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Modest diatom responses to regional warming on the southeast Tibetan Plateau during the last two centuries

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Abstract A general mean annual temperature increase accompanied with substantial glacial retreat has been noted on the Tibetan Plateau during the last two centuries but most significantly since the mid 1950s. These climate trends are particularly apparent on the southeastern Tibetan Plateau. However, the Tibetan Plateau (due to its heterogeneous mountain landscape) has very complex and spatially differing temperature and precipitations patterns. As a result, intensive palaeolimnological investigations are necessary to decipher these climatic patterns and to understand ecological responses to recent environmental change. Here we present palaeolimnological results from a $^{210}Pb/^{137}Cs$-dated sediment core spanning approximately the last 200 years from a remote high-mountain lake (LC6 Lake, working name) on the southeastern Tibetan Plateau. Sediment profiles of diatoms, organic variables (TOC, C:N) and grain size were investigated. The ^{210}Pb record suggests a period of rapid sedimentation, which might be linked to major tectonic events in the region ca. 1950. Furthermore, unusually high ^{210}Pb supply rates over the last 50 years suggest that the lake has possibly been subjected to increasing precipitation rates, sediment focussing and/or increased spring thaw. The majority of diatom taxa encountered in the core are typical of slightly acidic to circumneutral, oligotrophic, electrolyte-poor lakes. Diatom species assemblages were rich, and dominated by *Cyclotella* sp., *Achnanthes* sp., *Aulacoseira* sp. and fragilarioid taxa. Diatom compositional change was minimal over the 200-year period (DCCA = 0.85 SD, $p = 0.59$); only a slightly more diverse but unstable diatom assemblage was recorded during the past 50 years. The results indicate that large-scale environmental changes recorded in the twentieth century (i.e. increased precipitation and temperatures) are likely having an affect on the LC6 Lake, but so far these impacts are more apparent on the lake geochemistry than on the diatom flora. Local and/or regional peculiarities, such as increasing precipitation and cloud cover, or localized climatic phenomena, such

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as negative climate feedbacks, might have offset the effects of increasing mean surface temperatures.

Keywords Diatoms · Tibetan Plateau · Mountain lake · Climate change · Lake sediments · Palaeolimnology

Introduction

The Tibetan Plateau region is generally considered to be highly sensitive to climate change associated with global warming. The majority of meteorological stations across the Tibetan Plateau indicate a recent significant rise in both mean annual and mean winter surface temperatures (Liu and Chen 2000), resulting in permafrost degradation (Wu and Zhang 2008), and the acceleration of melting glaciers (Su and Shi 2002). However, the Tibetan Plateau is known for its highly complex temperature and moisture patterns in relation to its heterogeneous mountain landscape (An et al. 2000; Niu et al. 2004; You et al. 2010). In the densely populated monsoon region of south Asia, understanding temperature and moisture patterns in the past is crucial to help better estimate impacts of future climate variability. Several palaeoclimate studies have therefore been undertaken across the Tibetan Plateau, focussing on the Holocene time period (Herzschuh et al. 2009; Kramer et al. 2010). However, few studies have investigated environmental changes on the Tibetan Plateau during the last two centuries – a time period also strongly affected by increasing urbanisation and agricultural activity.

Ice core records from all regions of the Tibetan Plateau (Dasuopu, East Rongbuk, Puruogangri, Guliya, and Dunde ice core) point to a general warming trend over the past 200 years (Thompson et al. 1989, 2000, 2006; Yang et al. 2006; Hou et al. 2007). However, focussing on individual regions of the plateau, differences in temperature and precipitation trends become apparent. On the southeastern Tibetan Plateau (i.e. provinces of western Sinchuan, northwestern Yunnan and the easternmost part of the Tibet autonomous region), where conditions are semi-humid, a few tree ring studies exist, providing partly contradictory information on climate trends of the recent past for this region (Bräuning and Mantwill 2004; Liang et al. 2009; Fan et al. 2010). Bräuning and Mantwill (2004) reconstructed a general increase in Indian summer monsoon activity after 1980 AD in their study area, although regional differences were noted in terms of temperature trends according to their tree ring width chronology. For example, some regions of terrestrial growth on the southeastern Tibetan Plateau were indicative of warmer temperatures whereas other regions suggested cooler temperatures from 1970–1990 AD. Liang et al. (2009) found that the last decade (1996–2006) represents the warmest period since 1765 AD, indicated by their tree ring width chronologies. In arid southern Tibet, ostracode and isotope studies suggest that a dry and cold climate prevailed between ca. 1600–1800 AD. After ca. 1800 AD the climate became more variable. Lake levels rose until ca. 1920 AD, declined thereafter, and rose again from ca. 1970 AD until present (Wrozyna et al. 2010). In contrast, on the northwestern Tibetan Plateau, relatively dry conditions prevailed between ca. 1700–1900 AD, followed by a wet phase from ca. 1900–1960 AD, and a return to dryer conditions since 1960 AD (Henderson et al. 2003). Lami et al. (2010) analysed the geochemistry and algal pigments of different lakes across the Tibetan Plateau to assess the variability of trophic conditions over the last approximately 100 years. They found that six out of eight lakes show a marked increase in lake productivity within the last 100 years, which they attribute to climatic warming and land-use changes. In summary, information on relations between climate patters during the last two centuries and aquatic ecosystem responses is sparse and partly variable for the Tibetan Plateau.

Diatoms have shown to be useful indirect indicators for past environmental conditions by responding to limnological (biotic and abiotic) changes triggered by a changing climate (Douglas and Smol 2001; Lotter et al. 2001). Numerous diatom-based palaeolimnological studies, with a focus on the last 100–200 years, have shown that alpine and arctic lakes are highly sensitive to changes in air temperature and precipitation. These studies are increasingly used to detect recent environmental change often associated with global warming (Lotter et al. 2002; Sorvari et al. 2002; Jones and Birks 2004; Solovieva et al. 2005; Rühland et al. 2008).

Here we present results from a $^{210}Pb/^{137}Cs$ dated sediment core from a remote high-mountain lake (LC6 Lake) on the southeastern Tibetan Plateau spanning the last ~200 years. Sediment profiles of diatoms, organic variables (TOC, C:N) and grain size were investigated. The aim of the paper is to examine the diatom response over a period of environmental change associated with generally significant temperature and precipitation increases and glacial retreat. As such, the paper presents one of the very few diatom records in the region and provides insights into the complexity of environmental change on the Tibetan Plateau.

Study site

The mountain lake (not named, working name LC6 Lake) is located in the Nyaintêntanglha Mountain range, on the southeastern Tibetan Plateau (Fig. 1). This mountain range is part of a large granite batholith in the interior of the plateau (Liu et al. 2004). The region is affected by two major circulation systems. The mid-altitude westerly circulation brings limited moisture to the region from November to March, while the South Asian Monsoon circulation is responsible for the majority of precipitation from May to September. This interplay results in abundant rainfall and high temperatures in summer, which is in contrast to the prevailing cool and relatively dry winters. The LC6 Lake lies at 4,230 m above sea level (a.s.l.). The closest weather station is in Nyingchi at 3,000 m a.s.l., 26 km to the south of the lake, which records mean T_{July} 15.6°C, mean T_{Jan} 0.2°C, and mean P_{ann} 657 mm (85% of P_{ann} falling between May and September). Based on a lapse rate of −0.5°C/100 m (Böhner 2006), we estimate mean T_{July} ∼9.6°C and mean T_{Jan} ∼−5.5°C in the LC6 Lake region.

Following calculations derived from Böhner (2006), annual precipitation is estimated to be about 1,450 mm, and evaporation rates around 800 mm at the lake site. According to the mean monthly temperature profile and monthly satellite images from the Landsat archive (USGS earth explorer 2010) we estimate an ice-cover duration on the lake of ∼4 months (December–March).

General information about the lake and its catchment are summarised in Table 1. The LC6 Lake has a small lake area of 0.6 km^2 and is mainly fed by runoff from surrounding moderately steep-sloping mountains that generally peak around 4,700 m a.s.l. The lake has one outflow, which cascades into a lake on a lower level to the southwest. With a maximum depth of 23 m, an approximate ice-cover duration of 4 months, and a summer surface water temperature of 10.3°C (measured on 21.08.2005) the lake is likely to mix at least once a year (spring/summer) after winter stratification. The vegetation in the catchment is characterised by dense *Rhododendron* shrubs and coniferous forests (*Picea likiangensis* var. *balfouriana* (Rehder and Wilson) Hillier, *Abies georgei* var. *smithii* [(Viguié and Gaussen) Cheng, Cheng and Fu], and patches of *Kobresia pygmaea* (Clarke) Clarke meadow. Lichens are also typical epiphytes on surrounding shrubs and

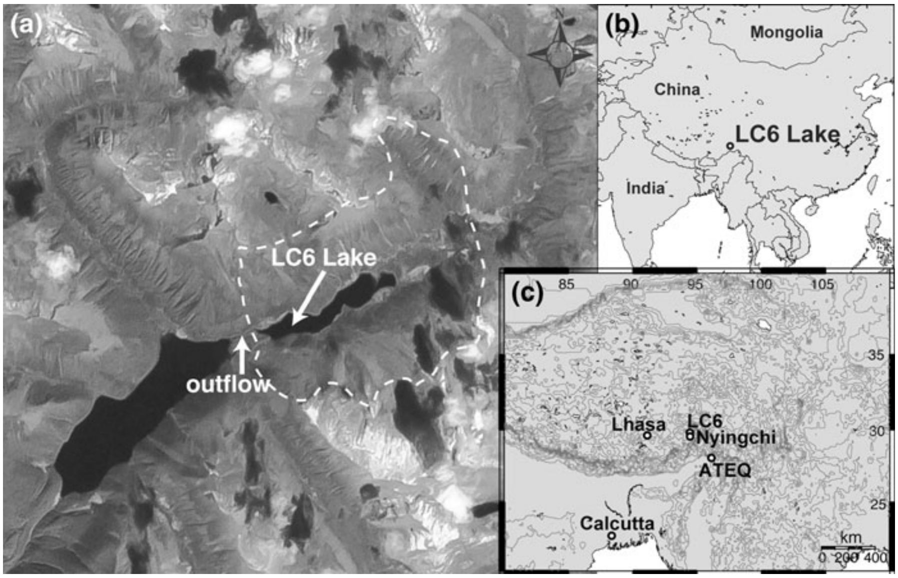

Fig. 1 **a** Core position, outflow and catchment area (*dashed line*) of LC6 Lake, **b** study site location; **c** topography and location of LC6 Lake and other locations mentioned in the text. Figures adopted from Landsat and The Map Creation Tool. ATEQ (Assam-Tibet earthquake August 1950)

Table 1 Selected physical and chemical characteristics of LC6 lake

LC6 lake	
Latitude	29.82515
Longitude	94.45615
Elevation	4,132 m a.s.l.
Genesis	Glacial lake
Lake area	2,000 × 300 m, ~0.6 km^2
Catchment area	~13.5 km^2
Max. water depth	23 m
Secchi depth	6.9 m
Conductivity	0.013 mS/cm
pH	7.0
Alkalinity	0.4 mmol/l
Inflow	Mountain runoff
Outflow	One cascading outlet into lake at lower level

trees. No signs of immediate, catchment-scale human impact was observed during fieldwork, suggesting that LC6 Lake is particularly suitable to highlight possible effects of climate change.

Materials and methods

Field sampling, sediment dating, physical and chemical data

In summer 2005, a 45-cm sediment core was taken at the deepest part (23 m) of LC6 Lake using a Glew gravity corer. The core was sectioned on site at 0.5-cm intervals directly after coring. For dating, sediment subsamples were analysed for ^{210}Pb, ^{226}Ra, and ^{137}Cs by direct gamma assay in the Liverpool University Environmental Radioactivity Laboratory. Radiometric dates were calculated using both the constant rate of supply (CRS) and constant initial concentration (CIC) ^{210}Pb dating models (Appleby and Oldfield 1978). Discrepancies between the ^{210}Pb models were resolved using the methods described in Appleby (2001). The 1963 depth was determined from the ^{137}Cs stratigraphic record. Dates of points below the base of the unsupported ^{210}Pb record were estimated by extrapolation of the ^{210}Pb depth/age curve using a best estimate of the sedimentation rate for this part of the core.

Total carbon, total nitrogen and total organic carbon (TOC) content of 47 sediment subsamples, with a constant spacing of 0.5 cm, were measured with a vario EL III elemental analyser. TOC was used as a variable for describing the abundance of organic matter in the sediments and C:N ratio was calculated to examine the relative importance of autochthonous and allochthonous sources of organic material within the sediment core. Grain size analysis was performed with a Beckmann Coulter LS 200 laser particle analyser on 47 organic and carbonate-free subsamples at 0.5-cm spacing. Grain size parameters calculated according to Tucker (1988)) were analysed to gain information on the sediment source and to provide support in understanding the age-depth model (using peaks in the sand fraction as an indication of a stronger or sudden in-wash from the catchment or lake basin).

Diatom analysis

Diatom sample preparation followed standard procedures using the water bath technique (Renberg 1990; Battarbee et al. 2001). Slides were mounted using the mounting medium Naphrax®. Diatom concentrations were estimated using DVB microspheres (Battarbee and Kneen 1982). Between 400 and 500 diatom valves were counted in each sample at 1,000× magnification. Taxonomic identifications primarily followed Krammer and Lange-Bertalot (1986–1991), Lange-Bertalot and Metzeltin (1996), Camburn and Charles (2000), and Zhu and Chen (2000). A full list of taxonomic names, corresponding authority and the synonyms of previously accepted names are provided as supplementary data (Table ESM1). In our stratigraphy we chose to merge *Aulacoseira distans* (Ehrenb.) Simonsen with its varieties *A. distans* var. *nivalis* (Smith) Haworth and *A. distans* var. *nivaloides* Camburn as they were difficult to distinguish even under high magnification and showed similar trends. Small benthic fragilarioid taxa (*Fragilaria spinarum* L-B and Metzeltin, *Staurosira construens* var. *venter* (Grun.) Williams and Round, *Staurosira construens* var. *binodis* (Ehrenb.) Hamilton, *Staurosira pinnata* (Ehrenb.) Williams and Round, *Pseudostaurosira pseudoconstruens* (Marciniak) Williams and Round) also were amalgamated as they have similar ecological preferences (Lotter and Bigler 2000) and showed similar trends. Diatoms are expressed as percent relative abundance of the total number of valves counted in each sample.

Numerical methods

Diatom-based biostratigraphic zones were identified by cluster analysis using constrained incremental sum of squares (CONISS) and the Edwards and Cavalli-Sforza's chord distance as the dissimilarity coefficient. Multivariate ordination techniques were undertaken on diatom species that were present with an abundance of 1% or greater in at least one sample. The main gradients of floristic variation in the diatom data were initially assessed using detrended correspondence analysis (DCA). As the gradient length of the first axis was only 1.08 standard deviation (SD) units, the linear ordination model of principal components analysis (PCA) was chosen for subsequent analysis (Lepš and Šmilauer 2003). PCA was performed on a correlation matrix, and species were centered and square-root transformed to stabilise their variance. Samples from the slump deposit between 27 and 8 cm core depth are available as supplementary data only. Detrended canonical correspondence analysis (DCCA) was used to estimate the overall species turnover measured in SD units, which provides an estimate of compositional change along an environmental or temporal gradient (Ter Braak and Verdonschot 1995). To estimate the amount of compositional change in our record in the last ~200 years, ^{210}Pb derived samples ages were used as the only constraining variable in DCCA. The decision whether the compositional turnover in our record is ecologically significant is based on the same protocols used by Smol et al. (2005). They used identical protocols to compare beta-diversity (compositional species turnover) in their Arctic sites to the beta-diversity in a set of reference sites (records from non-arctic, relatively unimpacted lakes) and established that changes greater than 1 SD unit were deemed ecologically substantial. In DCCA, species data were square-root transformed, no rare species down-weighting was applied, and non-linear rescaling and detrending by segments was used. All ordinations were performed using the program CANOCO 4.5 for Windows (Ter Braak and Šmilauer 2002).

Diatom diversity was calculated for each sample using the Hill N_2 statistic (or inverse Simpson index), which is an estimate of the effective number of taxa in each sample. Species richness was estimated using rarefaction analysis, a method to standardise and compare species richness from samples of different size (Heck et al. 1975). However, changes in diatom diversity and species richness have to be viewed with caution, as variations in sedimentation rates and sediment compaction towards the base of the core, may falsify their interpretation (Smol 1981). Calculations for diatom diversity and species richness were carried out in R (R Development Core Team 2008) using the vegan package (Oksanen et al. 2008).

Results

Dating

Detailed illustration of fallout radionuclides is shown in Fig. 2, and the results of radiometric dating are summarised in Fig. 3a. Although high ^{210}Pb concentrations in the near-surface layers suggest an intrinsically low sedimentation rate, the ^{210}Pb record is

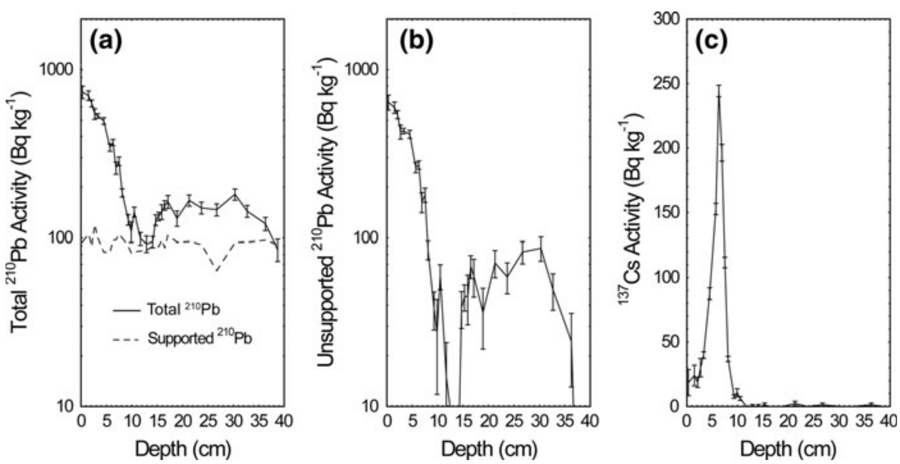

Fig. 2 Fallout radionuclides showing **a** total and supported ^{210}Pb, **b** unsupported ^{210}Pb, and **c** ^{137}Cs concentrations versus depth

rather unusual in that the total ^{210}Pb activity exceeds the supporting ^{226}Ra down to a depth of 38 cm. Three distinct zones can be identified. Unsupported concentrations decline steeply with depth in the top 10 cm, reaching very low levels between 11.4 and 14.4 cm. Below this there is a zone of higher and relatively uniform concentrations, extending down to a depth of 30 cm. Below 30 cm, unsupported concentrations decline at a rate comparable to that in the upper section of the core, falling below the limit of detection at around 38 cm (Fig. 2a, b). In contrast, the ^{137}Cs record is very conventional (Fig. 2c). Concentrations of this artificial radionuclide have a well-defined peak in the 6.0–6.6-cm section that almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons. ^{210}Pb dates calculated using the CRS dating model alone suggest that the very low ^{210}Pb concentrations between 11.4 and 14.4 cm record an episode of extremely rapid sedimentation (Fig. 3a). There was, however, a significant discrepancy between the ^{210}Pb dates and the very well-defined 1963 ^{137}Cs date, most probably due to the deposition of substantial amounts of additional ^{210}Pb during the course of this extreme event, possibly triggered by a landslide or within-lake sediment slump. Revised CRS model calculations for the upper part of the core using the ^{137}Cs date as a reference point (Appleby 2001) suggest that this event occurred in the late 1940s or early 1950s, and that since then sedimentation rates have been relatively uniform with a mean value of 0.15 cm year^{-1}. Even though rapid accumulation was most intense in those sediments between 11.4 and 14.4 cm, ^{210}Pb calculations suggest that the entire section of the core between 8 and 27 cm was deposited during the course of this event. Given this evidence, we have chosen to treat samples from the core section between 8 and 27 cm depth passively in subsequent statistical analyses. Calculations using the CIC model (Fig. 3a) indicate that sedimentation rates in the ^{210}Pb zone below 30 cm were similar to those in the post-1950 sediments, and hence that apart from the above episode, dry mass sedimentation rates (g cm^{-2} year^{-1}) at the core site have been relatively uniform during much of the past 100 years.

Based on these results, dates were extrapolated back to ca. 1800 AD. Because of sediment compaction, the volumetric sedimentation rate (cm year^{-1}) during the earlier period used in these calculations (0.11 cm year^{-1}) was however a little lower than for the more recent sediments.

Grain size, TOC, and C:N ratio

The grain size distribution is relatively uniform throughout the core with silt being the dominating grain size fraction (65–83%) and the sand and clay fraction both constituting ~11%. However, there are two distinct peaks in the sand fraction, accompanied by decreasing clay and silt values, at 28–23 cm and 9–8 cm core depth with the sand fraction rising to 26 and 23%, respectively (Fig. 3b). The TOC content separates the core into three sections (Fig. 3c). The

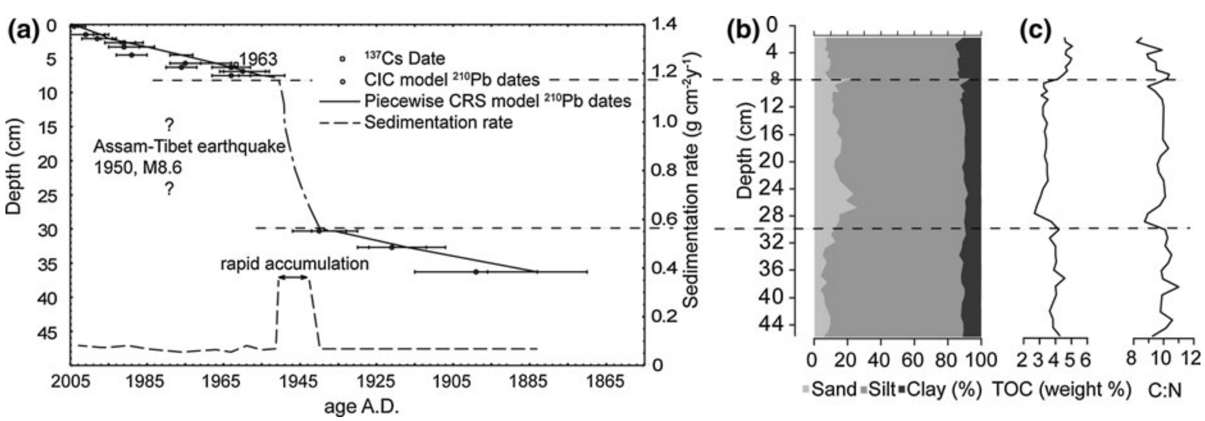

Fig. 3 **a–c** Radiometric chronology showing the 1963 depth determined from the ^{137}Cs. The piecewise CRS model ^{210}Pb dates and sedimentation rates, and the CIC model ^{210}Pb dates calculated for those sections of the core above 7.5 cm and below 30 cm thought to represent periods of uniform accumulation (**a**). Age chronology is compared with the grain size distribution (**b**) and the TOC content and C:N ratio (**c**)

bottom section of the core (45–29 cm) is marked by TOC values between 3.6 and 4.6 weight %, the middle section (29–8 cm) with lowest TOC values between 2.7 and 3.5 weight %, and the top section (8–0 cm) has highest values ranging between 4.1 and 5.1 weight %. The C:N ratio (Meyers and Lallier-Vergès 1999) was calculated with the weight % of TOC and total N and shows relative constant values around 10 from 45 to 6 cm (until 1963) of the core. Thereafter, the C:N ratio declines steadily to $\sim$8.5 at the top of the core (Fig. 3c).

Fossil diatom assemblage and numerical analysis

In the sediment core, a total of 158 species from 39 genera were identified (Table EMS1). The majority of taxa found in the core are typical of slightly acidic to circumneutral, oligotrophic, electrolyte-poor lakes and many are cosmopolitan species that are commonly found in freshwaters of nordic and alpine regions (Lotter and Bigler 2000; Sorvari et al. 2002; Rühland and Smol 2005). The most common taxa are monoraphid taxa (*Achnanthidium*, *Achnanthes* and *Psammothidium)*, *Cyclotella* and fragilarioid taxa contributing to the diatom assemblage with up to 40, 35 and 20% relative abundance, respectively. The most common species is the planktonic diatom *Cyclotella ocellata* (up to 35%). Changes in the relative abundances of all species throughout the core are minor. A subtle but consistent decline of *Cyclotella ocellata* (5–10%) is shown, accompanied by small increases in *Achnanthidium minutissimum* (Kutz.) Czarnecki, tychoplanktonic *Aulacoseira lirata* var. *lirata* (Ehrenb.) Ross and benthic *Fragilaria capucina* Desmazières and *Cymbella* sp. This trend in diatom compositional changes is related to equally subtle changes in diatom diversity (N2), which is highest in recent decades. These minor changes are driven mainly by a modest increase in *Aulacoseira* taxa concurrent with an equally modest decrease in *Cyclotella ocellata*. DCCA revealed a compositional change of 0.85 SD ($p = 0.59$). The cluster analysis CONISS calculated a total sum of squares of 1.8 and therefore no distinct first-order diatom biostratigraphic zones. The total diatom concentration in the pre- and post-slump deposit phase appears relatively stable with around 100,000 valves g^{-1} dry sediment. However, diatoms are more concentrated within the slump deposit with 250,000–550,000 valves g^{-1} dry sediment. Although minor, the diatom changes were most apparent before the 1880s and then again post 1960s. These subtle trends are summarised by PCA sample scores, which indicate that the unstable diatom assemblage after the 1960s is linked to monoraphid and *Aulacoseira* species (Fig. 5). PCA ordination results show that the main gradient is along the first component, accounting for 24% of the variation in the diatom data set and dividing the data set in taxa stronger associated with the phase of the sediment slump from taxa occurring in the post-slump phase. The second axis accounts for 10% of the variance in the data set and represents the gradient between taxa pre- and post-1950 AD. The most common diatoms and diatom functional groups are plotted stratigraphically and are compared to summaries of diatom compositional changes (PCA1 and PCA 2 samples scores), species turnover (DCCA 1), species diversity, and relative changes of planktonic, tychoplanktonic and benthic components (Fig. 4).

Discussion

Radiometric evidence for irregular sedimentation events and increasing sedimentation during recent decades

Low ^{210}Pb concentrations between 8 and 27 cm, the down-core TOC content, and grain size distribution suggest that this core section was most likely deposited during the course of one single, rapid event, possibly a landslide or, more likely, a within-lake sediment slump. The increased diatom concentration during that period suggests that a large component of the sediment slump comes from diatom-rich sediments from the slopes surrounding the core site. The relative small decline in TOC and small peak in the sand fraction further suggest that the sediment input is not solely from clastic-rich sediments. The age model suggests that this event happened between the late 1940s and early 1950s. This interpretation corresponds very well with the timing of the Assam-Tibet earthquake that was recorded in August 1950, in North India, just $\sim$280 km southeast to the site. Strasbourg calculated a magnitude of 8.6 on the Richter scale and classified the quake as one of the most important since the introduction of seismological observing stations. Ground motion could be felt from Lhasa to Calcutta

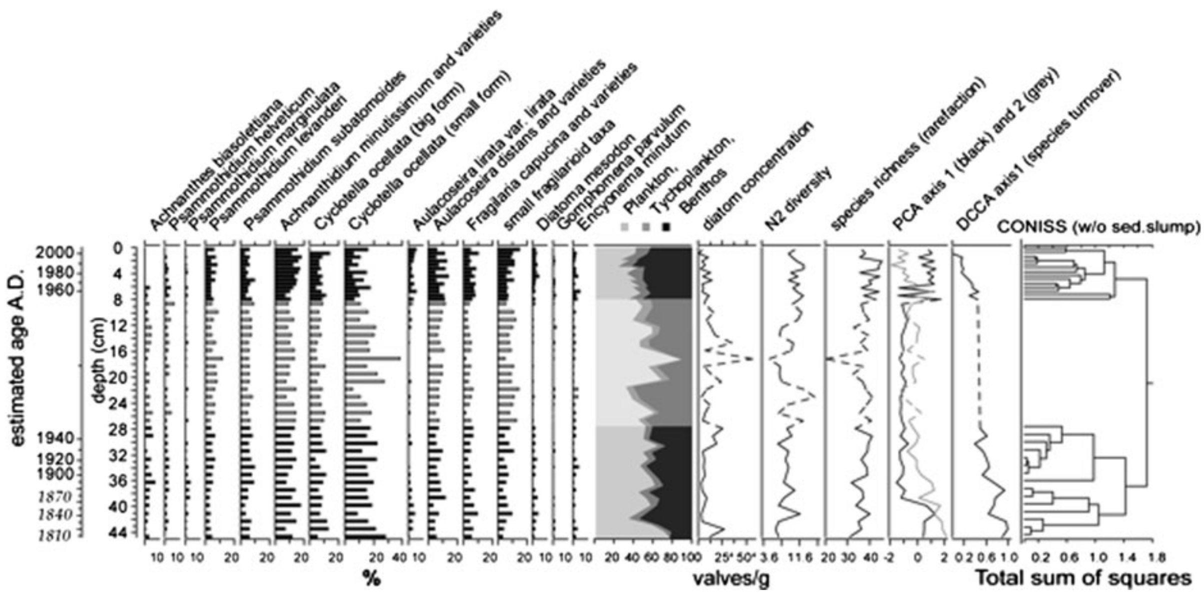

Fig. 4 Diatom stratigraphy of the LC6 Lake. Selected taxa are shown in relative abundance and comparison with autecology, species richness, N2 diversity, ordination scores (PCA 1 and PCA 2, DCCA 1). Area between 8 and 28 cm refers to the slump deposit. Ages AD *in italic* font indicate extrapolated dates

(USGS earthquakes 2010). Additionally, diatom samples from the 8–27-cm section plot within the same cluster in the PCA (Fig. 5), suggesting that species composition in this core section is very similar.

Even during the periods of uniform sedimentation, supply rates of ^{210}Pb are unusually high. The mean value (calculated from the post-1963 ^{210}Pb inventory) is well in excess of the values obtained from other Tibetan lakes, and substantially higher than the atmospheric flux. Two possible reasons for this are that the core is from a site in the lake subject to intense sediment focusing, or that substantial quantities of ^{210}Pb deposited in the catchment are transported into the lake during spring thaw. This is partially supported by instrumental climate data from the region, which indicate increasing precipitation rates and rising winter and spring temperatures over the last ~50 years (Liu and Chen 2000; You et al. 2007), possibly leading to higher input rates of ^{210}Pb.

Diatom response to recent environmental changes on the southeast Tibetan Plateau

According to established standards (Smol et al. 2005), the minimal diatom compositional changes over the 200-year period (<1SD) are ecologically insignificant. Similar low SD values were calculated for diatom records from northern Quebec, where diatom compositional change in agreement with instrumental data suggest no significant warming over the past 150 years (Smol et al. 2005).

Many studies on lakes in Arctic (Sorvari et al 2002; Rühland et al. 2003; Jones and Birks 2004; Smol et al. 2005; Solovieva et al. 2005; Holmgren et al. 2010) and alpine (Lotter and Bigler 2000; Koinig et al. 2002; Lotter et al. 2002) environments, however, have detected a significant shift from benthic- to planktonic-dominated assemblages around 1850 AD, as a result of longer ice-free periods linked to global warming after the end of the Little Ice Age. In these studies, earlier ice break up, triggered by rising mean winter and spring temperatures, led to a longer growing season, changes in the light and mixing regimes, and increased nutrient cycling that in turn enhanced especially planktonic growth. Hence, recent warming trends were detected in temperate regions of the Northern Hemisphere, and were accompanied by a significant shift from benthic (e.g. small fragilarioid species as well as heavily silicified *Aulacoseira* taxa) to planktonic (e.g. small *Cyclotella* sp.) taxa (Rühland et al. 2008).

Similar to many Arctic and alpine regions of the world, an overall increase in temperature has been recorded on the Tibetan Plateau after the end of the

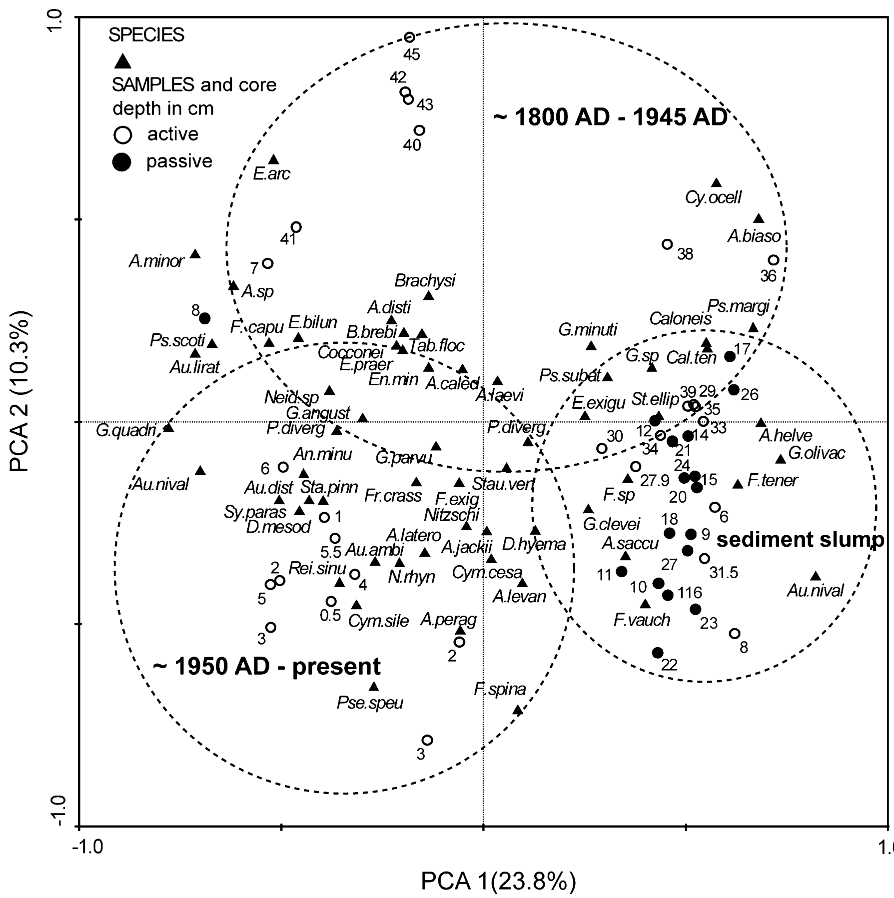

Fig. 5 Results of the Principle Component Analysis (PCA), showing diatom species with taxa >1% abundance. For species abbreviations see full species list in the supplementary data (Table EMS1). *Solid black* sample points were treated as passive samples as they form samples from the slump deposit. To ease visibility, species are displayed as symbols only (but treated as vectors, as appropriate for linear methods). *Dashed circles* indicate the time periods pre-slump deposit, slump deposit and post-slump deposit

Little Ice Age and post 1960 (Thompson et al. 2000; Hou et al. 2007). Continuous meteorological data for the Tibetan Plateau is available from the mid-1950s to the present and indicate an increase in mean winter temperatures of 0.16°C/decade between 1955 and 1996 (Liu and Chen 2000). You et al. (2007) analysed meteorological temperature and precipitation data from 10 stations in the Yarlung Zangbo River Basin and found similar climatic trends to our study area, indicating increasing mean winter and autumn temperatures of 0.37°C and 0.35°C/decade, respectively since 1961. Furthermore, You et al. (2007) identified a decreasing precipitation trend from the 1960s to the 1980s but a rising precipitation trend since the 1980s, which is most obvious in the autumn and spring season. According to their findings, Liu and Chen (2000) and You et al. (2007) suggest that particularly the southeastern Tibetan Plateau is most sensitive to global warming.

It is evident that the Tibetan Plateau has experienced substantial warming during the recent past. With rising temperatures we would expect a shortening in the ice-cover duration. However, the shift to warmer and moister conditions is not manifested in our diatom record from LC6 Lake. Species compositional changes are very subtle and a clear shift from benthic to planktonic taxa was not observed. In contrast, we find a directional decline (5–10%) in planktonic taxa, mainly *Cyclotella ocellata*, throughout the core, while benthic taxa show a small increase. PCA sample scores from the base of the core to approximately 1870 AD summarise changes in the diatom assemblage and may indicate post-Little Ice Age warming. However, all of these changes are likely ecologically insignificant. There is a more apparent increase in the relative abundance of tychoplanktonic taxa (*Aulacoseira distans* and varieties, *Aulacoseira lirata* var. *lirata),* small fragilarioid taxa and *A. minutissimum* since the mid-1950s, which is consistent with a minor increase in species richness and N2 diversity. TOC shows a modest increase whilst the C:N ratio declines moderately. Higher TOC in recent decades points to an overall increase in lake productivity, while C:N indicates an increased importance of algal productivity in the lake. Lami et al. (2010), found decreasing C:N ratios across Tibetan lakes over the last decades, which they link to climate warming and recent anthropogenic land-use changes. As no immediate, catchment-scale human impact is noticeable at our site, higher nutrient availability probably arises from changes in nutrient cycling linked to changes in the ice-cover duration (Douglas and Smol 2001) or increased meltwalter input from upstream glaciers. The presence of tychoplanktonic taxa at LC6 Lake and the growing importance of fragilarioid taxa, which are known to be *r*-strategists and therefore better adapted to rapid changing environments (Lotter and Bigler 2000) are indicative of higher ecosystem variability. Higher ecosystem variability during this time was also recorded in other palaeo-climate records across the Tibetan Plateau (Yang et al. 2004; Lami et al. 2010; Wrozyna et al. 2010). Major changes in the diatom concentration occur only in the sediment slump deposit and probably represent an artefact due to the change in the sedimentation rate. Variability in the diatom concentration throughout the rest of the record was statistically insignificant. Overall, the stability of the LC6 diatom assemblages throughout the core are indicative of very little change within the lake over the past approximately 200 years, and it seems warranted to further examine possible reasons for the apparent insensitivity of the diatom assemblage in response to environmental changes on the southeastern Tibetan Plateau.

Possible reasons for a modest diatom response to recent environmental change

You et al. (2010) argue that increasing temperatures are not necessarily correlated with elevation. In contrast to earlier studies (Liu and Chen 2000), they contend that the significant temperature increases that are recorded from climate stations at 2,500–3,000 m a.s.l., are not as pronounced at climate stations at higher altitudes. According to Pepin and Lundquist (2008), the highest temperature changes appear at the 0°C isotherm where melting of snow and ice influences the surface albedo and consequently enhances further warming (cryosphere feedback). Nyingchi (3,000 m a.s.l., mean T_{Jan} 0.2°C), the closest climate station to LC6 Lake (Fig. 1), indicates a significant increase (approx. 1°C) in mean and minimum temperatures in all seasons since the 1960s (Liang et al. 2009). According to Pepin and Lundquist (2008) and You et al. (2010), the temperature trend magnitude at our site (4,132 m a.s.l., mean T_{Jan} ~−5.5°C) could have been smaller or less significant than in Nyingchi (3,000 m a.s.l.) due to reduced cryospheric feedback recorded at higher altitudes, possible explaining the lack for significant changes in the diatom record.

Furthermore, You et al. (2010) show that regions on the Tibetan Plateau with a low-growing vegetation type have larger temperature trend magnitudes than regions with denser vegetation. This may seem counterintuitive, but on the Tibetan Plateau, areas with dense vegetation in combination with increasing precipitation might result in increased cloud cover and decreasing insolation that may act to buffer the full effect of increasing temperatures. The very dense coniferous forests intermixed with *Rhododendron* in the catchment of LC6 could have acted as a temperature buffer. Dense epiphytic growth from lichens and mosses in these forests also indicate permanent high moisture and cloud cover in the valley of LC6 Lake. Increasing precipitation, cloud cover and decreasing insolation also is confirmed by instrumental data (Niu et al. 2004). Increasing precipitation rates and increased cloud cover might have confounded increasing temperature and associated increasing evaporation trends in the area. This could explain the minimal changes observed in our diatom assemblages and likely the aquatic habitat (mixing, stratification, lake water depth). Increasing winter and spring precipitation rates, likely linked to the intensification of the westerlies over the southern slope of the Tibetan Plateau (Zhang et al. 2004), can further lengthen the ice-cover duration and therefore counteract the tendency towards earlier ice melting as would be expected with increasing air temperatures (Lotter et al. 2002).

Another possibility for the limited diatom response is that the LC6 Lake possibly does not stratify (in summer), often a key factor in driving recent diatom changes reported around the globe (Sorvari et al. 2002; Rühland et al. 2008). Wind stress or smaller differences between summer and winter water temperature, in combination with increased precipitation and cloud cover could maintain a well-mixed water column, thus preventing major changes in habitat conditions and in diatom composition despite recent warming trends. Furthermore, one could argue that warming in one region might have negative feedbacks in other regions such as in the down-slope areas of glacier-covered and climate-sensitive mountain regions. Rühland et al. (2006) suggested that substantial increases in temperature in the Himalayas did not lead to the expected drying of the investigated peatland, but to a significant increase of moisture and maintenance of cooler conditions, triggered by the increased runoff of melting glaciers from the upstream regions. Su and Shi (2002) have recorded substantial glacial retreat on the southeastern Tibetan Plateau, especially in the mountain range studied here. Increased melting and mountain runoff from peaks upstream of LC6 Lake may have provided a constant supply of cold glacial melt waters to our study site, offsetting the effects of warming lake surface water temperatures at LC6 Lake and preventing or weakening the potential for thermal stratification. Unusually high supply rates of ^{210}Pb support this hypothesis, indicating that substantial quantities of ^{210}Pb deposited in the catchment are transported into the lake during spring thaw.

To rule out the effect of a local climatic phenomenon that might have had an influence on the stability of the diatom composition, further palaeoecological investigations on the southeastern Plateau are necessary. Our results highlight the spatial complexity of climate change on the Tibetan Plateau, and indicate the need for widespread regional coverage of palaeoecological data in order to better understand the regional dynamics of future global change.

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