Hydrobiologia (2012) 693:223–235
DOI 10.1007/s10750-012-1124-y

PRIMARY RESEARCH PAPER

Holocene environmental change at Lake Shudu, Yunnan Province, southwestern China

Richard T. Jones · Charlotte G. Cook · Enlou Zhang · Peter G. Langdon · Jason Jordan · Chris Turney

Received: 3 January 2012 / Revised: 20 March 2012 / Accepted: 24 April 2012 / Published online: 13 May 2012

Abstract A Holocene palaeorecord from Lake Shudu, Yunnan Province, southwestern China is dominated by (1) a pronounced basin-wide sedimentary hiatus after ca. 7.2 kcal yr BP, spanning some 4,000 years and (2) significant changes in sediment source/supply and an increase in heavy metal influx coupled with a shift to more eutrophic lake conditions from ca. 0.9 kcal yr BP, lasting ~300 years. The hiatus is most likely a due to a significant and abrupt reduction in sedimentation rates, the driver of which is unclear; although it appears likely to have been climatically driven. The environmental changes captured in the Lake Shudu palaeorecord provide unambiguous evidence of late Holocene anthropogenic activity, most likely linked to mining activity.

Keywords Holocene · Southwestern China · Asian monsoon · Lake sediments · Past climate change

Handling editor: Jasmine Saros & John M. Melack

R. T. Jones (✉)
Geography, College of Life and Environmental Sciences, University of Exeter, Amory Building, Rennes Drive, Exeter EX4 4RJ, UK
e-mail: r.t.jones@exeter.ac.uk

C. G. Cook · C. Turney
Climate Change Research Centre and School of Biological, Earth & Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia

E. Zhang
Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences, 73 East Beijing Road, Nanjing 210008, People's Republic of China

P. G. Langdon
School of Geography, University of Southampton, Highfield, Southampton SO17 1BJ, UK

J. Jordan
Department of Geography, Environment & Disaster Management, Coventry University, Coventry CV1 5FB, UK

Introduction

The present interglacial (the Holocene) was until recently considered to be a period of exceptional climatic stability (Dansgaard et al., 1993). Although it was first suggested by Denton & Karlén (1973) that the Holocene was not as climatically stable as implied by terrestrial and marine records, it was not until the 1990s that this view was seriously challenged. Changes in the concentration of lithic grains through Holocene North Atlantic sediments have been suggested to represent pervasive 900 and 500-yr cycles (loosely bundled together as a quasi-periodic '1500 yr' cycle), and appear to record the southward advection of cold, ice-bearing waters from the Labrador and Nordic Seas (Bond et al., 1993, 2001; Turney et al., 2005). In other parts of the world, abrupt climate changes have also been observed through the Holocene, including North Africa (deMenocal et al., 2000;

Chase et al., 2010) and South America (Moy et al., 2002; Mayr et al., 2007), though the relationship (if any) with those in the North Atlantic remains unclear. In Southeast Asia, a region dominated by monsoonal airflow, the records suggest contrasting trends with some sequences suggesting a strengthening of the Asian summer Monsoon during the mid to late Holocene (Thompson et al., 1997) with others implying a weakening of the system (Dykoski et al., 2005; Zhong et al., 2010). Determining the timing, magnitude and trend of past climate is crucial for understanding and managing future change across the region.

Regional setting

Extending from the southeastern edge of the Tibetan Plateau to northwestern Yunnan and western Sichuan Province, the Hengduan Mountain region encompasses some of China's most diverse and ecologically important landscapes. This is reflected in the designation of the Hengduan Mountains as a 'biodiversity hotspot' (Mackinnon et al., 1996; Mittermeier, 2005). Regional ecosystems, including mountain lakes located on or near the upper treeline are particularly sensitive to changing climatic conditions (Lopez-Pujol et al., 2006; National Development and Reform Commission, 2007). In addition, human activities including logging, mining and tourism have intensified in this region, particularly over the last three decades (Chen, 1998; Mittermeier, 2005; National Development and Reform Commission, 2007). However, regional environmental and climatic dynamics and human activity are largely unknown (Moseley, 2006). This is partly due to poor palaeorecord coverage for areas of the Hengduan Mountains including the southeastern edge of the Tibetan Plateau (Zhang & Mischke, 2009). Here, we present a Holocene palaeorecord from Lake Shudu, northwestern Yunnan Province, southwestern China. The aim of this research was to investigate the patterns and drivers of environmental change at the chosen study site over centennial to millennial timescales.

Lake Shudu (27°54.616′N; 99°56.974′E) is a medium-sized open lake located at ~3,600 m asl in the Hengduan Mountains, Zhongdian County, northwestern Yunnan Province (Fig. 1). This lake was chosen as the focus of our research because it is located ~600 m below the present treeline (within the alpine/subalpine ecotone), and is therefore highly sensitive to wider environmental and climatic changes (Korner & Paulsen, 2004; Lu et al., 2008; Fan et al., 2009). The lake catchment is ~14.2 km^2, surface area is 1.7 km^2 and diameter is 2.27 km. Maximum water depth is 7.8 m, lake water pH is 8.7, and electrical conductivity is 23.6 µS/cm. Calculated mean annual temperature is 13°C, and mean annual precipitation is ~965 mm (Peterson et al., 1998), congruent with a temperate (owing to the site's location at high altitude), but also monsoon-influenced climate. The vegetation of the lower slopes is dominated by stands of *Picea* and *Abies* (e.g. *Abies georgei*) planted in the 1970s. Evergreen sclerophyllous *Quercus*, *Betula* and *Salix purpurea* are found growing on the catchment slopes. Poaceae and Cyperaceae dominate the areas adjacent to the lake. Further details on the regional climate, catchment vegetation and geology are presented in Cook et al. (2011, 2012). Lake Shudu is located on the southeastern edge of the Tibetan Plateau, within the Shangri-La Pudacuo National Park (China's first national park) and the Three Parallel Rivers Scenic Area World Heritage Site (Nature Conservancy Council, 2011; UNESCO, 2010; 2011). The outflow is dammed, with a new dam constructed in the 1980s replacing an earlier structure of unknown age. Over the last decade, Lake Shudu has become an increasingly popular tourist destination. A small hotel and restaurant have been built on the western shoreline and walkways have been constructed around the lake to accommodate the growing number of visitors to the site (Zhou & Chen, 2006).

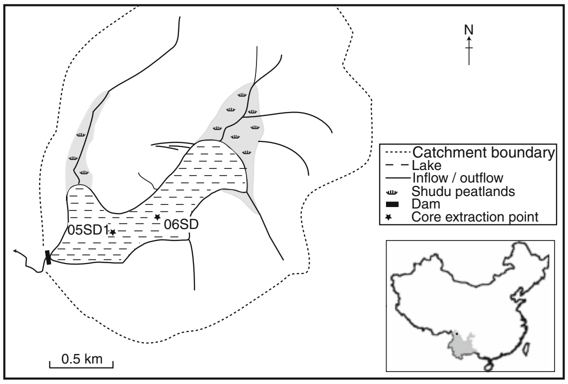

Fig. 1 Map of Lake Shudu and core extraction points, Yunnan Province, southwestern China, with *inset* map indicating the study site location in Yunnan Province, China

Materials and methods

A 1.2 m short core (05SD1) was recovered from Lake Shudu in ∼5.5 m of water, using a rope-operated piston corer. The core extraction point is shown on Fig. 1. The core did not extend down to the bedrock. The core was sub-sampled at 0.5 to 1-cm intervals, freeze-dried and subjected to multi-proxy analysis to determine particle size, magnetic susceptibility, Lead (*Pb*) and Copper (*Cu*) content, loss-on-ignition ($\%LOI_{org}$), diatoms/chironomids and pollen types and/or abundances. $\%LOI_{org}$ was undertaken on samples spaced at 2-cm intervals. Sediments were dried and combusted at 550°C following standard methods (Bengtsson & Enell, 1986). Samples were prepared for particle size analysis at 2-cm intervals following McCave & Syvitski (1991) and Last & Smol (2001). Samples were processed using a Saturn Digitiser and the results categorised using the Udden-Wentworth Scale. Low frequency magnetic susceptibility (χlf) measurements were taken at 1-cm intervals, using a Bartington MS2 Dual Frequency Magnetic Susceptibility Meter, following published preparation techniques (Walden et al., 1999). Readings are expressed as $\times\ 10^{-8}\ m^3\ kg^{-1}$. Samples spaced at 2-cm intervals down the core were prepared for geochemical analysis (see Boyle, 2001) and analysed using an Atomic Absorption Spectrometer to establish heavy metal (*Pb* and *Cu*) content, expressed in parts per million (ppm).

Samples spaced at 5 to 10-cm intervals were prepared for diatom analysis according to standard laboratory techniques (Barber & Haworth, 1981). Diatom species identification of a count of 300 frustules was carried out where possible (Van der Werf & Huls, 1957–1974; Hendey, 1964; Hartley et al., 1996). The most abundant species (i.e. <10% of the total count) are presented in Fig. 4. Nomenclature follows Hartley et al. (1996) with salinity, pH, trophic status and lifeform classification based upon Denys (1991), Vos & de Wolf (1993), Van Dam et al. (1994) and Kelly et al. (2005). Chironomid head capsule identification was undertaken on samples spaced at 10-cm intervals down the core, following standard methods and taxonomic literature, with a minimum of 50 head capsules counted per sample (Brooks et al., 2007). Pollen analysis was undertaken on sediment samples spaced at 4 to 8-cm intervals, following established techniques (Faegri & Iversen, 1981; Moore et al., 1991). The pollen sum (including trees, shrubs, herbs, grasses and sedges) is based on a count of 300 pollen grains per sample. Counts were converted to percentages, and pollen concentrations were determined by adding two tablets containing a known concentration of *Lycopodium* spores to each sample prior to counting, and calculated following Stockmarr (1971). Frequency and concentration diagrams were produced using Tilia v2.02 (Grimm, 2004). Pollen and spores were identified with reference to published guides (e.g. Institute of Botany and South China Institute of Botany, 1982; Wang et al., 1995; Beug, 2004; Qiao, 2004; Fujiki et al., 2005; Menitsky, 2005; Flora of China Editorial Committee, 2006) and assistance from Professor Tong, Department of Hydrology and Environmental Geology, Chinese Academy of Geological Science, Shijiazhuang, China. The 05SD1 proxies were zoned in CONISS using constrained cluster analysis and a paired group algorithm (Grimm, 2004).

Five AMS ^{14}C radiocarbon dates were obtained for 05SD1, based on bulk sediments (Table 1). Samples were dated at the University of Waikato and Beta Analytic and the results were calibrated to AD1950 calendar years before present (cal yr BP) using Oxcal v. 4.17 and IntCal09 (Bronk Ramsey, 1995, 2008, 2009; Reimer et al., 2009). Dates were tested for internal consistency using a Deposition Model (Fig. 2). The results indicate that dates are all in chronological order. However, there are clear signs of nonlinearity from ∼47 cm. This is coupled with a very low sedimentation rate (∼0.001 cm/yr) from 47 to 42 cm. Together these factors strongly suggest that there is a hiatus in this section of the core. Consequently, the 05SD1 chronology was produced by linear interpolation between the dated depths shown on Fig. 2. The extrapolated age span of the core is ca. 9.9 kcal yr BP to the present (i.e. AD2005). Unless otherwise stated, the 05SD1 dates quoted in this study are expressed in cal yr BP, rounded to the nearest century.

Results

General trends

Figures 3, 4, 5, and 6 show the 05SD1 physical, biological and palaeoecological proxies. The core

Table 1 Conventional and calibrated AMS ^{14}C radiocarbon dates for the 05SD1 core from Lake Shudu, Yunnan Province, China

Laboratory code	Mean core depth (cm)	Type	δ^{13}C (VPDB‰ ±0.1)	Conventional radiocarbon age (^{14}C yrs BP)	Error (±)	Modelled age (BP)[a] (1 SD)		Mean age[b] (cal ka BP)
						From	To	
Beta-235139	26.25	Bulk	−22.8	1,380	40	1,324	1,273	1,298.5
Wk-31516	42.25	Bulk	−21.0	2,153	25	2,301	2,262	2,281.5
Beta-235130	47.25	Bulk	−24.4	6,270	40	7,250	7,170	7,210
Wk-31517	79.25	Bulk	−25.8	7,866	25	8,646	8,596	8,621
Beta-235139	110.25	Bulk	−26.6	8,700	50	9,705	9,555	9,630

[a] Calibrated (modelled) ages were produced using Oxcal 4.1.7 and IntCal09 (Bronk Ramsey, 2009; Reimer et al., 2009)

[b] Mean ages are rounded to the nearest century

stratigraphy indicates the presence of grey silty clay (120–47 cm), with a marked increase in organic content (47–0 cm). The core is sub-divided into three zones (SDA, B and C). The physical proxy records (Fig. 3a–d) indicate that the core is primarily composed of silt with organic content ranging from ~10 to >40% and comparatively low but fluctuating χlf values (2–14 × 10^{-8} m^3 kg^{-1}). The upper sediments (~20–0 cm; ca. 0.9 kcal yr BP to AD2005) contain relatively high levels of *Cu* and *Pb* with a clear peak at ~14 cm (ca. 0.6 kcal yr BP). At the same time, there is an increase in sand captured in the particle size record (Fig. 3). We interpret these shifts as reflecting a phase of increased heavy metal influx. Within the biological record, diatom preservation/concentration rates are generally high, with the exception of the section of the core spanning 34–25 cm (ca. 1.8–1.2 kcal yr BP; Fig. 4). Chironomid head capsule concentrations range from <25 to >50 capsules per gram with a significant increase around ~46 cm (ca. 6.2 kcal yr BP; Fig. 5). Arboreal and herbaceous pollen dominate the pollen record (Fig. 6). Major shifts in the record are characterised by changes in the relative abundances of these pollen groups. Total pollen concentrations (Fig. 6) are quite stable throughout the core, although there are notable increases from ~34 cm. The 05SD1 age-depth model indicates that there is a hiatus in the record between 47 and 42 cm (Fig. 2), commencing at ca. 7.2 kcal yr BP and spanning some ~4,000 years. It is located on the SDB/SDC boundary and illustrated by a gap on Figs. 3, 4, 5, and 6.

Description of multi-proxy zones

Zone SDA (119–47 cm; ca. 9.9–7.2 kcal yr BP)

Sediments are primarily composed of fine-grained silt (Fig. 3a), suggesting the coring site was below storm-wave base. Mean magnetic susceptibility readings are ~4 × 10^{-8} m^3 kg^{-1} (Fig. 3b). Low frequency magnetic susceptibility measurements provide an insight into the total concentration of ferromagnetic minerals within a sample, allowing inferences to be made about changes in the type and/or sources of minerogenic material entering the lake (Walden et al., 1999). Magnetic susceptibility readings are relatively low and stable, suggesting that there were no fundamental changes in sediment source and/or supply during this period. *Cu* and *Pb* concentrations in the core were at background levels throughout this period (Fig. 3c). Relatively moderate and stable organic productivity rates are inferred from low levels of organic matter (OM) captured in the %LOI_{org} record (>10%) (Fig. 3d).

The diatom record (Fig. 4) is composed of a diverse assemblage with no single dominant species. The majority of the count is attributable to seven primary species, *Cyclotella antiqua*, *Cymbella cistula*, *Discostella stelligeroides*, *Epithemia adnata* var. *porcellus*, *Navicula placentula*, *Pinnularia viridis* and *Staurosirella pinnata*. The pH indicators from the assemblage (Fig. 4) show a strong alkaliphilous component (approximately 60% of the assemblage) congruent with a pH value of >7. The assemblage data suggests

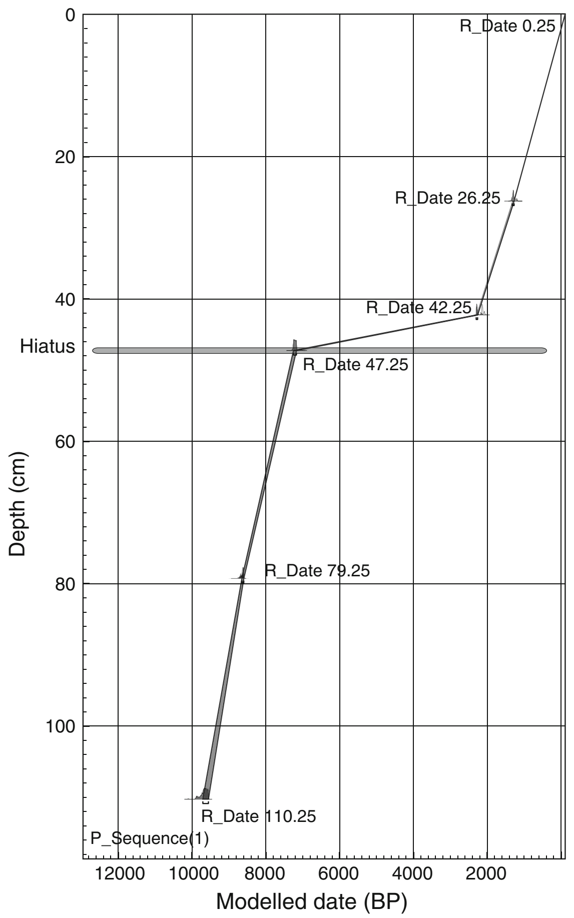

Fig. 2 Deposition model for the 05SD1 core, Lake Shudu, Yunnan Province, China. Model produced using a P_Sequence with the *k* value set to 1. The R_Date (marked with the core depth at which the date was obtained) expresses the likelihood distribution for the calibrated date as a function of radiocarbon concentration. The two *black lines* connecting each of the R_Dates indicate the modelled date (BP) ranges quoted to 1SD (see Table 1). Model produced using Oxcal v. 4.1.7 (Bronk Ramsey, 2009); r:5. Atmospheric data from Reimer et al. (2009). The location of a hiatus in the sediment record inferred from the proxies is defined by the *grey horizontal bar* at 47.25 cm

nutrient loading is mixed throughout the zone. The chironomid head capsules count is relatively low but stable (Fig. 5), suggesting a reasonably low productivity system, with stable but relatively low levels of food limiting overall chironomid abundance. Marked changes in the chironomid record include a shift in dominant species as the declining significance of *Chironomus anthracinus*-type is matched by rising values for *Procladius* (Fig. 5). The shift in significance between *C. anthracinus*-type and *Procladius* in this zone is unlikely to relate directly to changes in trophic status or anoxia, as both taxa are usually found at the high ends of these environmental gradients. More likely, the switch may relate to changes in lake depth and/or temperature. A recent data set of chironomid distribution in Yunnan lakes (Zhang et al., 2011) shows that these taxa, in Yunnan, occur at opposite ends of the lake depth and temperature gradients, and hence an increase in *Procladius* may relate to a cooler environment, and/or deeper lake. Total pollen concentrations are low, varying from ~800,000 grains/g at 119 cm (ca. 9.9 kcal yr BP) to <200,000 grains/g at 96 cm (ca. 9.2 kcal yr BP) (Fig. 6), suggesting that vegetation cover was sparse, perhaps resulting from cold, dry climatic conditions.

From ~104 cm (ca. 9.4 kcal yr BP), the diatom record (Fig. 4) captures a slight increase in planktonic species (including the meroplankton and tychoplankton) as *C. cistulla* and *P. viridis* increase from which elevated lake levels are inferred (Fig. 4). Levels of *Tanytarsus* type A and to a lesser extent *Psectrocladius* are seen to increase from ~80 cm (ca. 8.7 kcal yr BP), which is accompanied by a relative decline in *Procladius*. *Tanytarsus* A superficially resembles *Tanytarsus lugens* type from Brooks et al. (2007), but with two dorsal teeth and two surficial teeth, one smaller than the other, on the mandible. Difficulties associated with identifying *Tanytarsus* to species level means that it is not possible to draw any detailed environmental inferences, other than to note that this genus is a cold stenotherm (Zhang et al., 2011). The increase in *Psectrocladius* may be associated with an increase in macrophyte growth (Langdon et al., 2010), which could result from a relative decline in lake levels (decline in *Procladius*) and greater levels of light reaching the benthos facilitating macrophyte growth. Total pollen concentrations increase markedly from ~96 cm (ca. 9.2 kcal yr BP), suggesting an increase in terrestrial vegetation cover including arboreal taxa (Fig. 6). The lack of any major shifts in the physical proxies indicates that the impact on the catchment of any change in lake level was limited. Collectively, the proxies suggest that Lake Shudu was perhaps expanding and becoming more a more productive lacustrine habitat. Within the wider catchment, moderate rates of organic productivity were coupled with denser vegetation cover. These factors suggest warm, wet climatic conditions.

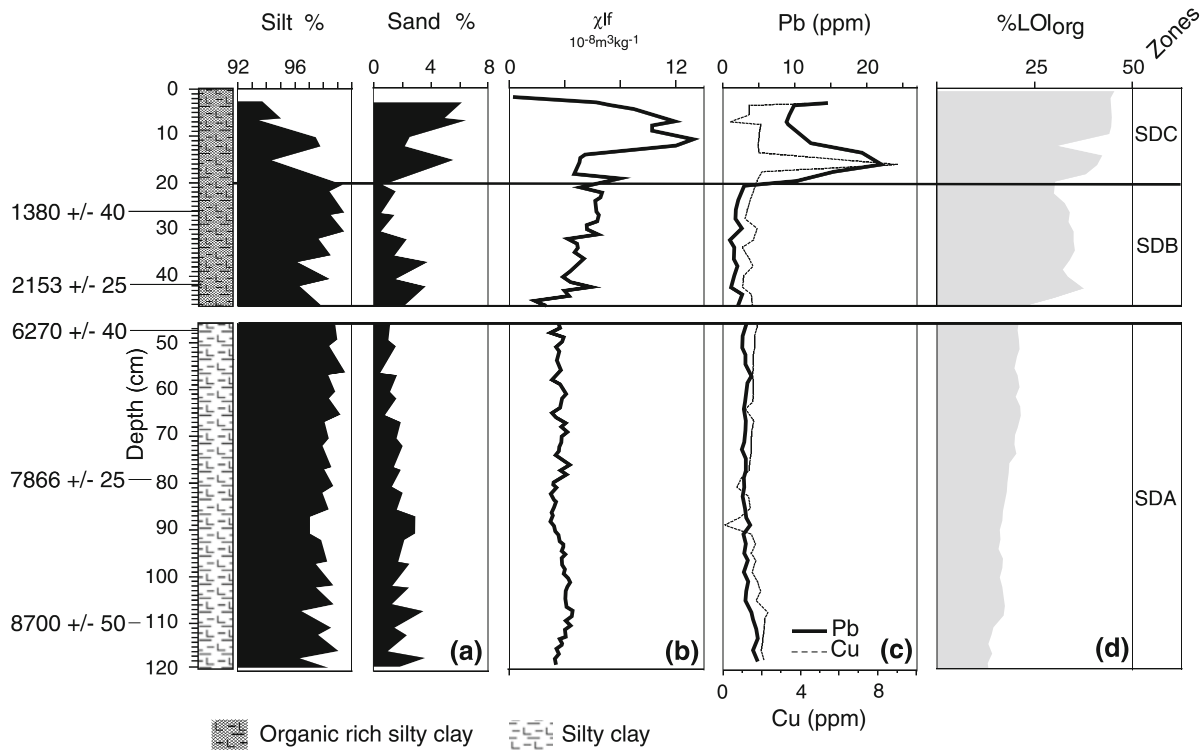

Fig. 3 Physical, geochemical and organic variables for the 05SD1 core, Lake Shudu. Multi-proxy zones SDA to C (boundaries indicated by *horizontal black lines*). From left to right: core chronology (uncalibrated AMS ^{14}C radiocarbon dates) and stratigraphy; core depths (cm); **a** particle size (silt/sand) NB clay levels were negligible; **b** low frequency magnetic susceptibility (χlf); **c** sediment geochemistry (the top axis relates to lead (*Pb*) content (*unbroken line*) whilst the bottom axis relates to copper (*Cu*) content (*dotted line*) expressed in parts per million (ppm); **d** loss-on-ignition, organic content (%LOIorg)

Zone SDB (47–20 cm; ca. 7.2–0.9 kcal yr BP)

Zone SDB is distinguished from SDA by increased OM (peaking at >30%), coarser particle sizes and elevated magnetic susceptibility readings (Fig. 3), suggesting a higher organic productivity and enhanced fluvial activity, coupled with a shift in sediment source and/or supply. The base of zone SDB is diatom-rich (Fig. 4). The diatom assemblage has a significant planktonic component (Fig. 4), perhaps indicating a well-established freshwater body with the presence of a sandy substrate. Four species are dominant; *C. antiqua*, *C. cistula*, *Fragilariforma constricta* and *S. pinnata*, with a noticeable rise in the importance of *Aulacoseira italica*, *Caloneis silicula*, *C. cistula*, and *Eunotia.* The rise in *A. italica*, a meroplanktic diatom, could reflect an increased in convective lake mixing and/or turbulence in the lake, supporting evidence from the particle size record for an increase in energy in the lake-catchment system at this time. Between ~34 and 26 cm (ca. 1.8–1.3 kcal yr BP), there is a noticeable deterioration in quality of the preserved frustules, coupled with a reduction in diatom concentrations (Fig. 4). Within the chironomid record, the transition to zone SDB is characterised by a marked increase in the number of head capsules preserved. Such a rise reflects an increase in productivity in the lake, likely in the form of greater food abundance and/or quality (Fig. 5). *Tanytarsus* A and *Psectrocladius* continue to dominate the record, (Fig. 5) but there is a marked decline in *Procladius*. *Chironomus anthracinus*-type continues the steady decline that began in zone SDA (Fig. 5). Within the pollen record there is a noticeable increase in total pollen concentrations (Fig. 6), which coincides with the onset of the poor preservation zone in the diatom record (Fig. 4). Higher total pollen concentrations are congruent with an increase in vegetation cover and/or pollen influx. Notably, changes within the physical proxies during the same period (~34–26 cm; ca. 1.8–1.3 kcal yr BP)

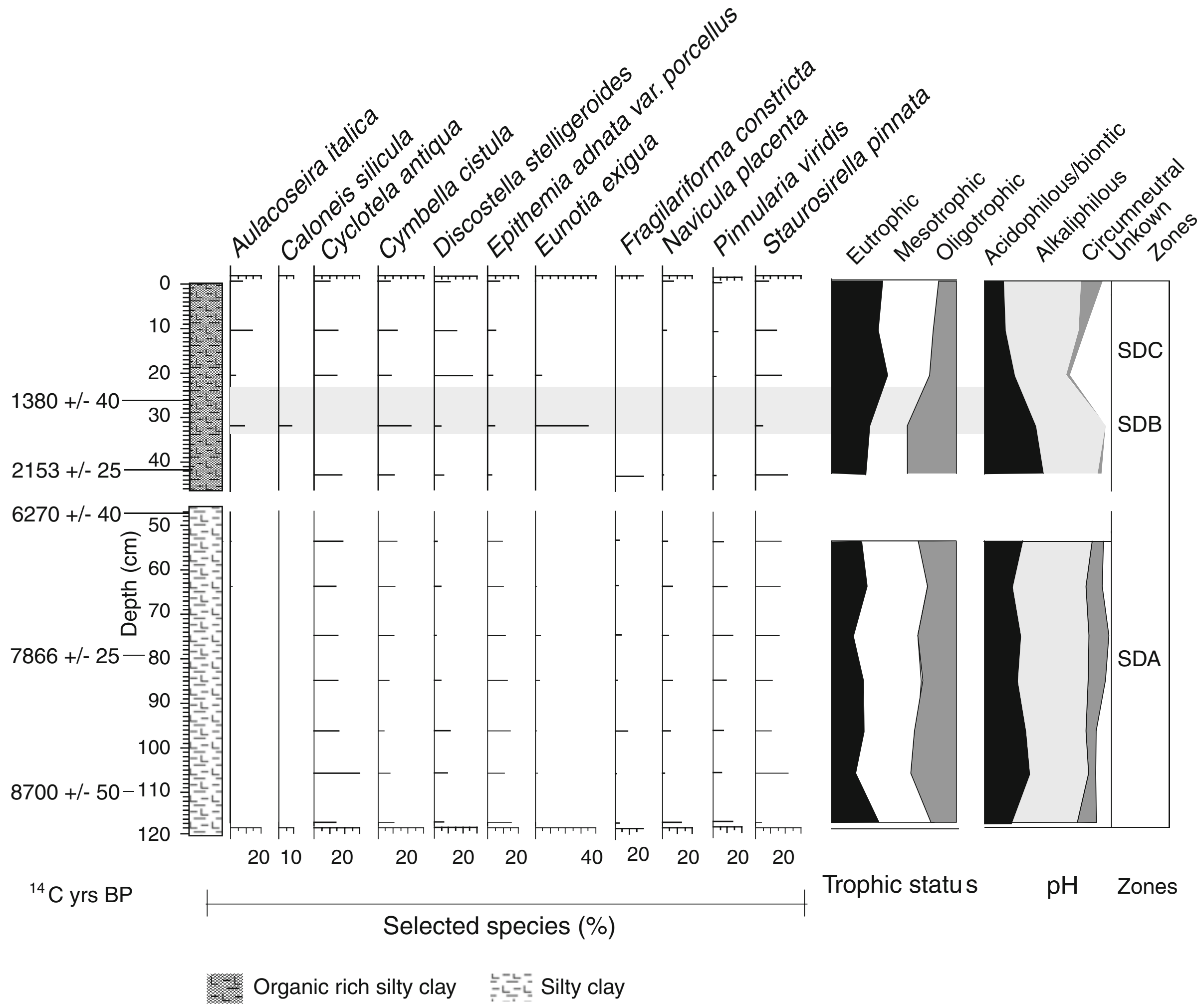

Fig. 4 Key indicator species (%) and palaeoecological conditions inferred from the Lake Shudu diatom record. The *dashed line* denotes the zone of poor diatom preservation. Uncalibrated ^{14}C dates, core stratigraphy and multi-proxy zones SDA, B and C are also shown for reference

are more subtle (Fig. 3). Magnetic susceptibility increases markedly at ~30 cm (ca. 1.5 kcal yr BP), perhaps indicating a marked change in sediment source and/or supply (Fig. 3b).

Zone SDC (20–0 cm; ca. 0.9 kcal yr BP to AD2005)

Sediments are composed of sandy silt rich in OM and heavy metals (Fig. 3a, c and d). Magnetic susceptibility readings are much higher compared with previous zones, suggesting a significant shift in sediment source and/or supply. Diatoms are well preserved and diverse, containing both planktonic and benthic species, which indicates the presence of a substantial water body on site. Five species account for over 60% of the total count. These include *A. italica*, *C. antiqua*, *C. cistula*, *D. stelligeroides* and *S. pinnata*. The assemblage shows a higher nutrient loading with the associated eutrophic conditions starting to increase. Notably, the biological and palaeoecological proxies are relatively stable throughout this zone. Marked changes occur in the physical, geochemical and organic proxies from ~19 to 15 cm (ca. 0.9–0.6 kcal yr BP), including a marked increase in sand and OM, higher levels of *Cu* and *Pb* and initially reduced magnetic susceptibility (Fig. 3). The diatom record indicates a shift to higher abundances of taxon

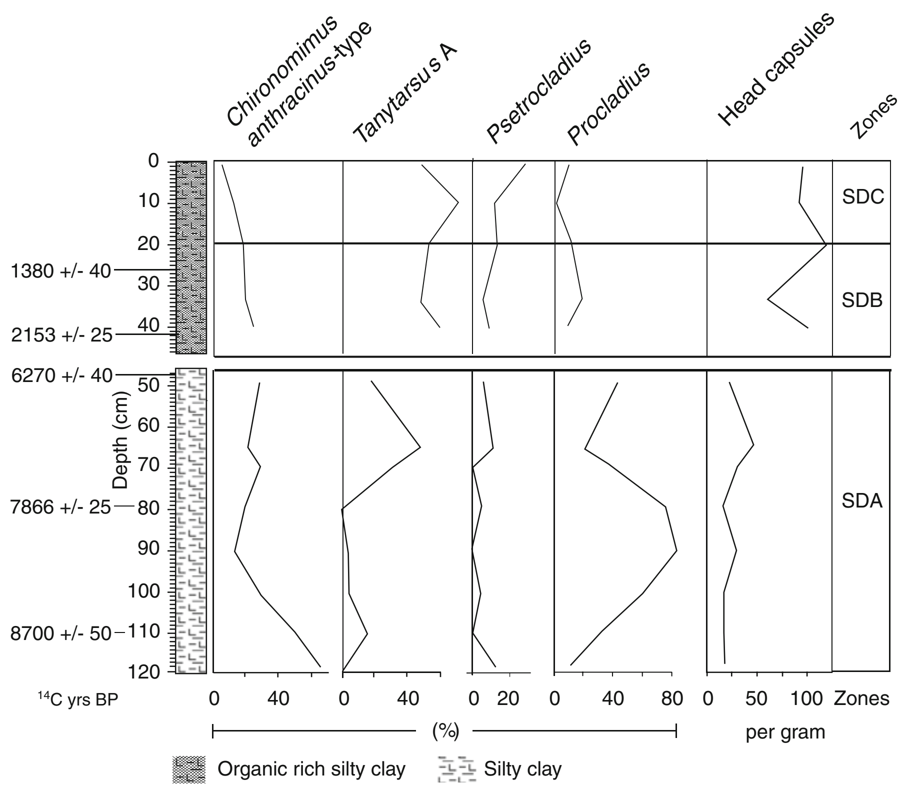

Fig. 5 Chironomid record obtained from the 05SD1 core, Lake Shudu. Percentage values for four key species in the record (*Chironomimus anthracinus*-type, *Tanytarsus* A, *Psetrocladius* and *Procladius*) are shown alongside head capsule counts. Uncalibrated ^{14}C dates and multi-proxy zones SDA, B and C are shown for reference

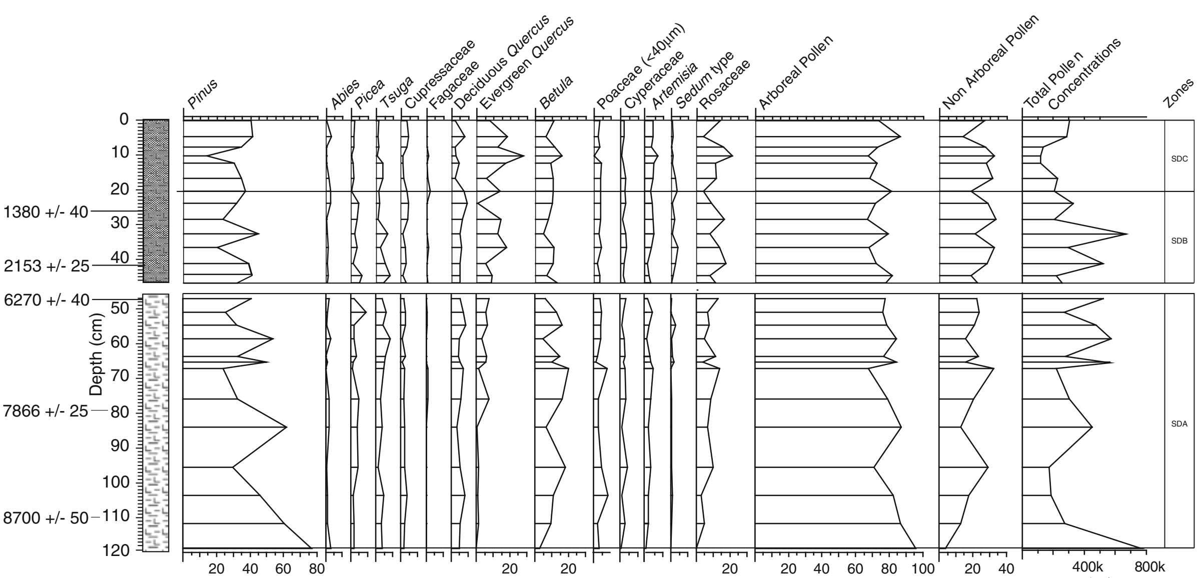

Fig. 6 Summary pollen diagram obtained from the 05SD1 core, Lake Shudu. The percentages of key taxa are shown alongside total arboreal/non-arboreal pollen and total pollen concentrations (grains/g). Uncalibrated ^{14}C dates, core stratigraphy and multi-proxy zones SDA, B and C are shown for reference

associated with eutrophic conditions (Fig. 4). Consequently, this implies enhanced lacustrine energy and organic productivity rates, an increase in material rich in heavy metals being deposited into the lake and an abrupt change in sediment source and/or supply (Fig. 3).

From ~15 cm, numbers of benthic diatom species remains fairly constant at ~15 cm (Fig. 3a). At the same time, the number of chironomid head capsules decreases, then levels off, suggesting stabilisation of biological productivity (Fig. 5). *Procladius* continues to decline in relative importance, whilst *Psectrocladius* is seen to peak at this time. *Tanytarsus* A continues to dominate the fauna though as it did in the previous zone. These shifts could relate to an increase in, or alteration of macrophyte communities in the lake (Langdon et al., 2010). The concentration of chironomid head capsules remains high, pointing to high levels of biological productivity in the lake and/or changes in the macrophyte community (Fig. 5). Notably, the pollen record indicates a marked decrease in total pollen concentrations and a reduction in the abundances of arboreal pollen, suggesting that there was a reduction in catchment vegetation cover during this time.

Discussion

Overall, the Lake Shudu 05SD1 palaeorecord indicates that during the early to mid Holocene (ca. 9.9–7.2 kcal yr BP) Lake Shudu was a relatively low energy, stable, meso-eutrophic lake, characterised by low levels of biological and organic productivity. However, over the course of the mid to late Holocene, the lake gradually expanded and catchment vegetation cover became denser, suggesting a long-term shift towards the establishment of a more fluvially dynamic, productive catchment over millennial timescales. Over this period, there is a marked increase in *Procladius*, which prefers deeper water, muddier environments (Fig. 5; Brooks et al., 2007; Zhang et al., 2011). In addition, flooding onto the lake margins may have increased the extent of the littoral zone, promoting the expansion of sub-aquatic macrophytes (e.g. Virkanen, 2000), and increasing abundances of *Psectrocladius*, a genus that prefers shallow, macrophyte-rich habitats (Fig. 5; Langdon et al., 2010). This trend was most probably driven by ameliorating climatic conditions, consistent with a strong Asian summer monsoon during the early to mid Holocene (Wang et al., 2005; Kramer et al., 2010) in response to the establishment of a warmer climate that followed the 30°N summer (June) solar insolation trend (Berger & Loutre, 1991).

During the late Holocene (0.9–0.6 kcal yr BP), the 05SD1 palaeorecord suggests that Lake Shudu was fundamentally altered, having undergone changes in sediment source/supply, and lake eutrophication. This, coupled with a marked increase in heavy metals associated with mining activities, perhaps suggests that anthropogenic rather than climatic factors were driving environmental change at Lake Shudu during this period. From ca. 0.6 kcal yr BP, levels of heavy metals decrease and there is a change in lake status (eutrophic to mesotrophic conditions), perhaps indicating the diminishing influence of human activities upon the catchment. There is no clear evidence for the damming of the lake in the late 1980s.

Notwithstanding these changes, however, the most prominent feature of the Lake Shudu 05SD1 core are the shifts spanning the period ca. 7.2 to 0.9 kcal yr BP, including a hiatus commencing sometime after 7.2 kcal yr BP (~6.3 ^{14}C kyr BP), which spans some ~4,000 years. Intriguingly, this hiatus is also present in another core (06SD) collected from the centre of Lake Shudu (Fig. 1), which has an upper age of ca. 6.8 kcal yr BP (~6.0 ^{14}C kyr BP) (Cook et al., in prep). The presence of a hiatus in both cores of comparable age perhaps suggests that it is a basin-wide phenomenon and may have been of regional significance. Here, we explore possible causes; (1) Slumping; (2) Human activity; (3) A shift to drier climatic conditions; (4) A shift to wetter climatic conditions.

(1) Deflation of sediments may represent an erosive unconformity triggered in response to events such as marginal slumping, turbidites or wave action (e.g. Sadler, 1999; Meyers & Sageman, 2004). However, these types of event are usually localised, whereas the hiatus appears in two cores extracted from different parts of the lake. Tectonic activity may trigger the formation of a hiatus in sedimentary sequences. However, this would most likely cause disturbance (mixing) of material in the sediment column, which would be apparent from the age reversals, etc. in the core chronology. However, there is no evidence of this

in the 05SD1 chronology, perhaps suggesting that this was not the primary cause of the hiatus.

(2) Human activity may also lead to the formation of sedimentary hiatuses. At several lakes across Yunnan Province, lacustrine sediments have been removed and used in construction (Walker, 1986). However, this tends to occur in relatively lowland catchments that are much more developed (i.e. where a town has been built close to a lake). In addition, the loss of sediments from Lake Shudu from both coring sites is quite uniform (i.e. sediments relating to the same depth/timespan have been removed). It is unlikely that the ad hoc excavation of sediments by humans would have resulted in uniform sediment removal. We therefore assume that human activities are not the primary cause of the hiatus.

(3) When dry climatic conditions are in force, lake dessication can trigger sedimentary deflation, resulting in the formation of a hiatus in the sediment sequence. Elsewhere, a decline in Asian monsoon intensity during the mid to late Holocene is inferred from a shift to more positive $\delta^{18}O$ values from ~9 ka BP in the Dongge Cave speleothem record located in southern-central China (Dykoski et al. 2005) and from ca. 6 kcal yr BP in organic and geochemical proxies obtained from Dahu swamp, eastern Nanling Mountains, southern China (Zhong et al., 2010). However, a shift to arid conditions should have triggered vegetation changes (including reduced pollen concentrations associated with a reduction in vegetation cover), but this is not apparent in the 05SD1 pollen record.

(4) Finally, a shift to wetter climatic conditions may have triggered an inwash event, causing scouring of the lakebed, removal of sediments from the basin, and lake level changes. In zone SDB, the shift to coarse sediments (Fig. 3) and a sharp rise in OM may be indicative of an inwash event and associated lake level changes (Jones & Jordan, 2007). The onset of the hiatus in the Lake Shudu sedimentary record corresponds with an increase in forest cover across China, peaking at ~6 ka BP (Ren, 2007) and a phase of high effective moisture levels and/or a strong Asian summer monsoon inferred from other Asian palaeorecords (e.g. Sun et al., 1986; Jarvis, 1993; Thompson et al., 1997; Wang, et al., 2005; Herzschuh, 2006, Cook & Jones, in press). However, there is no marked increase in pollen concentrations in the 05SD1 record prior to the hiatus (Fig. 6).

Conclusions

The 05SD1 palaeorecord provides an intriguing insight into environmental dynamics at Lake Shudu during the Holocene. The palaeorecord is characterised by two notable features. Firstly, a pronounced basin-wide hiatus occurs in the core sediments. The hiatus appears to have been formed sometime after 7.2 kcal yr BP and spans some ~4,000 years. The hiatus is most likely due to a significant and abrupt reduction in sedimentation rates. The driver of this event remains open to debate; although it appears most likely to have been climatically driven. However, the likely mode of change remains unclear, with contrasting opinions in the literature over whether the Asian summer monsoon intensity was weak or strong during the mid to late Holocene. Further work is required to more precisely constrain the timing, magnitude and mode of past climatic change in the Asian monsoon region. Secondly, from ca. 0.9 kcal yr BP, significant changes in sediment source/supply and an increase in heavy metals are coupled with a shift to more eutrophic lake conditions; a trend which lasts ~300 years. The environmental changes captured in the late Holocene section of the Lake Shudu 05SD1 palaeorecord provide clear evidence of anthropogenic activity during this time, most likely linked to mining activity in the area.

Acknowledgments We would like to thank the following people/organisations for their help to complete this research project; The Royal Society, the Chinese Academy of Sciences, Professor Shen Ji and the Australian Research Council (grant FL100100195) for research funding and support; Alistair Lovell, Jessica Jordan and Kim Deal for technical support; the drawing office at Exeter University and Alan Hogg and staff at the University of Waikato for AMS ^{14}C radiocarbon dating support. The manuscript was greatly improved by the useful comments of the referees.

References

Barber, H., & E. Y. Haworth., 1981. A Guide to the Morphology of the Diatom Frustule, with a Key to the British Freshwater Genera, Ambleside. Freshwater Biological Association.

Bengtsson, L. & M. Enell, 1986. Chemical analysis. In Berglund, B. E. (ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. Wiley, Chichester: 423–451.

Berger, A. & M. F. Loutre, 1991. Insolation values for the climate of the last 10 million years. Quaternary Science Reviews 10: 297–317.

Beug, H. J., 2004. Leitfaden der Pollenbestimmung. Dr Friedrich Pfeil, Munchen.

Bond, G., W. Broecker, S. Johnsen, J. McManus, L. Labeyrie, J. Jouzel & G. Bonani, 1993. Correlations between climate records from north Atlantic sediments and Greenland ice. Nature 365: 143–147.

Bond, G., B. Kromer, J. Beer, R. Muscheler, M. N. Evans, W. Showers, S. Hoffman, R. Lotti-Bond, I. Hajdas & G. Bonani, 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294: 2130–2136.

Boyle, J. F., 2001. Inorganic geochemical methods in palaeolimnology. In Last, M. & J. Smol (eds), Tracking Environmental Change Using Lake Sediments. Volume 2: Physical and Geochemical Methods. Kluwer, Dordrecht: 83–141.

Bronk Ramsey, C., 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. Radiocarbon 37: 425–430.

Bronk Ramsey, C., 2008. Deposition models for chronological records. Quaternary Science Reviews 27: 42–60.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51: 337–360.

Brooks, S. J., P. G. Langdon & O. Heiri, 2007. The Identification and Use of Palaearctic Chironomidae Larvae in Palaeoecology. Quaternary Research Association, London.

Chase, B. M., M. E. Meadows, A. S. Carr & P. J. Reimer, 2010. Evidence for progressive Holocene aridification in southern Africa recorded in Namibian hyrax middens: implications for African Monsoon dynamics and the "African Humid Period". Quaternary Research 74: 36–45.

Chen, C. D., 1998. Biodiversity of China: A Country Study. Environmental Science Press, Beijing.

Cook, C. G. & R. T. Jones, in press. Palaeoclimate dynamics in continental Southeast Asia over the last ~30,000 cal yr BP. Palaeogeography, Palaeoclimatology, Palaeoecology.

Cook, C. G., R. T. Jones & C. S. M. Turney, in prep. Evidence for a phase of reduced lake levels, enhanced aridity and Asian summer monsoon weakening during the early Holocene. Boreas.

Cook, C. G., R. T. Jones, P. G. Langdon, M. J. Leng & E. Zhang, 2011. New insights on Late Quaternary Asian palaeomonsoon variability and the timing of the Last Glacial Maximum in southwestern China. Quaternary Science Reviews 30: 808–820.

Cook, C. G., M. J. Leng, R. T. Jones, P. G. Langdon & E. Zhang, 2012. Lake ecosystem dynamics and links to climate change inferred from a stable isotope and organic palaeorecord from a mountain lake in southwestern China (c. 22.6–10.5 cal ka BP). Quaternary Research 77: 132–137.

Dansgaard, W., S. J. Johnsen, H. B. Clausen, D. Dahl-Jensen, N. S. Gundestrup, C. U. Hammer, C. S. Hvidberg, J. P. Steffensen, A. E. Sveinbjoörnsdottir, J. Jouzel & G. Bond, 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. Nature 364: 218–220.

deMenocal, P., J. Ortiz, T. Guilderson, J. Adkins, M. Sarnthein, L. Baker & M. Yarusinsky, 2000. Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. Quaternary Science Reviews 19: 347–361.

Denton, G. H. & W. Karlén, 1973. Holocene climatic variations—their pattern and possible cause. Quaternary Research 3: 155–205.

Denys, L., 1991. A Check-List of the Diatoms in the Holocene Coastal Deposits of the Western Belgian Coastal Plain with a Survey of Their Apparent Ecological Requirements 1. Geological Survey of Belgium.

Dykoski, C. A., R. L. Edwards, H. Cheng, D. Yuan, Y. Cai, M. Zhang, Y. Lin, J. Qing, Z. An & J. Revenaugh, 2005. A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. Earth and Planetary Science Letters 233: 71–86.

Faegri, K. & J. Iversen, 1981. Textbook of Pollen Analysis. Wiley, Chichester.

Fan, Z. X., A. Brauning, B. Yang & K. F. Cao, 2009. Tree ring density-based summer temperature reconstruction for the central Hengduan Mountains in southern China. Global and Planetary Change 65: 1–11.

Flora of China Editorial Committee, 2006. Flora of China. Retrieved March 22, 2011, from E-Floras: http://www.efloras.org.

Fujiki, T., Z. Zhou & Y. Yasuda, 2005. The Pollen Flora of Yunnan, China. Roli Books Pvt. Ltd, Singapore.

Grimm, E. C., 2004. TILIA and TILIA.GRAPH v.2.0.2. Illinois State Museum, Springfield.

Hartley, B., H. G. Barber, J. R. Carter & P. A. Sims, 1996. An Atlas of British Diatoms. Biopress, Bristol.

Hendey, N. I., 1964. An Introductory Account of the Smaller Algae of the British Coastal Waters Part V: Bacillariophyceae (diatoms). HMSO, London.

Herzschuh, U., 2006. Paleo-moisture evolution in monsoonal Central Asia during the last 50,000 years. Quaternary Science Reviews 25: 163–178.

Institute of Botany and South China Institute of Botany, 1982. Angiosperm Pollen Flora of Tropic and Subtropic China. Science Press, Beijing.

Jarvis, D. I., 1993. Pollen evidence of changing Holocene monsoon climate in Sichuan Province, China. Quaternary Research 39: 325–337.

Jones, R. T. & J. Jordan, 2007. Lake level studies: overview. In Encyclopedia of Quaternary Science. Elsevier: 1319–1336.

Kelly, M. G., H. Bennion, E. J. Cox, B. Goldsmith, J. Jamieson, S. Juggins, D. G. Mann & R. J. Telford, 2005. Common Freshwater Diatoms of Britain and Ireland: An Interactive Key. Environment Agency, Bristol.

Korner, C. & J. Paulsen, 2004. A world-wide study of high altitude treeline temperatures. Journal of Biogeography 31: 713–732.

Kramer, A., U. Herzschuh, S. Mischke & C. Zhang, 2010. Holocene treeline shifts and monsoon variability in the Hengduan Mountains (southeastern Tibetan Plateau), implications from palynological investigations. Palaeogeography, Palaeoclimatology, Palaeoecology 286: 23–41.

Langdon, P. G., Z. Ruiz, S. Wynne, C. D. Sayer & T. A. Davidson, 2010. Ecological influences on larval chironomid communities in shallow lakes: implications for palaeolimnological interpretations. Freshwater Biology 55: 531–545.

Last, W. M. & J. P. Smol (eds), 2001. Tracking Environmental Change Using Lake Sediments: Volume 2: Physical and

Geochemical Methods. Developments in Paleoenvironmental Research. Kluwer, Dordrecht.

Lopez-Pujol, J., F. Zhang & G. E. Song, 2006. Plant biodiversity in China: richly varied, endangered, and in need of conservation. Biodiversity and Conservation 5: 3983–4026.

Lu, H. Y., N. Q. Wu, X. D. Yang, C. M. Shen, L. P. Zhu, L. Wang, Q. Li, D. K. Xu, G. B. Tong & X. J. Sun, 2008. Spatial patterns of Abies and Picea surface pollen distribution along the elevation gradient in the Qinghai-Tibetan Plateau and Xinjiang, China. Boreas 37: 254–262.

Mackinnon, J., M. Sha, C. Cheung, G. Carey, X. Zhu & D. Melville, 1996. A Biodiversity Review of China. WWF International, Hong Kong.

Mayr, C., M. Wille, T. Haberzettl, M. Fey, S. Janssen, A. Lücke, C. Ohlendorf, G. Oliva, F. Schäbitz, G. H. Schleser & B. Zolitschka, 2007. Holocene variability of the Southern Hemisphere westerlies in Argentinean Patagonia (52°S). Quaternary Science Reviews 26: 579–584.

McCave, I. N. & J. P. M. Syvitski, 1991. Principles and methods of geological particle size analysis. In Syvitski, J. (ed.), Principles Methods and Application of Particle Size Analysis. Cambridge University Press, Cambridge: 3–21.

Menitsky, Y. L., 2005. Oaks of Asia. Science Publishers, Plymouth.

Meyers, S. R. & B. B. Sageman, 2004. Detection, quantification, and significance of hiatuses in pelagic and hemipelagic strata. Earth and Planetary Science Letters 224: 55–72.

Mittermeier, R., 2005. Hotspots Revisited: Earth's Biologically Richest and Most Endangered Terrestrial Ecoregions. Chicago University Press, Chicago.

Moore, P. D., J. M. Webb & M. E. Collinson (eds), 1991. Pollen Analysis. Blackwell Science, Oxford.

Moseley, R. K., 2006. Historical landscape change in Northwestern Yunnan, China. Mountain Research and Development 26: 214–219.

Moy, C. M., G. O. Seltzer, D. T. Rodbell & D. M. Anderson, 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. Nature 420: 162–165.

National Development and Reform Commission, P. R. China, 2007. China's National Climate Change Programme.

Nature Conservancy Council, 2011. China: Places we Protect: China's First National Park. Retrieved March 21, 2011, from www.nature.org: http://www.nature.org/ourinitiatives/regions/asiaandthepacific/china/placesweprotect/Pudacuo-National-Park.xml.

Peterson, T. C., R. Vose, R. Schmoyer & V. Razuvaev, 1998. Global Historical Climatology Network (GHCN) quality control of monthly temperature data. International Journal of Climatology 18: 1169–1179.

Qiao, B., 2004. Color Atlas of Air-Borne Pollens and Plants in China. Peking Union Medical College Press, Beijing.

Reimer, P. J., M. G. L. Baillie, E. Bard, A. Bayliss, J. W. Beck, P. G. Blackwell, C. Bronk Ramsey, C. E. Buck, G. S. Burr, R. L. Edwards, M. Friedrich, P. M. Grootes, T. P. Guilderson, I. Hajdas, T. J. Heaton, A. G. Hogg, K. A. Hughen, K. F. Kaiser, B. Kromer, G. McCormac, S. W. Manning, R. W. Reimer, D. A. Richards, J. R. Southon, S. Talamo, C. S. M. Turney, J. van der Plicht & C. E. Weyhenmeyer, 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0-50,000 years cal BP. Radiocarbon 51: 1111–1150.

Ren, G., 2007. Changes in forest cover in China during the Holocene. Vegetation History and Archaeobotany 16: 119–126.

Sadler, P. M., 1999. The influence of hiatuses on sediment accumulation rates. GeoResearch Forum 5: 15–40.

Stockmarr, T., 1971. Tablets with spores used in absolute pollen analysis. Pollen et spores 13: 615–621.

Sun, X., Wu, Y., Qiao, Y., Walker, D., 1986. Late pleistocene and holocene vegetation history at kunming, yunnan province, southwest China. Journal of Biogeography 13: 441–476.

Thompson, L. G., T. D. Yao, M. E. Davis, K. A. Henderson, E. Mosley-Thompson, P. Lin, J. Beer, H. A. Synal, J. Cole-Dai & J. F. Olzan, 1997. Tropical climate instability, the last glacial cycle from a Qinghai–Tibetan ice core. Science 276: 1821–1825.

Turney, C., M. Baillie, S. Clemens, D. Brown, J. Palmer, J. Pilcher, P. Reimer & H. H. Leuschner, 2005. Testing solar forcing of pervasive Holocene climate cycles. Journal of Quaternary Science 20: 511–518.

UNESCO, 2010. Sichuan Giant Panda Sanctuaries—Wolong, Mt Siguniang and Jiajin Mountains. Retrieved January 21, 2010, from www.UNESCO.org: http://whc.unesco.org/en/list/1213.

UNESCO, 2011. World Heritage List: The Three Parallel Rivers of Yunnan Protected Areas. Retrieved March 21, 2011, from www.UNESCO.org: http://whc.unesco.org/en/list/1083/.

Van Dam, H., A. Mertens & J. Sinkeldam, 1994. A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. Journal of Aquatic Ecology 28: 117–133.

Van der Werf, A. & H. Huls, 1957–1974. Diatomienflore Van Nederland, 8 Parts. Otto Koeltz Science Publishers, Koenigstein.

Virkanen, J., 2000. The effects of natural environmental changes on sedimentation Lake Kuttanen, a small closed lake in Finnish Lapland. The Holocene 10: 377–386.

Vos, P. C. & H. de Wolf, 1993. Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects. Hydrobiologia 269(270): 285–296.

Walden, J., F. Oldfield & J. Smith (eds), 1999. Environmental Magnetism: A Practical Guide: Technical Guide No. 6. Quaternary Research Association, London.

Walker, D., 1986. Late Pleistocene-early Holocene vegetational and climatic changes on Yunnan Province, southwest China. Journal of Biogeography 13: 477–486.

Wang, F., N. Qian, Y. Zhang & H. Yang, 1995. Plant Pollen Morphology of China. Science Press, Beijing.

Wang, Y. J., H. Cheng, R. L. Edwards, Y. Q. He, X. G. Kong, Z. S. An, J. Y. Wu, M. J. Kelly, C. A. Dykoski & X. D. Li, 2005. The Holocene Asian Monsoon: links to solar changes and North Atlantic climate. Science 308: 854–857.

Zhang, C. & S. Mischke, 2009. A Lateglacial and Holocene lake record from the Nianbaoyeze Mountains and inferences of lake, glacier and climate evolution on the eastern Tibetan Plateau. Quaternary Science Reviews 28: 1970–1983.

Zhang, E., P. G. Langdon, H. Tang, R. T. Jones, X. Yang & J. Shen, 2011. Ecological influences affecting the distribution of larval chironomid communities in the lakes on Yunnan Plateau, SW China. Fundamental and Applied Limnology 179: 103–113.

Zhong, W., J. Xue, Y. Zheng, J. Ouyang, Q. Ma, Y. Cai & X. Tang, 2010. Climatic changes since the last deglaciation inferred from a lacustrine sedimentary sequence in the eastern Nanling Mountains, south China. Journal of Quaternary Science 25: 975–984.

Zhou, W. & B. Chen, 2006. Biodiversity of Bitahai Nature Reserve in Yunnan Province, China. Biodiversity and Conservation 15: 839–853.