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Reconstructing climate variability on the Tibetan Plateau – comparing aquatic and terrestrial signals

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Abstract

Spatial and temporal temperature and moisture patterns across the Tibetan Plateau are very complex. The onset and magnitude of the *Holocene climate optimum* in the Asian monsoon realm, in particular, is a subject of considerable debate as this time period is often used as an analogue for recent global warming. In the light of contradictory inferences regarding past climate and environmental change on the Tibetan Plateau, I have attempted to explain mismatches in the timing and magnitude of change.

Therefore, I analysed the temporal variation of fossil pollen and diatom spectra and the geochemical record from palaeo-ecological records covering different time scales (late Quaternary and the last 200 years) from two core regions in the NE and SE Tibetan Plateau. For interpretation purposes I combined my data with other available palaeo-ecological data to set up corresponding aquatic and terrestrial proxy data sets of two lake pairs and two sets of sites. I focused on the direct comparison of proxies representing lacustrine response to climate signals (e.g., diatoms, ostracods, geochemical record) and proxies representing changes in the terrestrial environment (i.e., terrestrial pollen), in order to asses whether the lake and its catchments respond at similar times and magnitudes to environmental changes. Therefore, I introduced the established numerical technique procrustes rotation as a new approach in palaeoecology to quantitatively compare raw data of any two sedimentary records of interest in order to assess their degree of concordance.

Focusing on the late Quaternary, sediment cores from two lakes (Kuhai Lake 35.3°N; 99.2°E; 4150 m asl; and Koucha Lake 34.0°N; 97.2°E; 4540 m asl) on the semi-arid northeastern Tibetan Plateau were analysed to identify post-glacial vegetation and environmental changes, and to investigate the responses of lake ecosystems to such changes. Based on the pollen record, five major vegetation and climate changes could be identified: (1) A shift from alpine desert to alpine steppe indicates a change from cold, dry conditions to warmer and more moist conditions at 14.8 cal. ka BP, (2) alpine steppe with tundra elements points to conditions of higher effective moisture and a stepwise warming climate at 13.6 cal. ka BP, (3) the appearance of high-alpine meadow vegetation indicates a further change towards increased moisture, but with colder temperatures, at 7.0 cal. ka BP, (4) the reoccurrence of alpine steppe with desert elements suggests a return to a significantly colder and drier phase at 6.3 cal. ka BP, and (5) the establishment of alpine steppe-meadow vegetation indicates a change back to relatively moist conditions at 2.2 cal. ka BP. To place the reconstructed climate inferences from the NE Tibetan Plateau into the context of Holocene moisture evolution across the Tibetan Plateau, I applied a five-scale moisture index and average link clustering to all available continuous pollen and non-pollen palaeoclimate records from the Tibetan Plateau, in an attempt to detect coherent regional and temporal patterns of moisture evolution on the Plateau. However, no common temporal or spatial pattern of moisture evolution during the Holocene could be detected, which can be assigned to the complex responses of different proxies to environmental changes in an already very heterogeneous

mountain landscape, where minor differences in elevation can result in marked variations in microenvironments.

Focusing on the past 200 years, I analysed the sedimentary records (LC6 Lake 29.5°N, 94.3°E, 4132 m asl; and Wuxu Lake 29.9°N, 101.1°E, 3705 m asl) from the southeastern Tibetan Plateau. I found that despite presumed significant temperature increases over that period, pollen and diatom records from the SE Tibetan Plateau reveal only very subtle changes throughout their profiles. The compositional species turnover investigated over the last 200 years appears relatively low in comparison to the species reorganisations during the Holocene. The results indicate that climatically induced ecological thresholds are not yet crossed, but that human activity has an increasing influence, particularly on the terrestrial ecosystem. Forest clearances and reforestation have not caused forest decline in our study area, but a conversion of natural forests to semi-natural secondary forests.

The results from the numerical proxy comparison of the two sets of two pairs of Tibetan lakes indicate that the use of different proxies and the work with palaeoecological records from different lake types can cause deviant stories of inferred change. Irrespective of the timescale (Holocene or last 200 years) or region (SE or NE Tibetan Plateau) analysed, the agreement in terms of the direction, timing, and magnitude of change between the corresponding terrestrial data sets is generally better than the match between the corresponding lacustrine data sets, suggesting that lacustrine proxies may partly be influenced by in-lake or local catchment processes whereas the terrestrial proxy reflects a more regional climatic signal. The current disaccord on coherent temporal and spatial climate patterns on the Tibetan Plateau can partly be ascribed to the complexity of proxy response and lake systems on the Tibetan Plateau. Therefore, a multi-proxy, multi-site approach is important in order to gain a reliable climate interpretation for the complex mountain landscape of the Tibetan Plateau.

Zusammenfassung

Die räumlichen und zeitlichen Temperatur- und Feuchtigkeitsmuster auf dem Tibet-Plateau sind sehr komplex. Im Einzugsbereich der asiatischen Monsune sind insbesondere der Beginn und das Ausmaß des *Klimaoptimums* während des Holozäns von wissenschaftlichem Interesse, da diese Periode oft als Analogie für die derzeitige globale Klimaerwärmung herangezogen wird. In Hinblick auf sich teilweise widersprechende Paläoklima- und Umweltrekonstruktionen für das Tibet-Plateau, ist es mein Ziel, die bestehenden Unstimmigkeiten bezüglich des Zeitpunktes und des Ausmaßes des Umweltwandels zu erklären.

Dafür wurden von mir zeitliche Variationen fossiler Pollen- und Diatomeenspektren und geochemische Untersuchungen an Seesedimenten unterschiedlicher Zeitskalen (Spätquartär und die letzten 200 Jahre) aus zwei Kernregionen auf dem NO und SO Tibet-Plateau analysiert. Zur Unterstützung der Interpretation wurden die hier erhobenen Daten mit bereits vorhandenen paläoökologischen Aufzeichnungen der Lokalitäten kombiniert, um Datensätze der entsprechenden aquatischen und terrestrischen Proxy-Daten (Stellvertreterdaten) zweier Seenpaare aus den beiden Regionen gegenüberstellen zu können. Hierbei konzentrierte ich mich auf den direkten Vergleich von Proxies, die die Seenentwicklung reflektieren (z.B. Diatomeen, Ostracoden, geochemische Eigenschaften), mit Proxies, die Veränderungen der terrestrischen Umgebung des Sees beschreiben (terrestrische Pollen). Durch diesen Vergleich lässt sich beurteilen, ob Veränderungen im See selbst mit Umweltveränderungen in dem jeweiligen Einzugsgebiet zeitlich übereinstimmen. Dafür habe ich die bereits etablierte numerische Methode Procrustes-Rotation als neuen Ansatz in der Paläoökologie eingeführt. Damit ist ein quantitativer Vergleich von Rohdaten zweier beliebiger sedimentärer Datensätze möglich, um den Grad der Übereinstimmung zu prüfen.

Mit Fokus auf dem Spätquartär, wurden zwei Seen (Kuhai See 35,3° N; 99,2° E; 4150 m ü. NN., und Koucha See 34,0° N; 97,2° O; 4540 m ü. NN) vom semi-ariden nordöstlichen Tibet-Plateau analysiert, um die postglazialen Vegetations- und Umweltveränderungen, sowie die Reaktion von Seeökosystemen auf solche Umweltveränderungen zu untersuchen. Basierend auf den Ergebnissen der fossilen Pollenspektren konnten fünf wesentliche Phasen der Vegetations- und Klimaentwicklung identifiziert werden: (1) Der Wandel von alpinen Wüsten zu alpinen Steppen um 14,8 cal. ka BP deutet auf einen Wechsel von kalten und trockenen zu wärmeren und feuchten Umweltbedingungen, (2) das Auftreten alpiner Steppen mit Tundraelementen weist auf eine relativ hohe effektive Feuchtigkeit und eine schrittweise Erwärmung seit 13,6 cal. ka BP hin, (3) das Erscheinen hochalpiner Wiesen um 7,0 cal. ka BP deutet auf eine Veränderung zu noch feuchteren, aber auch kühleren Bedingungen hin, (4) das Widerauftreten alpiner Steppen mit Wüstenelementen zeigt eine Rückkehr zu einer deutlich kälteren und trockeneren Phase um 6,3 cal. ka BP an, und (5) die Ausbreitung alpiner Steppen-Wiesenvegetation um 2,2 cal. ka BP verweist auf eine Umkehr zu relativ feuchten Klimabedingungen.

Um die hier rekonstruierten Umwelt- und Klimaereignisse des nordöstlichen Tibet-Plateaus in einen größeren Zusammenhang hinsichtlich holozäner Klimaentwicklung des gesamten Plateaus setzen zu können, und um schlüssige zeitliche und räumliche Klimatrends auf dem Plateau erkennen zu können, habe ich auf alle vorhandenen Paläoklimadatensätze einen Fünf-Skalen Feuchtigkeitsindex und eine Clusteranalyse angewandt. Es konnten jedoch keine einheitlichen zeitlichen und räumlichen Trends der holozänen Klimaentwicklung nachgewiesen werden, was meiner Analyse entsprechend, auf die komplexen Reaktionen verschiedener Proxies auf Umweltveränderungen in einer ohnehin sehr heterogen Berglandschaft, zurückgeführt werden kann.

Mit dem Fokus auf den letzten 200 Jahren, wurden zwei Seesedimentkerne (LC6 See 29,5° N 94,3° E, 4132 m ü.NN, und Wuxu See 29,9° N, 101,1° E, 3705 m ü. NN) vom südöstlichen Tibet-Plateau untersucht. Meine Ergebnisse zeigen, dass trotz des im Allgemeinen angenommenen erheblichen Temperaturanstiegs in diesem Zeitraum, die Pollen- und Diatomeenspektren vom südöstlichen Tibet-Plateau nur sehr marginale Veränderungen in ihren Profilen aufweisen. Die Veränderung der Gesellschaftszusammensetzungen über die letzten 200 Jahre erscheint im Vergleich zu denjenigen während des Holozäns relativ gering. Die Ergebnisse weisen darauf hin, dass klimatisch-bedingte ökologische Schwellenwerte noch nicht überschritten wurden, dass aber der menschliche Einfluss insbesondere auf das terrestrische Ökosystem zunehmenden Einfluss hat. Rodungen und Aufforstungen haben in unserem Untersuchungsgebiet zwar nicht zu einem Waldrückgang geführt, aber zu einer Umstrukturierung der natürlichen Wälder in naturnahe Sekundärwälder.

Die Ergebnisse des numerischen Proxy-Vergleichs beider Seenpaare zeigen, dass die Verwendung von verschiedenen Proxies und die Arbeit mit paläo-ökologischen Datensätzen unterschiedlicher See-Typen zu abweichenden Klimaableitungen führen können. Unabhängig vom untersuchten Zeitraum (Holozän oder die letzten 200 Jahren) oder der Region (SO oder NO Tibet-Plateau), ist die Übereinstimmung zweier Datensätze hinsichtlich der Richtung, des Zeitpunktes und des Ausmaßes der abgeleiteten Paläo-Umweltverhältnisse in der Regel zwischen den entsprechenden terrestrischen Datensätzen besser als zwischen den entsprechenden lakustrinen Datensätzen. Dies deutet darauf hin, dass lakustrine Proxies stark durch See-interne oder lokale Prozesse beeinflusst werden, während die terrestrischen Proxies eher regionale Umweltsignale widerspiegeln. Die derzeitige Uneinigkeit über stimmige zeitliche und räumliche Klimatrends auf dem Tibet-Plateau kann daher teilweise der Komplexität der verschieden Proxies und ihrer individuellen Empfindlichkeiten gegenüber Umweltveränderungen, sowie der unterschiedlichen Reaktionsweise verschiedenartiger See-Systeme auf dem Plateau zugeschrieben werden. Meine Ergebnisse zeigen, dass ein *„Multi-Proxy-Multi-Site-Ansatz“* für zuverlässige Paläoklimaableitungen für das Tibet-Plateau von zentraler Bedeutung ist.

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1 Introduction

Preface

Future climate predictions for Asia indicate a 21st century warming that is likely to be well above the global mean, especially in central Asia, the Tibetan Plateau and northern Asia. South and East Asia are expected to be affected by longer lasting, more intense and more frequent precipitation events, while central and northern Asia might face increased drought (IPCC 2007, see Christensen et al., 2007). Observational data of the last 50 to 60 years (e.g., Liu and Chen, 2000) and latest daily news on the severe Indian and Chinese droughts (2002 and 2004) contrasting with the current (2010) floods in Pakistan and India prove this "inconvenient truth". As a result of extreme or absent monsoon rains, millions of people are faced with the loss of their property and farming land, failure of harvest, hunger, spreading diseases, and struggling economies. Consequently, the pressure and urge to comprehend and forecast monsoon and climate variability is rising. As we cannot look into the future, we are restricted to learn from the past, using e.g., the *mid-Holocene thermal optimum* as an analogue for the recent global warming. An excellent tool to gain insights in past environmental and climate evolution are palaeolimnological studies, which can possibly help to foresee how monsoonal Asia will develop under the current rate of global warming.

The Tibetan Plateau plays an essential role in the monsoon formation over Asia (Prell and Kutzbach, 1992). However, the complex mountain landscape and poor coverage of suitable long-term climate archives across the Plateau lead to a number of unanswered questions, mainly rising from the discordance over the varying timing, duration and amplitude of the *mid-Holocene thermal optimum* (e.g., He et al., 2004). Thus, future climate predictions for the highly populated monsoonal Asia remain vague.

Palaeolimnological investigations covering both, the Holocene time scale and the recent past (last 200 years) will help to decipher temporal and spatial climate patterns across the Tibetan Plateau. Comparing ecosystem response on both time scales might help to evaluate if the ecosystem change under current climate and human pressures is similar to change rates during the Holocene and how far we are from reaching ecosystem thresholds. Moreover, the Tibetan Plateau today is a very distinctive ecosystem and habitat to a unique and possibly slowly dying flora and fauna (Wu and Wu, 1996; Klein et al., 2007). Particularly studies of past vegetation dynamics, can explain past and present land cover changes and help to assess whether alpine meadows will be replaced by upward shifting forest, or grasslands by deserts under a warming climate and increasing anthropogenic pressures. Understanding these processes is relevant for nature conservation and land management action plans.

1.1 Scientific background

1.1.1 The Tibetan Plateau today – an introduction to the study area

The magnificence and superlative character of the Himalaya and the Tibetan Plateau today is the product of the 40 million years lasting and persistent subduction of the Indian subcontinent under the Eurasian continent (Chung et al., 1998). This process has formed the world's highest mountain rage and the largest and highest plateau stretching over ca. 2.5 million km^2 on an average elevation of above 4000 m above the sea level (m a.s.l.).

The Tibetan Plateau today has a multifaceted topography resulting in a unique, rich and varied landscape with complex climate and vegetation patterns, ranging from sparsely vegetated glacier forefields to subtropical broadleaved forests, from arid deserts to semi-arid grasslands and alpine meadows, offering diverse habitats for a unique plant and wildlife. The Tibetan Plateau and particularly its eastern and southeastern ridge and the adjacent areas of southeast China have been listed as one of the world's biodiversity hotspots (Myers et al., 2000; http://biodiversityhotspots.org/xp/Hotspots). More than 12 000 plant species of over 1500 genera are recorded in the region, and it is estimated that more then 20% of the total species are endemic to this region (Wang et al. 1993; Wu and Wu, 1996).

Apart from its ecological significance, the Plateau has also a high cultural and economic relevance. Providing fertile grazing grounds and rangeland, the Plateau is still home to old cultures and religions, adapted to unique but vanishing life forms. Especially, the Tibetan nomadic pastoralism, a thousand of years old way of life, is quickly disappearing as a result of ecological and political changes (Miller, 1998; Manderscheid, 2001). Furthermore, six of the world's largest rivers originate in the Himalaya-Tibet region, virtually making the Plateau the water tower of Asia, providing one fifths of the world's population with freshwater.

1.1.2 The climatic relevance of the Tibetan Plateau

Possibly most important, the Tibetan Plateau plays a major role in dictating regional and global climate patterns (Hahn and Manabe, 1957; Kutzbach et al. 1993; Liu et al, 2003), which is due to its immense size and elevation, and the different thermal properties of land and oceans. In summer (May – September), when the annual insolation is at its maximum, the Plateau heats up forming a strong low-pressure cell over the Asian continent. Following the pressure gradient, warm and moist air masses will consequently be drawn inland from the Indian and Pacific Ocean, resulting in generally strong rainfalls in South and East Asia. In winter (October – April), when strong radiative cooling of the vast elevated Asian landmass leads to the formation of the Siberian/Mongolian High, polar air masses are pushed in from the North, resulting in cold and dry conditions on the Plateau (Domrös and Peng, 1988). The seasonal character connected with an alternating wind directions of at least 120° is by definition a typical Monsoon circulation (Flohn, 1960).

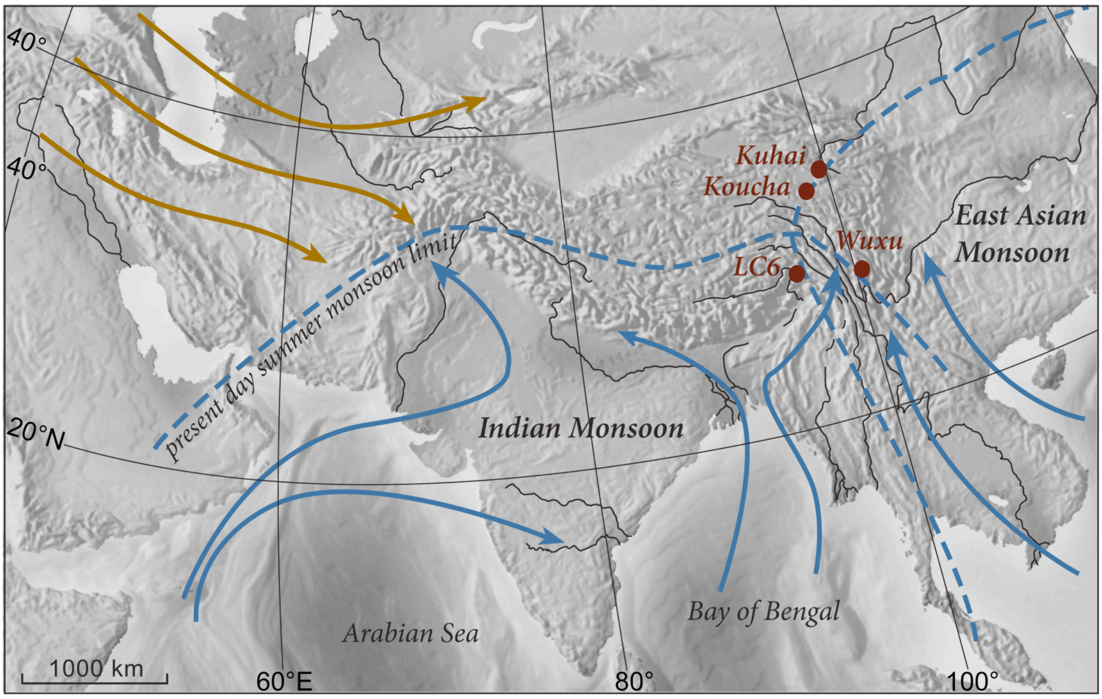

Figure 1.1: Map of monsoonal Asia, depicting the dominating circulation systems (blue: summer monsoons; brown: westerlies) and study sites. Wind directions and present-day limit of Asian summer monsoon after NCEP/NCAR 50-year reanalyses. DEM map source: Mountain High Maps 2.5.

The Asian monsoon is composed of two subsystems, the Indian and the East Asian summer monsoon, which are roughly divided at 105°E (Fig. 1.1). The Indian summer monsoon delivers air masses from the Arabian Sea and the Bay of Bengal to the western, central and eastern regions of the Tibetan Plateau. The East Asian summer monsoon, with air masses coming from the Pacific Ocean, mainly influences the eastern part of the Plateau. Both circulation systems interact, but also exhibit significant differences in their relative strength, which are linked to different geographic boundary conditions (contrasting sea-land distributions) (Wang et al., 2005). The Asian monsoon dominates the entire eastern hemisphere tropics and subtropics and also interacts with the El Niño/Southern Oscillation (ENSO), though the relationship is not yet fully understood (Kumar et al., 1999; Wang, 2006). Furthermore, the Indian summer monsoon is influenced by the westerlies (Dash et al. 2005; Schiemann et al. 2009), which are in turn closely related to the North Atlantic climate conditions. The extent of this influence also remains ambiguous. The interplay of the dominant circulation systems leads to a general moisture gradient across the Plateau, with the eastern fringe of the Plateau and the southern slopes of the Himalayas being the wettest, and a gradual drying towards the Northwest (western Tibet).

Today, the Tibetan Plateau is assumed to be one of the most sensitive regions responding to global climate change (IPCC 2007, see Christensen et al. 2007). Mean annual temperatures are rising about 0.16°C/decade, a warming rate exceeding those of the northern hemisphere and areas of the same latitudal zone (Liu and Chen, 2000). Consequently, permafrost is degrading (Cheng et al., 2007; Wu and Zhang, 2008; Yang et al., 2010b), glaciers are melting to an alarming degree (Su and Shi, 2002; Aizen et al.; 2007; Berthier et al., 2007), and first studies indicate that alpine meadows are being replaced by the upward shifting forest line, and grasslands are substituted by deserts (Baker and Mosley, 2007; Klein et al., 2007; Cui and Graf, 2009). Furthermore, recent high inter-annual variability of monsoonal activity and accumulating extreme events are challenging the nature, lives and economies in wide parts of South and East Asia (Goswami et al., 2006). Therefore, much of the attention is focused on forecasting monsoonal strength and variability.

Unfortunately, climate models for future climate prediction are so far largely restricted to input data from a relatively thin climate station network. Meteorological stations across the Tibetan Plateau have limited spatial cover and continuous records on precipitation and temperature data, reach back to the 1950s only (Lui and Chen, 2000). In addition, it is difficult to separate natural climate variability over the last decades from the increasing influence of anthropogenic factors in these records. Thus, future climate predictions for this vast and heterogeneous landscape remain vague. Understanding climate variability and its consequences in the future, involves understanding natural climate variability of the past. Hence, if we are to understand past and future natural long-term variability of monsoon strength, longer (palaeo-climate) records are needed.

1.1.3 Palaeoclimate in monsoonal Asia – state of the art

Several studies investigating past Asian monsoon dynamics have been undertaken and summarise climate and environmental changes of the atmosphere, oceans and land surface over various timescales.

Valuable long-term climate archives, often exceeding the last glacial maximum, are the marine sediment records from the Arabian and Chinese Sea (Wang et al., 1999; Gupta et al., 2003; Sun et al., 2003), providing information of wind strength, precipitation and sea surface temperatures, but do not necessarily reflect climate on the continents (Staubwasser, 2006). Palaeosol sequences from the Chinese Loess Plateau (e.g., An et al., 1991; Chen et al., 1997; Zhao et al., 2010) on the other hand capture changes on the continents but rather reflect periglacial environments. The ice cores from the Dunde, Guliya and Dasuopu ice caps (Thompson, 1997 and 2000), and the speleothems from the Hulu, Dongge and Qunf (Oman) caves (e.g., Wang et al., 2001; Fleitman, 2003; Yuan et al., 2004; Dykoski et al., 2005; Wang et al., 2008a) provide us with valuable insights of monsoon variability on millennial to orbital-scale changes, but are spatially sparse and limited. Additionally, tree-ring studies (e.g., Bräuning, 2006; Wang et al., 2008b; Yang et al., 2010a) reveal important, partly annually to seasonally resolved, information on temperature and moisture changes covering the last one to two millennia. Studies of peat deposits from the Hongyuan and Hani peat bogs (Yan et al., 1999; Zhou et al., 2002; Large et al., 2009) are limited mainly to the eastern Tibetan Plateau but additionally capture ecosystem changes as they hold well-preserved plant remains. All climate archives mentioned above have enormously fed our knowledge of past monsoon dynamics and revealed a close linkage between monsoon intensities and global climate dynamics. However, all these records are spatially rather limited and leave open gaps and unknowns in the rather complex mountain landscape of the Himalaya and Tibetan Plateau. Lakes are numerous and well distributed across the Tibetan Plateau and therefore provide an excellent archive for climate reconstructions. Consequently, lake sediment records, e.g., from Lake Qinghai (Lister et al., 1991; Henderson et al., 2003; Shen et al., 2005) are increasingly used to reconstruct past climate variability on the Tibetan Plateau.

The forcing mechanisms for monsoon variability are complex and not yet fully understood. On a very long time scale, the main initial driving mechanism for the monsoon is the tectonic uplift of the Tibetan Plateau during the early to mid Eocene (Kutzbach et al, 1993; Chung et al., 1998; Harris, 2006), which created a high elevated "heat plate" that could interact with the thermally differing oceans. A recent study by Boos and Kuang (2010) claims that the narrow orography of the Himalayan Mountain front alone is driver for the Asian summer monsoons. On shorter timescales, orbital-driven insolation is agreed to be the major driver (Fleitmann et al., 2003; Yuan et al., 2004; Kutzbach et al., 2008; Wang et al., 2008), causing regularly occurring cycles (every ~ 100 000 yrs, ~ 41 000 yrs, ~ 23 000 yrs) of stronger and weaker monsoon strength. Palaeo-climate records covering the last 20 000 years have shown that the maximum monsoon activity correlates with the maximum solar insolation during early and mid Holocene, suggesting a warmer and wetter climate than today, which is linked to a further northward extension of the limit of monsoon influence.

However, results of latest studies have shown that temporal and spatial temperature and moisture pattern are more complex and spatially variable than previously assumed. Several reviews have concluded that sites influenced by the Indian summer monsoon experienced their moisture optimum during the early Holocene, whereas sites influenced by the East Asian summer monsoon and the westerlies experienced the moisture optimum during the mid Holocene (e.g., An et. al, 2000; He et al., 2004; Herzschuh, 2006; Chen et al., 2008). Moreover, differences in temperature and moisture evolution on smaller spatial scales, especially during the recent past, are apparent (Liu and Chen, 2000; Niu et al., 2004; You et al., 2010). Thus, notwithstanding the general agreement that monsoon activity is linked to solar radiation, numerous studies argue that monsoonal strength can be influenced by several other factors that alter the seasonal pressure gradient between land and ocean. The underlying mechanisms are not yet fully understood, but there are lines of evidence that the amount of snow cover over Asia and the timing of snowmelt influences the surface albedo and therefore monsoon strength (Bhanu Kumar, 1988; Qian et al., 2003). Soil moisture can also influence monsoon activity and vice versa through positive feedbacks; strong precipitation moistens soils and moist soils cause stronger evaporation and enhance precipitation in return (Douville et al., 2001). Also, vegetation has a strong influence on the surface albedo and therefore heating capacity of the land. Global climate model simulations have shown that changes in the vegetation cover (type, leaf area index, density) can contribute to variations in monsoon strength (Kutzbach et al., 1996; Ganopolski et al., 1998; Yasunari et al., 2006). Considering the importance of the Tibetan Plateau as an important driver of the Asian monsoons, land cover changes on the Tibetan Plateau – either climate or human-induced – might contribute significantly to monsoon variability (Yasunari et al., 2006). Interactions with the El Niño/Southern Oscillation (ENSO) (Kumar et al., 1999; Yang et al., 2000) and the westerlies (Dash et al. 2005; Vandenberghe et al., 2006; Schiemann et al. 2009) may further influence the strength of the Asian monsoon, leading to a monsoon weakening in El Niño strong years. However, the extent of this influence remains ambiguous (Kumar et al., 1999). Increasingly important but still a matter of debate, is the relevance of anthropogenic pollutants (e.g., carbon dioxide and other greenhouse gas emissions) that function as aerosols and interfere with monsoon dynamics and lead to rising air temperatures, increasing precipitation and enhanced interannual variability (Menon et al., 2002; Meehl and Arblaster, 2003; Duan et al., 2006).

Climate developments over the last 200 years are of particular interest as it is a time period strongly affected by increasing urbanization and agricultural activity. The few available and applicable ice core records (Dasuopu, East Rongbuk, Puruogangri, Guliya, and Dunde ice caps) from the Tibetan Plateau have demonstrated environmental changes that are linked to Asian monsoon variability, suggesting large spatial-scale warming since 1800 AD (Thompson et al. 1989; Thompson et al. 2000; Thompson et al. 2006; Yang et al. 2006; Hou et al. 2007). Furthermore, meteorological data indicate significant increases in mean annual and mean winter air temperature since the 1950s, possibly indicating the anthropogenic contribution to recent global warming (Liu and Chen, 2000). Again, ice core records are spatially limited and cannot fully reflect climate development in this complex mountain landscape, and meteorological data do not reach back long enough to add to our understanding of natural variability. Hence, palaeo-ecological studies from the numerous Plateau lakes offer a great tool to gain insights in past environmental and climate evolution, both on the Holocene, but also on a much shorter time scale. However, to date only few and spatially widespread proxy studies have investigated most recent environmental changes on the Tibetan Plateau in detail, inferring partly asynchronous or contradictory climate development (Lami et al., 1998; Henderson et al., 2003; Bräuning and Mantwill, 2004; Yang et al., 2004; Liang et al., 2009; Lami et al., 2010; Wrozyna et al., 2010).

1.1.4 Lacustrine and terrestrial proxies as indicators of environmental change

Palaeolimnological studies from lakes on the Tibetan Plateau have tightened the fragmentary network of studies and have helped to further our understanding of past climate patterns. These palaeolimnological studies cover a moderate selection of biotic and abiotic proxies, which have been used as direct or indirect tools to infer environmental or climatic changes. Lake development and the history of its catchment were assessed by the temporal variation of geochemical, sedimentological and biological parameters in deposited lake sediments ('proxy' data). Changes in the lake system itself, i.e. changes in the water chemistry, lake productivity and/or aquatic organism groups, are primarily reflected in down-core analyses of the geochemical composition (e.g. organic carbon and nitrogen content) (Mischke et al., 2008; Mischke et al., 2009a; Zhu et al., 2009), in the isotopic content of fossil aquatic organisms or bulk sediments (Fontes et al., 1996; Yan et al., 1999; Henderson et al., 2003; Mischke et al., 2009a; Wrozyna et al., 2010), biomarker (e.g. *n*-alkanes) distribution (Herzschuh et al., 2005; Zheng et al., 2007; Seki et al., 2009), aquatic non-pollen palynomorphs (Kramer et al., 2010a, Wünnemann et al., 2010) and aquatic pollen assemblages (Herzschuh et al., 2005; Wünnemann et al., 2010), and other aquatic organism groups, such as ostracods (Hui et al., 1996; Mischke et al., 2007; Mischke et al. 2009b, Wrozyna et al., 2010), diatoms (Van Campo et al, 1993; Hui et al., 1996; Li et al., 1999; Yang et al., 2003 and 2004), and chironomids (Zhang et al., 2007). Changes in the catchment or terrestrial environment are primarily reflected in the temporal course of the mineral content and the grain size distribution (Kaiser et al., 2009; Mischke et al., 2009a, Wang et al., 2009; Zhang and Mischke, 2009), inferring e.g., sediment sources or wind strength. Terrestrial pollen mirror the terrestrial vegetation and allow the reconstruction of deserts, steppes, meadows, shrub lands and forests (e.g., Jarvis, 1993; Liu et al., 1998; Shen et al., 2005; Herzschuh et al., 2006a; Tarasov et al., 2006; Demske et al., 2009; Schlütz and Lehmkuhl, 2009; Herzschuh et al., 2010a; Kramer et al., 2010b) that may reflect climate conditions and human impacts.

Multiproxy studies; i.e. the combined analysis and interpretation of several proxies, have gained more and more importance, justified by their better reliability in reconstructing the past, by reflecting several aspects of different ecosystems (Smol, 2002; Lotter, 2003; Birks and Birks, 2006). Particularly interesting is the direct confrontation of lacustrine and terrestrial proxies, reflecting the lake itself and its catchment, respectively. This comparison seems highly valuable in order to assess possible differences in the timing and magnitude of response of both ecosystems. Lines of evidence indicate that any impact of climate fluctuations will not be uniform across ecosystems and that proxies reflecting aquatic and terrestrial environments are not necessarily following synchronous patterns (Blenckner and Hillebrand, 2002; Bradshaw et al., 2005; Fallu et al., 2005; Dalton et al., 2005; Fritz, 2008), indicating non-linear relationships to climate forcing (different response times of individual proxies, local peculiarities) causing contradictions in inferred change.

On the Tibetan Plateau and adjacent regions only very few studies integrated both lacustrine and terrestrial proxies in their studies (Van Campo and Gasse, 1993; Fontes et al., 1996; Gasse et al., 1996; Blyakharchuk et al., 2004; Herzschuh et al., 2005; Mischke et al., 2005; Westover et al., 2006; Ilyashuk and Ilyashuk, 2007; Mischke et al., 2008; Rudaya et al., 2009), but a direct comparison has not been done. Often climate is inferred from both proxy records without assessing the possible difference in their response, possibly contributing to the current confusion or discordance on temporal and regional climate patterns on the Tibetan Plateau.

A strict division in proxies indicating solely lacustrine processes or terrestrial processes is often difficult, if not impossible. Geochemical and sedimentological proxies in particular, might capture, both, in-lake and catchment processes (Birks and Birks, 2006). Terrestrial pollen and diatoms, which are the centre of focus in my dissertation, can be easier assigned to parameters reflecting terrestrial and lacustrine environments, respectively, and are therefore suitable for direct comparisons.

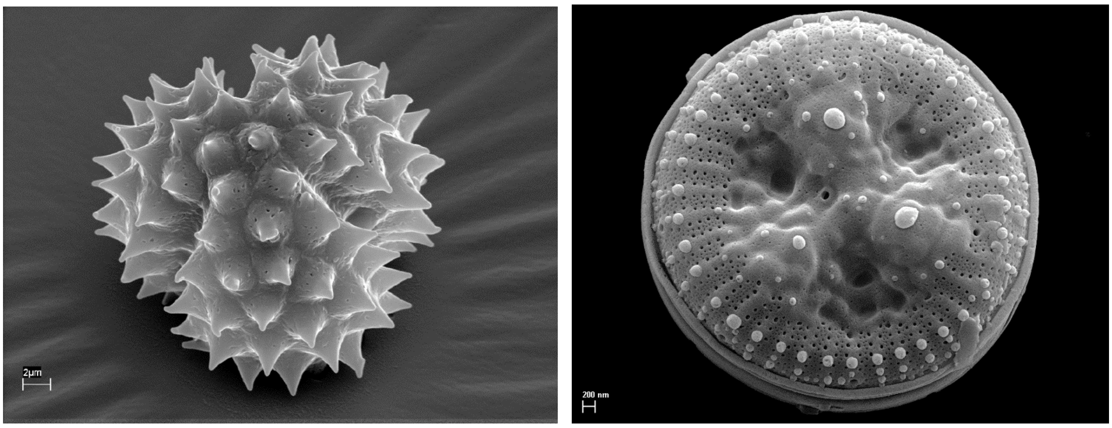

Figure 1.2: Scanning Electron Microscope images of the terrestrial pollen *Asterothamnus centrali-asiaticus* (left) and of the freshwater diatom *Cyclotella ocellata* (right). Source: U. Herzschuh and J. Wischnewski

Pollen grains are produced by plants in abundance and are liberated into the environment from their flowers. Pollen are either wind-dispersed or insect-dispersed. Depending on the dispersal type and shape, pollen grains are transported shorter or longer distances through the atmosphere and eventually fall down as pollen rain and accumulate in sediments of lakes, bogs, rivers or the sea. The composition of the pollen rain is understood as a function of the composition of the vegetation. Pollen analysis can therefore provide evidence for catchment vegetation over long time periods (Bennett and Willis, 2001). For nearly a century, pollen analysis is used for investigating past climatic changes, based on the assumption that vegetation is primarily driven by climatic factors, such as moisture and temperature (Seppä and Bennett, 2003). More recently, pollen analysis gained appreciation in palaeolimnology and multiproxy studies, as the role of the lake's catchment and its vegetation and soils is crucial in understanding lake biotic and sedimentary changes (Birks and Birks, 2006). On the Tibetan Plateau, pollen are a commonly applied proxy and several studies have successfully investigated last Lateglacial and Holocene climate variability (e.g., Kramer et al., 2010b), land cover change (e.g., Herzschuh et al., 2010a), and the influence and consequences of human interaction (e.g., Schlütz and Lehmkuhl, 2009). As knowledge on pollen morphology and indicator taxa is limited on the Tibetan Plateau, other means of inferring past vegetation and climate have been established. Non-arboreal pollen ratios (e.g., *Artemisia*/Chenopodiaceae ratio, *Artemisia*/Cyperaceae ratio) were introduced to better distinguish between steppe and alpine meadow vegetation and are used as a semi-quantitative measurement for moisture or summer temperatures on the northeastern Tibetan

Plateau (El-Moslimany, 1990; Herzschuh et al., 2006a). Quantitative climate reconstructions are established by applying transfer functions to a modern calibration data set. Shen et al. (2006a) and Herzschuh et al. (2010b) have generated modern pollen data sets from numerous lakes across the Tibetan Plateau covering wide temperature and precipitation gradients and reconstructed mean annual precipitation and mean July temperatures using a weighted average partial least square regression model.

Diatoms are microscopic unicellular siliceous algae, common everywhere if water and light are available for photosynthesis. Diatoms can be classified into different life forms; *planktonic* species float freely in the water column, *benthic* diatoms live near the bottom of a lake and are attached to a surface or plants (Stevenson, 1996). Like all algae, diatom abundance and productivity is controlled by many abiotic and biotic factors. The most important ones are salinity, pH, temperature, nutrients and zooplankton grazing (Battarbee, 1986). Due to their ecological diversity and short live cycles, changes in these biotic and abiotic factors are reflected rapidly in the diatom species composition, which makes them excellent indicators for changes in past and present environmental conditions. Diatoms have shown to be particularly useful indicators of past climate on different time scales (reviewed in 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 remote mountain 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). Also diatom-based studies that cover the last glacial period documented a strong correlation between diatom species composition and climate (Wilson et al., 2008; Ampel et al., 2009). All these studies hypothesize that diatoms react to earlier ice break up, triggered by increasing temperatures, which in turn alter the light and mixing regime in lakes, elongate the growing season and increase nutrient cycling. Despite their potential as climate indicators, diatoms have hardly been studied on the Tibetan Plateau. Van Campo and Gasse (1993) and Fan et al. (1996) carried out comprehensive multi-proxy studies, including diatoms, in western Tibet, reconstructing major climate shift during the Holocene. Li et al. (1999) reconstructed warm and cold phases over the Holocene period using the diatom sequence from Lake Angren, southern Tibet. Yang et al. (2003 and 2004) have established a diatom-based salinity transfer function and applied it to a sediment core from Chencuo Lake, southern Tibet, and successfully inferred moisture changes from reconstructed salinity changes over the last 300 years. Unfortunately, this handful of studies has limited value in the vast and complex mountain landscape and comparisons between these studies are difficult, as the lake systems being compared are very different, and the temporal resolution or time scales in general are not overlapping.

1.2 Aims and objectives of the thesis

The principal aim of this thesis is the reconstruction of the past environmental variability and the attempt to decipher the complex spatial and temporal climate patterns across the Tibetan Plateau by strengthening the network of long-term lake sediment records. Working in two core regions on the Tibetan Plateau (NE and SE Plateau), with the possibility to focus on different timescales (last ~ 15 000 years and last ~ 200 years) and the chance to infer environmental change from two distinct proxies representing different environments (lake and catchment) I was able to focus on specific questions. Essentially, they all relate to the complex nature of palaeo-environmental records and seek to provide a coherent thread through the presented work.

1. This study aims to investigate the vegetation development and climate evolution during the late Quaternary on the northeastern Tibetan Plateau. Special regard is given to the following questions:
    - How and when did the terrestrial vegetation change?
    - When comparing proximal pollen records, are vegetation changes within regions similar and synchronous?
    - Does the vegetation-inferred climate trend from the northeastern Tibetan Plateau correspond well with previously reconstructed climate trends in central Asia?
    - Are there coherent regional and temporal patterns of Holocene moisture evolution across the Tibetan Plateau?
2. With a focus on the last 200 years, this study wants to contribute to our understanding how recent global warming and human activity are affecting the remote areas of the southeastern Tibetan Plateau. Using fossil pollen and diatom records I focused on the following:
    - Can we detect environmental change in the pollen and diatom records from two remote boreal-montane lakes?
    - Can we detect causes of change and is it possible to disentangle the effects of natural climate variability and anthropogenic influences?
    - How does the recent magnitude of change compare to change on millennial time scales? Have ecosystem thresholds been surpassed?
3. With a direct comparison of distinct proxies and different lake types, this study wants to investigate biotic community response in lacustrine and terrestrial ecosystems to environmental change. The interest is focused on the following points:
    - Are climatic shifts inferred by the terrestrial vegetation record also reflected in lacustrine environments?
    - Do terrestrial and lacustrine proxies react similarly in timing, duration and magnitude to environmental forcing?
    - Is environmental change inferred from palaeo-ecological studies from proximal lakes similar and synchronous?

Figure 1.3 gives an overview of the study sites, analysed proxies and methods applied to address the main research questions.

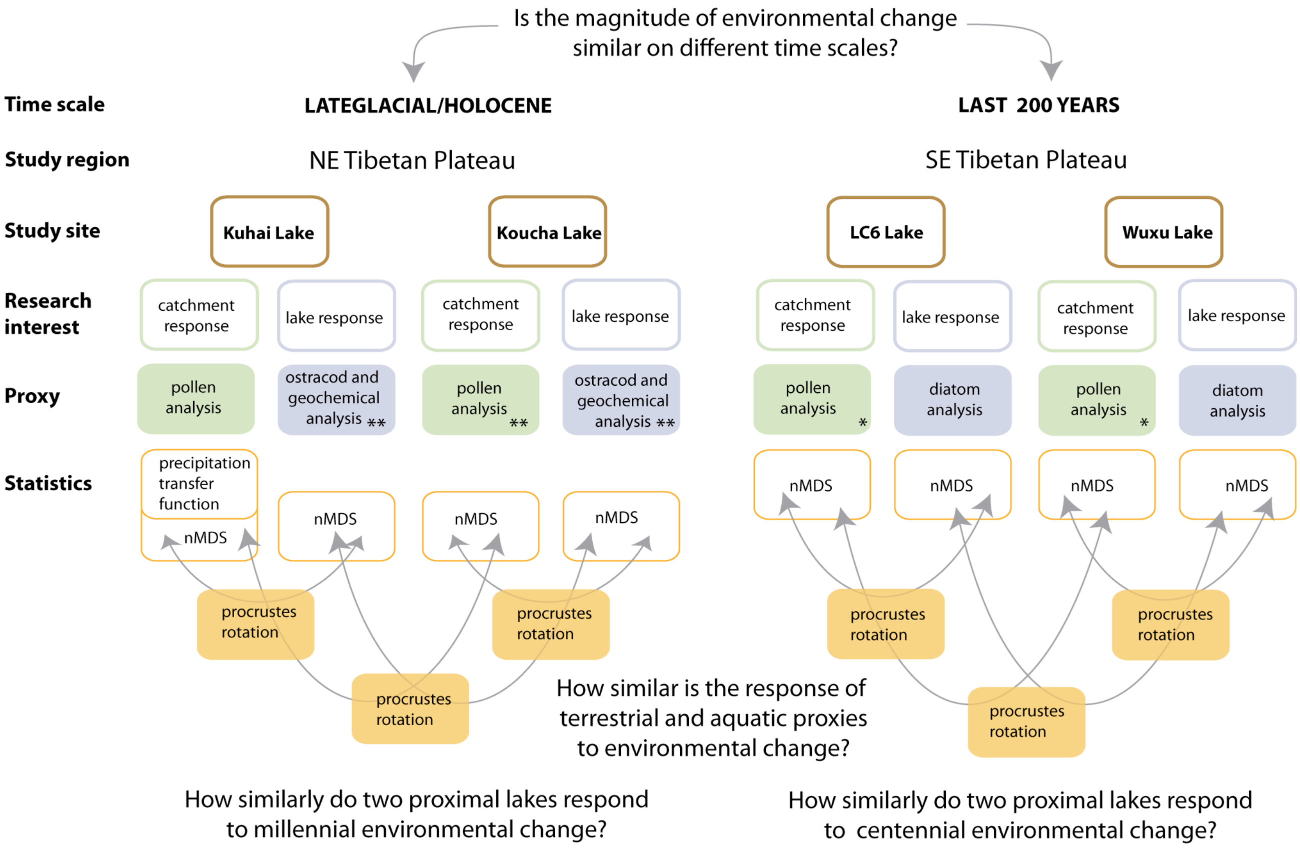

Figure 1.3: Study design, introducing study sites, proxies used and methods applied (nMDS = non-metric multidimensional scaling; *pollen counting by Annette Kramer and Zhaochen Kong; **previously published data by Herzschuh et al. (2009) and Mischke et al. (2008 and 2009a)

1.3 Organisation of thesis

1.3.1 Overview of Chapters

My thesis is an accumulative dissertation and therefore consists of three individual manuscripts (Chapters 2 – 4), which are either accepted in the Journal Quaternary Science Reviews (manuscript #1), in review in the Journal of Paleolimnology (manuscript #2) or in preparation to be submitted (manuscript #3). The manuscripts are framed by an introductory chapter (Chapter 1) including the scientific background and the aims and objectives of this thesis and a synthesis (Chapter 5), summarising the main results and conclusions of this work.

- Manuscript #1: **Reconstructing climate variability on the northeastern Tibetan Plateau since the last Lateglacial – a multi-proxy, dual-site approach comparing terrestrial and aquatic signals**, accepted at the Journal of Quaternary Science Reviews

  Authors: Juliane Wischnewski, Steffen Mischke, Yongbo Wang, Ulrike Herzschuh

This manuscript shows results from a pollen-inferred precipitation reconstruction since the last Lateglacial on the northeastern Tibetan Plateau. Furthermore, these results are compared to a formerly published sedimentary and ostracod data set from the same sediment core, to asses whether the lake and its catchment respond with similar timing and magnitudes to environmental changes. In addition these results are compared to palaeo-ecological data from a near by lake in order to assess regional patterns of Holocene climate evolution. To place the current study in the context of Holocene moisture evolution across the Tibetan Plateau, we applied a five-scale moisture index and average link clustering to all available continuous palaeo-climate records from the Tibetan Plateau to possibly find general patterns of moisture evolution on the Plateau.

- Manuscript #2: **Muted diatom responses to environmental change on the southeast Tibetan Plateau during the last two centuries**, in review at the Journal of Paleolimnology (including the reviewer's comments)

  Authors: Juliane Wischnewski, Anson W. Mackay, Peter G. Appleby, Steffen Mischke, Ulrike Herzschuh

  In this manuscript we present results from a sediment core from the southeastern Tibetan Plateau, covering the last 200 years. Down-core profiles of diatoms, organic parameters (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 increase and glacial retreat. The paper aims to provide insights to the complexity of environmental change on the Tibetan Plateau.

- Manuscript #3: **Pollen and diatom response to climate change and human impact on the southeastern Tibetan Plateau during the last two centuries**, in preparation to be submitted to Global Change Biology

  Authors: Juliane Wischnewski, Annette Kramer, Zhaochen Kong, Anson W. Mackay, Steffen Mischke, Ulrike Herzschuh

  Manuscript #3 presents the results of pollen and diatom records from two montane-boreal lakes (LC6 and Wuxu) on the southeastern Tibetan Plateau. Our aim is to evaluate the comparability of aquatic and terrestrial proxy response, climate variability, and human activity over the last 200 years using the same statistical approach as in manuscript #1. As such, this paper exhibits the first study in the region that directly compares aquatic and terrestrial proxy response o recent global warming within and between two different sites.

1.3.2 Authors' contributions

As first author, I initiated, wrote and coordinated all manuscripts and conducted all data analyses and interpretations of the fossil pollen and diatom spectra, unless otherwise stated. Ulrike Herzschuh and Anson Mackay contributed to the organisation of the three manuscripts mentioned above and provided valuable discussion and feedback throughout the writing process. Yongbo Wang helped to compile the review of moisture data from records across the Tibetan Plateau used in manuscript #1. Annette Kramer and Zhaochen Kong counted the pollen from LC6 and Wuxu Lake used in manuscript #3. Peter Appleby established the ^{210}Pb/^{137}Cs based age-depth model for LC6 and Wuxu Lake. Steffen Mischke carried out the coring at Kuhai, LC6 and Wuxu Lake and contributed helpful comments to all three manuscripts.

2 Reconstructing climate variability on the northeastern Tibetan Plateau since the last Lateglacial - a multi-proxy, dual-site approach comparing terrestrial and aquatic signals

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Abstract

A sediment core from a closed basin lake (Lake Kuhai) from the semi-arid northeastern Tibetan Plateau was analysed for its pollen record to infer Lateglacial and post glacial vegetation and climatic change. At Lake Kuhai five major vegetation and climate shifts could be identified: (1) a change from cold and dry to relatively warmer and more moist conditions at 14.8 cal. ka BP; (2) a shift to conditions of higher effective moisture and a stepwise warmer climate at 13.6 cal. ka BP; (3) a further shift with increased moisture but colder conditions at 7.0 cal. ka BP; (4) a return to a significantly colder and drier phase at 6.3 cal. ka BP; (5) and a change back to relatively moist conditions at 2.2 cal. ka BP. To investigate the response of lake ecosystems to climatic changes, statistical comparisons were made between the Lake Kuhai pollen record and a formerly published ostracod and sedimentary record from the same sediment core. Furthermore, the pollen and lacustrine proxies from Lake Kuhai were compared to a previously published pollen and lacustrine record from the proximal Lake Koucha. Statistical comparisons were done using non-metric multidimensional scaling and Procrustes rotation. Differences between lacustrine and pollen responses within one site could be identified, suggesting that lacustrine proxies are partly influenced by in-lake or local catchment processes, whereas the terrestrial (pollen) proxy shows a regional climate signal. Furthermore, we found regional differences in proxy response between Lake Kuhai and Lake Koucha. Both pollen records reacted in similar ways to major environmental changes, with minor differences in the timing and magnitude of these changes. The lacustrine records were very similar in their timing and magnitude of response to environmental changes; however, the nature of change was at times very distinct. To place the current study in the context of Holocene moisture evolution across the Tibetan Plateau, we applied a five-scale moisture index and average link clustering to all available continuous palaeo-climate records from the Tibetan Plateau to possibly find coherent temporal and regional patterns of moisture evolution on the Plateau. However, no common regional pattern of moisture evolution during the Holocene could be detected. We assign this to complex responses of different proxies to

environmental and atmospheric changes in an already very heterogeneous mountain landscape where minor differences in elevation can cause strong variation in microenvironments.

2.1 Introduction

In the last few years there have been a number of regional scale studies on the Tibetan Plateau, which have reconstructed past monsoon evolution and variability from lake sediments (e.g., Shen et al., 2005; Herzschuh et al., 2006a; Wu et al., 2006; Zhang and Mischke, 2009). However, the Tibetan Plateau, which stretches over ca. 2.2 x 10^6 km^2 on an average elevation of > 4500 m above sea level (m a.s.l.) has very complex temperature, precipitation and evaporation patterns making it difficult to draw a holistic picture of climate evolution of the Lateglacial and Holocene period. The interplay of the dominant circulation systems, i.e. East Asian and Indian summer monsoons, mid-latitude westerlies, and the dry, cold central Asian winter monsoon leads to a general moisture gradient across the Plateau, with the eastern fringe of the Plateau and the southern slopes of the Himalayas being the wettest, and a gradual drying towards the NW (western Tibet). The summer monsoons in particular are important as they influence the societal and economical activities of billions of people living in India, China and SE Asia. Their timing, duration and magnitude may dictate the success or failure of whole cultures, as they have done in the past (Staubwasser et al., 2003). Notwithstanding the well established link between monsoon activity and solar insolation (e.g., Fleitmann et al., 2003), sites across the Tibetan Plateau have shown significant differences in terms of timing, length and magnitude of the monsoon climate optimum (i.e. peak summer monsoon precipitation). This is not only true along the aforementioned gradient, but also amongst study sites within the same climatic region. Several reviews have concluded that sites influenced by the Indian summer monsoon experienced their moisture optimum during the early Holocene, whereas sites influenced by the SE Asian summer monsoon and the westerlies experienced the moisture optimum during the mid Holocene (e.g., An et. al, 2000; Herzschuh, 2006; Chen et al., 2008; Yang and Scuderi, 2010). However, even records from sites from the same region, under the influence of the same circulation system, can reveal different temporal moisture patterns, particularly with respect to the onset and the ending of the Holocene optimum (An et al., 2006, Yang et al., 2008b). Analysing and comparing vegetation evolution of proximal sites may be a good possibility to decipher this complex pattern of spatial and temporal differences in the moisture regime on the Tibetan Plateau. Furthermore, it is important to assess whether lakes react in a similar manner to climate-induced changes as the terrestrial vegetation. Therefore, multi-proxy studies are useful to strengthen conclusions drawn from one single site. In particular, the focus on vegetation response versus in-lake/catchment response may be both interesting and valuable, as often these systems are employed to infer environmental changes without assessing possible differences in timing and magnitude of their response to such changes. In central Asia multi-proxy studies, focusing on both lacustrine and terrestrial proxies, were used in the Sumxi Co Basin

(Van Campo and Gasse, 1993; Fontes et al., 1996; Gasse et al., 1996), in the Altai Mountains (Blyakharchuk et al., 2004; Westover et al., 2006; Ilyashuk and Ilyashuk, 2007; Rudaya et al., 2009) and on the NE Tibetan Plateau at Lake Koucha (Mischke et al., 2008; Herzschuh et al., 2009) and in the Qilian mountains (Herzschuh et al., 2005; Mischke et al., 2005). In western central Asia comparisons of terrestrial and lacustrine proxies have been undertaken at the Caspian Sea (Leroy et al., 2007) and at the Aral Sea (Sorrel at al., 2006; 2007). However, all these studies did not support their conclusions with statistical tests that could assess the degree of similarities or dissimilarities observed between two sites or between different proxies, which is crucial for evaluating the comparability of records for palaeo-climatological studies.

Various statistical methods that have been used to test the association between different data sets have been applied in several studies. Morrill et al. (2003) applied the moving t-test to identify abrupt climatic change in a suite of palaeo-climate records from the Asian summer monsoon influenced region. Smol et al. (2005) and Birks (2007) applied Detrended Canonical Correspondence Analysis (DCCA) to palaeo-records in the Arctic and in Norway, respectively, to gain quantitative estimates of compositional species turnover. A direct comparison of multivariate data sets was often assessed using the Mantel test (e.g., Douglas and Endler, 1982; Dutilleul et al., 2000) and Procrustes rotation (e.g., Peres-Neto and Jackson, 2001; Davidson et al., 2007). To date, however, no such analyses have been carried out on sites on the Tibetan Plateau.

Here we present a new pollen record from Lake Kuhai, which is compared to a lacustrine record from the same site (lacustrine data were published in Mischke et al., 2009a). We also compared the Kuhai pollen record to an earlier published sedimentary and pollen record from the proximal Lake Koucha (Mischke et al., 2008; Herzschuh et al., 2009) using ordination techniques and Procrustes rotation. We choose the Lake Koucha record for comparison as it is the closest, and currently the only record in the region, located on the same elevation as Lake Kuhai, and within the same vegetation zone (alpine steppe, high-alpine meadow). Quantitative precipitation data were obtained through the application of a regional pollen-climate transfer function to both records.

We focused on the following questions: (i) what kind of vegetation types can be reconstructed from the Lake Kuhai pollen record for the last ca.15 ka and can changes in climate be inferred from such vegetation shifts? (ii) Are the vegetation development and the inferred climate evolution at Lake Kuhai and Lake Koucha similar? (iii) Do the lake systems respond in a similar manner to climate-induced changes as the terrestrial vegetation? (iv) Finally, are there coherent regional and temporal patterns of moisture evolution during Holocene across the Tibetan Plateau?

2.2 Regional setting

Lake Kuhai and Lake Koucha, 230 km apart, lie in the northeastern Tibetan Plateau in the foothills of the Anemaqin Mountains and the Bayan Har Mountains, respectively (Fig. 2.1). These mountain ranges are the eastern most extension of the Kunlun Mountain range and form a high plateau of high mountains, sloping hills, broad valleys and lake basins with an elevation between 4000 and 5000 m a.s.l. The whole area is strongly affected by the Quaternary glaciations, which shaped the region into areas of moraines and glacial erosional landforms (Lehmkuhl and Owen, 2005).

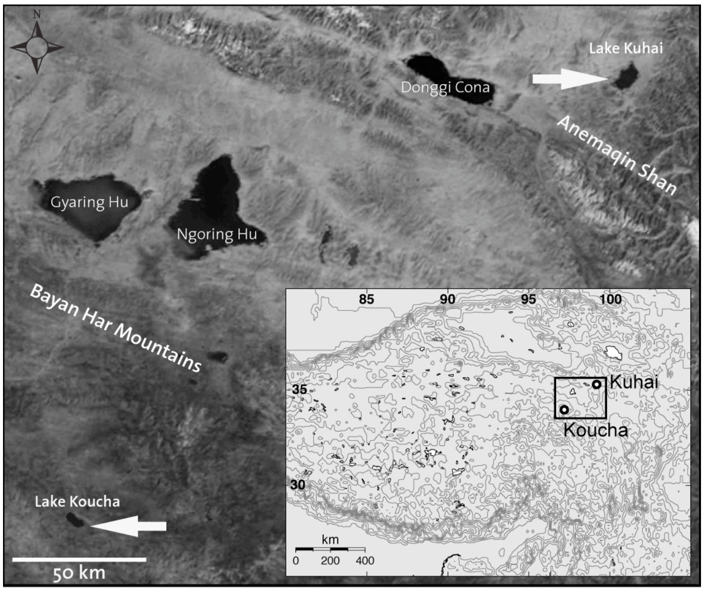


Figure 2.1: The northeastern Tibetan Plateau. Locations of Lake Kuhai and Lake Koucha. Figure adapted from Google Earth and Online Map Creation (2009).

Lake Kuhai (35.3°N; 99.2°E) is a closed basin lake situated north of the Anemaqin Mountains. The lake covers ca. 41 km^2 (ca. 8.3 km × 5.0 km) and lies at ca. 4150 m a.s.l. Due to the lack of an outlet Lake Kuhai is a saline lake with a maximum depth of 20.6 m. The lake is located at the present-day limit of the Asian summer monsoon and is also to a lesser degree affected by the westerlies (Winkler and Wang, 1993; Vandenberghe et al., 2006). As a result, relatively warm and wet summers with precipitation arriving mainly with the SE summer monsoon, alternate with cold and dry winters mainly controlled by the Mongolian-Siberian high. The closest climate station is Madou (4272 m a.s.l.), 100 km south-west of Lake Kuhai, which reveals a mean July temperature of 7.8°C, a mean January temperature of -15.9°C, and a mean annual temperature of -3.1°C. The mean annual precipitation, which is primarily restricted to the summer months, is ca. 310 mm (WorldClimate). The mean annual evaporation is in order of 1000 mm (Ling, 1999). Today the dominant vegetation surrounding the site comprises taxa mainly of *Kobresia pygmaea* and *Stipa purpurea* forming high-alpine meadows, with patches of alpine shrubs (*Salix orithrepha, Saussurea* spp. and *Dasiphora (Potentilla) fructicosa*) to the southeast (Hou, 2001; Kürschner et al., 2005). Yaks and sheep graze in the lake catchment.

Lake Koucha (34.0°N; 97.2°E, 4540 m a.s.l.) is situated in the southern foreland of the Bayan Har Mountains, a mountain branch of the Kunlun Mountain range, filling a glacially eroded wide depression (Heyman et al., 2008). Lake Koucha is a freshwater lake with a maximum depth of 6 m and covering ca. 18 km^2 (ca. 6.7 km × 2.6 km). Its single out-flowing stream is one of the upper tributaries of the Yellow River. As at Lake Kuhai, the climate of Lake Koucha is dominated by the Asian monsoon system and to a lesser extent by the westerlies, with cold and dry winters, cool summers and precipitation mainly occurring between June and September (Chengduo climate station at 33.8°N, 97.13°E, 4418 m a.s.l., T_{July}= 6.9°C, P_{ann}= 469 mm). The present day vegetation around the lake is characterised by dense *Kobresia* meadows, which change into sparse alpine vegetation at higher elevations. For further details on site description see Herzschuh et al. (2009) and Mischke et al. (2008).

2.3 Material and Methods

2.3.1 *Coring, lithology and age-depth model of the Lake Kuhai core*

A 7.78 m long core was collected (using an Uwitec piston corer "Niederreiter 60") from the centre of the lake, at 18.7 m water depth. The lower part of the core (below 5.75 m) reveals non-laminated fine sands and silty beds with a maximum thickness of 0.57 m. The upper part of the core (above 5.57 m) is dominated by alternating light and dark coloured laminae of lake mud with varying thickness from less than 1 to 4 millimetres. Only occasionally the layers are interrupted by non-laminated lake muds.

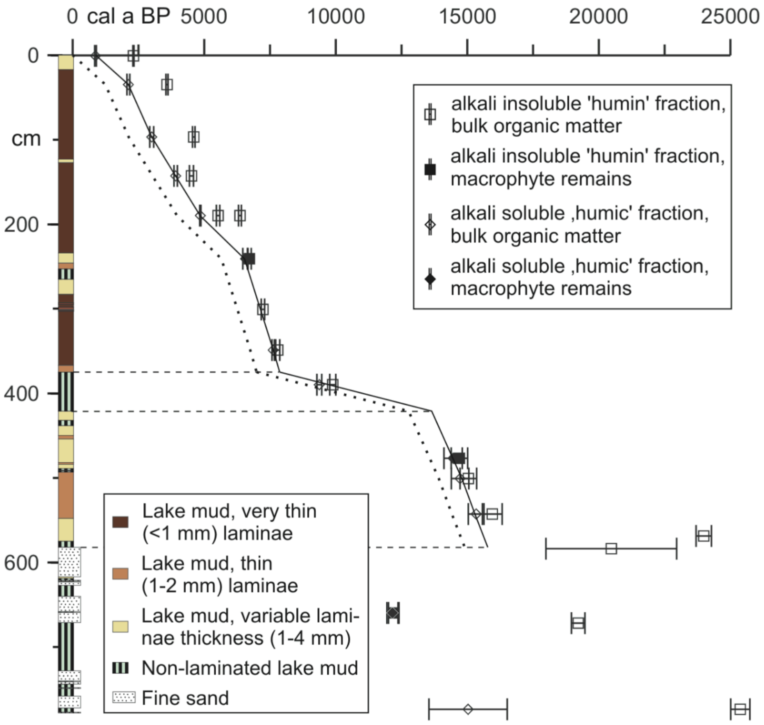


Figure 2.2: Lithology of the core from Lake Kuhai and calibrated radiocarbon dating results. The dotted line represents the reservoir effect-corrected age–depth relationship using the calibrated radiocarbon age of surface sediments at the core site. Broken horizontal lines illustrate the extrapolation of sample ages to account for lithological changes. The horizontal bars of the age results indicate 2s age uncertainties. Graphic originally published in Mischke et al. 2009.

Radiocarbon dating was performed on the alkali insoluble 'humin' fraction and the alkali soluble 'humic' fraction of 17 samples (Fig. 2.2). Apart from three stratigraphic levels where enough fossil plant material was found for dating, bulk organic matter was used to obtain ages. The surface sediment revealed a reservoir effect of 867 ± 31 cal. a BP for the alkali soluble 'humic' fraction. As the reservoir effect for the alkali insoluble 'humin' fraction was higher, the age-depth model was established using the calibrated ages of the alkali soluble fraction. For this purpose, radiocarbon ages were transformed to calendar years using the CALIB programme (Reimer et al., 2004). The age model restricts the presentation of the age-depth relation to 14.8 cal. ka BP (564 cm), though results of the entire core (778 cm) are presented. Full details on the sediments and the construction of the age-depth model are given in Mischke et al. (2009).

2.3.2 Pollen sample treatment and analysis

The treatment of the pollen samples followed standard laboratory methods (Fægri and Iversen, 1989), including treatment with hydrogen chloride (10%) to remove carbonates, potassium hydroxide (10%) to take out humic substances, and hydrofluoric acid (50%, 2 h boiling) to remove all siliceous particles, followed by acetolysis which removes cellulose, sieving (7 μm) in an ultrasound bath, and mounting in glycerine. Two tablets of *Lycopodium* spores (10 979 spores/tablet) were added to calculate the pollen concentrations. The sediment core was analysed at 60 horizons and at the least 300 terrestrial pollen grains were counted for each level. However, only 200 grains were counted in samples older than 14.8 cal. ka BP, as the pollen concentration was very low (2000 - 10 000 grains/cm^3). Pollen identifications were based on the relevant literature (Moore et al., 1991; Wang et al., 1997; Beug, 2004). Pollen percentages were calculated by adding the total pollen count of arboreal and terrestrial non-arboreal taxa to 100%. The resulting pollen percentages were used to construct the pollen diagram and for numerical analyses. The definition of the local pollen zone boundaries was based on the results of a Constrained Incremental Sum of Squares cluster analysis (CONISS) using the Edwards and Cavalli-Sforza's chord distance measure with TILIA software (Grimm, 1991).

2.3.3 Data sets, numerical analysis and data interpretation

The comparison of lacustrine and pollen records was made to evaluate their similarity or dissimilarity and degree of response to environmental changes. The lacustrine record reflects the response of predominantly in-lake and partly hydrological catchment processes to climate, whereas the pollen record reflects the response of regional scale vegetation to climate. Hence, the following four data sets were established: (1) The *Lake Kuhai pollen record* represents the vegetation response from the Lake Kuhai region. This new record consists of pollen counts on 60 horizons from the Lake Kuhai sediment core. (2) The *Lake Kuhai lacustrine record* reflects primarily in-lake, but also catchment response to climate-induced changes. This data set comprises elementary composition data (Ca, Mg, S, Sr), LOI_{550}, LOI_{950}, $\delta^{13}C_{ostracod}$ and ostracod data obtained from the same sediment core as in (1). This record was published by Mischke et al. (2009). (3) The *Lake Koucha pollen record* represents the vegetation response to environmental changes in the Lake Koucha region. This pollen record of 66 samples was published by Herzschuh et al. (2009). (4) The *Lake Koucha lacustrine record* reflects in-lake and catchment response to climate-induced changes in the Lake Koucha region and is comprised of elementary composition data

(Ca, Mg, S, Sr), total organic carbon (TOC), carbonate content, $\delta^{13}C_{ostracod}$ and ostracod data. This record was published by Mischke et al. (2008).

To allow statistical based comparisons between Lake Kuhai and Lake Koucha data sets, all variables in all four data sets were equally interpolated in 250-year intervals for the time interval 0 to 13 cal. ka BP using simple linear interpolation. Thereafter, all data sets were resampled in 250-year time intervals ranging from 0 to 13 cal. ka BP, allowing the comparison of like-for-like data. All interpolations and resampling were carried out using AnalySeries 2.0.4.2. (Paillard et al., 1996).

Ordination methods, which are effective tools for analysing multivariate data sets, were used to explore the patterns of variation in the data sets. The ordination technique non-metric Multidimensional Scaling (nMDS) was preferred over other ordination techniques (e.g. Principal Components Analysis, Detrended Correspondence Analysis), as it proved to be a more robust technique for indirect gradient analysis and for data sets with high beta diversity (Minchin, 1987). NMDS provides an optimal low dimensional mapping that preserves the rank ordering of sites avoiding the assumption of data normality (Kruskal, 1964; Clarke and Ainsworth, 1993). Bray- Curtis and Gower's coefficient were used to calculate the dissimilarity matrix (Faith et al., 1987), which was then applied to nMDS. NMDS was run on two, three and four dimensions, respectively, to test the stress value, which is an indicator for the goodness of fit between original distances and fitted values. The three- and four-dimensional model produced an insignificant reduction in stress, thus a two-dimensional model, being the most parsimonious model, was chosen.

In order to further explore the similarity/dissimilarity between different data sets, and to test the significance of any relationship found, Procrustes rotation and the associated PROTEST permutation test were applied to the ordination (nMDS) results. Procrustes rotation assesses the overall degree of correlation association between two or more ordination results through a Procrustean superimposition approach, where the results of the ordination are scaled and rotated to find an optimal superimposition that maximises their fit (Gower, 1971; Peres-Neto and Jackson, 2001). The lower the rotation sum of squares and the root mean square error (RMSE), the better the agreement between ordination results and their position of optimal fit. PROTEST is a permutation-based procedure, which assesses the degree of concordance between two matrices, producing a correlation-like statistic derived from the symmetric Procrustes sum of squares and an associated p value indicating the likelihood of the relationship occurring by chance (Jackson, 1995). As a control, the correlation of the data sets was also tested on the raw data using the Mantel test. Procrustes rotation and PROTEST were applied for the time frame 13.0 cal. ka BP to present, ignoring the dominant shift, in all data sets and all proxies, at the transition to the Bølling/Allerød to receive a more detailed picture on the trends during Holocene and the time period just before. All ordinations, Procrustes analyses and PROTEST (Peres-Neto and Jackson, 2001) were carried out in R (R Development Core Team, 2008) using the vegan package (Oksanen et al., 2008). The PROTEST function in R, which performs a random permutation test, was modified to allow restricted permutations for time series data (Besag and Clifford, 1989).

Climate evolution on the NE Tibetan Plateau is inferred from the pollen record. However, knowledge on pollen morphology and indicator taxa from vegetation records from arid central Asia is limited. Thus, the use of pollen ratios as semi-quantitative measures for temperature and precipitation is generally accepted (Herzschuh et al., 2006b; Herzschuh, 2007). Here, we applied the *Artemisia*/Cyperaceae ratio (A/Cy) as a semi-quantitative measure for temperature on the northeastern Tibetan Plateau.

For the quantitative reconstruction of annual precipitation in the Kuhai region a pollen-transfer function was applied to the fossil pollen record of Lake Kuhai. The modern pollen data set used for calibration consists of 112 modern surface-sediment samples from eastern Tibetan Plateau lakes which cover a wide range of mean annual precipitation and temperature values (104-670 mm and 4.0-17.4°C, respectively) (Herzschuh et al., 2010b). The transfer function employed a weighted averaging partial least squares regression model (WA-PLS, C_1), as it obtained the lowest root mean square error of prediction (RMSEP= 105 mm) and a high coefficient of determination (r^2= 0.77) between observed and predicted values for annual precipitation. The model was tested with and without the total pollen count of arboreal taxa to rule out the influence of long distance transport to the model. The reconstruction excluding arboreal taxa gave values that were on average 70 mm lower, however, the trends were consistent throughout the profile compared with the run with arboreal taxa included. Therefore, annual precipitation values based on the complete species set are presented only. More details on the modern pollen calibration set and the associated transfer function are described in Herzschuh et al. (2010).

To allow a semi-quantitative comparison of moisture information from different sites, a five-scale (-2, -1, 0, +1, +2) moisture index was applied to all available continuous palaeo-climate records from the Tibetan Plateau (Table 2.1, Fig. 2.9b). Criteria for record selection followed previous works from Herzschuh (2006). Lowest values (-2) indicate driest conditions, highest values (+2) indicate wettest conditions, whereas (0) indicates moisture conditions similar to today. These relative moisture curves were established on 100-year intervals, covering the Holocene time period (10 – 0 cal. ka BP). To detect regional patterns in moisture evolution over time, we thereafter, implemented a cluster analysis on the moisture codes (Fig. 2.9c). Gower's dissimilarity coefficient was chosen to create the distance matrix. Cluster analysis was implemented on different linkage methods. All methods produced similar high cophenetic correlation scores (0.48 – 0.68) and similar clusters, suggesting a very good representation of original distances in the dendrogram in all cases. However, the unweighted group average method (average link) was chosen for further analyses as it creates compact clusters, and it produced a high cophenetic score (0.68). Clustering was carried out in R (R Development Core Team, 2008) using the vegan and analogue package (Simpson, 2007; Oksanen et al., 2008; Simpson and Oksanen, 2009).

Table 2.1: Palaeo-climate records from the Tibetan Plateau used for temporal and spatial moisture comparison during the Holocene

N°	Name/section	N	E	Elev. m asl	Archive	Dating	Methods[**]	Reference
1	Lake Kuhai	35.3	99.2	4150	Lake	AMS ^{14}C	P, E, G, M, S, Os, dC, dO, X, O	Mischke et al., 2009a
2	Lake Koucha	34.0	97.2	4540	Lake	AMS ^{14}C	P, S, X, O, C, dC, dO, Os, M, E	Mischke et al., 2008, Herzschuh et al., 2009
3	Zoigê Plateau	32.4	103.3	3492	Peat	AMS & LS[*] ^{14}C	P, dC	Yan et al., 1999
4	Qinghai Lake	37.0	100.0	3194	Lake	^{14}C	S, P, X, C, O, dC, C/N	Shen et al., 2005
5	Zigetang Lake	32.0	90.9	4560	Lake	^{14}C	P	Herzschuh et al., 2006a
6	Hidden Lake	29.8	92.5	4980	Lake	^{14}C	P	Tang et al., 2000
7	Sumxi Co	34.6	80.3	5058	Lake	^{14}C	M, dC, dO, P, Os, D, O	Gasse et al., 1991
8	Hongyuan	32.7	102.5	3466	Peat	AMS ^{14}C	C, Co	Zhou et al., 2002
9	Siling Co	31.8	89.0	4500	Lake	^{14}C	C, dO, dC	Morinaga et al., 1993
10	Dunde	38.1	92.4	5325	Ice Core	Laminations	P	Liu et al., 1998
11	Tsokar Lake	33.2	78.0	4527	Lake	AMS ^{14}C	P, S	Demske et al., 2009
12	Naleng Lake	31.1	99.8	4200	Lake	AMS ^{14}C	P	Kramer et al., 2010b, 2010c
13	Ren Co	30.7	96.7	4450	Lake	^{14}C	P	Tang et al., 2000
14	Bangong Co	33.7	79.0	4241	Lake	^{14}C,U/Th	P	Van Campo et al., 1996
15	Yidun Lake	30.3	99.5	4470	Lake	AMS ^{14}C	P	Shen et al., 2006a

[*] LS – liquid scintillation ^{14}C dating

[**] Methods: C – carbonate content, C/N – carbon/nitrogen ratio, D – Diatoms, dC –carbon stable isotope, dO – oxygen stable isotope, E – element conc., G – grainsize, M – minerals, O – organic content, Os – ostracods, P – pollen, S – sediment describtion, X – X ray diffraction.

2.4 Results

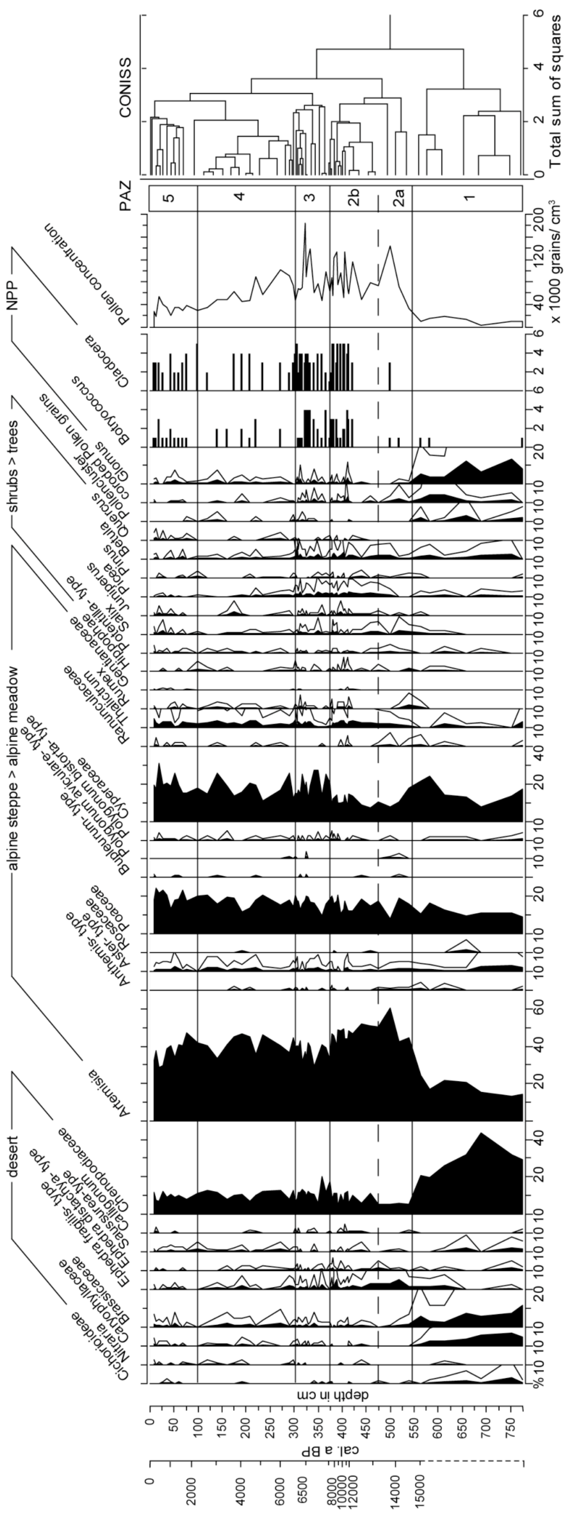
2.4.1 Lake Kuhai pollen record and precipitation reconstruction

Results from the pollen analysis are shown in Fig. 2.3. Stratigraphic changes and the results of the precipitation reconstruction are summarised in Table 2.2. *Artemisia*, Cyperaceae (*Kobresia* sp.), Poaceae and Chenopodiaceae dominate the whole pollen spectra, contributing to >10% each and adding up to >80% in most samples. Brassicaceae, Caryophyllaceae, *Ephedra, Thalictrum* and *Betula* contributed to the pollen spectra with moderately high abundances (1-5% in most samples). Based on the information from CONISS the record was divided into five pollen assemblage zones (PAZ).

In PAZ 1 (775.5 - 563.5 cm, > 14.8 cal. ka BP) the overall pollen concentration is very low. The assemblage is dominated by Chenopodiaceae, ranging between 19 and 43% abundance, accompanied by relatively high Brassicaceae (2 - 11%) and Caryophyllaceae (2 - 6%) values. The *Artemisia*/Cyperaceae ratio is low (1.7 - 2.0). Characteristic is the high frequency of the non-pollen palynomorph *Glomus* (3 - 13%). In PAZ 2 (563.5 - 373.5 cm, 14.8 cal. ka BP - 7.0 cal. ka BP) the total pollen concentration increases markedly. *Artemisia* pollen rise up to 60%, whilst Chenopodiaceae declines to < 5%. The *Artemisia*/Cyperaceae ratio increases to 3-8. Characteristic is the appearance of *Thalictrum* and *Ephedra* pollen and an increase in arboreal taxa (4 - 9%), such as *Salix*, *Picea*, and *Pinus*. PAZ 3 (373.5 - 301.5 cm, 7.0 cal. ka BP - 6.3 cal. ka BP) is characterised by an increase in Cyperaceae (up to 30%) whilst *Artemisia* decline, leading to a lower *Artemisia*/Cyperaceae ratio (1 - 3). PAZ 4 (301.5 - 99.5 cm, 6.3 cal. ka BP - 2.2 cal. ka BP) is marked by a decline in the total pollen concentration, which is linked to a decline in arboreal taxa (0.6 - 3.5%) and Cyperaceae (26 - 10%). Characteristic is the reappearance of *Nitraria*, Caryophyllaceae and Brassicaceae. In PAZ 5 (99.5 - 7.5 cm, 2.2 cal. ka BP - 0.3 cal. ka BP) *Artemisia* decline to 28 - 40%, whilst Poaceae (17 - 24%) and Cyperaceae (15 - 31%) increase, leading to a decline in the *Artemisia*/Cyperaceae ratio.

Table 2.2: Summary of the vegetation and lake evolution (Mischke et al., 2009a) of Lake Kuhai over the last >14.8 cal. ka BP

Depth (cm)	**Age (cal. ka BP)**	**Characteristic pollen taxa, pollen ratios (this study)**	**Reconstructed precipitation P_{ann} (mm) (this study)**	**Lake development (Mischke et al., 2009a)**	**Conclusion**	**PAZ**
778.5-563.5	> 14.8	Dominated by high Chenopodiaceae (19-43%), Brassicaceae (2-11%), and Caryophyllaceae (2-6%) values. A/Cy ratios are low (1.7-2.0). Characteristics are low total pollen concentration and very high *Glomus* frequencies (3-13%).	217 mm on average, Min 195 mm, Max 270 mm	Shallow small water body or several small water bodies	Dry, cold, alpine desert	1
563.5-475.5	14.8-13.6	Characterised by strong increase in total pollen concentration, dominated by *Artemisia* (24-60%), Cyperaceae and Poaceae. Strong decrease in Chenopodiaceae pollen. Relative high A/Cy ratios (3-8). Characteristic taxa are *Salix*, *Ephedra*	307 mm on average, Min 279 mm, Max 334 mm	Increasing lake levels	Semi-wet, semi-warm alpine steppe with tundra elements	2a
475.5-373.5	13.6-7.0	Similar as 2a, but declining A/Cy ratio (3-6). Characteristic taxa are *Thalictrum* and high total arboreal pollen frequencies (4-9%).	378 mm on average, Min 339 mm, Max 445 mm	Highest lake level and freshwater (12.8 -7.1 cal. ka BP)	Semi-wet, warm, alpine steppe	2b
373.5-301.5	7.0-6.3	Increase in Cyperaceae and decline in *Artemisia*, low A/Cy ratio (1-3)	391 mm on average, Min 283 mm, Max 526 mm	Lower lake level and increase in salinity	Wet, cold, high-alpine meadow	3
301.5-99.5	6.3-2.2	Decline in total pollen concentration on the expense of arboreal pollen (0.6-3.5%) and *Artemisia* (33-46%). A/Cy ratios also decline to 1-3. Characteristic taxon is Brassicaceae.	331 mm on average, Min 220 mm, Max 467 mm	Drop in lake level and rise in salinity(6.1 -5.4 cal. ka BP)	Dry, cold, alpine steppe with desert elements in the plains, high-alpine meadow in surrounding mountains	4
99.5-7.5	2.2-0.3	Characterised by a decrease of *Artemisia* (28-40%) and an increase of Cyperaceae (15-31%) and Poaceae (17-24%). Further decline in A/Cy ratio (0.9-3)	398 mm on average, Min 298 mm, Max 505 mm	Higher runoff since 2.7 cal. ka BP, increase in lake level since 0.6 cal. ka BP	Wet, cold, alpine steppe - meadow	5



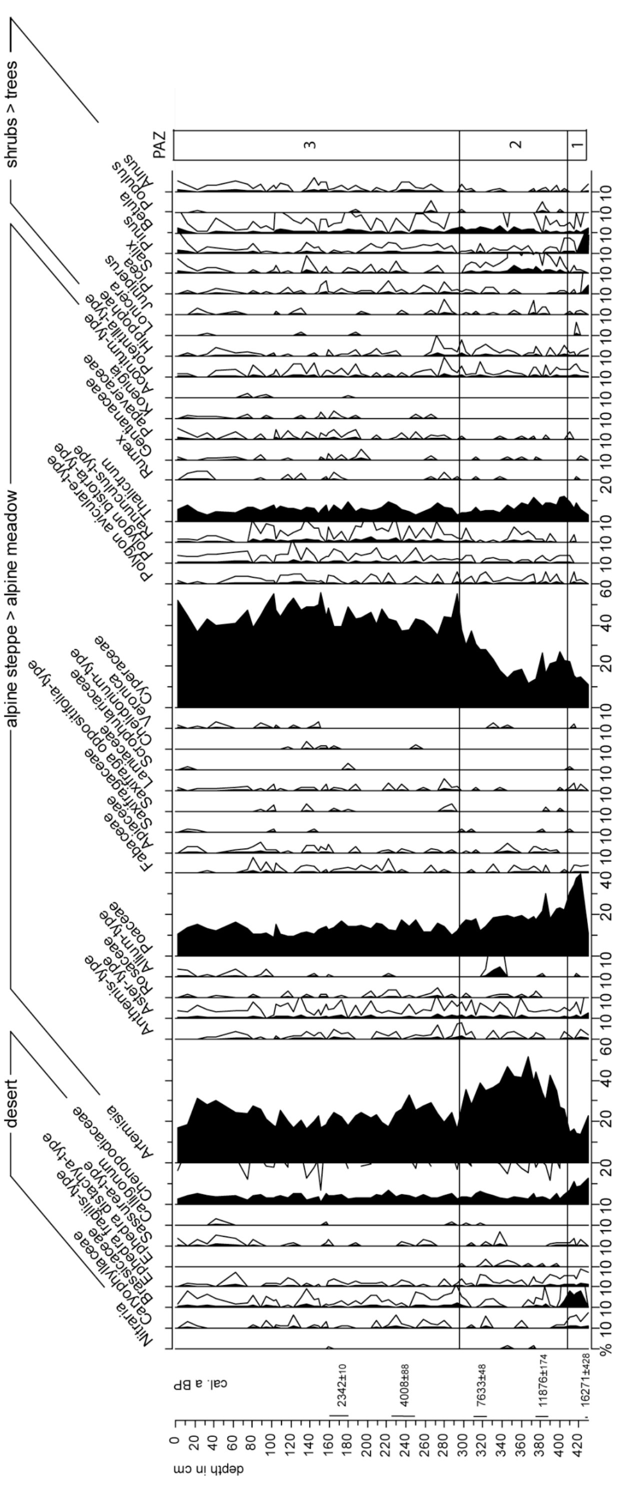


Figure 2.3 (left): Stratigraphic diagram presenting the results of palynological analysis of the Kuhai sediment core. Species in the pollen diagram are arranged in vegetation zones. The black filled silhouette represents original pollen abundance; the transparent silhouette in the background exaggerates the original abundance of rare species by four to ease visibility. The non-pollen palynomorphs (NPP) Botryococcus and Cladocera are presented as semi-quantitative data.

Figure 2.4 (right): Stratigraphic diagram presenting the results of palynological analysis of the Lake Koucha sediment core. The black filled silhouette represents original pollen abundance; the transparent silhouette in the background exaggerates the original abundance of rare species by a factor of six to ease visibility. The diagram is adapted and modified from Herzschuh et al. 2009.

A nMDS was performed to explore the relationships between samples and species composition in the Lake Kuhai pollen data set. The run on two-dimensional space produced a stress value of 24% (Table 2.3), which according to Clarke (1993) and Kruskal and Wish (1978) indicates a decent fit between the original distance of objects and the fitted values. Fig. 2.5 illustrates the nMDS ordination results based on Bray-Curtis distances in a biplot. The plot mirrors the different PAZ indicating major differences in species assemblages through time. Taxa grouping on the left side of the plot (e.g. Brassicaceae, Caryophyllaceae, and Rosaceae) are predominantly associated with samples older than 14.8 cal. ka BP, summarising elements of sparse alpine steppe and alpine deserts. Taxa on the right side of the plot (e.g. *Artemisia*, Poaceae, Cyperaceae, *Thalictrum*, *Betula* and *Juniperus*) are strongly correlated with samples younger than 14.8 cal. ka BP, summarising herbs, shrubs and trees typical of high-alpine meadow, alpine steppe and forest-steppe vegetation. Within the latter group the plot places older samples associated with *Ephedra*, *Betula* and *Picea* towards the positive end of the nMDS2 axis and the youngest samples at the negative end of the nMDS2 axis, which are strongly associated with Gentianaceae and Poaceae.

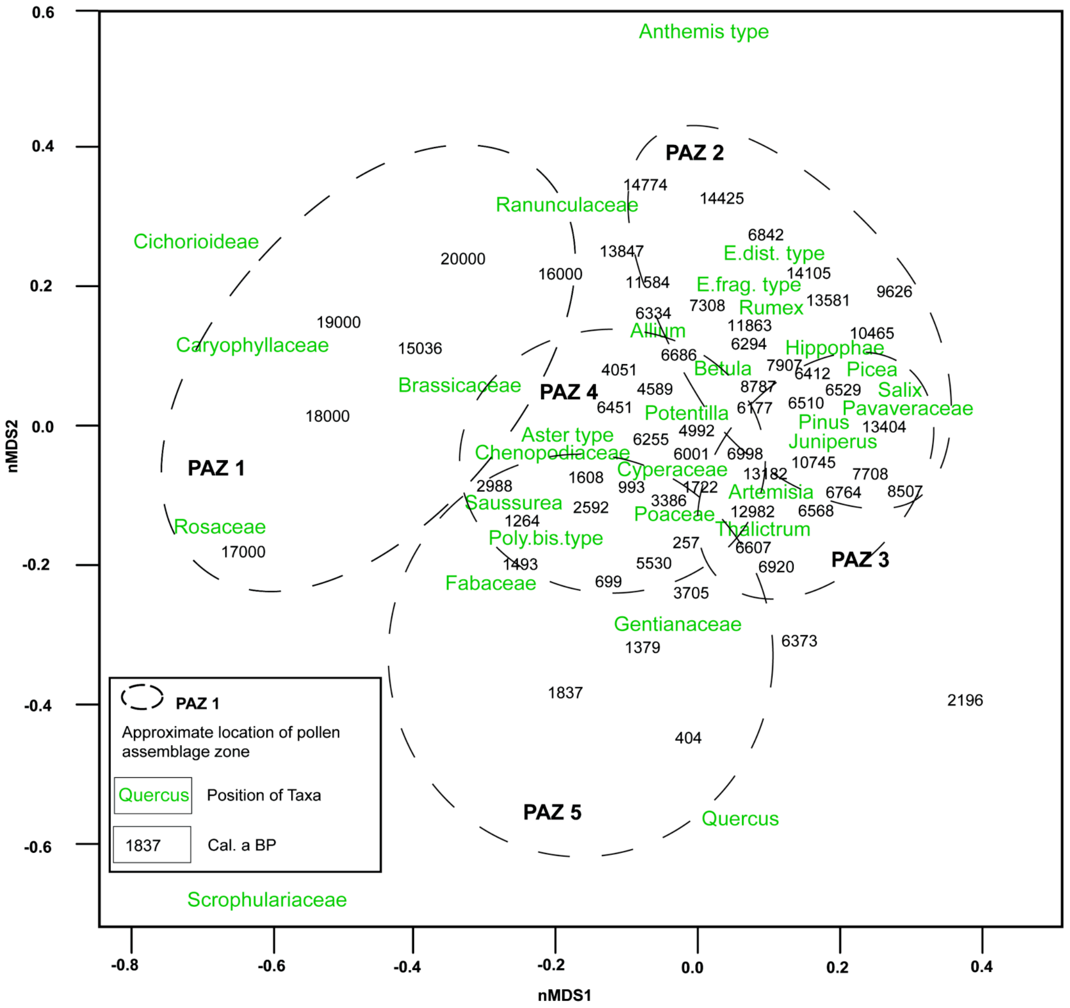


Figure 2.5: nMDS ordination results (2D) of Lake Kuhai pollen data using the Bray-Curtis distance coefficient. Only species occurring in at least 3 samples with > 1% abundance are shown.

Mean annual precipitation was inferred by the application of a pollen precipitation transfer function to the fossil Kuhai record (Fig. 2.6c). The precipitation reconstruction yielded values between 194 and 526 mm. Inferred annual precipitation for PAZ 1 was between 195 and 270 mm (on average 51% less than the present day value). It is the zone with the lowest precipitation rates in the record. These low values are clearly linked to the high abundance of Chenopodiaceae, Brassicaceae and Caryophyllaceae. PAZ 2 was marked by a sharp increase in annual precipitation rates. This resulted from the sudden increase in alpine steppe and scrubland taxa, such as *Artemisia, Salix* and *Betula*, and the decline of desert taxa. In PAZ 2 the increase in annual precipitation was steeper between 14.8 cal. ka BP - 13.6 cal. ka BP (PAZ 2a) with values between 280 and 335 mm (on average 31% less than the present day value) but flattened out towards the top of the zone (PAZ 2b) with values between 340 and 445 mm (on average 15% less than the present day value). The maximum annual precipitation values for the Lake Kuhai profile occurred in PAZ 3 with values between 280 and 526 mm (on average 12% less than the present day value). PAZ 4 was characterised by lower precipitation rates, ranging from 220 to 467 mm (26% below present day), which was indicated by the decline in arboreal taxa, and parallel increase in desert associated taxa, such as Brassicaceae and Caryophyllaceae. In PAZ 5 inferred precipitation increased again with values reaching as high as 298- 505 mm (10% below the present day value). Thus, despite the fact that the maximum annual precipitation value occurred in the PAZ 3, the zone with the highest mean annual precipitation rate was PAZ 5.

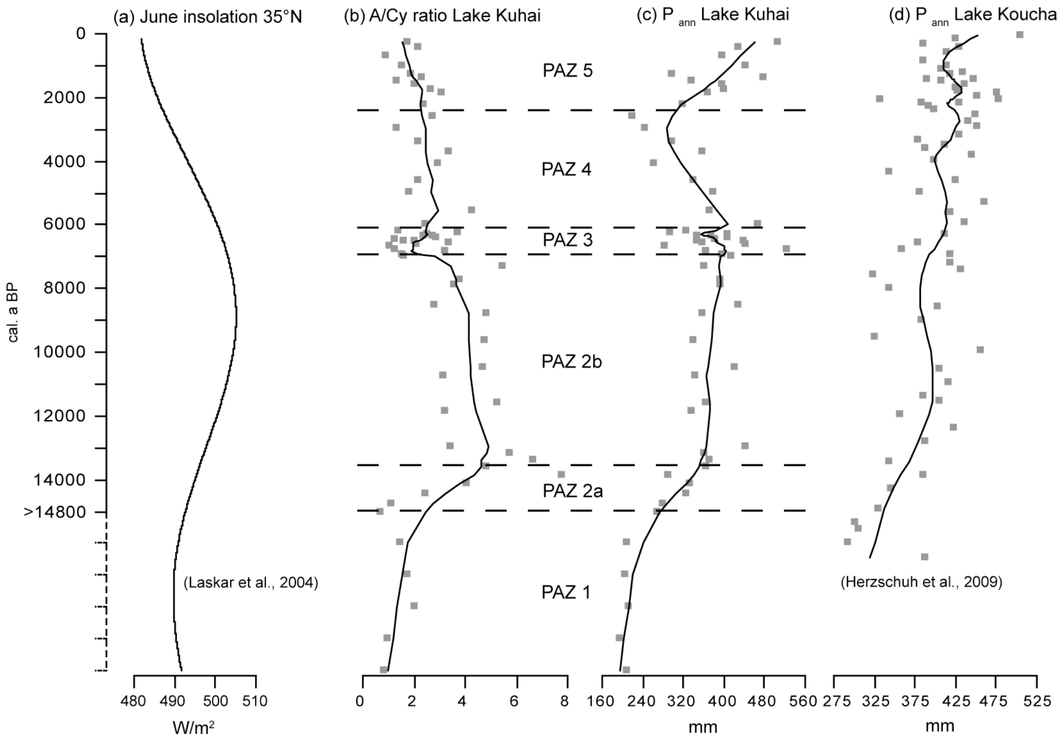


Figure 2.6: Comparison of Lake Kuhai record with Lake Koucha record. (a) Insolation data from Laskar et al., 2004. (b) Artemisia/Cyperaceae ratio of Lake Kuhai with lowess smoother. (c) Reconstructed annual precipitation for Lake Kuhai area, using a WA-PLS (C 1) regression model. Solid line is lowess smoother. (d) Reconstructed annual precipitation for Lake Koucha area, using a WA-PLS (C 1) regression model from Herzschuh et al., 2009. Solid line is lowess smoother.

2.4.2 *Procrustes rotation and PROTEST*

Procrustes rotation typically uses ordination results for the comparison of data sets. Therefore, nMDS was performed on the four harmonised data sets (supplementary information). All nMDS analyses produced moderately low stress values in a 2-dimensional ordination, suggesting a good fit between fitted values and the original distance (Table 2.3).

Table 2.3: NMDS stress scores and the applied distance measure. Kuhai pollen (original data set) contains original pollen data set from >14.8 cal. ka BP - 0 cal. ka BP. Other data sets are harmonised (simple linear interpolation) data matrices in 250-year intervals, covering 13.0 cal. ka BP - 0 cal. ka BP.

Data set	Distance measure	nMDS stress score (%) (2 dimensions)
(1) Lake Kuhai pollen record (original data set)	Bray Curtis	24
(1a) Lake Kuhai pollen record (250 yr time interval)	Bray Curtis	20
(2) Lake Kuhai lacustrine record (250 yr time interval)	Gower	8
(3) Lake Koucha pollen record (250 yr time interval)	Bray Curtis	24
(4) Lake Koucha lacustrine record (250 yr time interval)	Gower	11

Procrustes rotation was done on like-for-like data and results are given in Table 2.4. Fig. 2.7 is the illustration of the goodness of fit between two ordination results from two different data sets. The size of residuals for each time slice between 13.0 cal. ka BP and 0 cal. ka BP is shown. Low residuals indicate a good agreement between data sets, high residuals indicate a weak agreement. Procrustes and PROTEST results indicate that the best fit was produced between both lacustrine records, followed by the fit between the Lake Kuhai pollen record and the Lake Kuhai lacustrine record. Nonetheless, a number of time slices display a lower degree of similarity in their ordination results. The fit between both pollen records as well as the fit between the Lake Koucha pollen and Lake Koucha lacustrine record produced relatively high p values, suggesting a poor match between data sets (Table 2.4).

Table 2.4: Procrustes rotation and PROTEST diagnostics

Tested records	Procrustes rotation sum of squares	RMSE	PROTEST (r)	p value
(a) Kuhai pollen vs. Kuhai lacustrine	0.53	0.10	0.68	0.019
(b) Koucha pollen vs. Koucha lacustrine	0.61	0.11	0.62	0.057
(c) Kuhai pollen vs. Koucha pollen	0.56	0.10	0.66	0.057
(d) Kuhai lacustrine vs. Koucha lacustrine	0.48	0.09	0.72	0.019

2.4.3 *Cluster analysis of Tibetan moisture records*

Average link clustering produced three notably different groups as indicated by their dissimilarity scores (Fig. 2.9c). Lake Kuhai, Lake Koucha and a peat record from the NE Plateau (Zoigê Plateau peats) cluster within one group together with lake records from the SE and SW Tibetan Plateau. Lake Qinghai, Lake Zigetang and the Dunde ice core record group within the second cluster. A third cluster summarises, with the exception of Bangong Co Lake, records from the S and SE Tibetan Plateau.

2.5 Discussion

2.5.1 Critical assessment of the data

We are aware of limitations that may have reduced the robustness of our vegetation and climate reconstruction.

(1) The definition of the pollen source area and the estimation of the proportion of long distance transported pollen are generally difficult for large lakes such as Lake Kuhai (Jacobson and Bradshaw, 1981). On the one hand long distance transport increases with increasing lake size (Jacobson and Bradshaw, 1981), on the other hand it was found to be higher in sparse Tibetan deserts and steppes than in forests and meadows (Shen et al., 2005; Herzschuh et al., 2006a; Herzschuh, 2007). The Lake Kuhai pollen spectra may therefore be influenced by a varying long distance transport signal.

(2) The annual precipitation inferred from the transfer function model for the top of the profile was 140 mm above the present day local mean of annual rainfall. The size of Lake Kuhai is considerably larger than other lakes in the calibration set and therefore has a much larger pollen source area that may include areas of lower elevation with vegetation corresponding to warmer and/or moister climates. The pollen precipitation transfer function therefore overestimates absolute values of annual precipitation. The difference between modelled and measured values can also result from no-analogue scenarios, i.e. the change in lake size during the Lateglacial period and the Holocene possibly resulted in changes in the pollen source area and could cause erroneous transfer function results. Furthermore, the reliability of quantitative climate reconstructions from glacial flora is limited due to formerly low CO_2 concentrations that supported the expansion of drought resistant vegetation causing under-estimation of precipitation from pollen records (Jackson and Williams, 2004; Wu et al., 2007). Therefore, whilst absolute precipitation values contain slight error, moisture trends may be interpreted with more confidence.

(3) The pollen samples were evenly distributed throughout the Lake Kuhai profile, but due to changes in the sedimentation rate, the temporal resolution of the pollen record ranged between ca.150 yrs in PAZ 5 and ca. 400-800 yrs at the Pleistocene-Holocene boundary. Therefore, it was not possible to either detect the exact timing of the onset of the climate optimum, or to isolate the possible impacts of the Younger Dryas or 8.2 ka event (Alley and Ágústsdóttir, 2005). To be able to statistically compare Lake Kuhai and Lake Koucha, both records were interpolated and resampled to gain a common age stratigraphy. This may have produced deviant results for time slices that were not actually analysed. However, all interpolated and resampled data were thoroughly compared to the original data set to guard against false interpretations.

2.5.2 Lake Kuhai response to climate variability

Sparse alpine desert vegetation and low reconstructed precipitation were characteristic of the Lake Kuhai area prior to 14.8 cal. ka BP. The relatively high abundance of *Betula* and *Picea* pollen during that period, likely linked to long distance transport, confirms these findings of low regional vegetation cover (Herzschuh et al., 2009; Schlütz and Lehmkuhl, 2009). Likewise, Mischke et al. (2009) found that Lake Kuhai at that time was a small shallow water body with low organic and carbonate content and poorly sorted lake sediments confirming that cold and dry climate conditions dominated the region before 14.8 cal. ka BP.

The expansion of alpine steppe vegetation during Bølling/Allerød and the early Holocene (14.8 cal. ka BP - 7.0 cal. ka BP) and reconstructed intermediate precipitation rates indicate higher temperature and moisture availability than before. Likewise, Mischke et al. (2009) found highest lake levels between 12.8 cal. ka BP and 7.1 cal. ka BP for Lake Kuhai inferred from its lacustrine record. By 7.0 cal. ka BP high-alpine meadows expand (dominated by *Kobresia*) at the expense of alpine steppe vegetation, which led to an increase in the reconstructed precipitation rates. However, this pollen-based moisture reconstruction is in contradiction to the finding of lake level lowering and increasing salinity by Mischke et al. (2009). Herzschuh et al. (submitted) proposed that besides climate change an increase in the atmospheric CO_2 during the early and mid-Holocene could have supported the expansion of mesic *Kobresia* on the TP in areas formerly dominated by drought-resistant *Artemisia*. In that case the pollen-based moisture reconstruction would over-estimate the moisture increase during that time.

The occurrence of typical desert elements in the alpine steppes around the lakes and very low reconstructed annual precipitation rates indicate strong aridity between 6.3 cal. ka BP and 2.2 cal. ka BP. Mischke et al. (2009) recorded a significant drop in water level and further rising salinity between 6.1 cal. ka BP and 5.4 cal. ka BP, confirming the arid conditions reconstructed from the Lake Kuhai pollen record. However, *Kobresia* meadows in high-alpine mountain regions did not retreat during that time as indicated by a further decline of the A/Cy ratio.

A wide expansion of alpine steppe meadow vegetation with a high content of *Kobresia* and high reconstructed annual precipitation rates in the last 2000 years correspond very well with the findings from Mischke et al. (2009), who recorded a significant increase in runoff volumes entering the lake around 2.7 cal. ka BP and increased lake levels since 0.6 cal. ka BP, indicating high effective moisture for the most recent period of the Holocene.

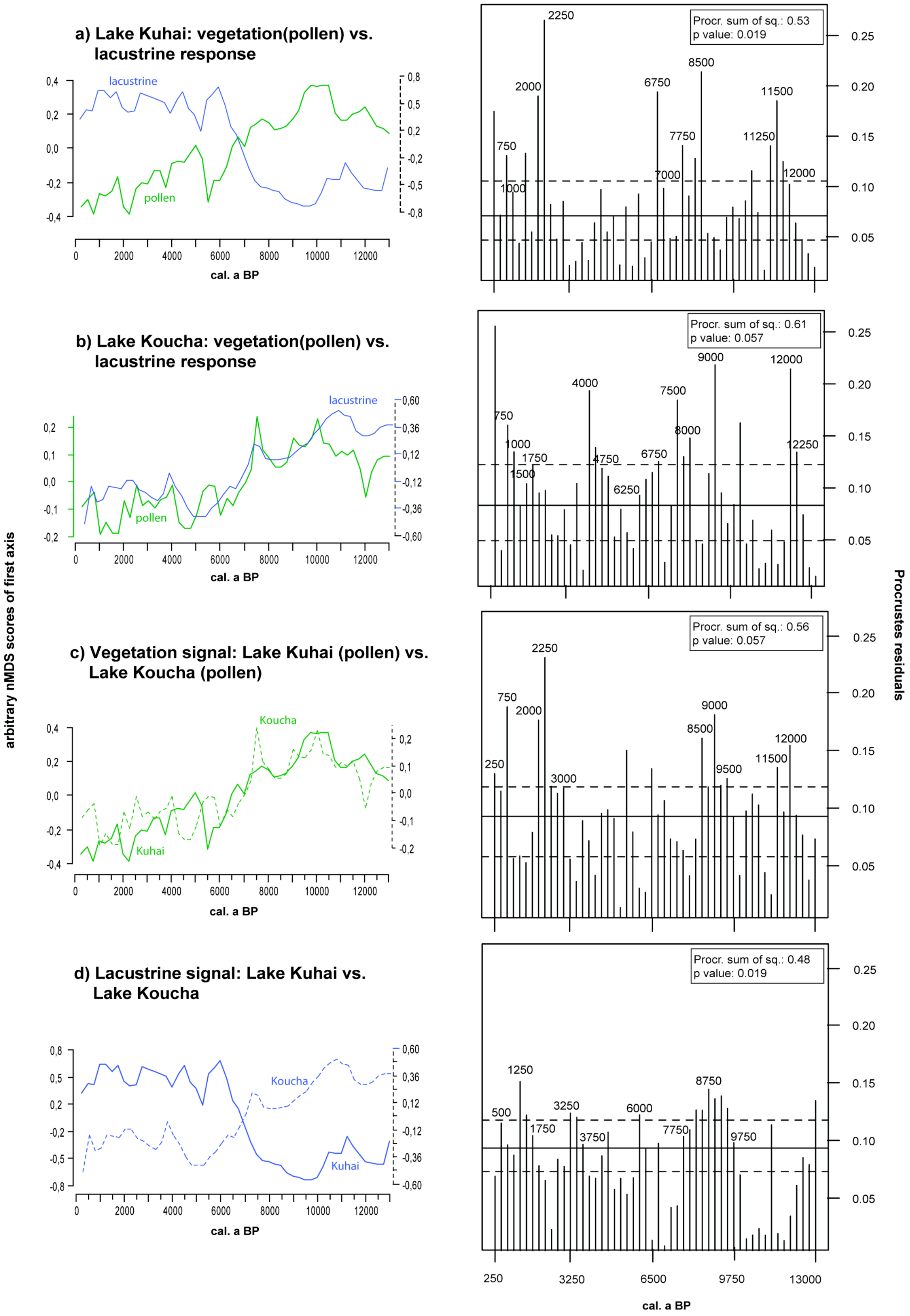


Figure 2.7: NMDS axis 1 scores and impulse diagram of Procrustean rotation residuals. NMDS and Procrustes rotation were preformed on harmonised data sets in 250-year intervals between 13 cal. ka BP and 0 cal. ka BP. Height and occurrence of peaks in the impulse diagram indicate the degree of dissimilarity between the two data sets compared. Dashed and solid lines across indicate the first, second and third quartile, respectively.

This general good agreement between the pollen and lacustrine record from Lake Kuhai was also established by our ordination and Procrustes rotation results, confirming our hypothesis that Lake Kuhai and its surrounding vegetation respond in analogous ways to climate and/or atmospheric induced changes. Both records show a similar timing and magnitude of response to environmental impulses (Fig. 2.7a). However, time periods of a less good fit were identified. High Procrustes residuals were found between ca. 12.0 cal. ka BP and 11.2 cal. ka BP, around 8.5 cal. ka BP - 7.7 cal. ka BP, and the period around 2.2 cal. ka BP, which mainly correspond with rather rapid changes in the elementary composition and grainsize distribution in the lacustrine record, and only time-lagged and smoothed changes in the pollen assemblage. This suggests that the lacustrine record partly responds more quickly to short lived, perhaps local events, whereas the pollen record provides a more smoothed regional scale response.

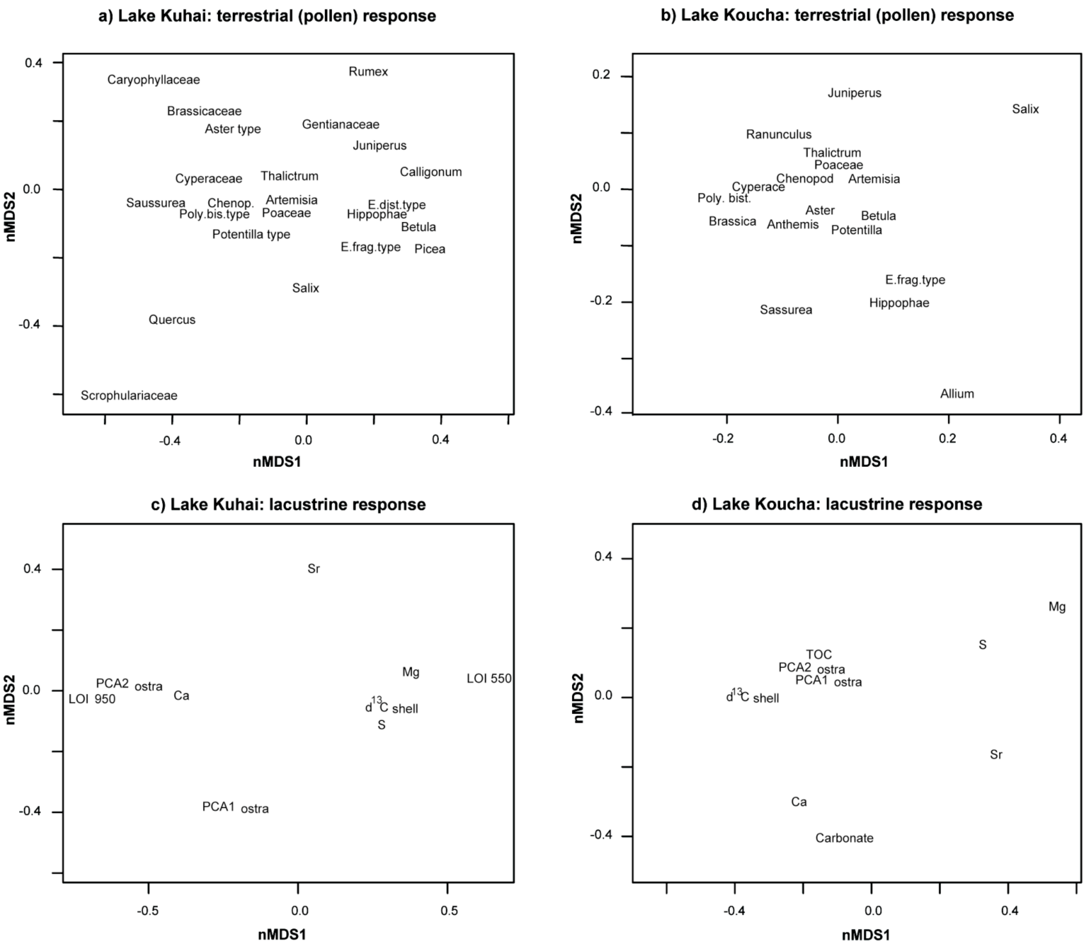
Other multi-proxy studies have shown differences in proxy response (Larocque and Bigler, 2004; Dalton et al., 2005; Anderson et al., 2008) and have pointed out the difficulties in linking these differences to external forcing, and not to in-lake processes and individual proxy response. Dalton et al. (2005) showed in a comprehensive multi-proxy study at Lochnagar, Scotland, that the correlation between sedimentary and biological proxies varied from good to poor. They explained these differences by proxy-specific sensitivities and insensitivities to environmental changes, but also assumed that inconsistency in the sampling resolution causes a mismatching between proxies.

This underlines the importance of a multi-proxy approach and the combination of lacustrine and terrestrial proxies (both biotic and abiotic) to prevent misleading regional climate interpretation due to local events on the one hand, but also to assure the detection of short lived and local climate events on the other hand.

2.5.3 *Regional ecosystem development*

Mischke et al. (2008) and Herzschuh et al. (2009) reported on lake sediments from Lake Koucha, a site 230 km southwest of Lake Kuhai (Fig. 2.1), to date representing the nearest palaeo-ecological record to Lake Kuhai on the upper Tibetan Plateau. The Lake Koucha lacustrine record revealed that the highest lake level occurred between 7.3 cal. ka BP and 4.3 cal. ka BP (Mischke et al., 2008), whereas the major shift in the Lake Koucha pollen record from *Artemisia*-dominated steppes to *Kobresia*-dominated meadows occurred at ca. 6.6 cal. ka BP (Fig. 2.4). *Kobresia* meadows dominate in the vicinity of the lake until present (Herzschuh et al., 2009). Our Procrustes analyses yielded a poor Procrustean rotation fit with high residuals confirming these discrepancies (Fig. 2.7b).

The Lake Koucha records were directly compared with the corresponding Lake Kuhai records to evaluate the differences or similarities of regional ecosystem response to climate and/or atmospheric variability. The comparison of the Lake Koucha and Lake Kuhai pollen record revealed a general similarity between both vegetation records even though the climate inferences were at times partially contradictory (Fig. 2.6c, 2.6d and 2.7c). The species composition in both records was very alike, with *Artemisia*, Cyperaceae, Poaceae and Chenopodiaceae dominating both pollen spectra, contributing to more than 70% in most of the samples (see Fig. 2.3 and 2.4). However, due to its smaller lake size the Lake Koucha has a significant smaller pollen source area and pollen spectra are therefore less influenced by far transported pollen grains as indicated by the smaller arboreal pollen sum in Lake Koucha pollen record. Also due to its position further to the south and at higher altitude the share of *Kobresia* meadows in the modern vegetation of the pollen source areas is higher than at Lake Kuhai which is also indicated by the generally higher content of Cyperaceae in the Lake Koucha pollen spectra. However, both catchments were characterised by a significant change from alpine steppe-desert vegetation to alpine steppe vegetation with tundra elements at the Bølling/Allerød interstadial, which lasted until 6.6 (Koucha)/7.0 (Kuhai) cal. ka BP, thereafter *Kobresia* meadows expanded. However, after 6.3 cal. ka BP the Lake Kuhai record revealed a marked increase in desert elements whilst this trend is not so obvious at Lake Koucha. The last ca. 2000 years have been relatively variable in both records showing a tendency of a decreasing *Artemisia*/Cyperaceae ratio. Hence, apart from the period 6.3 cal. ka BP - 2.2 cal. ka BP where desert elements increased in the alpine steppes around Lake Kuhai, there was analogous vegetation development. The ordination and Procrustes rotation results confirm these observations. Procrustes rotation produced a fairly poor fit ($p = 0.057$) between both pollen records. According to the nMDS scores, the main direction of pollen response was very similar (Fig. 2.7c, 2.8a and b), however, the timing and magnitude of change varied between the two records, suggesting that vegetation had different response times to atmospheric induced changes (in terms of climate or CO_2 concentration changes). This is particularly likely when one vegetation zone is closer to a transition point than another. Higher residuals were found between 9.5 cal. ka BP - 8.5 cal. ka BP, 3.0 cal. ka BP - 2.0 cal. ka BP and 750 cal. a BP - 250 cal. a BP (Fig. 2.7c). Between 9.5 cal. ka BP - 8.5 cal. ka BP and 3.0 cal. ka BP - 2.0 cal. ka BP relatively fast changes occurred in Lake Kuhai pollen assemblage whilst relatively stable vegetation conditions prevailed at the Lake Koucha pollen record, suggesting that the Lake Kuhai vegetation was closer to a transition point. High residuals between 750 cal. a BP - 250 cal. a BP could be indicators of anthropogenic influence in both regions and could be the cause of higher variability and therefore mismatches in both data sets. Notwithstanding the slight discrepancies in the timing and magnitude of vegetation response, there was a good accord between the two records of vegetation change, strongly indicating parallel forcing. Nevertheless, the implication of the precipitation transfer function produced partially different results for both lakes, which on the one hand can be explained by the deviant vegetation development at Lake Kuhai between 6.3 cal. ka BP and 2.2 cal. ka BP, and on the other hand by a varying pollen source area and altitude differences between both lakes.



a) Lake Kuhai: terrestrial (pollen) response

b) Lake Koucha: terrestrial (pollen) response

c) Lake Kuhai: lacustrine response

d) Lake Koucha: lacustrine response

Figure 2.8: nMDS (2D) ordination species plot from harmonised data sets in 250-year intervals and from 13 cal. ka BP - 0 cal. ka BP.

The lacustrine records from Lake Kuhai and Lake Koucha, on the other hand, show a rather complicated picture: The Procrustean rotation produced a highly significant fit with very low residuals, suggesting a similar response to atmospheric-induced changes (Fig. 2.7d). The nMDS scores of the first ordination axis, suggested that the timing and magnitude of lake response was very similar between the data sets and resulted in the significant Procrustean fit, however, the direction of change was for some time periods totally different (Fig. 2.7d, 2.8c and d). This implies that whilst both lakes received the same atmospheric/environmental impulse, as suggested by both pollen records, the lake-systems reacted, at times, in contradictory ways. For instance, Mischke et al. (2008 and 2009) reconstructed opposite lake level states for the early Holocene (high at Lake Kuhai; low at Lake Koucha) and therefore different climate trends, for Lake Koucha and Lake Kuhai. Our results indicate that both catchments were very likely influenced by the same moisture impulses. Our study shows that the increase of e.g., TOC or Ca in one lake and the parallel decrease of TOC or Ca in a proximal lake do not necessarily reflect divergent atmospheric or environmental impulses, but rather reflect the unique nature of each lake system and/or each proxy.

This complexity often makes it difficult to disentangle response to in-lake or catchment processes from external or regional climate forcing. These problems in interpretation are exacerbated when lacustrine records are analysed in isolation, as there is a possibility of effects from local events, or lake specific processes. This is particularly true when lakes have a different genesis and/ or morphology as it is often the case on the Tibetan Plateau and which is also true for Lake Kuhai (closed saline lake) and Lake Koucha (open freshwater lake). Additionally, the influence of the different extent of degrading permafrost across the Tibetan Plateau during early Holocene may have played an essential role in site-specific lake development and therefore lacustrine proxy response. Pollen records have the potential to respond to a more regional and smoothed climate signal, however vegetation changes may have been driven by CO_2 changes (Prentice and Harrison, 2009) additionally to climate and/or human forcing. Therefore, a combination of lacustrine and terrestrial records is vital.

There are few other studies, which followed the multi-proxy approach at more than one site but very often a direct comparison of the different proxies between sites was not done. Ilyashuk and Ilyashuk (2007) looked at chironomid-inferred climate changes in two proximal lakes in the Altai Mountains detecting no considerable discrepancies in the climatic and environmental inferences. However, both chironomid records revealed discrepancies during the early/mid Holocene possibly caused by differences in the hydrological regime of both lakes (open basin vs. closed basin lake). The comparison with the pollen and chironomid records of these lakes (Blyakharchuk et al., 2004; Westover et al., 2006) revealed some discrepancies in the pollen and chironomid based reconstructions. Ilyashuk and Ilyashuk (2007) explained these discrepancies with different controlling factors of aquatic and terrestrial biological indicators.

According to Battarbee (2000) even lakes that are in close proximity can have fundamentally different properties and different climate sensitivity thresholds and therefore respond to external forcing in unique ways, which, in combination with often uncertain age models, makes it difficult to move from a local to a regional scale. For that reason, the only way to gain knowledge on general climate pattern on the Tibetan Plateau is to establish a dense network of multi-site and multi-proxy records and high resolution dating to separate local and lake specific processes from regional processes (Ammann and Oldfield, 2000; Battarbee, 2000; Lotter, 2003; Lotter and Birks, 2003).

2.5.4 Lake Kuhai ecosystem response in comparison to other palaeo-climate records from monsoon sensitive regions

Reviewing available literature and comparing the moisture evolution inferred from the Lake Kuhai pollen record with other palaeo-climate records from the Tibetan Plateau, it was not straightforward to find moisture trends that matched in time and space. The initial increase in moisture and warming at about 14.8 cal. ka BP as indicated by the Lake Kuhai pollen record, is generally in phase with several other records on the Tibetan Plateau. Both, the pollen record from Lake Koucha and also from Lake Qinghai, which are the closest pollen records to Lake Kuhai, show a similar shift from alpine desert vegetation with high percentages in Chenopodiaceae, *Ephedra*, and Brassicaceae pollen to alpine steppe vegetation dominated by *Artemisia* pollen and increasing abundances of *Betula* and *Picea* (Shen et al., 2005; Herzschuh et al., 2009). Furthermore, other sedimentary, peat and pollen records further southeast on the Tibetan Plateau indicate major climatic shifts during the Lateglacial (Yan et al., 1999; Zhang and Mischke, 2009; Kramer et al., 2010b). Significant increases in lake levels in the westernmost records of Lake Sumxi Co and Lake Bangong and a $\delta^{18}O$ rise in the Guliya ice core at ca.14.0 cal. ka BP additionally suggest a synchronous warming and increased moisture across the Tibetan Plateau during the Lateglacial which is generally in phase with the Greenland Interstadial-1 (Thompson et al., 1997; Björk et al., 1998).

However, moisture trends in pollen and non-pollen records during the Holocene are less uniform and differ significantly between records. To allow a semi-quantitative comparison of moisture information from different sites across the Tibetan Plateau we applied a five-scale moisture index to all available continuous palaeo-climate records from the Tibetan Plateau (Fig. 2.9b).

The moisture coding (Fig. 2.9b), based on the pollen-based precipitation reconstruction (Fig. 2.6c), revealed that Lake Kuhai experienced a period of relatively high effective moisture much earlier than other records (12.9 cal. ka BP - 6.2 cal. ka BP). Generally wet sites on the Tibetan Plateau show evidence of highest effective moisture much later (e.g., Zoigê Plateau peats at 4.5 cal. ka BP - 2.5 cal. ka BP, Yidun Lake at 9.0 cal. ka BP – 2.5 cal. ka BP, Naleng Lake at 9.5 cal. ka BP – 4.4 cal. ka BP) but also sites that have a similar moisture regime as the Kuhai Lake region today suggest that highest effective moisture conditions were not earlier than 9.0 cal. ka BP - 7.2 cal. ka BP (Bangong Co Lake), 8.3 cal. ka BP - 6.8 cal. ka BP (Sumxi Co Lake) or 7.3 cal. ka BP – 4.4 cal. ka BP (Zigetang Lake).

The timing of the decline to drier and colder climate conditions around 6.3 cal. ka BP recorded at Kuhai Lake is generally in phase with numerous records on the Tibetan Plateau (e.g., Sumxi Co Lake at 6.3 cal. ka BP, Zoigê Plateau peats at 6.3 cal. ka BP, Siling Co Lake at 6.3 cal. ka BP), which is synchronous with gradual decreasing of northern hemisphere solar insolation and hence, with a weakened summer monsoon activity (Overpeck et al., 1996; Dykoski et al., 2005).

The re-establishment of increased available moisture and a colder climate from 2.2 cal. ka BP reflected by the Lake Kuhai pollen record is in agreement with a number of records from Central Asia (e.g., Dunde ice core, Yidun Lake, Lake Koucha). This initial trend to colder conditions seems to be correlated with the largest glacier advance on SE Tibetan Plateau during the last two millennia between 1.8 cal. ka BP – 1.3 cal. ka BP (Yang et al., 2008a).

This record-time-slide comparison, however, is independent from the site location across the Tibetan Plateau. For a more temporal *and* regional picture we applied a cluster analysis (Fig. 2.9c). Apart from the very coarse generalisation that wettest conditions end between 7.0 cal. ka BP - 4.0 cal. ka BP and that the majority of sites is drier in the second part of the Holocene, results have shown that there is no obvious spatial pattern through time (Fig. 2.9a, 2.9b). Fig. 2.9 shows that even sites that are located close to each other (Fig. 2.9a) reveal different moisture trends over time (Fig. 2.b), and therefore plot in different clusters (Fig. 2.9c).

Lake Kuhai clusters together with Lake Koucha, a peat record from the NE Tibetan Plateau (Zoigê Plateau peats) and Yidun Lake from the SE Tibetan Plateau, suggesting that their moisture development during the Holocene could be linked to the variability of the SE Asian summer monsoon. However, Sumxi Co Lake and Tsokar Lake from the western Tibetan Plateau, where the influence of the SE Asian summer monsoon is less likely, cluster within the same group. The second cluster from Naleng Lake to Siling Co Lake possibly summarises records that are strongly influenced by the Indian summer monsoon, however, the cluster also includes records from the western and NE part of the Tibetan Plateau (i.e., Bangong Co Lake and Hongyuan peats) which disprove that hypothesis. Within the third cluster, Qinghai Lake and the Dunde ice core exhibit sites that could be stronger influenced by the westerlies, but Zigetang Lake from the central Tibetan Plateau does not meet this criteria. Overall, these results indicated that the moisture development during the Holocene on the Tibetan Plateau is not strictly linked to regional circulation regimes.

We understand that the moisture coding and the resulting clusters underlie certain weaknesses and uncertainties, which might have lead to false conclusions. Age control introduces a degree of uncertainty and the possible influence of human impact on these records is often not discussed or difficult to quantify. Animal husbandry could be traced back to earlier than 1000 a BP in the Nianbaoyeze Mountains (Jarvis and Clay-Poole, 1992; Schlütz, 1999), but a consistent pattern in space and time cannot be identified. Furthermore, this study has established that reconstructions of moisture trends based on single proxies within a study site and on different proxies between studies sites make comparison problematic. In addition, we demonstrated that interpretation of these proxies remains complex, as it is often difficult to disentangle the effects of moisture and/or temperature changes and the effects of local and regional processes. Furthermore, pollen are one of the most frequently used proxies for climatic change and may have markedly contributed to the lack of uniformity in the inferred climatic signal. Herzschuh et al. (submitted) proposed that vegetation on the upper Tibetan Plateau is particularly sensitive to atmospheric CO_2 concentration changes, complicating the interpretation of pollen records. The vulnerability of the vegetation depends on the vegetation composition and on the absolute CO_2 concentration and its magnitude of change. Herzschuh et al. (submitted) argue that especially pollen records in the semi-arid transition zone from alpine steppes to high-alpine meadows may have responded to even small CO_2 changes during the Holocene, causing misleading climate inferences from pollen records in that region.

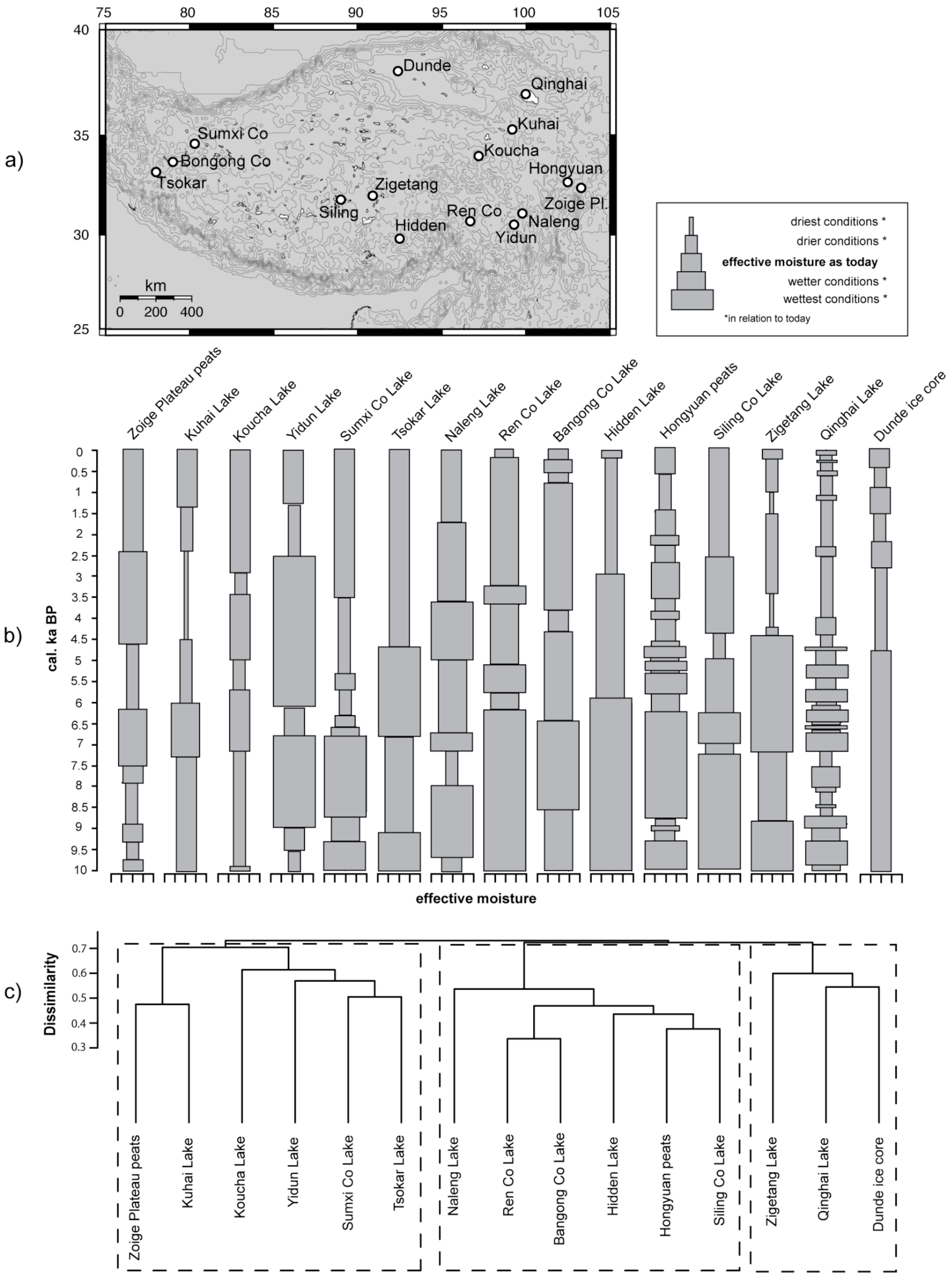


Figure 2.9: Comparison of effective moisture in the Lake Kuhai area with other pollen and non-pollen records from the Tibetan Plateau, using a five-scale moisture index. The increasing or decreasing width of the grey filled boxes corresponds to the higher or lower effective moisture relative to today's moisture within each record (2.9b). Clustering was carried out with the average link clustering method. Dashed lines indicate significantly different clusters of lakes (2.9c).

Hence, with all the records available at present and the current level of understanding and interpretation of proxy response to climate variability it is still very difficult to find coherent regional and temporal patterns of moisture evolution on the Tibetan Plateau. At a high altitude, in particular, even small differences in elevation can cause significant differences in microenvironments. Herzschuh (2006) proposed that asynchronous climate changes on the Tibetan Plateau might be caused by spatial differences between dominant circulation mechanism and by local differences in the uplift and decent of air masses. Here, we propose that the unique nature of each catchment and lake system and the distinct reaction of lacustrine and terrestrial (both abiotic and biotic) proxies to atmospheric/climatic and local environmental change due to their different sensitivities and time lags in their response, add to that complexity of reconstructed moisture patterns across the Plateau which make it difficult to identify temporal and spatial patterns of climate evolution on the Tibetan Plateau. To be most effective, a dense network of multi-site, multi-proxy studies in combination with fine resolution dating is necessary to decipher the effects of in-lake or catchment processes and climate forcing and to deepen our knowledge on general climate patterns within the complicated mountain landscape.

2.6 Conclusions

Our pollen and lacustrine records from Lake Kuhai and Lake Koucha, show that cold and dry climate conditions prevailed before 14.8 cal. ka BP on the NE Tibetan Plateau. Much warmer and wetter conditions dominated the early and mid Holocene, with highest effective moisture between 12.9 cal. ka BP and 6.2 cal. ka BP. Major vegetation shifts took place during Bølling/Allerød. The often-discussed abrupt climate shift at the Pleistocene/Holocene transition is not pronounced in our lake records. No strong evidence of human impact is detected. In addition, the comparison between lacustrine and pollen records from Lake Kuhai and Lake Koucha demonstrates that lacustrine record response may be driven by in-lake or catchment processes. To move from a local to a regional scale the combination of both, lacustrine and terrestrial records, is necessary. Furthermore, the comparison between sites (Lake Kuhai vs. Lake Koucha) illustrates that even sites in close proximity may react differently, and therefore may lead to conflicting inferences. To rule-out the possibility of local peculiarities, multi-site investigations are essential. The attempt to group Holocene records across the Tibetan Plateau into regional clusters of similar climate history partially failed. No coherent regional and temporal patterns of moisture evolution on the Tibetan Plateau could be identified. Uncertainties in age models, spatial differences in circulation mechanisms, changing atmospheric CO_2 concentration during the Holocene and its possible influence on vegetation dynamics, the possibility of local noise in proxy records, and the uncertainty of possible anthropogenic impacts make it difficult to find a good explanation of moisture evolution during the Holocene on the Tibetan Plateau.

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3 Muted diatom responses to environmental change 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, a dense network of palaeolimnological investigations is necessary to decipher these climatic patterns and to understand bioecological response to recent environmental change. Here we present palaeolimnological results from a 210Pb/137Cs dated sediment core from a remote high mountain lake (LC6 Lake, working name) on the southeastern Tibetan Plateau spanning approximately the last 200 years. Sediment profiles of diatoms, organic parameters (TOC, C:N) and grain size were investigated. The 210Pb record suggests a period of rapid sedimentation, which might be linked to major tectonic events in the region ca. 1950. Furthermore, unusually high 210Pb 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, but were 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 20th 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 assemblage. Local and/or regional peculiarities, such as increasing precipitation and cloud cover, localized

climatic phenomena or other biogeochemical processes, may have antagonised the effects of increasing mean surface temperatures.

3.1 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 temperatusres (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., 2010c). However, to date few and spatially widespread studies have investigated environmental changes on the Tibetan Plateau during the last two centuries – a time period strongly effected 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; Thompson et al., 2000; Thompson et al., 2006; Yang et al., 2006; Hou et al., 2007). However, focussing on individual regions of the Plateau, differences in temperature and precipitation trends become obvious. 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, to our knowledge, only two 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). Bräuning and Mantwill (2004) reconstructed a general increase in Indian summer monsoon activity after 1980 A.D. in their study area, although regional differences were noted in terms of temperature trends. For example, some growth regions on the southeastern Tibetan Plateau were indicative of warmer temperatures whereas other growth regions suggested cooler temperatures from 1970-1990 A.D.. Liang et al. (2009) found that the last decade (1996 – 2006) represents the warmest period since 1765 A.D., indicated by their tree ring width chronologies. In arid southern Tibet, ostracode and isotope studies suggest that a dry and cold climate prevailed from ca. 1600 – 1800 A.D.. After ca. 1800 A.D. the climate became more variable. Lake levels rose until ca. 1920 A.D., declined thereafter, and rose again from ca. 1970 A.D. until present (Wrozyna et al., 2010). In contrast, on the northwestern Tibetan Plateau, relatively dry conditions prevailed at ca. 1700 – 1900 A.D., followed by a wet phase from ca. 1900 – 1960 A.D., and a return to dryer conditions since 1960 A.D. (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 last ca. 100 years.

They found that six out of eight lakes show a marked increase in lake productivity within the last 100 years, which they assign to climatic warming and land-use changes. In summary, information on patterns of climate change and associated aquatic ecosystem response is sparse and partly contradictory for the past two centuries on the Tibetan Plateau.

Diatoms have shown to be particularly useful indicators of past 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 remote mountain 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 parameters (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 increase and glacial retreat. As such, the paper exhibits one of the very few diatom records in the region and provides insights to the complexity of environmental change on the Tibetan Plateau.

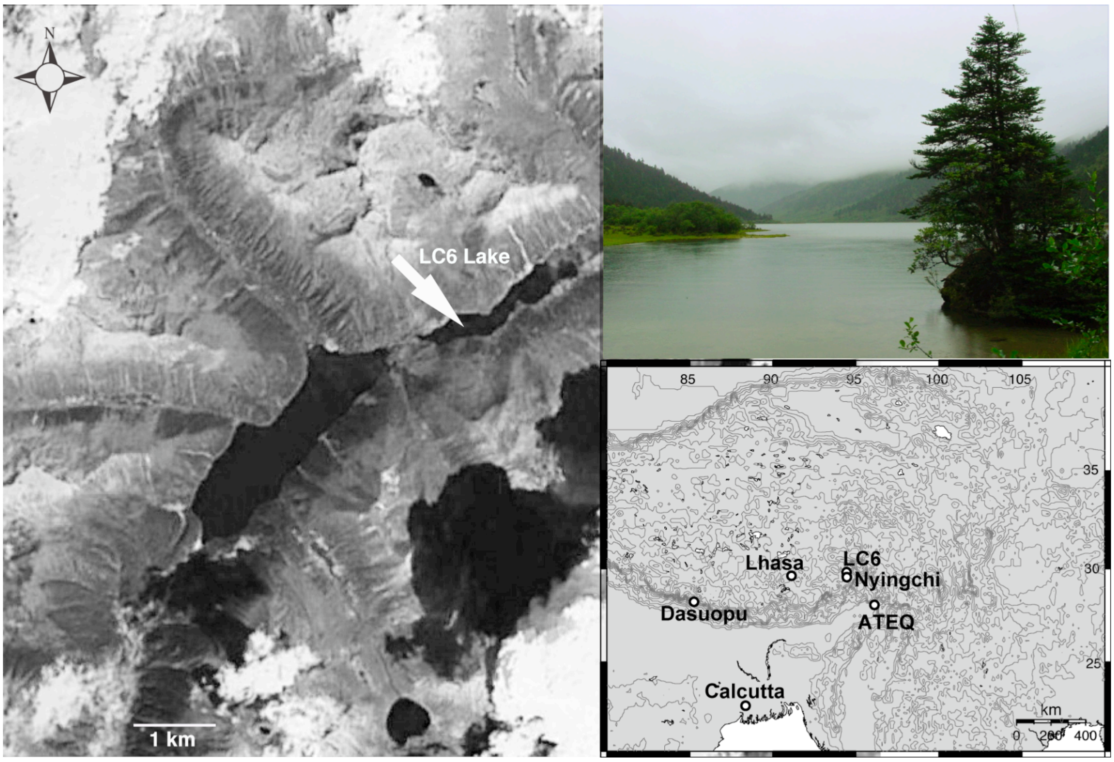

Figure 3.1: Location of the LC6 Lake and core position. Figure adopted from google earth and The Map Creation Tool. ATEQ (Assam-Tibet earthquake August 1950).

3.2 Study site

The mountain lake (not named, working name LC6 Lake) is located in the Nyaintêntanglha Mountain range, on the southeastern Tibetan Plateau (Fig. 3.1). 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 cool and relatively dry winters. The LC6 Lake lies at 4230 m above sea level (a.s.l.). The closest weather station is in Nyingchi at 3000 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} 657mm (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 temperatures for July ~ 9.6°C and for January ~ - 5.5°C in the LC6 Lake region. Precipitation generally increases with elevation (Domrös and Peng, 1988), but as it is not solely dependent on elevation, but is strongly influenced by exposure and slope, it is difficult to estimate annual precipitation values for our site. According to the mean monthly temperature profile and monthly satellite images from the Landsat archive (USGS earth explorer) we estimate an ice cover duration on the lake of ~ 4 months (December – March).

Table 3.1: Selected physical and chemical characteristics of LC6 Lake

LC6 Lake	
Latitude	29.82515
Longitude	94.45615
Elevation	4132m a.s.l.
Genesis	Glacial lake
Lake area	2000 x 300 m, 0.6 km^2
Catchment area	~ 7.2 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

General information about the lake and its catchment are summarised in Table 3.1. 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 which generally peak around 4700 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 have a dimictic mixing regime. The vegetation in the catchment is characterised by dense *Rhododendron* shrubs and coniferous forests (*Picea likiangensis* var. *balfouriana* (Rehder & Wilson) Hillier, *Abies georgei* var. *smithii* (Viguié & Gaussen) Cheng, Cheng & Fu), and patches of *Kobresia pygmaea* (Clarke) Clarke meadow. Lichens are also typical epiphytes on surrounding shrubs and 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.

3.3 Materials and Methods

3.3.1 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 at site in 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 calculated 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, 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 parameter for describing the abundance of organic matter in the sediments and C:N ratio was calculated to examine the relative importance of autochtonous and allochtonous 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 were analysed to gain information on the sediment source and possible 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). They were calculated according to Tucker (1988).

3.3.2 Diatom analysis

Diatom slide preparation followed standard procedures using the water bath technique (Renberg, 1990; Battarbee et al., 2001). Slides were mounted using the mounting medium Naphrax®. Diatom concentration was estimated using DVB microspheres (Batterbee and Kneen, 1982). Between 400 and 500 valves were counted at x 1000 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 (Appendix). To ease the understanding some diatoms were grouped in the biostratigraphy. For example, the *Cyclotella ocellata* complex includes *Cyclotella ocellata* Pantocsek and a very small form of *Cyclotella ocellata*, which was initially counted separately, but was later amalgamated with its bigger type after a cross check under the Scanning Electron Microscope (Genkal and

Popovskaya, 2008). *Aulacoseira distans* (Ehrenb.) Simonsen was merged with its varieties *A. distans* var. *nivalis* (Smith) Haworth and *A. distans* var. *nivaloides* Camburn as they were difficult to distinguish. Small benthic fragilarioid taxa (*Fragilaria spinarum* L-B & Metzeltin, *Staurosira construens* var. *venter* (Grun.) Williams & Round, *Staurosira construens* var. *binodis* (Ehrenb.) Hamilton, *Staurosira pinnata* (Ehrenb.) Williams & Round, *Pseudostaurosira pseudoconstruens* (Marciniak) Williams & Round) were amalgamated as they have similar temporal trends and ecological preferences (Lotter and Bigler, 2000). Diatoms are expressed as percent relative abundance of the total number of valves counted in each sample.

3.3.3 Numerical methods

Diatom-based biostratigraphic zones were identified by cluster analysis using constrained incremental sum of squares (CONISS; Grimm, 1991) 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 or sample. The main gradients of floristic variation in the diatom data were first assessed by using detrended correspondence analysis (DCA). As the gradient length of the first axis was only 1.08 standard deviation (SD) units, the linear ordination technique principal components analysis (PCA) was chosen for subsequent analysis (Lepš and Šmilauer, 2003). PCA was preformed on a correlation matrix; species were centered and square-root transformed to stabilise their variance. Samples from the slump deposit between 27-8 cm core depth (see chronology results) 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 study of Smol et al. (2005). They used a reference set of lakes in arctic regions and established that for diatoms, changes greater than 1 SD unit was 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 preformed 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). 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).

3.4 Results

3.4.1 Dating

The results of the radiometric dating are summarised in Fig. 3.2a. For detailed illustration of the fallout radionuclides see Fig. 3.3. The ^{210}Pb record is rather unusual in that although high concentrations in the near surface layers suggest an intrinsically low sedimentation rate, total ^{210}Pb activity exceeds that of 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 11.4-14.4 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. 3.3a, 3.3b). In contrast, the ^{137}Cs record is very conventional (Fig. 3.3c). 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. Raw ^{210}Pb dates calculated using the CRS dating model alone suggest that the very low ^{210}Pb concentrations between 11.4-14.4 cm record an episode of extremely rapid sedimentation (Fig. 3.2a). 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 y^{-1}. Even though rapid accumulation was most intense in those sediments between 11.4-14.4 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. Calculations using the CIC model (Fig. 3.2a) 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} y^{-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 y^{-1}) during the earlier period used in these calculations (0.11 cm y^{-1}) was however a little lower than for the more recent sediments.

3.4.2 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 contributing with ~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. 3.2b). The TOC content separates the core in three sections (Fig. 3.2c). The bottom section of the core

(45-29 cm) is marked by TOC values between 3.6 - 4.6 weight percent, the middle section (29-8 cm) with lowest TOC values between 2.7 - 3.5 weight percent, and the top section (8-0 cm) has highest values ranging between 4.1 - 5.1 weight percent. The C:N ratio was calculated with the weight percentages of TOC and total N and shows relative constant values around 10 from 45-6 cm (until 1963) of the core. Thereafter, the C:N ratio declines steadily to ~ 8.5 at the top of the core (Fig. 3.2c).

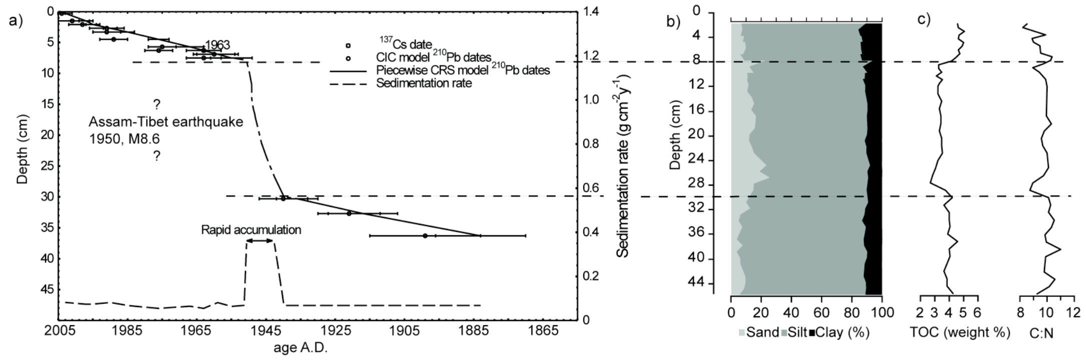

Figure 3.2: Radiometric chronology showing the 1963 depth determined from the ^{137}Cs. The piecewise CRS model ^{210}Pb dates and sedimentation rates, and the CIC model ^{210}Pb dates calculated for those sections of the core above 7.5 cm and below 30 cm thought to represent periods of uniform accumulation (a). Age chronology is compared with the grain size distribution (b) and the TOC content and C:N ratio (c).

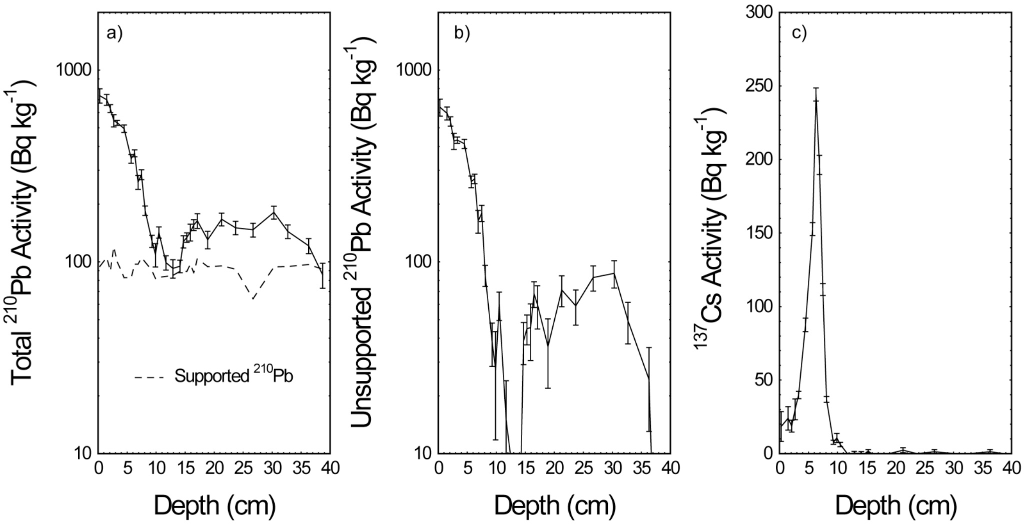

Figure 3.3: Fallout radionuclides showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb, and (c) ^{137}Cs concentrations versus depth.

3.4.3 *Fossil diatom assemblages and numerical analysis*

In the sediment core, a total of 158 species from 39 genera were identified (see Appendix for full species list). 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 with small increases of tychoplanktonic *Achnanthidium minutissimum* (Kutz.) Czarnecki,, *Aulacoseira lirata* var. *lirata* (Ehrenb.) Ross and benthic *Fragilaria capucina* Desmazières and *Cymbella* species. This trend in diatom compositional changes is related to equally subtle changes in diatom diversity (N2), which is highest in recent decades, and changes between benthic and planktonic/tychoplanktonic components of the assemblage throughout the core. Although minor, the diatom changes were most apparent before the 1880s and then again post 1960s. This is also confirmed by the PCA results, which indicate that the unstable diatom assemblage after the 1960s is linked to monoraphid and *Aulacoseira* species (Fig. 3.4). 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 most common diatoms and diatom functional groups are plotted stratigraphically and are compared with trends in diatom compositional change (PCA 1 and PCA 2), species turnover (DCCA 1), species diversity, and relative changes of planktonic, tychoplanktonic and benthic components (Fig. 3.5).

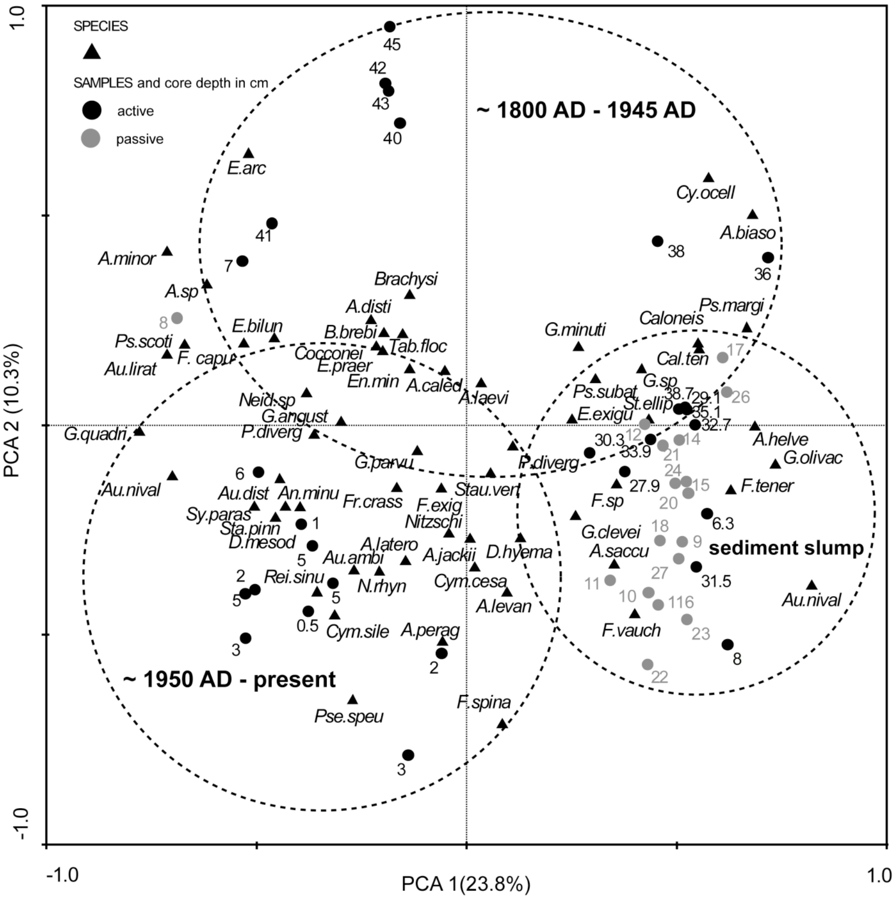

Figure 3.4: Results of the Principle Component Analysis (PCA), showing diatom species with taxa >1% abundance. For species abbreviations see full species list in the supplementary data (Appendix). Grey sample points were treated as passive samples as they form samples from the slump deposit. To ease visiability, 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.

3.5. Discussion

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

Low ^{210}Pb concentrations between 8 – 27 cm, the down-core TOC content, and grain size distribution suggest that this core section was most likely accumulated during the course of one single rapid event, possibly a landslide or a within-lake sediment slump. The age model suggests that this event happened between the late 1940s and early 1950s. This interpretation correlates very well with the timing of the Assam-Tibet earthquake that was recorded in August 1950, in North India, just ~ 280 km southeast to the site. Strasbourg calculated a magnitude of 8.6 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 (USGS earthquakes). Additionally, diatom samples from the 8-27-cm section plot within the same cluster in the PCA (Fig. 3.4), suggesting that the species in this core section are very similar. Given this evidence, we have chosen to treat samples from the core section between 8-27 cm depth passively in subsequent statistical analyses.

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 (Lui and Chen, 2000, You et al., 2007), possibly leading to higher input rates of ^{210}Pb.

3.5.2 Biological response to recent environmental changes on the Southeast Tibetan Plateau

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). Diatom compositional changes over the 200-year period were minimal reflected in a DCCA compositional change of less than 1 SD unit, which is, according to the standards established in Smol et al. (2005), 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). This and the very low total sum of squares revealed by the cluster analysis are indicative of very little composition change over the last 200 years.

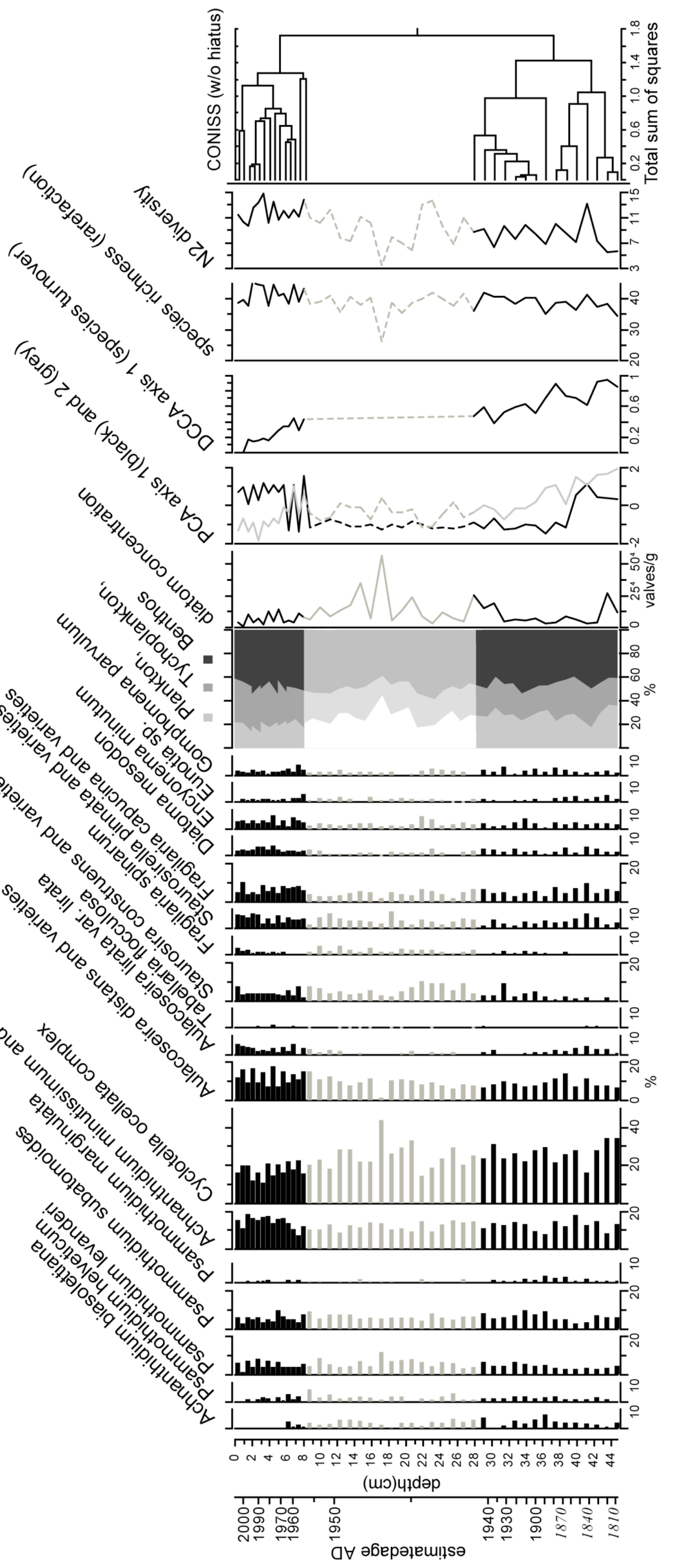

Figure 3.5: Diatom stratigraphy of the LC6 Lake. Selected taxa are shown in relative abundance and comparison with autecology, species richness, N2 diversity, ordination scores (PCA 1 and PCA 2, DCCA 1). Grey shaded area refers to slump deposit. Ages A.D. in italics indicate extrapolated dates.

Many studies on lakes in Arctic (Sorvari et al 2002; 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, would lead to a longer growing season and changes in the light and mixing regime and increased nutrient cycling that in turn would enhance especially planktonic growth. Hence, recent warming trends in these remote arctic and mountain lake systems were also detected in temperate regions of the Northern Hemisphere and were manifested by a significant shift from benthic (e.g. small fragilarioid species as well as heavily silicified *Aulacoseira* taxa) to planktonic (e.g. small *Cyclotella* species) taxa (Rühland et al. 2008). A decreasing planktonic to benthic ratio, on the other hand, can also be interpreted as an indication for decreasing lake levels due to stronger evaporation in the course of global warming which is relevant in closed lake systems. Falling lake levels lead to a greater photic zone and therefore enhance benthic and epiphytic habitat growth (Wolin and Duthie 2001).

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 Little Ice Age and post 1960. Continuous meteorological data for the Tibetan Plateau is available from the mid-1950s to the present. Liu and Chen (2000) found a general and significant unprecedented warming trend of air temperature since the mid-1950s over the Tibetan Plateau, which is especially true for winter temperatures, that increased about 0.16°C/decade between 1955 and 1996. This is also consistent with recent reports on alarming glacier retreat in the Himalayan mountains (Su and Shi, 2002). 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. Annual and seasonal mean air temperatures show significant increasing trends since 1961, particularly in the winter and autumn season with an increase of 0.37°C and 0.35°C/decade, respectively. 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, Chen and Lui (2000) and You et al. (2007) suggest that the Tibetan Plateau and particularly the southeastern region are most sensitive to global warming. Ice core records from the Himalayan mountains (Dasuopu ice core; East Rongbuk ice core), from the central region (Puruogangri ice core), from the northwestern Tibetan Plateau (Guliya ice core) and from the northeastern Tibetan Plateau (Dunde ice core), indicate that a general warming trend can also be observed on the Tibetan Plateau over at least the past 200 years after the end of the Little Ice Age (Thompson et al., 1989; Thompson et al., 2006; Yang et al., 2006; Thompson et al., 2000; Hou et al., 2007).

It is clear that the TP is experiencing substantial warming over the recent past. With rising winter and autumn temperatures and increasing precipitation we would expect a shortening in the ice cover length and/or a change in the lake level. However, this apparent shift to warmer and moister conditions particularly during the last 50 years is not manifested in our diatom record from LC6 Lake. Species compositional changes are only very subtle and a shift from benthic to planktonic taxa as mentioned above could not be observed. In contrast, we found a directional decline (5-10%) in planktonic taxa, mainly *Cyclotella ocellata*, throughout the core, while benthic taxa show a small increase. PCA scores from the base of the core to approx. 1870 BP suggest changes occurring in the diatom assemblage and may indicate post-Little Ice Age recovery. However, these changes are ecologically insignificant as also indicated by a very low DCCA total sum of squares score. More apparent is the increase of tychoplanktonic taxa (*Aulacoseira distans* and varieties, *Aulacoseira lirata var. lirata)* since the mid- 1950s. This increase is coherent 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 increase in lake productivity, which is likely being driven by changes in the diatom composition, but other algal groups might have contributed to this change in response to possibly increased availability of nutrients. Also the declining C:N ratio points to the increasing importance of algal productivity in the lake. The presence of tychoplanktonic taxa 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) is 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). Overall however, the stability of the LC6 diatom assemblages throughout the core is indicative of very little change within the lake over the past ca. 200 years and it seems prudent to further examine possible reasons for the apparent insensitivity of the diatom assemblage towards environmental changes on the southeastern Tibetan Plateau.

3.5.3 Possible reasons for a muted biological response to recent environmental change

Several studies have shown that impacts of recent climate change on the Tibetan Plateau were spatially and temporally heterogeneous (Zhu et al., 2001; Niu et al., 2004, You et al., 2010), and that even studies from proximal sites reconstruct contradictory or inconclusive temperature and precipitation trends. For example, Yang et al. (2004) reconstructed decreasing lake levels for the past 40 years at Chencuo Lake possibly as a result of temperature increase, whilst Wrozyna et al. (2010) found increasing lake levels (explained by increasing precipitation) over the past 100 years at Lake Nam Co, just 200 km to the north of Chencuo Lake. Furthermore, Bräuning and Mantwill (2004) reconstructed cooling climate trends since the 1970s using tree rings on the southeastern Tibetan Plateau, whilst Liang et al. (2009) reconstructed unusual warming using tree ring data from the same region. Thus, temperature and precipitation patterns are very complex in the heterogeneous mountain landscape of the Tibetan Plateau, and evidence of recent climatic warming is not apparent in every record.

You et al. (2010) argue that increasing temperatures are not necessarily correlated to elevation. In contrast to earlier studies (Lui and Chen, 2000), they argue that the significant temperature increases that are recorded from climate stations at 2500-3000 m a.s.l., are not of the same magnitude 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 (3000 m a.s.l.), the closest climate station to LC6 Lake (see Fig. 3.1), 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 (4132 m a.s.l.) could have been smaller or less significant due to reduced cryospheric feedback 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 counter-intuitive, but on the Tibetan Plateau, areas with dense vegetation in combination with increasing precipitation may result in increased cloud cover and decreasing sunshine that may act to buffer the full effect of increasing temperatures. The hills and mountains around LC6 Lake are covered with very dense coniferous forests intermixed with *Rhododendron sp.*, which could have acted as a temperature buffer. These dense forests, which also exhibit dense epiphytic growth from lichens and mosses, also indicate permanent high moisture and cloud cover in the valley of LC6 Lake. Increasing precipitation, cloud cover and decreasing sunshine duration is also confirmed by instrumental data (Niu et al., 2004). Increasing precipitation rates and increased cloud cover might have antagonized increasing temperature and associated increasing evaporation trends in the area, which could explain a relative minimal changes to the aquatic habitat (mixing, stratification, lake water depth). Increasing precipitation rates, particularly in winter and spring, can further lengthen the ice cover duration and therefore counteract the tendency towards earlier ice melting due to increasing air temperatures (Lotter at el., 2002). Increasing winter and spring precipitation rates are likely linked to the intensification of the westerlies over the southern slope of the Tibetan Plateau (Zhang et al., 2004).

Furthermore, one could argue that the amplitude of temperature change (~1 C° or less in the last 50 years) was not high enough to trigger changes in the diatom assemblage. Lotter et al. (2002) suggest that a temperature rise of 2°C over last two centuries in the Swiss alps might still be within the range of biological tolerance and explain the insensitivity of a diatom record this way. Cameron et al. (2002) found only very muted diatom response to climate changes in a Norwegian mountain lake, where temperatures increased by 1°C since 1900, suggesting that the biological record is insensitive to climate change of this magnitude. Furthermore, studies in the

Rwenzori Mountains, Uganda, also show muted diatom composition responses in these alpine lake systems, despite significant retreats in mountain glaciers over the last few centuries (Panizzo et al., 2008).

Still, we cannot rule out the possibility that within lake processes, like a constant groundwater influx over the past 200 years, or a stable very localized climate (e.g. cold air pool) may have had a influence on the diatom composition and therefore have overwritten regional environmental changes (Telford and Lamb, 1999; Whiteman et al., 2004). However, significant groundwater influence is unlikely, considering the impermeable nature of the granitic bedrock geology in the LC6 Lake catchment. To rule out the effect of a local climatic phenomenon, further palaeo-ecological investigations on the southeastern Plateau are necessary. To our knowledge, no other diatom studies covering the last two centuries exist on the southeastern Tibetan Plateau.

3.6 Conclusions

Despite the instrumental evidence of general warming trends and sustained glacial recession on the southeastern Tibetan Plateau, diatom analyses of the LC6 Lake sediment core revealed only very subtle ecological changes during the past 200 years. However, the ^{210}Pb record suggests a period of rapid sedimentation around 1950 BP, which might be linked to major tectonic events, and ^{210}Pb concentrations in recent decades possibly indicate increased precipitation or spring thaw in the region. We therefore conclude that 20th century environmental changes are apparent at the LC6 Lake, but this is so far more evident in the geochemistry than in the diatom composition. Local or regional peculiarities may have antagonised the effects of increasing mean surface temperatures. Increasing precipitation trends, localized climatic phenomenon or other biogeochemical processes with unknown historical patterns might have affected the species composition more strongly. Our results highlight the spatial complexity of climate change on the Tibetan Plateau, and indicate the need for widespread regional coverage of palaeo-ecological data in order to better understand the regional dynamics of future global change.

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4 Pollen and diatom response to climate change and human impact on the southeastern Tibetan Plateau during the last two centuries

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Abstract

Rapid population growth and economic development lead to increased climate and anthropogenic pressures on the Tibetan Plateau, causing significant land cover changes with partly severe and irreversible consequences for ecosystems and mankind. To assess whether these pressures are also affecting the remote montane-boreal lakes on the southeastern Tibetan Plateau, pollen and diatom data from two lakes were synthesized to explore the interplay of aquatic and terrestrial ecosystem response, climate variability and human activity over the past 200 years. The ordination technique non-metric Multidimensional Scaling was used to explore patterns of variation in the pollen and diatom data sets. Procrustes rotation was applied to assess the similarity and time-consistency of response to environmental change between the corresponding pollen and diatom data of each lake. Detrended canonical correspondence analysis was used to develop quantitative estimates of compositional turnover as beta-diversity for the period of investigation. All pollen and diatom records have a very stable species composition throughout their profiles and show only very subtle responses to environmental changes. The species turnover investigated over the last 200 years appears relatively low in comparison to the species reorganizations known from the periods during the mid- and early-Holocene. Our results indicate that climatically-induced ecological thresholds are not yet crossed, but that human activity had an increasing influence, particularly on the terrestrial ecosystem. Synergistic processes of post Little Ice Age warming, 20th century climate warming and extensive reforestations since the 19th century have promoted the growth of semi-natural pine-oak forests, intermixed with fir and larch.

4.1 Introduction

Due to its potential to influence regional and global climate patterns, the Tibetan Plateau has become a focus study area of past and recent climate and ecosystem change. Studies focusing on the recent past (last 200 years) report a significant mean annual and winter temperature increase (Liu and Chen, 2000; You et al., 2007), permafrost degradation (Wu and Zhang, 2008) and significant glacial retreat (Su and Shi, 2002; Berthier et al., 2007), suggesting that the Tibetan Plateau, and particularly the southeastern Tibetan Plateau, is very sensitive to global warming. Additionally, the plateau has been under the pressure of rapid population growth and economic development. The population of whole China has increased 2.5 times (Zhang et al., 2000). Livestock and meat production on the Tibetan Plateau has increased by up to three times since 1978 (Du et al., 2004) and the demand in timber has resulted in extensive forest clearances since the 1950s (Zhang et al., 2000), particularly at the steep forested slopes of the southeastern Tibetan Plateau (Studley, 1999). Overgrazing leads to grassland degradation and desertification (Cui and Graf, 2009); primary forests, at its best, re-grows as secondary forest. Major decline in natural woodlands however, results in the loss and fragmentation of natural habitats and consequently causes an alarming loss in plant and wildlife species (Studley, 1999; Zhang et al., 2000). In summary, the pressures on the Tibetan Plateau are manifold and whether these are caused by climate change or human activity, they result in significant land cover changes with partly severe and irreversible consequences for ecosystems and mankind.

At the same time, the Tibetan Plateau is known for its heterogeneous mountain landscape and therefore highly complex temperature and moisture patterns (An et al., 2000; Niu et al., 2004; You et al., 2010). Additionally, anthropo-zoogenic pressures are not evenly spread and lead to regions on the plateau that are more effected by land cover changes than others (Cui and Graf, 2009). Therefore, global climate models are still imprecise in estimating possible future land cover changes on the Tibetan Plateau as they lack the spatial and temporal resolution of climatic, ecosystem and anthropogenic parameters in that topographically challenging landscape (Cui and Graf, 2009). Therefore, it is necessary to establish a dense and integrated network of instrumental, palaeolimnological and archaeological studies, to help to dissolve the uncertainties of climate variability and the anthropo-zoogenic activities and associated land cover changes in the past and present, to assess their future impact on the ecosystem of the Tibetan Plateau.

However, to date only few and spatially widespread proxy studies have investigated environmental changes on the Tibetan Plateau focusing on the last few centuries (Lami et al., 1998; Henderson et al., 2003; Bräuning and Mantwill, 2004; Yang et al., 2004; Liang et al., 2009; Lami et al., 2010; Wrozyna et al., 2010; Wischnewski et al., submitted) – a time period strongly effected by increasing land use activity. Pollen and diatoms in particular, have not received much attention on centennial and decadal time scales, despite their potential to reflect vegetation, land use and climate change reliably (Douglas and Smol, 2001; Lotter et al., 2001; Herzschuh et al., 2006c; Zhao et al., 2008; Schlütz and Lehmkuhl, 2009).

Here we present the results of pollen and diatom records from two montane-boreal lakes (LC6 and Wuxu) on the southeastern Tibetan Plateau. Our aim is to evaluate the comparability of aquatic and terrestrial proxy response, climate variability, and human activity using rigorous statistical methods. We focus on the following questions: (a) Do pollen and diatom records reflect similar and synchronous species shifts in response to environmental changes on the southeastern Tibetan Plateau? (b) How sensitive are the pollen and diatom assemblages to environmental change in the past 200 years, and is the magnitude of species turnover comparable to the magnitude of change at other sites on similar and longer time scales? (c) What are the potential causes and threads of ecosystem change on the southeastern Tibetan Plateau? As such, this paper exhibits one of the very few studies in the region that directly compares aquatic and terrestrial proxy response within and between two different sites.

4.2 Regional setting and study sites

Wuxu lake and the LC6 lake (working name) are located on the southeastern Tibetan Plateau. This part of the plateau is characterized by a strong and varied relief of the Hengduan Mountains, which stretch across western Sichuan, northwestern Yunnan and the easternmost part of the Tibet autonomous region. Altitudes of over 5000 m above sea level (asl) in the northern parts of the southeastern Tibetan Plateau drop to less pronounced features of ~ 1500 m asl towards the southern limit of the Tibetan Plateau (northwestern Yunnan) causing steep environmental gradients in the region. Mean annual summer temperatures range from 8°C to 20°C and mean annual precipitation varies from 400 mm to 1400 mm (Sun, 1999; Yu et al., 2001). The southeastern Tibetan Plateau is affected by two major circulation systems. The mid-altitude westerly circulation brings limited moisture to the region from November to March, while the Asian Monsoon circulation, particularly the Indian monsoon system, is responsible for the majority of precipitation from May to September (Domröß and Peng, 1988; Su and Shi, 2002). This results in abundant rainfall and high temperatures in summer, which contrast to cool and relatively dry winters.

Adapted to the strong relief and aforementioned climate gradients, the vegetation is also highly variable on the southeastern Tibetan Plateau. Primary *Tsuga* forests with patches of *Abies ernestii*, *Picea wilsonii* and *Betula albo-sinensis* characterize the landscape between 2500 and 3200 m asl. However, most areas below ~3000 m asl are overwritten by human cultivation, mainly legumes, rice and wheat. *Pinus yuanensis* and sclerophyllous *Quercus* grow at altitudes between 2500 and 3500 m asl in form of secondary pine-oak forests in consequence of probably human-induced fires (Shen et al., 2006b; Dearing et al., 2008). Montane forests composed of conifers (*Abies squamata*, *A. faxonia*, *Picea likiangensis* and *P. purpurea*) and deciduous elements (*Betula utilis*, *B. platyphylla* and *Rhododendron*) are common up to 4400 m asl (Hou, 2001). Above 4000 m asl subalpine shrub communities with *Juniperus*, *Salix* shrubby

Quercus and *Rhododendron* species, are most common. With gaining height these vegetation forms change into alpines meadows composed of mainly *Kobresia* and *Polygonum* species. The subnival belt around 4900-5200 m asl is overgrown with sparse cushion and rosette plants vegetation (Caryophyllaceae, Brassicaceae and *Saussurea*) (Yu et al., 2001).

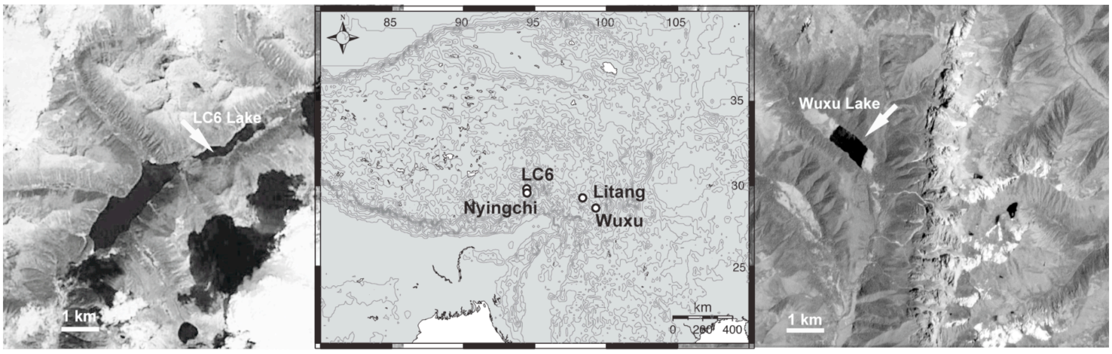


Figure 4.1: Location of LC6 lake and Wuxu lake and corresponding coring locations. Nyingchi and Litang are the closest climate stations. Figure adapted from Google Earth, Landsat, and the Online Map Creation Tool.

The LC6 lake is located in the Nyaintêntanglha Mountain range, a western branch of the Hengduan Mountains (Fig. 4.1). The LC6 lake lies at 4230 m asl. The closest weather station is in Nyingchi at 3000 m asl, 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} 657mm (85% of P_{ann} falling between May and September). Based on a lapse rate of - 0.5°C/100 m (Böhner, 2006), mean temperatures for July are ~ 9.6°C and for January ~ - 5.5°C at the LC6 lake. Precipitation is not solely dependent on elevation, but very much on exposure and slope. Therefore, estimates on precipitation directly at the lake are difficult. However, precipitation tends to increase with elevation (Domröß and Peng, 1988). The LC6 lake has a small watershed of 0.6 km^2 and is mainly fed by runoff from surrounding, moderately steep sloping, mountains which generally peak around 4700 m asl. The lake has one outflow, which cascades into a lake on a lower level to the southwest. Dense *Rhododendron* shrubs and coniferous forests (*Picea likiangensis* var. *balfouriana*, *Abies georgii* var. *smithii*), and patches of *Kobresia pygmaea* meadow characterise the vegetation in the catchment. Lichens are typical epiphytes on surrounding shrubs and trees. No signs of immediate, catchment-scale human impact were observed during fieldwork.

Wuxu lake is located ~ 680 km to the west of LC6 lake in an eastern branch of the Hengduan Mountians (Fig. 4.1). Wuxu lake lies on 3705 m asl. The closest weather station is Litang at 3948 m asl, 140 km northwest of the lake, which records mean T_{July} 10.5°C, mean T_{Jan} -6°C, and mean P_{ann} 720 mm (90% falling between May and September). The watershed is comparable with that of LC6 lake and a small catchment area comprised of steep sloping mountains to the sides of the lake and a tributary feeding from perennial snow covered peaks and glaciers to the northwest, feed into the lake system. Wuxu lake has one outflow to the southeast. The vegetation in the catchment is characterized by coniferous (*Picea likiangenis, Abies* *squamata*) and sclerophyllous trees (*Quercus aquifoliodes, Q. pamosa*), intermixed with *Rhododendron* and *Salix* shrubs. A day trip away from Jiulong, Wuxu lake is destination of minor tourism. Some Tibetan summer tents are pitched along the shorelines and yaks graze in the area during summer. General information about both lakes and their catchment are summarized in Table 4.1.

Table 4.1: Selected physical and chemical characteristics of LC6 Lake and Wuxu Lake

	LC6 Lake	**Wuxu Lake**
Latitude	29.82515	29.15319
Longitude	94.45615	101.406
Elevation	4132 m asl	3705 m asl
Genesis	Glacial lake	Glacial lake
Lake area	2000 x 300 m, 0.6 km^2	1000 x 500 m, 0.5 km^2
Catchment area	~ 7.2 km^2	~6.5 km^2
Max. water depth	23 m	30.8 m
Secchi depth	6.9 m	5.3 m
Conductivity	0.013 mS/cm	0.033 mS/cm
pH	7.0	7.67
Alkalinity	0.4 mmol/l	0.4 mmol/l
Inflow	Mountain runoff	Mountain runoff
Outflow	One cascading outlet into lake at lower level	One outlet

4.3 Material and methods

4.3.1 *Field sampling and dating*

LC6 lake and Wuxu lake were sampled in summer 2005 and winter 2007, respectively. A 45 cm sediment core was taken at the deepest part (23 m) of lake LC6; at lake Wuxu 40 cm sediment core were taken at 30 m water depth. Both cores were taken using a Glew gravity corer and were sectioned at site in 0.5 cm intervals directly after coring.

Both cores were dated using ^{210}Pb, ^{226}Ra, and ^{137}Cs analyses 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). The 1963 depth was determined from the ^{137}Cs stratigraphic record. Discrepancies between the ^{210}Pb models were resolved using the methods described in Appleby (2001). For lake LC6, dates of points below the base of the unsupported ^{210}Pb record were calculated by extrapolation of the ^{210}Pb depth/age curve using a best estimate of the sedimentation rate for this part of the core. For Lake Wuxu, we are momentarily waiting for the results of two additional radiocarbon dates from bulk sediments that are obtained by the AMS (accelerated mass spectrometry) method at the Leibnitz-Laboratory for Radiocarbon Dating and Isotope Research, Kiel to establish an age chronology for the core section below 11 cm, where unsupported ^{210}Pb was already depleted. Currently, the dates of points below the base of the unsupported ^{210}Pb record are calculated by extrapolation of the ^{210}Pb depth/age curve using a best estimate of the sedimentation rate for this part of the core. The extrapolated period, however, captures ~ 300 years. The assumption of a constant sedimentation rate over such a long time period is venturous, therefore ages older ~ 1800 AD are for now under reserve.

4.3.2 Pollen analysis

Sediments for pollen analyses for both lakes were treated using standard laboratory methods (Fægri and Iversen, 1989), including treatment with HCl (10%), KOH (10%), and HF (50%, 2 h boiling), followed by acetolysis, sieving (7 μm) in an ultrasound bath, and mounting in glycerine. Two tablets of *Lycopodium* spores (10 979 spores/tablet) were added to calculate the pollen concentrations. At LC6 lake, 30 horizons (5 to 12 year intervals) were analysed and at least 600 (mean 1070) terrestrial pollen were counted for each level. For lake Wuxu, 26 horizons (7 to 20 year intervals) were analysed with counts between 360 and 650 (mean 470) terrestrial pollen for each level. Pollen identifications followed relevant literature (Moore et al., 1991; Wang et al., 1997; Beug, 2004; Fujiki et al., 2005) Pollen percentages were used to develop pollen diagrams and implement numerical methods. Only pollen taxa occurring in at least one sample with >1% were included in the analyses.

4.3.3 Diatom analysis

For diatom analysis standard procedures using the water bath technique (Renberg, 1990; Battarbee et al. 2001). Slides were mounted using Naphrax®. Diatom concentration was estimated using divinylbenzene microspheres (Battarbee and Keen, 1982). At LC6 lake 400 to 500 valves were counted for 45 horizons (2 to 11 year intervals). At Wuxu lake 630 to 1200 valves were counted for 27 horizons (7 to 20 year intervals), using phase contrast at x1000 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). Diatom taxa with percentages of >1% in at least on sample were used for the biostratigraphy and all statistical methods.

4.3.4 Data treatment and statistical analysis

The significance of pollen- and diatom-based biostratigraphic zones was calculated by cluster analysis using constrained incremental sum of squares (CONISS; Grimm, 1991) and the Edwards and Cavalli-Sforza's chord distance as the dissimilarity coefficient.

The ordination technique non-metric multidimensional scaling (nMDS) was used to explore patterns of variation in the pollen and diatom data sets (Minchin, 1987). The dissimilarity matrix, needed for nMDS, was calculated using the Bray- Curtis coefficient (Faith et al., 1987). NMDS was run on a two-dimensional model, being the most parsimonious model compared to higher dimensional models, which did not produce significantly lower stress values (a measure of the variation explained).

Detrended canonical correspondence analysis (DCCA) was applied to estimate the overall compositional turnover measured in SD units (or beta diversity), which provides an estimate of compositional change along an environmental or temporal gradient (ter Braak and Verdonschot, 1995). To estimated the amount of compositional change of the LC6 and Wuxu lake records over the last ~200 years, ^{210}Pb derived sample ages were used as the only constraining variable in DCCA. 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. To place the degree of compositional turnover into relation, SD units were compared to results from other studies that used DCCA as a tool to estimate compositional species turnover (Smol et al., 2005; Birks, 2007; Herzschuh et al., 2010a; Hobbs et al., 2010).

To assess whether the corresponding pollen and diatom data sets of the LC6 lake and Wuxu lake show significant similarities and time-consistency in their variability over time, Procrustes rotation and the associated PROTEST permutation test were implemented (Gower, 1971; Jackson, 1995; Peres-Neto and Jackson, 2001). As Procrustes and PROTEST require ordination scores of like-for-like data, the four data sets LC6 diatom, (2) LC6 pollen, (3) Wuxu diatom, and (4) Wuxu pollen had to be harmonized and adapted to a common time scale. Therefore, all diatom and pollen taxa from the original data sets were interpolated (linear interpolation) and then re-sampled in five-year intervals from 2000 to 1810 AD.

All nMDS, Procrustes analysis and PROTEST were performed in R (The R Development Core Team, 2008) using the vegan package (Oksanen et al., 2008). The PROTEST function in R, which performs a random permutation test, was modified to allow restricted permutations for time series data (Besag and Clifford, 1989). DCCA was implemented using the program CANOCO 4.5 for Windows (ter Braak and Šmilauer 2002) and the interpolation and re-sampling was carried out in AnalySeries 2.0.4.2. (Paillard et al., 1996).

4.4 Results

4.4.1 Dating

For the LC6 lake, results of the radiometric dating are summarized in Figure 4.2. The ^{210}Pb record divides the LC6 sediment core in three discrete zones. Unsupported concentrations decline steeply with depth in the top 10 cm, reaching very low levels between 11.4-14.4 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. The ^{137}Cs record is very conventional and shows 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. The discrepancy between raw ^{210}Pb dates calculated using the CRS dating model and the well-defined 1963 ^{137}Cs date suggest that an extreme event, possibly a landslide or sub-surface sediment slump is captured in the sediment core between 8 and 27 cm. Revised CRS model calculations for the upper part of the core, using the ^{137}Cs date as a reference point (Appleby, 2001), suggest that the rapid sedimentation event occurred in the late 1940s or early 1950s, which could be coincident with the Assam-Tibet earthquake that was recorded in August 1950, in North India, just ~ 280 km southeast to the site. Apart from the above episode, dry mass sedimentation rates (g cm^{-2} y^{-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 y^{-1}) during the earlier period used in these calculations (0.11 cm y^{-1}) was however a little lower than for the more recent sediments. A detailed description and interpretation of the LC6 lake age-depth model is given in Wischnewski et al., in review.

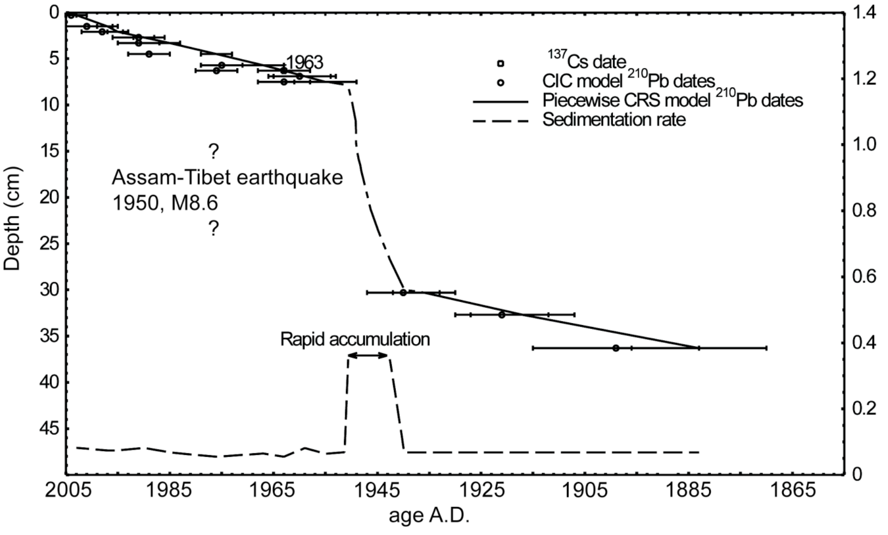


Figure 4.2: Radiometric chronology for LC6 lake showing the 1963 depth determined from the ^{137}Cs, the piecewise CRS model ^{210}Pb dates and sedimentation rates, and the CIC model ^{210}Pb dates calculated for sections above 7.5 cm and below 30 cm

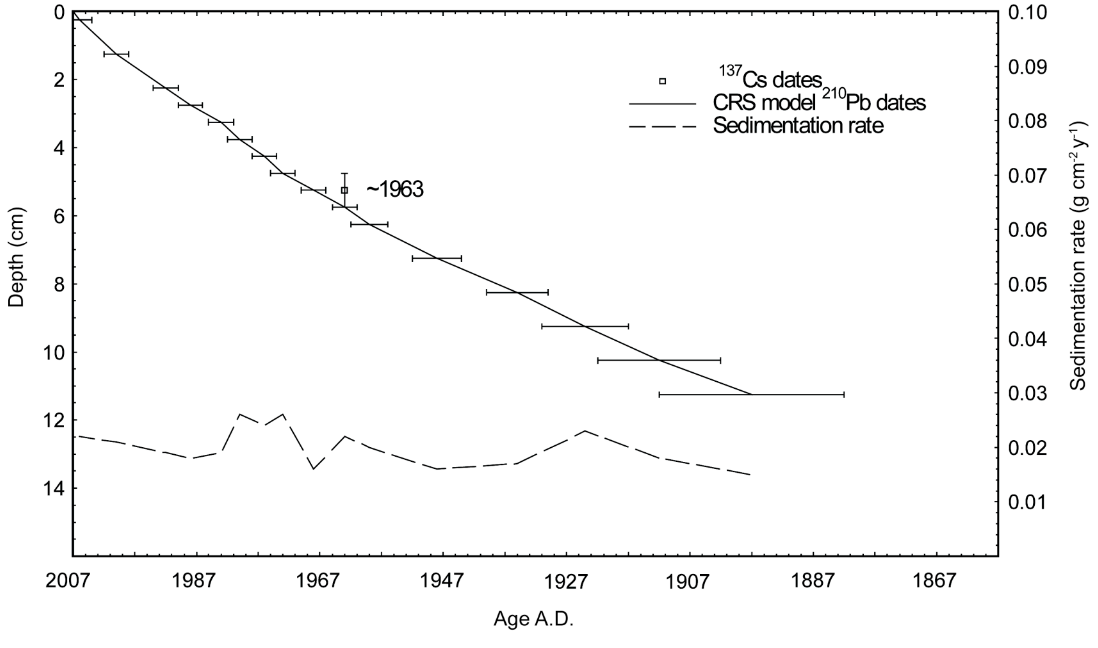


Figure 4.3: Radiometric chronology of the Wuxu Lake sediment core showing the CRS model ^{210}Pb dates and sedimentation rates, and also the approximate 1963 depth determined from the ^{137}Cs stratigraphy.

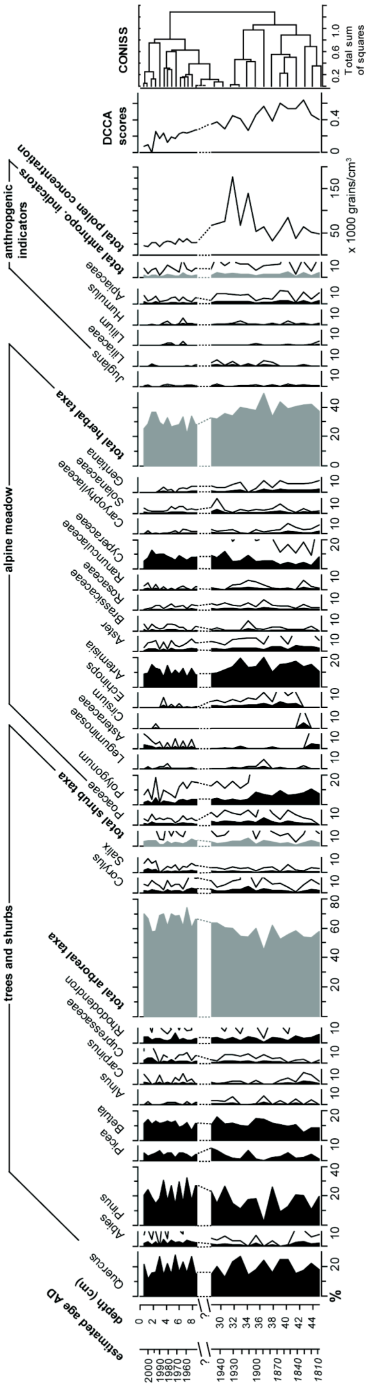
The radiometric dating results for Wuxu Lake are summarized in Figure 4.3. Unsupported ^{210}Pb activity declines more or less exponentially with depth, suggesting relatively uniform sedimentation rates (0.10 cm $^{y-}$1) during the past 100 years. Small irregularities appear between 4-6 cm depth, corresponding to the early 1960s, but differences between the CRS model and the alternative CIC model were relatively small. ^{137}Cs activity has a well-defined peak in the 5-5.25 cm section, which almost certainly marks 1963. The ^{210}Pb dates place 1963 slightly below the depth suggested by the ^{137}Cs record, possibly caused by the short-term fluctuations in the sedimentation rate mentioned above. The equilibrium between total ^{210} Pb activity and supporting ^{226}Ra was reached at 12 cm depth. For now, dates were extrapolated back to ~ 1600 AD using a constant sedimentation rate of 0.10 cm y^{-1}. These age estimates will be validated with the owing radiocarbon dates.

4.4.2 *Pollen analysis*

The results of the pollen analysis for LC6 Lake are summarized in Figure 4.4. The cluster analysis CONISS calculated a total sum of squares of 1.3. Therefore, no distinct first-order pollen biostratigraphic zones were established. The pollen spectrum is dominated by arboreal and shrub taxa, amongst which *Pinus* (~ 19%), *Quercus* (~ 19 %), *Betula* (~ 11%), *Picea* (~ 4%), and *Rhododendron* (~ 3%) are the most dominating taxa. Herbaceous taxa contribute with mainly *Artemisia* (~ 12%), Cyperaceae (~ 7%) and *Polygonum* (~ 4%) to the spectra in moderate amounts. In general, arboreal taxa show a slight increase since the late 1890s, mostly linked to the increase of *Pinus*, *Betula*, *Abies* and *Salix*, whereas herbal taxa decline on the expense of *Polygonum*, *Artemisia*, Poaceae and *Gentiana*. Taxa indicating possible a grazing impact (i.e., Apiaceae, Liliaceae) show slight increases in the 1870s to 1940s and taxa most likely introduced through human cultivation (i.e., *Humulus*, Fabaceae) increased in the 1870s to 1940s and in the 1970s. The two-dimensional nMDS produced a stress value of 18.7% (Table 4.2), which according to Clarke (1993) and Kruskal and Wish (1987) indicates a good fit between the original distance of objects and the fitted values. The nMDS underlines the apparent trend to the dominance of arboreal taxa with the end of the 19th century (Fig. 4.8b). The DCCA revealed a non-significant compositional turnover of 0.46 SD (p= 0.15) for the last 200 years.

Figure 4.5 summarizes the results from the Wuxu lake pollen record. Similar to the LC6 lake, no distinct first-order biostratigraphic zone were calculated by the cluster analysis CONISS (total sum of squares of 1.3). The pollen spectra are dominated by arboreal taxa, such as sclerophyllous *Quercus* (~ 37%), *Pinus* (~ 23%), *Betula* (~ 6%) and *Abies* (~ 5%). Herbal taxa, mainly comprised of *Artemisia*, Cyperaceae and Poaceae contribute with abundances between 2-4%. As at LC6 lake, herbal taxa decrease since the 1870s in favor for arboreal taxa (mainly *Pinus* and *Quercus*). Indicator taxa for human cultivation contribute with insignificant amounts to the pollen spectra and do not show distinct appearances, however, taxa (e.g., *Rumex, Sanguisorba*) suggesting higher grazing influence are present throughout the core with abundances of ~ 1-2%. The two-dimensional nMDS has a stress value of 22.8% (Table 4.2), reflecting the increase in arboreal taxa since the 1870s (Fig. 4.8a). The

DCCA yielded a non-significant compositional turnover of 0.31 SD (p=0.09) over the last 200 years.



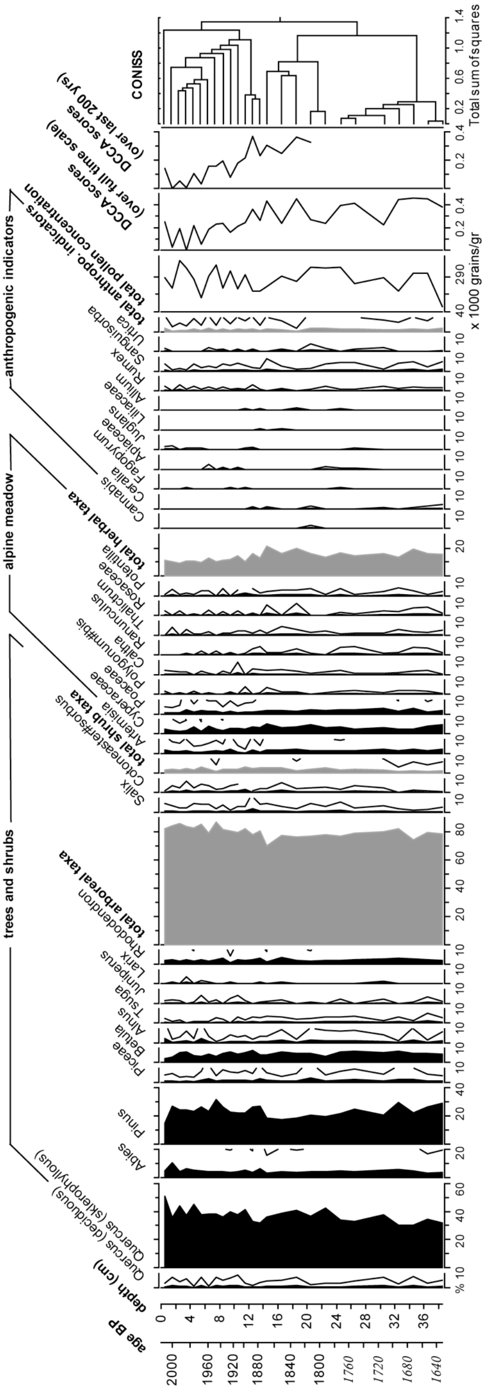
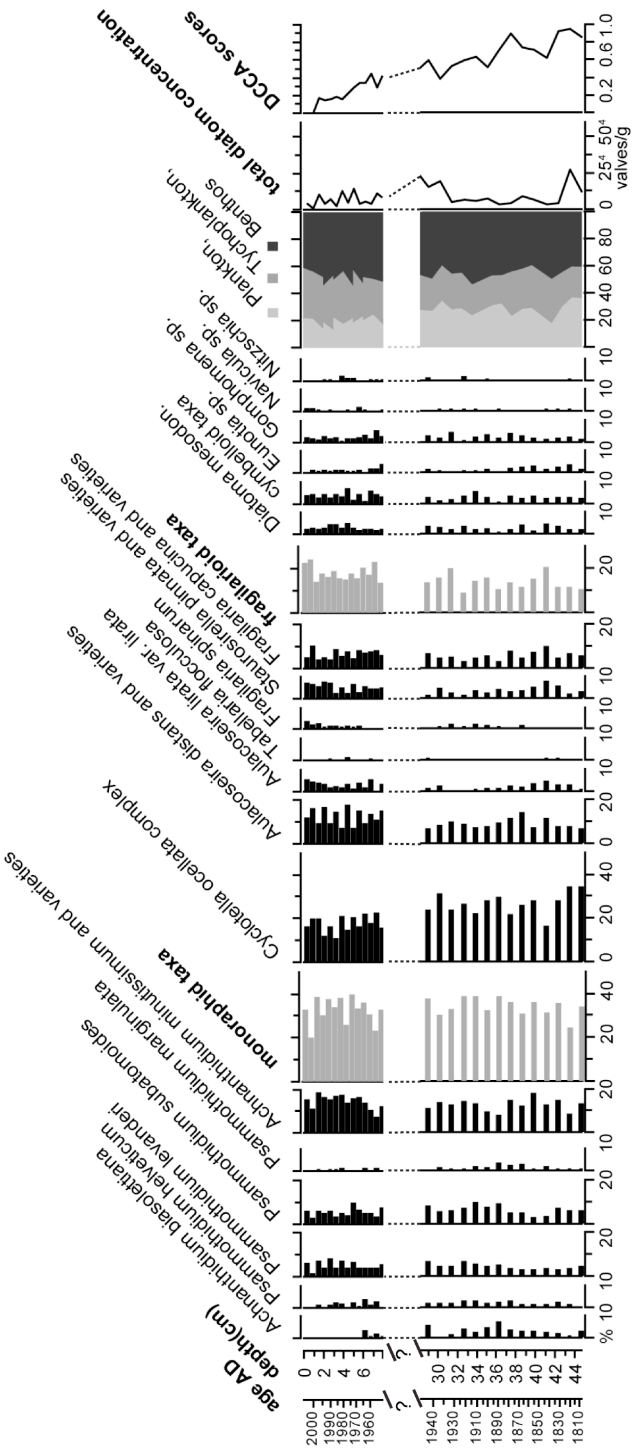


Figure 4.4 (left): Pollenstratigraphy of LC6 Lake. Only taxa with an abundance of >1% in at least one sample are shown. The black filled silhouettes represent original pollen abundance; transparent silhouettes in the background exaggerate the original abundance of rare species by 4 to ease visibility. The gap captures the sediment slump between 8 – 27 cm.

Figure 4.5 (right): Pollenstratigraphy of Wuxu Lake. Only taxa with an abundance of >1% in at least one sample are shown. Black filled silhouettes represent actual abundance, white silhouettes in background illustrates abundance exaggerated by factor 4 to ease visibility. Ages AD in *italic* font are under reserve whilst waiting for validation from the radiocarbon dating.



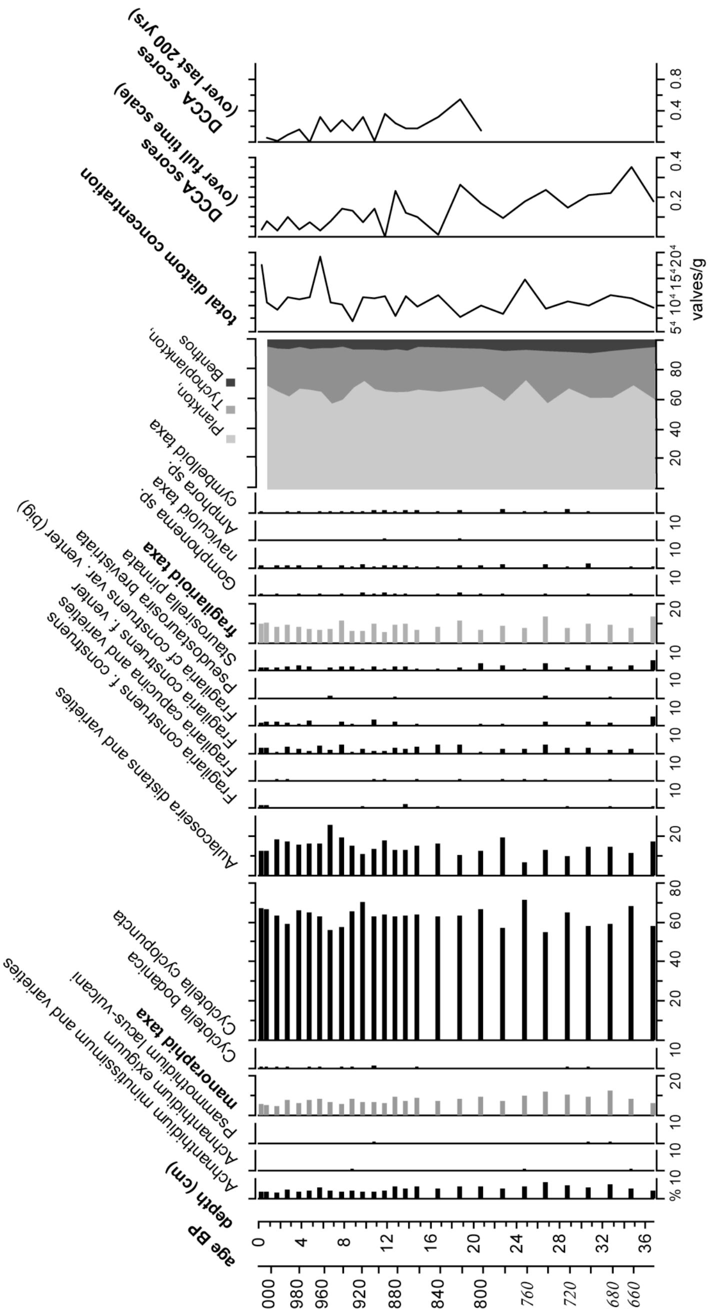


Figure 4.6 (left): Diatom stratigraphy of LC6 Lake. Selected taxa are shown in relative abundance. The gap captures the sediment slump between 8 – 27 cm.

Figure 4.7 (right): Diatom stratigraphy of Wuxu Lake. Selected taxa are shown in relative abundance. Ages AD in *italic* font are under reserve whilst waiting for validation from the radiocarbon dating.

4.4.3 Diatom analysis

The diatom stratigraphies of LC6 and Wuxu lake are illustrated in Figures 4.6 and 4.7, respectively. The common feature of both diatom data sets is the small degree of compositional turnover throughout both cores. In both cases CONISS revealed a low total sum of square (1.0 for Wuxu, 1.7 for LC6), indicating the absence of first-order biostratigraphic zones. The DCCA yielded a compositional turnover of 0.32 SD (p= 0.03) for Wuxu lake and 0.85 SD (p= 0.59) for LC6 lake over the last 200 years.

The LC6 lake diatom record revealed 158 species from 39 genera, which are dominated by monoraphid taxa (*Achnanthidium sp.*, *Achnanthes sp.* and *Psammothidium sp.)*, *Cyclotella sp.* and fragilarioid taxa, which contribute with up to 40%, 35% and 20% relative abundance. The most common species is the planktonic diatom *Cyclotella ocellata* (up to 35%). A subtle but consistent decline of *Cyclotella ocellata* is detectable throughout the core, accompanied with small increases of *Achnanthidium minutissimum*, tychoplanktonic *Aulacoseira lirata* var. *lirata* and benthic *Fragilaria capucina* and *Cymbella* species (Fig. 4.6).

At Wuxu lake, 120 taxa from 38 genera were identified. The species assemblage was dominated by the planktonic taxa *Cyclotella cyclopunctata* (~ 63%) and *Aulacoseira distans* (~ 15%). Taxa and varieties from the *Achnanthidium minutissimum* (~ 5%) and fragilarioid taxa such as *Fragilaria construens f. venter* (~ 3%) and *Staurosirella pinnata* (2%) contribute with small percentage abundances to the benthic component of the diatom assemblage. However, no significant species shift was detected throughout the record, only subtle changes appear from the 1840s onwards, linked to the appearance of some fragilarioid taxa (Fig. 4.7).

4.4.4 Procrustes rotation and PROTEST

Procrustes and PROTEST require ordination scores of like-for-like data. Therefore, a nMDS was implemented on all interpolated and re-sampled data sets. All four nMDS produced stress values between 16% and 21% (Table 4.2) suggesting a good fit between fitted values and the original distance (Kruskal and Wish, 1987; Clarke, 1993).

Table 4.2: NMDS stress scores and applied distance measure. Data sets 1 - 4 refer to analyses on original pollen and diatom counts; data sets 5 -8 refer to analyses on harmonised (interpolated and resampled in 5 year intervals between 1810 and 2000 AD) pollen and diatom counts.

Data set	Distance measure	nMDS stress score (%) for 2D model
1. LC6 Lake Pollen (original data)	Bray Curtis	18.74
2. LC6 Lake Diatoms (original data)	Bray Curtis	21.96
3. Wuxu Lake Pollen (original data)	Bray Curtis	22.85
4. Wuxu Lake Diatoms (original data)	Bray Curtis	20.78
5. LC6 Lake Pollen (resampled between 1810 -2000)	Bray Curtis	16.41
6. LC6 Lake Diatoms (resampled between 1810 -2000)	Bray Curtis	19.33
7. Wuxu Lake Pollen (resampled between 1810 -2000)	Bray Curtis	20.77
8. Wuxu Lake Diatoms (resampled between 1810 -2000)	Bray Curtis	20.44

Procrustes rotation and the associated PROTEST function were performed on (a) both pollen data sets, (b) both diatom data sets, (c) pollen and diatom data sets of the LC6 lake, and (d) on the pollen and diatom data sets of Wuxu lake. Table 4.3 summarizes the diagnostics of Procrustes rotation and PROTEST and Figure 4.9 illustrates the goodness of fit between all data sets compared. The size of residuals for each time slice between 1810 AD and 2000 AD are shown. Low residuals indicate a good agreement between data sets, high residuals indicate a weak agreement. Results show that the best fit was produced for the intra-site comparisons. The pollen and diatom record from LC6 lake (Fig. 4.9c) and the pollen and diatom record from Wuxu lake (Fig. 4.9d) produced both highly significant fits (p=0.02). A good fit was also produced between the corresponding pollen records from LC6 lake and Wuxu lake (p=0.05) (Fig. 4.9a). However, several time slices display a lower degree of similarity as indicated by higher residuals. The poorest fit was produced between the corresponding diatom records from both lakes, as suggested by a relatively high p value (p= 0.13)(Fig. 4.9b).

Table 4.3: Procrustes rotation and PROTEST diagnostics. PROTEST is the correlation on a symmetric Procrustes rotation using nMDS axis scores and the associated p value (based on 39 permutations). Bold print indicates a significant fit between data sets.

Comparisons	Procrustes rotation sum of squares	RMSE	PROTEST (r)	P value
(a) LC6 Pollen vs. Wuxu Pollen	0.73	0.14	0.52	**0.0512**
(b) LC6 Diatoms vs. Wuxu Diatoms	0.82	0.14	0.43	0.1281
(c) LC6 Pollen vs LC6 Diatoms	0.50	0.11	0.70	**0.02**
(d) Wuxu Pollen vs Wuxu Diatoms	0.75	0.14	0.49	**0.025**

4.5 Discussion

4.5.1 Biological response to climate and human-induced changes on the southeastern Tibetan Plateau

Regional vs. local response

The pollen record from the LC6 Lake and the pollen record from Wuxu Lake, located 680 km to the west, have a very similar species composition and changes in the species composition are temporally consistent. This concordance between both data sets is shown by the significant procrustean fit (p= 0.05; Table 4.3) (Fig. 4.9a), suggesting that the timing, magnitude and direction of change in both pollen records is very similar over the last 200 years and that changes are likely to occur in response to regional, as opposed to local, environmental or human-induced changes. Both pollen records show a dominance of evergreen oak-pine forests (sclerophyllous *Quercus*, *Pinus*) intermixed with *Abies, Picea* and *Betula* throughout their profiles. Broadleaved taxa like *Rhododendron* and *Salix* are the main elements in the secondary canopy. As such, the vegetation is characteristic for the montane forest belt on the southeastern Tibetan Plateau, typically found between 3000-4000 m asl (Yu et al., 2001; Kramer et al., 2010c). At LC6 lake, herbal taxa, mainly comprised of *Polygonum*, *Artemisia* and Cyperaceae, are a stronger component as at Wuxu lake. This most likely represents the stronger influence of components from alpine meadows, as LC6 lake is located ~ 400 m higher than Wuxu lake and therefore closer to the sub-alpine shrubland and alpine meadows, typically covering the slopes above 4000 m asl on the southeastern Tibetan Plateau (Yu et al., 2001).

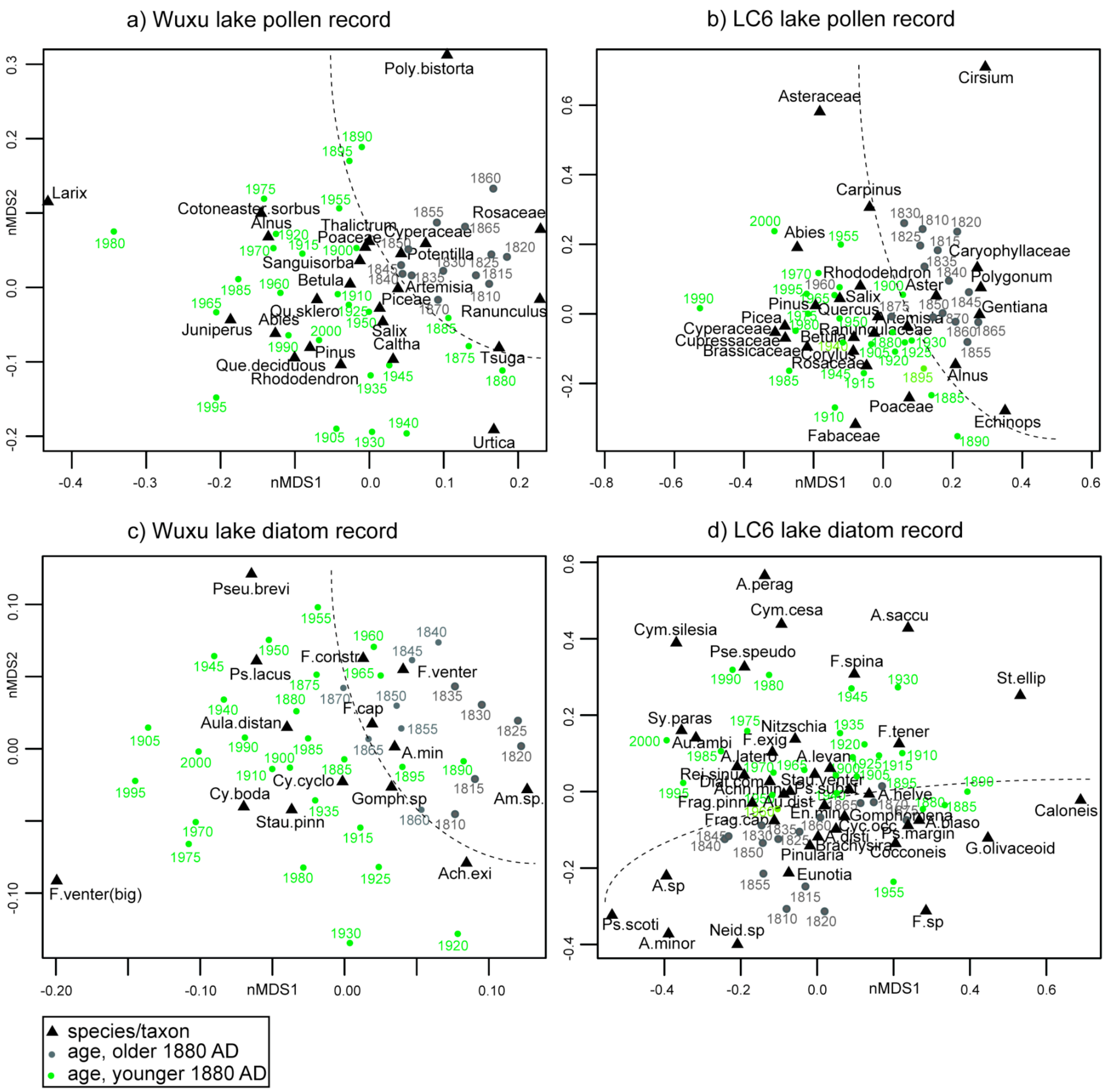


Figure 4.8: nMDS ordination results (2D) on interpolated and resampled data sets.

Comparing the diatom records of both lakes with each other, the picture is different. The Procrustean rotation produced an insignificant fit (p= 0.12) (Fig. 4.9b), indicating that the timing, duration or magnitude of change of the diatom assemblage in response to environmental changes varies between both lakes and that care needs to be taken when making regional climate inferences from the diatom record alone. Local circumstances may have overwritten a regional climate signal. Procrustean residuals (Fig. 4.9b) indicate that mismatches between both aquatic data sets were greatest between 1810-1840 AD and between 1940-1975 AD, which correspond with time periods when compositional turnover is highest in both lake systems (compare DCCA scores in Figures 4.4 and 4.5). Possible causes for higher compositional species turnover during these periods is discussed below. The diatom records of LC6 lake and Wuxu lake are plankton dominated systems and are habitat to slightly acidic to circumneutral taxa. Many are cosmopolitan species that are commonly found in freshwaters of high-latitude and alpine regions (Lotter and Bigler, 2000; Sorvari et al., 2002; Rühland and Smol, 2005).

Compositional turnover

The overall characteristic of both pollen records, is the very stable species composition throughout the entire profile. Species shifts are only very subtle over the last 200 years (LC6 lake) and 400 years (Wuxu lake). The very low total sum of squares from the CONISS analyses and a very small compositional turnover (DCCA score of less than 0.5 SD) confirm this. Similar low values as at LC6 lake and Wuxu lake were found from the pollen record at Lake Zigetang (0.44 SD) and Lake Koucha (0.41 SD) on the central and northeastern Tibetan Plateau, estimated over the last 9000 years (Herzschuh et al., 2010a). For comparison, Birks (2007) investigated compositional turnover on Holocene pollen-stratigraphical sequences from southern Norway and associated DCCA axes scores above 1.0 SD units with high compositional turnover.

Compared to the dramatic vegetation shifts on the Tibetan Plateau at the transition from the late glacial to the early Holocene or during the mid-Holocene (Jarvis, 1993; Demske et al., 2009; Herzschuh et al., 2009), the degree of vegetation change over the last two to four centuries is less significant. Kramer et al. (2010) reconstructed a 2-3°C temperature rise at the Pleistocene/Holocene boundary (at Naleng lake, southeast Tibet) which triggered the spreading of forest on the expense of the steppe and meadow ecotone. The same record shows a considerable reorganization of the vegetation during the shorter lived cold event around 8.1 cal. kyr BP, when temperatures dropped by 1-2 °C (Kramer et al., 2010c). You et al. (2007) states a ~ 1.4°C warming over last 40 years for the southeastern Tibetan Plateau, but changes in the vegetation structure did not show a similar strong compositional turnover as over the Holocene time scale, suggesting that the length and magnitude of the recent warming period at our sites has not yet led to the crossing of climatically-induced ecological thresholds, but that other parameters such as human activity, are increasingly impacting these ecosystems. However, previous environmental conditions, e.g. at the Pleistocene/Holocene boundary, were different and trees were not the dominant vegetation type and the vegetation density was generally low (Kramer et al., 2010c). With the onset of warmer and moister conditions in the early Holocene, trees could migrate into new niches as climate became more favourable to their growth. During the late Holocene and the recent past these niches were already occupied, so a temperature increase alone would not necessarily cause similar results.

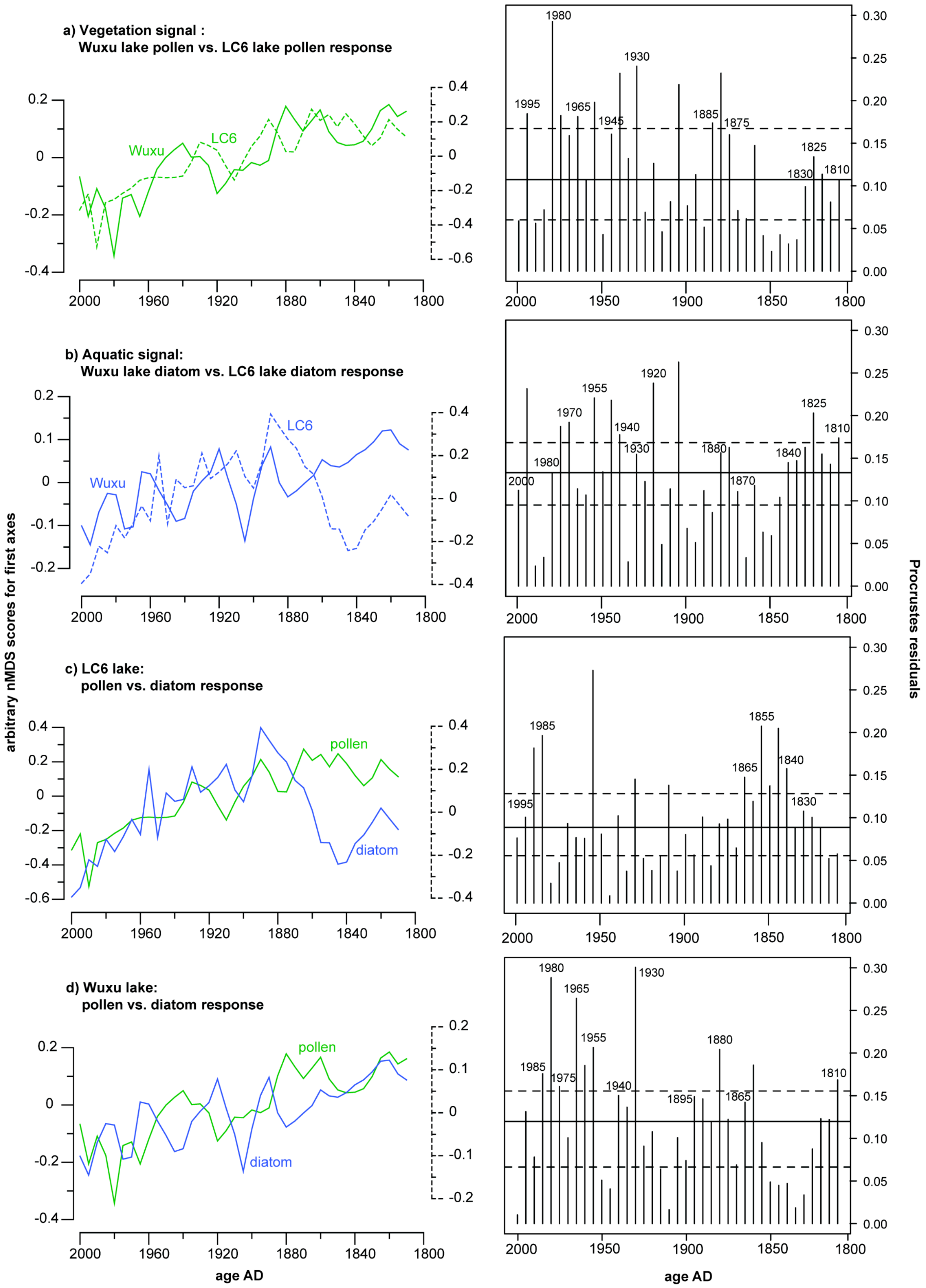


Figure 4.9: Between-lake and within-lake comparisons. Results from nMDS axis 1 scores and impulse diagram of Procrustes Rotation residuals. Height and occurrence of peaks in impulse diagram indicate the degree of dissimilarity between two data sets compared. Dashed and solid lines across indicate the first, second and third quartile, respectively.

Similar to the pollen records, the overall compositional change in both diatoms records is very small as well, which is confirmed by low total sum of square scores from the CONISS analyses and by a low compositional turnover, inferred from the DCCA (0.3 SD, Wuxu lake – 0.85 SD, LC6 lake). For comparison, similar low SD values (0.84 SD) 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). Such stable diatom species assemblages are maybe surprising, particularly in the light of the significant temperature and precipitation changes (Liu and Chen, 2000; You et al., 2007) and alarming glacial retreat (Su and Shi, 2002) recorded for the SE Tibetan Plateau over the past two centuries. Rühland et al. (2008) identified in an extensive study from arctic, alpine and temperate lakes across the northern hemisphere strong reorganizations in the diatom communities, starting in the mid-19th century, which they link to primarily climate warming. They explain that an earlier ice break up, triggered by rising mean winter and spring temperatures, would lead to a longer growing season and changes in the light and mixing regime and increased nutrient cycling that in turn would enhance especially planktonic growth. Hence, recent warming trends in these remote arctic and mountain lake systems were manifested by a significant shift from benthic (e.g. small fragilarioid species) to planktonic (e.g. small *Cyclotella* species) taxa. These taxa shifts could not be detected at LC6 or Wuxu lake. So far no diatom records in the region exist for comparison of compositional turnover rates between the recent past and the Holocene. Diatom records from the arid western and northeastern part of the Tibetan Plateau indicate that Holocene changes in the monsoon strength have led to significant lake level and salinity changes that resulted in at times complete reorganizations of the diatom flora in these lake systems (Van Campo, 1993; Hui et al., 1996; Xue et al., 2003) - a magnitude of change that is not comparable to the slight species shifts over the past two centuries in our records. The limited response of the diatom assemblage at LC6 and Wuxu lake during the past two centuries suggests that either both diatom assemblages are insensitive to recent environmental changes, and that both sites have not yet crossed climatically-induced ecological thresholds, as also suggested by the corresponding pollen records, or that processes, such as increasing precipitation and cloud cover counteract with the impacts of increasing temperatures (Wischnewski et al., in review).

4.5.2 Causes of terrestrial and aquatic ecosystem change

Apart from the low overall compositional change, minor species shifts could be identified in both pollen records. The LC6 pollen record revealed an increase in herbaceous pollen, like *Polygonum*, Asteraceae, Caryophyllaceae from ~ 1840 until the 1890s, whilst the Wuxu lake showed increases in Rosaceae, *Thalictrum* and the *Caltha*-type at a similar time period from ~ 1840 to the 1870s. All taxa mentioned above are characteristic elements of the alpine meadow vegetation, suggesting that cold climate conditions in the middle and second half of the 19th century may have triggered the altitude-downward expansion of this colder adopted vegetation type.

This cold period could also be detected in several other records of the Tibetan Plateau. Yang et al. (2004) reconstructed higher lake levels, due to colder and moister conditions, between 1845-1885 AD through the application of a diatom-salinity transfer function at Lake Chencuo (SE Tibetan Plateau). Zhang et al. (2010) reconstructed a cold period before the 1920s in a 160-year record using *n*-alkanes. Ice core records (Thompson et al., 2006; Yang et al., 2006) and several tree-ring studies (Bräuning and Mantwill, 2004; Bräuning, 2006; Liang et al., 2009; Yang et al., 2009; Yang et al., 2010a) also identified pronounced cold periods during the 19th century. These cold periods correspond well with periods of low solar activity (Dalton minimum at 1810 AD) at the end of the "Little Ice Age" (Bard et al., 2000) and strong volcanic eruptions between 1810-1820 AD (Crowley, 2000), suggesting that the expansion of alpine meadows in the LC6 and Wuxu lake catchment in the second half of the 19th century is a response to natural climate variability. The 20 to 40-year time lag of the expansion of alpine meadows around 1840 AD and the Dalton minimum around 1810 AD may result from the vegetative delay to changing temperature and precipitation conditions (Heegaard et al., 2006).

Shifts in the corresponding diatom records during that time period are negligible, apart from a slight but short-lasting shift to more benthic taxa around 1840 at LC6 lake, possibly indicating longer ice coverage during the colder climate conditions. This concordance between the terrestrial and the aquatic record within each lake is also proven by the Procrustes analyses that produced significant fits ($p= 0.02$ for LC6 records, $p= 0.025$ for Wuxu records) for both lakes (Fig. 4.9c, 4.9d), indicating that the lake and its terrestrial environment react similar to environmental impulses.

After ~ 1880, both pollen records reveal an increase of arboreal taxa, with an increasing trend lasting until present. This is contradictory to studies that show evidence of forest decline on the Plateau since the mid-Holocene (Shen et al., 2005; Kramer et al., 2010c), and other studies that report on alarming forest loss and habitat defragmentation since the 1950s (Studley, 1999, Zhang et al., 2000). Whilst there is still an ongoing discussion whether forest decline since the mid-Holocene was primarily caused by climatic conditions, human impact, or a combination of both (Yang et al., 2005, Herzschuh et al., 2010c; Schlütz and Lehmkuhl, 2009; Kramer et al., 2010c), the severe loss of natural forest in the recent past (last 2000 years), and particularly in the past decades (since the 1950s) is attributed to anthropogenic forest clearances as a consequence of the high timber, grazing and agricultural ground demand of a constantly growing Chinese population (Studley, 1999; Zhang et al., 2000; Elvin et al., 2002; Dearing et al., 2008). The forest increase since ~ 1880 in the LC6 and Wuxu lake catchments is mainly linked to species of *Quercus*, *Pinus*, Cupressaceae, *Abies* and *Larix*. *Pinus*, *Larix* and genera of the Cupressaceae family are fast growing tree species that are used within governmental programs for reforestation purposes (Bao and Jiang, 1998; Zhang et al., 2000), suggesting that at least a part of the forest increase results from reforestation, rather than natural forest growth. A historical study of Lake Erhai (SW China) (Elvin et al., 2002) provides evidence that the region suffered from an environmental crisis as early as the end of the Ming dynasty (CE 1368 – 1644) and beginning of Qing dynasty (CE 1644-1911).

Rapid population growth and exploitation in form of widespread forest clearances for timber and agricultural grounds have resulted in severe soil erosion and major floods, threatening people's lives and their farmlands. In consequence, reforestation in some parts on the SE Tibetan Plateau started as early as the 1780s (Elvin et al., 2002). Also, the Wuxu pollen record shows high abundances of grazing indicators (Apiaceae, *Rumex, Sanguisorba*) from the 1760s – 1800, indicating anthropo-zoogenic pressures in the study region. Furthermore, *Quercus-Pinus* forests are often described as secondary forests, developing after human disturbance. Their growth is promoted by human-induced fires for the purpose of forest clearance (Winkler, 1996; Yang et al., 2005; Shen et al., 2006b). However, the high abundance of *Quercus* in both pollen records is most likely an overrepresentation of the real distribution, as *Quercus* is known to be a strong pollen producer (Jarvis and Clay-Poole, 1992). Furthermore, *Quercus* and *Pinus* pollen are prone to long distance transport and often found in the modern pollen rain even at elevations they do not naturally grow (Jarvis and Clay-Poole, 1992). The dominance of pine-oak forest in both pollen records, may therefore partly reflect elements of the evergreen needle-leaved and deciduous broad-leaved mixed forests from the adjacent but lower elevated hills (2000-3000 m) from Sichuan and Yunnan Provinces (Yu et al., 2004). The strong increase of *Pinus*, Cupressaceae (at LC6 lake), *Larix* and *Abies* (at Wuxu lake) since the mid-1990s can be linked to China's latest attempts to reforest wide parts of the degraded landscapes in the North, Northwest and Southwest (Three-North Protective Forest Program, start 1978; Natural Forest Conservation Program, start 1998)(Fang et al., 2001; Zhang et al., 2000). Other studies on the southeastern Tibetan Plateau support this trend. Shen et al. (2006b) identified a sharp increase in *Pinus* over the past 25 years, and Fang et al. (2001) shows evidence of significant increase in total forest biomass carbon storage since the 1970s, indicating secondary forest growth.

Apart from anthropogenic pressures, changing climate in combination with a national fire ban that was set to prevent burning practices by herders (Baker and Moseley, 2007) might have also had influence on the slight forest increase in the LC6 and Wuxu lake catchment. Ice core records indicate warmer and moister conditions over the past ~ 200 years)(Thompson et al., 2000; Thompson et al., 2006; Hou et al., 2007). Furthermore, instrumental data suggest that not only have annual temperatures on the SE Tibetan Plateau increased since 1961, but that temperatures during each of the four seasons also increased since 1961, particularly in the winter and autumn season with an increase of 0.37°C and 0.35°C/decade, respectively (You et al., 2007). You et al. (2007) also identified rising precipitation trends for the SE Tibetan Plateau since the 1980s, which are most obvious in the autumn and spring season. The increase in sclerophyllous *Quercus* since ~1880, observed at the Wuxu lake pollen record, could be the response to these climatic trends. A dry early spring (temperatures rise before the onset of the monsoon) and milder winters would promote predominantly sclerophyllous taxa (Jarvis, 1993). *Abies*, on the other hand, has often been associated with increasing effective moisture (Yan et al., 1999; Kramer et al., 2010c;), hence the increase of *Abies* in the second half of the 20th century in both pollen records, may be linked to increasing precipitation rates as reported by You et al. (2007). Hence, the synergistic processes of post Little Ice Age warming, 20th century climate warming and extensive reforestations since the 19th century have promoted the growth of semi-natural pine-oak forests, intermixed with fir and larch.

Changes in both diatom records after 1880 AD are lesser than changes in the pollen spectra, but a slight increase in tychoplanktonic and small fragilarioid taxa after the 1930s/50s can be observed in both records. Tychoplanktonic and fragilarioid taxa, which are known to be *r*-strategists, are better adapted to rapid changing environments (Lotter and Bigler, 2000) and therefore indicative for 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). Nevertheless, the stability of both diatom assemblages throughout the cores is indicative of very little change within the lake systems over the past ~200 years. Hobbs et al. (2010) compared compositional turnover for the last two centuries in arctic, alpine (above the altitudinal tree line) and temperate montane-boreal lake systems and found lowest species turnover rates in diatom records from montane-boreal lakes in North America (0.42-0.79 SD). Rühland et al. (2008) found generally weaker and time-lagged (~ 100 years) diatom response to primarily climate-induced changes at temperate lakes in comparison to arctic and alpine lakes. Even though LC6 and Wuxu lake are located above 3700 m asl, they closer compare to the temperate montane –boreal lake systems in North America than to the treeless alpine and arctic lake systems as they are free from ice cover for most of the year and surrounded by dense forests. At temperate montane-boreal lakes with a longer open water season, thresholds for diatom taxonomic shifts are more gradually met (Hobbs et al., 2010). According to mean monthly temperature and monthly satellite imagines from the Landsat archive (USGS earth explorer), LC6 lake and Wuxu lake are currently eight to ten months of the year ice-free, suggesting that much higher magnitudes of temperature change would be necessary to significantly shorten the growing season and effect the diatom composition. Additionally, temperate lakes are potentially not so sensitive to small changes in climate or nutrient input (Rühland et al., 2008), in part due to the edaphic stability of their catchments (Heegaard et al., 2006). Furthermore, several studies have shown that the composition and distribution of aquatic organisms is often correlated to changes in the terrestrial environment of the lake (Heegaard et al., 2006). The relative stable vegetation composition in the LC6 and Wuxu lake catchment over the past two decades, could have contributed to the limited aquatic response.

Several studies have shown that apart from climate change, also enhanced atmospheric pollution from anthropogenic sources can trigger changes in the diatom assemblage (Wolfe et al., 2003; Hobbs et al., 2010). Data from 74 stations across China (Tang et al., 2010) show that wide parts, particularly the SW suffered from acid rain since the 1970s, reaching severe levels (pH <4.5) in the 1980s and 1990s, thereafter leveling off. However, since the year 2000 rapid economic growth lead to higher energy consumption and hence rising emissions of SO_2 and NO_x (Wang and Wang, 1995; Tang et al., 2010). Due to poor data availability is it difficult to say, how strongly the remote and montane sites on the Tibetan Plateau are affected by acid rain, but single weather stations in the SW of China (Tang et al., 2010) and a case study from the Nam Co region (Cong et al., 2007) indicate that these sites are impacted to a degree. The geology in the catchments of the LC6 and Wuxu Lake is characterized by granitic and metaphorphic stones, hence the lakes should respond sensitively to acidification processes. However, no obvious shifts in the diatom assemblage of the LC6 and Wuxu Lake suggest a trend towards more acidophilous taxa. Koinig et al. (1998), on the other hand, have shown a close relationship between rising air temperature and associated snow melt and increasing pH values, as a consequence of increased weathering. In their alpine study site, pH levels increased parallel with increasing mean air temperatures, despite elevated deposition of airborne pollutants. We therefore propose, that the limited diatom response may also be caused by the counterbalancing processes of pH increase due to higher weathering and pH decrease due to enhanced nitrogen deposition in most recent years. Additionally, the impacts of high levels of acids in the precipitation can be balanced by the neutralizing capacity of alkaline soil dust, an important feature in the semi-arid parts of the Tibetan Plateau (Larssen and Carmichael, 2000). Other possible reasons, such as local temperature peculiarities, or increasing cloud cover, that could explain the limited diatom response to the well-established climatic changes on the southeastern Tibetan Plateau are summarized in Wischnewski et al. (submitted to JOPL).

In summary, it is difficult to access the causes of terrestrial and aquatic change and to separate the impacts of the climate warming from human activity on the SE Tibetan Plateau. Human footprints are detectable throughout the full length of both pollen records, but rising temperatures may have supported the subtle but constant growth of secondary pine-oak forests over the last century. This slight forest increase since ~ 1880 is contrary to other studies that report forest decline, but may be attributable to reforestation, rather then natural forest growth. However, it remains difficult to assess how strong human activity has shaped and conversed the forest landscapes on the southeastern Tibetan Plateau over the last two centuries, as it is difficult to establish how the natural forest in these landscapes looked like.

4.5.3 Critical data assessment

We are aware of limitations in our data and analytical design that may have reduced the robustness of our biological reconstructions and the within-lake and between-lake comparisons.

(1) The age correlation and direct comparison of two sediment cores is generally problematic and uncertainties in the age models of both lake sediment cores have to be kept in mind. Irregularities in the accumulation rates can lead to age discrepancies (Binford, 1990). As mentioned in section 4.1, within the Wuxu lake sediment core appear small accumulation rate irregularities between 4-6 cm depth and the LC6 lake sediment core captures a rapid sedimentation event, leading to uncertain ages between 8-27 cm depth. However, the artificial radionuclide ^{137}Cs acts as a reliable age marker (Arnaud et al., 2006). Furthermore, to gain ages below the equilibrium of

total ^{210}Pb activity and supporting ^{226}Ra, ages were extrapolated assuming constant accumulation rates. However, sediment compaction and unknown irregularities in sediment accumulation rates may have lead to false extrapolated ages (Binford, 1990). ^{14}C dating will be used for the Wuxu lake sediment core to back up the $^{210}Pb/^{137}Cs$ chronology, where extrapolation of ages based on a constant sediment accumulation rate exceeded a 100-year period.

(2) The interpolation and re-sampling of the four data sets may have produced deviant results for time slices that were not actually directly counted or analysed.

(3) An additional difficulty are the taxonomic challenges on the southeastern Tibetan Plateau. The area has a particularly high plant biodiversity (Studley, 1999) and knowledge on the local pollen morphology is limited (Herzschuh et al., 2009). Furthermore, also diatom biodiversity is relatively high and lots of very small taxa (i.e. *Achnanthes* sp., *Fragilaria* sp.) hamper the identification with light microscopy. However, significantly contributing taxa were crosschecked with scanning electron microscope.

(4) The comparison of two different lakes under the assumption of uniform manner of responses may also be misleading. According to Battarbee (2000) even lakes that are in close proximity can have fundamentally different properties and different climate sensitivity thresholds and therefore respond to external forcing in unique ways, which can be particularly true for the heterogeneous and complex mountain landscape of the southeastern Tibetan Plateau. LC6 lake and Wuxu lake were chosen for comparison as they are both glacial tongue lakes and open systems, with similar lake size, water depth, pH, and alkalinity, located in the same vegetation zone. According to instrumental station data, temperature and precipitation patterns in both catchments are comparable over the year. However, Wuxu lake is located approx. 400 m lower in altitude (3707 m), has a threefold higher conductivity (0.03 mS/cm), a two meter lower secchi depth (5.3 m), and is possibly exposed to slightly higher anthropogenic impact. The surrounding vegetation is similar, but the diatom composition is plankton dominated at Wuxu lake and much stronger influenced by the benthic component at LC6 lake. These discrepancies may have caused varying sensitivities towards climate or human pressures.

4.6 Conclusions

Despite instrumental and palaeo-climatological evidence of recent climate warming on the southeastern Tibetan Plateau, diatom and pollen records from two montane-boreal lakes show only very subtle species compositional changes over the past two centuries. The subtle species changes observed, are synchronous in both pollen records, but time inconsistent in the corresponding diatom records, suggesting that the terrestrial records summarize primarily regional environmental changes, whereas the diatom records possibly capture only local responses. The combination of aquatic and terrestrial proxies is therefore valuable, to move from a local to a regional scale, but also to understand the many facets of the microenvironments in that complex mountain landscape of the Tibetan Plateau.

The overall limited response of the pollen and diatom assemblages from LC6 and Wuxu lake over the last 200 years points out that both lakes and their catchments seem to be resilient against the current rate and magnitude of climate warming. In comparison to the extensive reorganizations of the vegetation in the Holocene that underwent temperature magnitudes changes of 1-3°C, the current shifts in species and species abundance are relatively small. So far, no significant reorganizations of the vegetation and the aquatic system can be observed from our records, suggesting that climatically-induced ecological thresholds are not yet crossed.

More influential and alarming than the current rate of climate warming are the consequences of human-caused land cover change, that have already caused forest degradation and habitat defragmentation in wide parts of China. Even though our remote montane-boreal sites are not severely affected yet, anthropogenic signs are clearly visible. It is, however, impossible to separate the impacts of climate warming from anthropogenic impacts, in fact synergistic processes are more likely. Humans are shaping the landscapes of the southeastern Tibetan Plateau for several thousands of years by extensive forest clearances and reforestations as a consequence of rapid population and economic growth, which was particularly strong over the past two centuries. Although, human activities have not caused forest decline in our study area, they have initiated a conversion of the forest structure, i.e. a trend to less resilient, secondary pine-oak forests, whilst post-Little Ice Age and 20th century warming have contributed to their growth, promoting the regeneration of these semi-natural forests on the southeastern Tibetan Plateau. However, a further temperature increase of 3.7°C in the Tibetan Plateau, as predicted in a coupled atmosphere-ocean global climate model (Lal and Harasawa, 2001), and any artificial disturbance, will surpass the threshold of these vulnerable secondary forests and cause the degeneration of the vegetation structure and defragmentation with severe ecological consequences, like reduced water retention capacity, biodiversity reduction and increasing natural disasters (Yan et al., 2005; Cui et al., 2007).

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5 Synthesis

5.1 Environmental change on the Tibetan Plateau since the last Lateglacial

The reconstruction of monsoon variability since last Lateglacial on the Tibetan Plateau is a challenging task. Within the scope of *Manuscript # 1* I analysed the temporal course of vegetation changes since ~ 14.8 cal. ka BP using an 8 m-sediment core from Kuhai Lake on the northeastern Tibetan Plateau. Vegetation changes most likely went in hand with moisture changes (precipitation and/or effective moisture) in the region and could therefore be used to infer past monsoon dynamics. A pollen-precipitation transfer function, which was applied to the Kuhai Lake data set, provided quantitative mean annual precipitation rates. To assess whether environmental change in the region is similar amongst different sites, I compared the Kuhai Lake pollen record with the proximal Koucha Lake pollen record. To place the Kuhai Lake pollen record in the context of Holocene moisture evolution across the whole Tibetan Plateau, I compiled pollen and non-pollen information on Holocene moisture development from all available continuous palaeo-climate records across the Plateau in order to establish whether general (regional and/or temporal) patterns of moisture evolution exist on the Tibetan Plateau. In the following, the main results are outlined.

Sparse alpine desert vegetation and low reconstructed precipitation were characteristic of the Kuhai Lake area prior to 14.8 cal. ka BP, indicating dry and cold climate conditions. The expansion of alpine steppe vegetation during Bølling/Allerød and the early Holocene (14.8 cal. ka BP - 7.0 cal. ka BP) and reconstructed intermediate precipitation rates indicate higher temperatures and moisture availability than before. By 7.0 cal. ka BP high-alpine meadows expand (dominated by *Kobresia*) at the expense of alpine steppe vegetation, which led to the reconstruction of maximum precipitation rates, suggesting maximum Monsoon strength between 7.0 cal. ka BP and 6.3 cal. ka. BP. However, this pollen-based moisture reconstruction is in contradiction to the finding of lake level lowering and increasing salinity at Kuhai Lake by Mischke et al. (2009a). Herzschuh et al. (submitted) proposed that besides climate change an increase in the atmospheric CO_2 during the early and mid-Holocene could have supported the expansion of mesic *Kobresia* on the TP in areas formerly dominated by drought-resistant *Artemisia*. In that case the pollen-based moisture reconstruction would over-estimate the moisture increase during that time. The occurrence of typical desert elements in the alpine steppes around the lakes and very low reconstructed annual precipitation rates indicate strong aridity between 6.3 cal. ka BP and 2.2 cal. ka BP. However, *Kobresia* meadows in high-alpine mountain regions did not retreat during that time. A wide expansion of alpine steppe meadow vegetation with a high content of *Kobresia* and high-reconstructed annual precipitation rates in the last 2000 years, indicate high effective moisture for the most recent period of the Holocene.

Herzschuh et al. (2009) reported on a pollen record from Lake Koucha, a site 230 km southwest of Lake Kuhai, to date representing the nearest palaeo-ecological record to Lake Kuhai on the upper Tibetan Plateau. The direct and numerical comparison of the Lake Koucha and Lake Kuhai pollen record revealed a general similarity between both vegetation records even though the climate inferences were at times partially contradictory. Both catchments were characterised by a significant change from alpine steppe-desert vegetation to alpine steppe vegetation with tundra elements at the Bølling/Allerød interstadial, which lasted until 6.6 cal. ka BP (Koucha)/7.0 cal. ka BP (Kuhai), thereafter *Kobresia* meadows expanded. However, after 6.3 cal. ka BP the Lake Kuhai record revealed a marked increase in desert elements whilst this trend is not so obvious at Lake Koucha. The last ca. 2000 years have been relatively variable in both records showing a tendency of a decreasing *Artemisia*/Cyperaceae (*Kobresia*) ratio. Hence, apart from the period 6.3 cal. ka BP - 2.2 cal. ka BP where desert elements increased in the alpine steppes around Lake Kuhai, there was analogous vegetation development, strongly indicating parallel forcing on the NE Tibetan Plateau.

Compiling information on inferred Holocene moisture evolution from the Tibetan Plateau using all available continuous palaeo-climate records and comparing the Lake Kuhai pollen record with these records, it was not straightforward to find synchronous moisture trends. The initial increase in moisture and warming at about 14.8 cal. ka BP as indicated by the Lake Kuhai pollen record, is generally in phase with several other records on the Tibetan Plateau (e.g., Gasse et al., 1991; Shen et al., 2005, Zhang and Mischke, 2009). However, moisture trends inferred from pollen and non-pollen records during the Holocene are less uniform and differ significantly between records. A cluster analysis indicates that apart from the very coarse generalisation that wettest conditions ended between 7.0 cal. ka BP - 4.0 cal. ka BP and that the majority of sites were drier in the second part of the Holocene, there is no coherent regional and temporal pattern of moisture evolution across the Tibetan Plateau (Fig. 2.9). The previous assumption that sites influenced by the Indian summer monsoon experienced their moisture optimum during the early Holocene, whereas sites influenced by the East Asian summer monsoon and the westerlies experienced the moisture optimum during the mid Holocene (e.g., An et. al, 2000; He et al., 2004; Herzschuh, 2006; Chen et al., 2008), could not generally be confirmed by the analyses undertaken here. Overall, the results indicated that the moisture development during the Holocene on the Tibetan Plateau is not strictly linked to regional circulation regimes and underlying mechanisms are still a matter of debate. Uncertainty in age control, possible human impact, and the strong sensitivity of certain pollen types towards atmospheric CO_2 changes, certainly contribute to the existing uncertainty on climate trends. Results of this study show that possibly the unique nature of each catchment and lake system and the distinct reaction of lacustrine and terrestrial (both abiotic and biotic) proxies to atmospheric/climatic and local environmental change add to that complexity of reconstructed moisture patterns across the Plateau.

5.2 Environmental change on the Tibetan Plateau over the last 200 years

Comparing ecosystem response on the Lateglacial/Holocene time-scale to ecosystem response on the recent past (i.e., the last 200 years) might help to evaluate if the environmental change under current climate and human pressures is similar to change rates during the Holocene. Therefore, the change of climate and ecosystems in the recent past is of particular interest. A major challenge is to disentangle processes of natural climate variability, i.e. post Little Ice Age warming and the effects of human-induced environmental/climate change as a consequence of rapid population and economic growth in South and East Asia promoting anthropogenic global warming. *Manuscripts # 2* and *# 3* are concerned with the environmental history of the southeastern Tibetan Plateau over the past 200 years. Two sediment short cores from LC6 Lake and Wuxu Lake were investigated for their pollen and diatom spectra in an attempt to address the above-mentioned confront – detecting and disentangling possible environmental and human-induced changes in these remote mountain-boreal lakes. The main results are summarised in the following.

The overall characteristic of both pollen records from LC6 Lake and Wuxu Lake, is the very stable species composition throughout the entire profiles. Species shifts are only very subtle over the last 200 years, as indicated by the pollen profiles themselves and statistical analyses (CONISS and DCCA). Both pollen records show a dominance of evergreen oak-pine forests (sclerophyllous *Quercus*, *Pinus*) intermixed with *Abies*, *Picea* and *Betula* and broadleaved taxa like *Rhododendron* and *Salix* in the secondary canopy. As such, the vegetation is characteristic for the montane forest belt on the southeastern Tibetan Plateau, typically found between 3000-4000 m asl (Yu et al., 2001; Kramer et al., 2010c). Similar to the pollen records, the overall compositional change in both diatoms records is very small over the past 200 years. Both records are dominated by planktonic *Cyclotella* species, monoraphid (*Achnanthes* sp., *Achnanthidium* sp.) and fragilariod (*Fragilaria* sp., *Staurosirella* sp.) taxa, typical for slightly acidic to circumneutral, oligotrophic, electrolyte-poor lakes, commonly found in freshwaters of high-latitude and alpine regions (Lotter and Bigler, 2000; Sorvari et al., 2002; Rühland and Smol, 2005).

Compared to the dramatic vegetation shifts on the Tibetan Plateau at the transition from the Lateglacial to the early Holocene or during the mid-Holocene (Jarvis, 1993; Demske et al., 2009; Herzschuh et al., 2009), the degree of vegetation change over the last two to four centuries is a different order of magnitude. Kramer et al. (2010c) reconstructed a 2-3°C temperature rise at the Pleistocene/Holocene boundary (at Naleng Lake, southeast Tibet) which triggered the spreading of forest on the expense of the steppe and meadow ecotone. The same record shows a considerable reorganisation of the vegetation during the shorter lived cold event around 8.1 cal. ka BP, when temperatures dropped by 1-2 °C (Kramer et al., 2010c). You et al. (2007) states a ~ 1.4°C warming over last 40 years for the southeastern Tibetan Plateau, but changes in the vegetation structure did not show a similar strong compositional turnover as over the Holocene time scale. This suggests that the length and magnitude of the recent warming period at our sites has not yet led to the crossing of climatically-induced ecological thresholds. However, local or regional conditions, like increased precipitation and cloud cover, may have antagonised the effects of increasing temperature and resulted in a muted diatom and pollen response.

Despite the overall minor changes in the pollen and diatom assemblages of LC6 Lake and Wuxu Lake, subtle species shifts indicate climatic and anthropogenic impacts, especially in the pollen records. Both pollen records reveal an increase of characteristic elements of the alpine meadow vegetation between ~ 1840 - ~ 1880s, suggesting that cold climate conditions in the middle and second half of the 19th century may have triggered the altitude-downward expansion of this colder adapted vegetation type. Taking the vegetative delay to changing temperature and precipitation into account (Heegaard et al., 2006) this cold period corresponds well with periods of low solar activity during the Dalton minimum at 1810 AD (Bard et al., 2000), suggesting a signal of natural climate variability. Shifts in the corresponding diatom records during that time period are negligible, apart from a slight but short-lasting shift to more benthic taxa around 1840 at LC6 Lake, possibly indicating longer ice coverage during the colder climate conditions. After ~ 1880 both pollen records show an increase in arboreal taxa – a trend lasting until present. This is contradictory to studies that show evidence of forest decline since the mid-Holocene (Shen et al., 2005; Kramer et al., 2010), and other studies that report on alarming forest loss and habitat defragmentation since the 1950s (Studley, 1999; Zhang et al., 2000). The forest increase in the LC6 and Wuxu lake catchments is mainly linked to species of *Quercus*, *Pinus*, Cupressaceae, *Abies* and *Larix*. *Pinus*, *Larix* and genera of the Cupressaceae family are fast growing tree species that are used within Chinese governmental programs for reforestation purposes (Bao and Jiang, 1998; Zhang et al., 2000), suggesting that at least a part of the forest increase results from reforestation, rather than natural forest growth. *Quercus-Pinus* forests are often described as secondary forests, developing after human disturbance. Their growth is promoted by human-induced fires for the purpose of forest clearance (Winkler, 1996; Yan et al., 2005; Shen et al., 2006b), indicating an anthropogenic influence. However, the increase in sclerophyllous *Quercus* since ~1880, observed at the Wuxu Lake pollen record, could also be the response to post Little Ice Age and 20th century climate warming. Jarvis (1993) found that a dry early spring (temperatures rise before the onset of the monsoon) and milder winters would promote the growth of predominantly sclerophyllous taxa. *Abies*, on the other hand, has often been associated with increasing effective moisture (Yan et al., 1999; Kramer et al., 2010c), hence the increase of *Abies* in the second half of the 20th century in both pollen records, may be linked to increasing precipitation rates as reported by You et al. (2007). Hence, the synergistic processes of post Little Ice Age warming, 20th century climate warming and extensive reforestations since the 19th century have promoted the growth of semi-natural pine-oak forests, intermixed with fir and larch.

In summary however, the small changes observed in both pollen and diatom records from the two montane-boreal sites on the southeastern Tibetan Plateau are not of the same magnitude as the partly dramatic species shifts observed in palaeo-climate records from other climate-sensitive regions in the Arctic or in alpine regions (Smol et al., 2005; Hobbs et al., 2010).

5.3 Lacustrine and terrestrial proxies as indicators of environmental change

The direct comparison of proxies that represent changes a lake system with proxies representing changes in the terrestrial environment is highly valuable to assess whether the lake system and its catchment respond to possible environmental changes in a similar manner. In *manuscripts #1* and *#3* I applied rigorous statistical methods to the corresponding aquatic and terrestrial proxies from four lakes or catchments in order to assess if possible differences in proxy sensitivity or response time contribute to the current discordance on coherent regional and temporal climate patterns across the Tibetan Plateau. The main results are outlined in the following.

Procrustes rotation (see Chapter 2.3.3) has proven to be a suitable method to implement a direct and numerical comparison between two proxy data sets. Up to now, approaches to infer climate change in the Tibetan Plateau have qualitatively compared different proxies to establish regional or proxy relationships (Van Campo and Gasse, 1993; Fontes et al., 1996; Gasse et al., 1996; Blyakharchuk et al., 2004; Herzschuh et al., 2005; Mischke et al., 2005; Westover et al., 2006; Ilyashuk and Ilyashuk, 2007; Rudaya et al., 2009). Here we employed numerical techniques, applicable to the raw data of any sedimentary record, to quantitatively compare proxy records of interest and rigorously establish not only how well the records match in general, but also to identify time periods of better or worse fit. In other words, the degree of similarity or dissimilarity of change over any time scale between proxies and/or lakes can be statistically quantified.

The results for the Tibetan Lakes indicate that the use of different proxies and the work with palaeo-ecological records from different lake types can cause deviant stories of inferred change. Irrespective of the timescale (Holocene or last 200 years) or region (SE or NE Tibetan Plateau) analysed, the agreement in terms of the direction, timing, and magnitude of change between the corresponding terrestrial data sets was generally better than the match between the corresponding aquatic data sets (Fig. 5.1).

Within-lake comparison, i.e. pollen records vs. diatom/ostracod/geochemistry records, generally produced good and statistically significant fits, supporting the hypothesis that a lake and its catchment react similar to environmental changes. However, several time windows, especially during periods of colder climate conditions (~12.0 cal. ka BP, ~ 2.0 cal. ka BP, ~ 1820-1860 AD) or periods with stronger anthropogenic impact and higher variability (~ 2.0 cal. ka BP, ~ 1880 AD, since ~ 1950s), the aquatic signal deviates stronger from the terrestrial signal. Often this deviation is linked to rather rapid changes in the aquatic data sets whilst the pollen data sets show a more smoothed response, suggesting that the aquatic proxies are more prone to possibly local or short-lived events whilst the pollen records show a more regional signal.

The between-lake comparisons varied in the goodness of their fit, depending on the type of proxies used. When comparing two proximal lakes with each other (i.e., Kuhai vs. Koucha or LC6 vs. Wuxu), and just focussing on the pollen records, the direction, timing and magnitude of change over time was generally very similar, indicating regional climate forcing. However, when using the corresponding aquatic data sets at these same lakes, the direction, timing or magnitude of change was at times contradictory, suggesting that each lake system may have its unique way to respond to environmental changes (Fig. 5.1). The direct comparison of Kuhai Lake, a saline closed basin lake, with Koucha Lake, a freshwater open basin lake, illustrated this nicely: Using aquatic proxies Mischke et al. (2008 and 2009a) reconstructed opposite lake level states for the early Holocene (high at Lake Kuhai; low at Lake Koucha) and therefore different climate trends, whilst the pollen-inferred trends were very similar and indicated that both catchments were very likely influenced by similar environmental forcing.

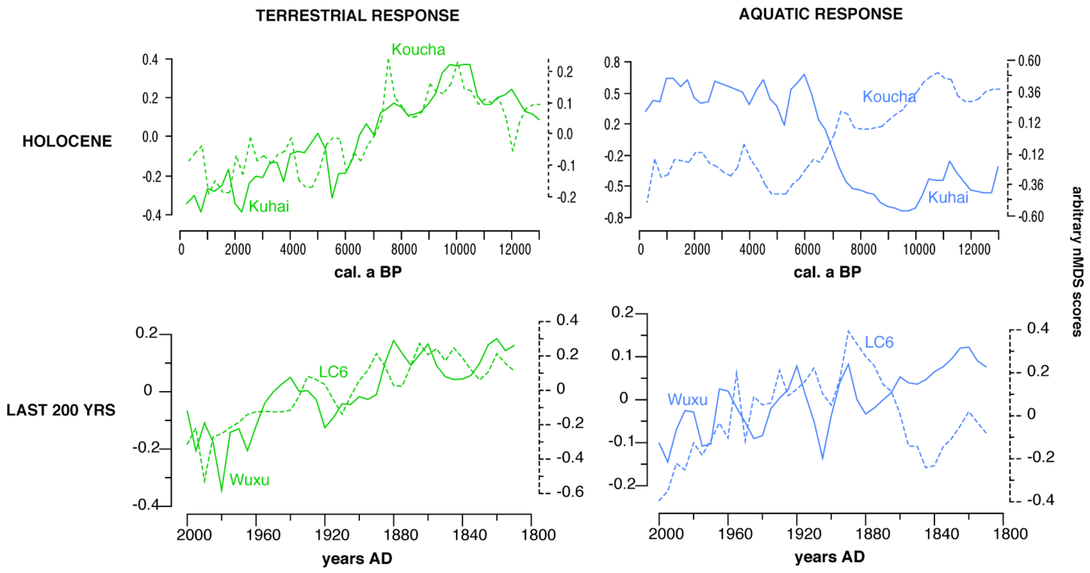

Figure 5.1: Between-lake comparisons using nMDS scores as a measure of change, indicating direction, timing and magnitude of change. Blue lines represent aquatic (diatoms/ostracods/geochemistry) response; green lines represent pollen response to environmental change.

Using palaeo-ecological data from different lake types is inevitable in the complex mountain landscape of the Tibetan Plateau but strongly contributes to asynchronous histories of inferred environmental change. Depending on their geographical position, geological and morphological background or exposure to wind and solar insolation, lakes types on the plateau may range from freshwater to saline lakes, from open to closed basin lakes, their catchments might be permafrost influenced or not, or they might be effected by human impact in varying degrees. In addition to this variation in space, this complexity might also vary through time. Therefore, care needs to be taken when making regional climate inferences from the aquatic record alone. Local peculiarities may have overwritten a regional climate signal.

5.4 Conclusions and implications beyond the scope of this study

Investigating temporal and spatial climate variability on the Tibetan Plateau, we are faced with three major challenges: (1) a very complex mountain landscape with numerous microenvironments, (2) a relatively poor coverage of palaeo-ecological studies with a continuous and suitable resolution and reliable age models, and (3) asynchronous climate patterns inferred from these studies, which still hamper our understanding of climate evolution on the Tibetan Plateau. My work on different time scales on four palaeo-ecological records from two core regions in the Tibetan Plateau using different proxies and rigorous statistical methods has contributed to our understanding of past climate variability and ecosystems response to environmental changes on the Tibetan Plateau.

The pollen and lacustrine records from Lake Kuhai and Lake Koucha, indicate that cold and dry climate conditions prevailed before 14.8 cal. ka BP on the NE Tibetan Plateau. Much warmer and wetter conditions dominated the early and mid Holocene, with highest effective moisture between 12.9 cal. ka BP and 6.2 cal. ka BP. Major vegetation shifts took place during Bølling/Allerød. The often-discussed abrupt climate shift at the Pleistocene/Holocene transition is not pronounced in our lake records. Comparing these results with all other available and continuous pollen and non-pollen palaeo-climate records from the Tibetan Plateau I found that so far no coherent regional and temporal climate pattern exists and that even records from sites that are located close to each other may result in different inferred climate histories. Different possible causes (age models, changing atmospheric CO_2 concentrations, local noise in proxy records, anthropogenic impact) contribute to the current discordance on inferred climate patterns across the Tibetan Plateau.

Despite instrumental evidence of increasing mean annual and mean winter temperatures on the Tibetan Plateau (e.g., Liu and Chen, 2000), environmental change over the past 200 years inferred from two pollen and diatom records from the southeastern Tibetan Plateau seems insignificant. Both pollen and diatom spectra show no obvious species shifts throughout the record. In comparison with the species reorganisations in the early and mid-Holocene that underwent temperature magnitude changes of 1-3°C, changes in the last 200 years are minor in magnitude, suggesting that climate-induced thresholds are not yet crossed. Nevertheless, signs of human activity are visible in these remote montane sites, particularly in the vegetation records. Although, human activities have not caused forest decline in the study area, they have initiated a conversion of the forest structure, i.e. a trend to less resilient, secondary pine-oak forests, whilst post-Little Ice Age and 20th century warming have contributed to their growth, promoting the regeneration of these semi-natural forests on the southeastern Tibetan Plateau. The separation of natural from anthropogenic-induced processes, however, was difficult – synergistic processes are most likely.

In this study I introduced the established numerical technique Procrustes rotation (Gower, 1971; Peres-Neto and Jackson, 2001) as a new approach in Palaeoecology to quantitatively compare raw data of any sedimentary record of interest in order to assess their degree of concordance. The direct and numerical comparisons from the four Tibetan lakes have proven that the use of different proxies and the work with palaeo-ecological records from different lake types can cause quite deviant histories of inferred change and that care needs to be taken when inferring climate from one record alone. Generally it is the vegetation record that captures a smoothed regional response, whilst proxies representing the lacustrine environment are possibly more prone to short lived or local events, indicating that different proxies may have varying sensitivities and response times to climate or environmental change. A combination of terrestrial and aquatic proxies would help to decipher the effects of in-lake or catchment processes and climate forcing. In addition to the complexity of proxy response, I found that the complex nature of different lake types on the Plateau complicates the interpretation of palaeo-ecological records and potentially causes contradictions in inferred climate change. So if we are to understand the climate of the past, we have to follow a multi-proxy, multi-site approach, in order to move from the local to a regional scale.

5.5 Outlook

This study has outlined that environmental change inferred from different proxies and different lake types has contributed to the current discordance of inferred Holocene climate pattern across the Tibetan Plateau. Sedimentary pollen spectra have proven to reflect regional long-term environmental forcing better than lacustrine proxies, which are often prone to short-lived or local events. In order to reconstruct a complete and reliable picture of past climate variability and to disentangle the different influences of the East Asian monsoon, Indian monsoon and the westerlies, more palynological investigations, particularly from the understudied central, northwestern and southwestern Plateau, are needed to establish transects of consistent and comparable studies across the Tibetan Plateau. These palaeo-proxy records should then ideally be analysed and compared with numerical techniques, using the raw data, rather then proxy-inferred change from these records.

Appendix

Appendix 1: Complete diatom taxa list of the LC6 Lake sediment core, indicating species name and authorities, synonyms and abbreviations used in Figures.

Code	Species and Authority	Synonym	Abbreviation
ACH0037B	*Achnanthes biasolettiana* Lange-Bertalot, 1989		A.biaso
ACH00XY1	*Achnanthes bremeyeri* Lange-Bertalot, 1989		A.breme
ACH00XY2	*Achnanthes caledonica* Lange-Bertalot & Moser , 1994		A.caled
ACH0023A	*Achnanthes conspicua* A. Mayer, 1919		A.consp
ACH0016C	*Achnanthes delicatula var.hauckiana* (Grun. in Cleve & Grun.) Lange-Bertalot & Ruppel, 1980		A.delic
ACH0039A	*Achnanthes didyma* Hust., 1933		A.didym
ACH0155A	*Achnanthes distincta* Messikommer, 1954		A.disti
ACH0163A	*Achnanthes helvetica* (Hustedt) Lange-Bertalot in LB & K, 1989		A.helve
ACH0134C	*Achnanthes helvetica var. minor* Flower & Jones, 1989		A.minor
ACH0170A	*Achnanthes joursacense* Herib., 1903		A.joura
ACH0149A	*Achnanthes kranzii* Lange-Bertalot & Krammer, 1989		A.kranz
ACH0017A	*Achnanthes kryophila* J.B. Petersen, 1924		A.kryo
ACH0083A	*Achnanthes laevis* Ostr., 1910		A.laevi
ACH0018A	*Achnanthes laterostrata* Hust., 1933		A.latero
ACH0044A	*Achnanthes levanderi* Hust., 1933		A.levan
ACH0013C	*Achnanthes minutissima var. jackii* (Rabenh.) Lange-Bertalot & Ruppel, 1980		A.jackii
ACH0098A	*Achnanthes montana* Krasske, 1929		A.monta
ACH0019A	*Achnanthes nodosa* A. Cleve-Euler, 1900		A.nodos
ACH0007A	*Achnanthes oestrupii* (A. Cleve-Euler) Hust., 1930		A.oestr
ACH0011A	*Achnanthes peragalli* Brun & Herib. in Herib., 1893		A.perag
ACH0182A	*Achnanthes rosenstockii* Lange-Bertalot, 1989		A.rosen
ACH0116A	*Achnanthes rossii* Hust., 1954		A.rossii
ACH0119A	*Achnanthes saccula* J.R. Carter in J.R. Carter & Watts, 1981		A.saccu
ACH9999A	*Achnanthes* species		A.sp
ACH0034A	*Achnanthes suchlandtii* Hust., 1933		A.suchl
ACH0161A	*Achnanthes ventralis* (Krasske) Lange-Bertalot, 1989		A.ventra
CAN0012A	*Achnanthidium minutissimum* (Kutz.)Czarnecki, 1994	*Achnanthes minutissima*	An.minu
AMP0010A	*Amphora fogediana* Krammer, 1985		Am.foge
AMP0013A	*Amphora inariensis* Krammer, 1985		Am.inari
AMP0011A	*Amphora libyca* Ehr., 1840		Am.liby
AMP0001A	*Amphora ovalis* (Kutz.) Kutz., 1844		Am.oval
AMP0012A	*Amphora pediculus* (Kützing) Grunow, in Schmid et al., 1875		Am.pedi
AMP9999A	*Amphora* species		Am.sp
SWA0002A	*Aulacoseira ambigua* (Grun. in Van Heurck) Simonsen, 1979		Au.ambi
SWA0005A	*Aulacoseira distans var. distans* (Ehrenb.) Simonsen, 1979		Au.dist
SWA0005E	*Aulacoseira distans var. nivalis* W. Smith) E.Y. Haworth,, 1988		Au.nivalis
SWA0005B	*Aulacoseira distans var. nivaloides* Camburn, 1987		Au.nivaloi
SWA0004A	*Aulacoseira lirata var. lirata* (Ehrenb.) R. Ross in Hartley, 1986		Au.lirata
BRA0006A	*Brachysira brebissonii* R. Ross in Hartley, 1986		B.brebi
BRA00XY1	*Brachysira intermedia* (Østrup) Lange-Bertalot,		B.inter
BRA0010A	*Brachysira neoexilis* Lange-Bertalot, 1994		B.neoex
BRA9999A	*Brachysira* species		B.sp
BRA0005A	*Brachysira zellensis* (Grun.) Round & Mann, 1981		B.zellen
CAL9999A	*Caloneis* species		Cal.sp
CAL0018A	*Caloneis tenuis* Gregory (Krammer), 1985		Cal.ten
CAV00XY2	*Cavinula intractata* (Hust.) Lange-Bertalot,		C.intra
CAV0003A	*Cavinula lacustris* (Greg.) Mann & Stickle, 1990	*Navicula lacustris*	Cav.lacu
CAV00XY1	*Cavinula lapidosa* (Krasske) Lange-Bertalot, 1989		C.lapis
CAV0004A	*Cavinula pseudoscutiformis* (Hust.) Mann & Stickle, 1990	*Navicula pseudoscutiformis*	Cav.pseud
CAV9999A	*Cavinula* species		C.sp
CHM9999A	*Chamaepinnularia* species		Chamae.sp
COC0001C	*Cocconeis placentula var. lineata* (Ehrenb.) Van Heurck, 1885		Co.linea
COC0001A	*Cocconeis placentula var. placentula* Ehrenb., 1838		Co.plance
COC0001B	*Cocconeis placentula var.euglypta* (Ehrenb.) Grun., 1884		Co.eugly
CRA0005A	*Craticula halophila* (Grun. ex Heurck) Mann, 1990	*Navicula halophila*	Cra.halo
CYT0022A	*Cyclotella bodanica* Grunow, in Schneider, 1878		Cy.bodan
CYT0054A	*Cyclotella krammeri* Hakansson, 1990		Cy.kramm
CYT0009A	*Cyclotella ocellata* Pant., 1902		Cy.ocell

Code	Species and Authority	Synonym	Abbreviation
CYT0055A	*Cyclotella schumannii* (Grunow) Hakansson, 1990		Cy.schum
CYM0016A	*Cymbella amphicephala* Naegeli ex Kutz., 1849		Cym.amph
CYM0015A	*Cymbella cesatii* (Rabenh.) Grun. in A. Schmidt, 1881		Cym.cesa
CYM0006A	*Cymbella cistula* (Ehrenb. in Hempr. & Ehrenb.) Kirchner, 1878		Cym.cist
CYM0038A	*Cymbella delicatula* Kutz., 1849		Cym.deli
CYM0018A	*Cymbella gracilis* (Rabenh.) Cleve, 1894		Cym.graci
CYM0085A	*Cymbella lapponica* Grun. ex Cleve, 1894		Cym.lappo
CYM0009A	*Cymbella naviculiformis* Auersw. ex Heib., 1863		Cym.navic
CYM9999A	*Cymbella* species		Cym.sp
DID0007A	*Diadesmis perpusilla* (Grun.) Mann, 1990	*Navicula gallica*	Diades.per
DID9999A	*Diadesmis* species		Diades.sp
DIA0002A	*Diatoma hyemale* (Roth) Heib., 1863		D.hyema
DIA0002B	*Diatoma hyemale var. mesodo* (Ehrenb.) Kirchner, 1878	*Diatoma mesodon*	D.mesod
DIP0065A	*Diploneis parma* Cleve, 1891		Dip.parm
ENY0011A	*Encyonema minutum*(Hilse in Rabenhorst) Mann, 1990	*Cymbella minuta*	En.min
ENY0014A	*Encyonema perpusillum*(Cleve) Mann, 1990	*Cymbella perpusilla*	En.perpu
ENY0016A	*Encyonema silesiacum* (Bleisch in Rabenhorst) Mann, 1990	*Cymbella silesiaca*	Cym.silesia
EPI0001A	*Epithemia sorex* Kutz., 1844		Ep. Sor
EUN0013A	*Eunotia arcus* Ehrenb., 1837		E.arc
EUN0070A	*Eunotia bilunaris* (Ehrenb.) F.W. Mills, 1934		E.bilun
EUN0070B	*Eunotia binularis var.mucophila* LB & Norpel, 1991		E.mucoph
EUN00XY1	*Eunotia botuliformis* Wild, Nörpel-Sch. & Lange-Bertalot, 1993		E.botul
EUN0015A	*Eunotia denticulata* (Breb. ex Kutz.) Rabenh., 1864		E.denti
EUN0009A	*Eunotia exigua* (Breb. ex Kutz.) Rabenh., 1864		E.exigu
EUN0108A	*Eunotia intermedia* (Hust) Norpel, Lange-Bertalot & Alles, 1991		E.inter
EUN0114A	*Eunotia muscicola* Krasske, 1939		E.musci
EUN0003A	*Eunotia praerupta* Ehrenb., 1843		E.praer
EUN9999A	*Eunotia* species		E.sp
EUN0105A	*Eunotia subarcuatoides* Alles, Norpel, Lange-Bertalot, 1991		E.subarc
EUN0021A	*Eunotia sudetica* O. Mull., 1898		E.sudet
EUN0045A	*Euntotia nymanniana* Grun. in Van Heurck, 1881		E.nyma
FRA00XY1	*Fragilaria arcus var. recta* Cleve, 1898		F.arcus
FRA0009A	*Fragilaria capucina* Desm., 1825		F.capuc
FRA00XY3	*Fragilaria capucina var. vaucheriae* (Kützing) Lange-Bertalot, 1980		F.vauch
FRA0009M	*Fragilaria capucina var.distans* (Grunow) Lange-Bertalot,		F.distan
FRA0009H	*Fragilaria capucina var.gracilis* (Østrup) Hustedt, 1950		F.gracilis
FRA0002E	*Fragilaria construens var.subsalina* Hust., 1925		F.subsal
FRA0014B	*Fragilaria leptostauron var.dubia* (Grun.) Hust., 1931		F.lepto
FRA0013A	*Fragilaria oldenburgiana* Hust., 1959		Frag.olden
FRA9999A	*Fragilaria* species		F.sp
FRA0070A	*Fragilaria spinarum* L-B & Metzeltin, 1996		F.spina
FRA0060A	*Fragilaria tenera* (W. Smith) Lange-Bertalot, 1980		F.tener
FRA0061A	*Fragilaria zeilleri var.elliptica* Heribaud, 1902		F.zeill
FRF0002A	*Fragilariforma bicapitata* (A. Mayer) Williams & Round, 1988	*Fragilaria bicapita*	F.bicap
FRF0003A	*Fragilariforma constricta* (Ehrenb.) Williams & Round, 1988	*Fragilaria contricta*	F.constric
FRF0001A	*Fragilariforma virescens* (Ralfs) Williams & Round, 1988	*Fragilaria virescens*	F.vires
FRU00XY1	*Frustulia quadrisinuta* Lange-Bertalot, 1996		Fr.quadr
FRU0002A	*Frustulia rhomboides* (Ehrenb.) De Toni, 1891		Fr.rhom
FRU0002K	*Frustulia rhomboides var.crassinervia* (Breb. ex W. Sm.) R. Ross, 1947		Fr.crass
FRU9999A	*Frustulia* species		Fr.sp
GOP0001A	*Gomphoneis olivaceum* (Hornemann) P. Dawson ex R. Ross & Sims, 1978	*Gomphonema olivaceum*	G.oliva
GOP0003A	*Gomphoneis quadripunctatum* (Ostr.) P. Dawson ex R. Ross & Sims, 1978	*Gomphonema olivaceum var.quadripunctatum*	G.quadri
GOM0006A	*Gomphonema acuminatum* Ehrenb., 1832		G.acumin
GOM0020A	*Gomphonema affine* Kutz., 1844		G.affin
GOM0003A	*Gomphonema angustatum* (Kutz.) Rabenh., 1864		G.angusta
GOM0073A	*Gomphonema angustum* Agardh, 1831		G.angust
GOM0030A	*Gomphonema auritum* A. Braun ex Kutz., 1849		G.aurit
GOM0029A	*Gomphonema clavatum* Ehr., 1832		G.clavat
GOM0024A	*Gomphonema clevei* Fricke in A. Schmidt, 1902		G.clevei
GOM0004A	*Gomphonema gracile* Ehrenb., 1838		G.gracil
GOM00XY1	*Gomphonema minutiforme* Lange-Bertalot & Reinchardt,		G.minuti
GOM0015A	*Gomphonema montanum* Schum., 1867		G.montan
GOM0001F	*Gomphonema olivaceum var.olivaceoides* (Hust.) L-B, 1989		G.olivaceoid
GOM0013A	*Gomphonema parvulum* (Kutz.) Kutz., 1849		G.parvu
GOM9999A	*Gomphonema* species		G.sp

Code	Species and Authority	Synonym	Abbreviation
GOM0011A	*Gomphonema subclavatum* (Grun. in Schneider) Grun. in Van Heurck, 1880		G.subcla
GOM0025H	*Gomphonema vibrio* Ehrenb., 1843		G.vibri
HAT9999A	*Hantzschia* species		Han.sp
NAV0037A	*Navicula angusta* Grun., 1860		N.angusta
NAV0007A	*Navicula cryptocephala* Kutz., 1844		N.crypt
NAV00XY1	*Navicula lesmonensis* Hust., 1957		N.lesmo
NAV0537A	*Navicula notha* Wallace, 1960		N.notha
NAV0003A	*Navicula radiosa* Kutz., 1844		N.radio
NAV0008A	*Navicula rhyncocephala* Kutz., 1844		N.rhyn
NAV0090A	*Navicula rotunda* Hust., 1945		N.rotun
NAV0133A	*Navicula schassmannii* Hust., 1937		N.schass
NAV9999A	*Navicula* species		N.sp
NAV0114A	*Navicula subrotundata* Hust., 1945		N.subrot
NAD00XY1	*Naviculadicta pseudostauron* Lange-Bertalot, 1996		Nav.pseudo
NAD9999A	*Naviculadicta* species		Nav.spp
NEI9999A	*Neidium* species		Neid.sp
NIT0202A	*Nitzschia alpina* Hustedt, 1943		Ni.alpi
NIT0002A	*Nitzschia fonticola* Grun. in Van Heurck, 1881		Ni.fonti
NIT0009A	*Nitzschia palea* (Kutz.) W. Sm., 1856		Ni.palea
NIT0005A	*Nitzschia perminuta* (Grun. in Van Heurck) M. Perag., 1903		Ni.permi
NIT9999A	*Nitzschia* species		Ni.sp
PIN0008A	*Pinnularia divergens* W. Sm., 1853		P.divergens
PIN0016A	*Pinnularia divergentissima* (Grun.in Van Heurck) Cleve, 1896		P.diverg
PIN0006A	*Pinnularia mesolepta* (Ehrenb.) W. Sm., 1853		P.meso
PIN0011A	*Pinnularia microstauron* (Ehrenb.) Cleve, 1891		P.micro
PIN0180A	*Pinnularia neomajor* Krammer, 1992		P.neom
PIN9999A	*Pinnularia* species		P.sp
PIN0161A	*Pinnularia subrostrata* (A. Cleve) A. Cleve-Euler, 1955		P.subrost
PIN0056A	*Pinularia rupestris* Hantzsch in Rabenh., 1861		P.rupes
PTH0003A	*Planothidium lanceolata* (Breb.) Round & Bukhtiyarova	*Achnanthes lanceolata*	P.lance
PST0012A	*Psammothidium marginulata*(Grun.) Round & Buktiyarova	*Achnanthes marginulata*	Ps.margin
PST00XY1	*Psammothidium scoticum* (Flower & Jones, 1989) L. Bukhtiyarova & F.E. Round, 1996	*Achnanthes scotica*	Ps.scoti
PST0005A	*Psammothidium subatomoides* (Hustedt) L. Bukhtiyarova & F.E. Round, 1996	*Achnanthes subatomoides*	Ps.subat
PSE0002A	*Pseudostaurosira pseudoconstruens* (Marciniak) Williams & Round, 1987	*Fragilaria pseudoconstruens*	Pse.speudo
PSE00XY1	*Pseudostaurosira robusta* (Fusey) D.M. Williams & Round, 1987	*Fragilaria robusta*	Pse.robus
REI0001A	*Reimeria sinuata* (Greg.) Kociolek & Stoermer, 1987	*Cymbella sinuata*	Rei.sinu
ROS0001A	*Rossithidium linearis*(W.Sm.) Round & Bukhtiyarova	*Achnanthes linearis*	R.linear
SEL0001A	*Sellaphora pupula* (Kutz.) Mereschkowsky, 1902		Sella.pup
SEL0007A	*Sellaphora rectangularis* (Greg.) L-Bertalot,		Sell.rec
SEL0002A	*Sellaphora seminulum* (Grun.) Mann, 1990	*Navicula seminulum*	Sel.seminu
SEL9999A	*Sellaphora* species		Sella.sp
STA0001A	*Stauroforma exiguiformis* (Lange-Bertalot) Flower, Jones & Round, 1996	*Fragilaria exigua*	F.exig
STR9999A	*Stauroneis* species		Stauro.sp
STS0001B	*Staurosira construens var. venter* (Grun.) Williams & Round	*Fragilaria construens var.venter*	Stau.venter
STS0001C	*Staurosira contruens var. binodis* (Ehrenb.) Hamilton	*Fragilaria construens var.binodis*	Stau.binod
STS0002A	*Staurosira elliptica* (Schumann) Williams & Round, 1987	*Fragilaria elliptica*	St.ellip
STL0002A	*Staurosirella pinnata* (Ehrenb.) Williams & Round, 1987	*Fragilaria pinnata*	Sta.pinna
STP0005A	*Stenopterobia delicatissima* (Lewis) M. Perag., 1897		Steno.deli
SUR0010A	*Surirella robusta* Ehrenb., 1840		Suri.robu
SUR9999A	*Surirella* species		Suri.sp
SUR0007A	*Surirella tenera* Greg., 1856		Suri.tene
SYN0007B	*Synedra amphicephala var. austriaca* (Grun. in Van Heurck) Hust., 1932	*Fragilaria gracillicima*	Sy.amphi
SYN0004A	*Synedra parasitica var. parasitica* (W. Sm.) Hust., 1930	*Fragilaria parasitica*	Sy.paras
TAL0001A	*Tabellaria flocculosa* (Roth) Kutz., 1844		Tab.flocc
TET00XY1	*Tetracyclus glans* (Ehrenb.) F.W. Mills, 1935		Tetra.glan

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