characterized by relatively constant TEX_{86}-inferred water temperatures in the range of ~7.6°C –8.7°C. Shifts of ~1°C have been inferred based on δ^{18}O records from several perialpine lakes during the Holocene [*Schwalb et al*., 1994; *Von Grafenstein et al*., 1999] and are in good agreement with the observed variation in the Holocene TEX_{86}-inferred temperature record.

[19] Climate proxy records available from both marine and terrestrial archives have improved our understanding of centennial- and millennial-scale variability of past climate. Most terrestrial proxies mainly reflect summer temperature changes. The application of thaumarchaeotal GDGTs as palaeoproxies in lake sediments is a relatively new approach. The Lake Lucerne record reflects high-resolution and rapid temperature shifts that compare in an excellent way with other proxy records and therefore confirm that the TEX_{86} proxy can be used as a continental palaeothermometer, recording the temperature of deeper water masses of the lake. Despite the relatively slow response of deeper water masses on changes in air temperature, the Lake Lucerne TEX_{86} record shows rapid and abrupt shifts that most likely reflect climate changes in Central Europe. These changes are in phase with those recorded in the Greenland ice core record, providing evidence that short-lived weakening of the thermohaline circulation in the North Atlantic affected both climate in Greenland and Central Europe [*von Grafenstein et al*., 1999]. Our TEX_{86} record confirms the difference observed between δ^{18}O records from Central Europe and Greenland, that is, relatively stable versus declining δ^{18}O records during the Late Glacial Interstadial, suggesting progressively decreasing temperatures in Greenland versus constant temperatures in Central Europe. An intriguing difference between the local δ^{18}O records and the TEX_{86} record is, however, that the δ^{18}O at the end of termination 1a is almost as high as at the start of the Holocene (Figures 2a, b), whereas TEX_{86}-inferred are ~2°C lower than at the start of the Holocene. This might be caused by the added effect of the release of light oxygen isotopes from the decaying ice caps, whereas the TEX_{86} record is exclusively recording temperature.

4. Conclusion

[20] In this study we present a high-resolution record of temperature of Lake Lucerne covering the Late Glacial up to the Early Holocene. The comparison between the ice-core and the GDGT-based temperature record shows that there is a strong correlation between inferred temperature changes on Greenland and in the Alps. It is also clear that the TEX_{86} proxy is capable to reflect high-resolution and rapid (decadal- to century-scale oscillations) environmental fluctuations, and thus can be used to generate records comparable with those obtained from ice cores.

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