J Paleolimnol (2008) 40:413–429
DOI 10.1007/s10933-007-9170-6

ORIGINAL PAPER

Tracking eutrophication in Taihu Lake using the diatom record: potential and problems

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Received: 4 August 2007 / Accepted: 23 October 2007 / Published online: 20 November 2007

Abstract Taihu Lake is the third largest freshwater lake in China and has been experiencing eutrophication problems for several decades. Diatoms in short sediment cores from three bays in northern Taihu Lake were studied in addition to 1-year of seasonal phytoplankton samples in order to evaluate the rate and magnitude of nutrient enrichment. The dominant species found in the phytoplankton samples appeared in high percentages in the surface sediment samples, suggesting that the latter faithfully record the modern diatom flora. The diatom preservation status varied among the three cores, while in all cores the preservation deteriorated with sediment depth. Due to the superior diatom preservation in the core from Mashan Bay, the fossil diatom record of this core and an established diatom total phosphorus (TP) transfer function were used to reconstruct the nutrient history of Taihu Lake. Diatom assemblages changed from *Aulacoseira*-dominated to other eutrophic planktonic species, such as *Stephanodiscus minutulus*, *Cyclostephanos tholiformis*, *Cyclotella atomus*, *C. meneghiniana* and *S. hantzschii* in ca. 1980. Diatom-inferred TP concentrations exhibited little change prior to 1980, with values around 50 µg/l. However, after 1980 TP concentrations increased significantly and remained in excess of 100 µg/l, reflecting eutrophication of Taihu Lake. Comparison with TP measurements in the water column from 1988 to 2004, as well as the analogue analysis among fossil and modern samples, demonstrates that the diatom-TP inference model can reliably hindcast past TP concentrations. Therefore, the baseline TP value of about 50 µg/l, can be used as a restoration target for Taihu Lake. However, due to the complexity of this very large, shallow aquatic ecosystem, caution should be exercised when employing the diatom record to track eutrophication. Further studies on the mechanism of diatom distribution, evolution and preservation are recommended for Taihu Lake.

Keywords Diatoms · Eutrophication · Taihu Lake · Reconstruction · Total phosphorus · Lake sediments

Introduction

The deteriorating quality of lake waters has been one of the 20th century's largest and most wide-spread environmental problems (Smith 1998), especially in developing countries such as China (Liu and Diamond 2005). In China there are more than 6,600 lakes

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with areas greater than 10 km^2 (Wang and Dou 1998), providing rich resources to residents in the catchment. However, more and more lakes are experiencing eutrophication, salinization and pollution problems due to the increasing human pressure (Wang 2006). One such example is Taihu Lake (N30°05′–32°08′, E119°08′–121°55′), a shallow freshwater lake with an area of 2,338 km^2 and an average depth of 1.98 m. Taihu is the third largest freshwater lake in China and it serves many important purposes such as storage of flood water, supply of drinking water, irrigation, fish farming and as a tourist attraction. It is the major source of drinking water for the municipalities of Wuxi, Suzhou, and Shanghai (indirectly), which are some of the most prosperous regions in China. Consequently, Taihu Lake plays an overwhelmingly important role in the socioeconomic development of the country. Unfortunately, the lake has been severely polluted by nutrients, organic waste, and toxic substances over recent decades. The economic loss caused by the water pollution is approximately 1.2 billion US dollars per year (Wang et al. 2003). Among these problems, eutrophication is the most common and harmful, resulting in significant negative implications for the overall water quality and biodiversity of the lake; for example, the water becomes turbid, algae blooms occur, submerged macrophytes disappear, fish stocks change toward less desirable species and biodiversity decreases (Qin et al. 2004).

In view of this situation, water protection has become a high-priority issue for the government at all levels. Many actions have been taken during the past decade, such as control of the pollutant input, biological restoration and transfer water from the Yangtze River to Taihu Lake (Nanjing Institute of Geography and Limnology (NIGLAS) 2006). However, the nutrient status remains high without any significant improvement (Qin et al. 2007). One possible explanation for the lack of recovery is that nutrients are released from the sediment (Zhang et al. 1998; Dickman et al. 2001; Yuan et al. 2003; Zhu et al. 2005). Numerous studies demonstrate that P released from the sediment, especially in shallow lakes, can constitute a substantial part of the total loading and sometimes even exceeds the external loading of P (Jeppesen et al. 1990; Knuttila et al. 1994; and for a review in Søndergaard et al. 2001). Taihu Lake is situated in a sub-tropical monsoonal climate region with high precipitation (about 1,000–1,600 mm annually), and experiences high frequency of flooding due to its proximity to the Yangtze River, potentially bringing nutrients into the lake from the catchment. Earliest cultivation in the catchment recorded by archaeology and fossil pollen dates to ca. 7,000 yr B.P. (Sun et al. 1981; Huang 2003), indicating that this region has a long history of human disturbance. Consequently relatively high background nutrient concentrations might be expected and the restoration objective should reflect this, but there are limited data, extending back only two decades (with sporadic monitoring data for 1950s–1970s), to inform management decisions for Taihu Lake.

In the absence of long-term historical data, biological indicator groups preserved in lake sediment cores can be employed to reconstruct the history of lake eutrophication. Such information is essential before remedial measures can be considered (Anderson 1993; Battarbee 1999). Among those biological indicators, diatoms (class *Bacillariophyceae*) have been most widely used because of their taxonomic distinction, abundance, good preservation in lake sediments, and their rapid response to changes in lake trophic status (Lotter 1998; Stoermer and Smol 1999; Reid 2005). Numerous diatom nutrient reconstruction studies have been conducted across North America and Europe (Bennion et al. 2000; Bradshaw and Anderson 2001; Schönfelder et al. 2002; Bradshaw et al. 2005; Taylor et al. 2006), and many such studies have compared historical measured phosphorus data with diatom-inferred values to validate the performance of the models (Bennion et al. 1995, 2005; Marchetto and Bettinetti 1995; Hall et al. 1997; Rippey et al. 1997; Lotter 1998). Nonetheless, most of these studies focused on deep lakes, and more work for a broader range of lake types has been recommended (Sayer 2001). Taihu is a large shallow lake with relatively long-term monitoring data (two decades), thus providing a good site for validation. However, to date, our knowledge of diatom assemblages and their palaeolimnological potential in Taihu Lake is rather poor.

In a multi-proxy palaeolimnological research programme conducted on Taihu Lake, Rose et al. (2004) observed poor diatom preservation in cores from Meiliang Bay, which prevented further palaeoenvironmental interpretation using fossil diatoms.

Laboratory experiments have shown that diatom dissolution is mainly linked to pH, temperature, salinity, and ionic strength (Barker et al. 1994; Bidle et al. 2002), while in lake sediments it is affected not only by chemical factors but also by physical limnology, biological interactions, and bioturbation (Ryves et al. 2006). Given the large area of Taihu Lake and its high spatial variability in water quality and ecological structure, it is possible that diatom distribution and preservation may vary greatly across the lake.

Three bays, Meiliang, Mashan and Gonghu, in the north part of Taihu were selected for study (Fig. 1). Specific objectives were: (1) to compare the diatom distribution and preservation in the cores from the three bays, with reference to monthly phytoplankton and surface sediment samples, in order to evaluate potential for palaeoecological studies; (2) to reconstruct the lake nutrient history based on diatom shifts and diatom-inferred TP; (3) to validate the reconstruction using monitoring data. This study provides the first attempt to investigate the problems and possibilities of using diatoms for palaeolimnological research in Taihu Lake.

Description of sites studied

Taihu Lake is located in the middle reaches of the Yangtze River. Its flat topographic catchment results

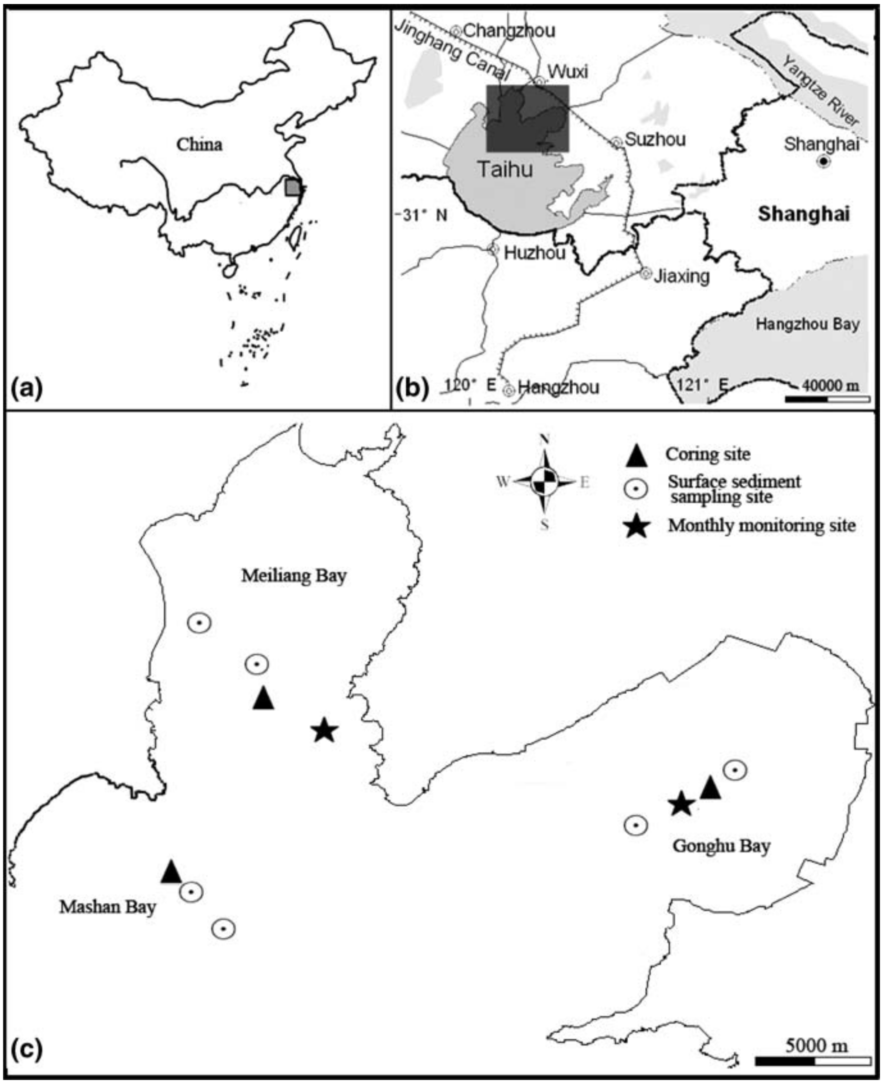


Fig. 1 Maps of the study area. (**a**) The location of Taihu Lake, China. (**b**) Surroundings of Taihu Lake, shaded area is expanded in (**c**). (**c**) Sampling sites in northern Taihu Lake

in the complex hydraulic connection with surrounding rivers. Approximately 80–90% of the total inflow comes from the mountainous west and southwest of the watershed through the estuaries of Dapu and Xiaomeikou, and flows out through East Taihu Bay and the Wangyu River in the northeast which in turn flush into the Huangpu River and Yangtze River (Fig. 1). The annual average precipitation is about 1,141 mm, but due to the large surface area the evaporation is high, reaching 4.6×10^8 m^3 (on August 1978). The water level fluctuates markedly on an annual basis depending on the amount of precipitation, and this results in variable water quality. Due to the shallow water depth and the wave effect produced by the wind (with more than 125 days per year with wind speed >8 m/s lasting at least 1 h every year, Zhu et al. 2005), there is no seasonal stratification for the vertically well mixed water column. The sediment distribution in Taihu Lake is spatially variable. According to surveys of the sediment depth, sediment is distributed in littoral zones, mostly along the western shoreline, with almost no accumulation in the lake center due to its flat and hard bottom, and sediment depth in the west is much greater than that of the east (Qin et al. 2007).

Human activities in the nearby cities (e.g., Wuxi City and Suzhou City) have expanded markedly since the 1950s, while the provision of environmental infrastructures (especially the treatment of wastewater) has not kept pace with the rapid socioeconomic development. Consequently, domestic, industrial, and agricultural wastewater is increasingly discharged into the lake without appropriate treatment, thus water quality and ecological status have deteriorated rapidly. Nutrient concentrations have increased dramatically, with total nitrogen levels rising from 1.84 mg/l in 1960 to 4.99 mg/l in 1999, and total phosphorus levels increased from 32 μg/l in 1988 to 105 μg/l in 1999 (average for the whole lake). Currently approximately 21% of the lake area is classified as eutrophic with the remaining 79% classed as meso-eutrophic. Phytoplankton diversity has decreased since 1981, but cyanobacteria populations (*Microcystis* and *Anabaena*) have increased (Pu and Yan 1998) and can comprise 85% of summer phytoplankton biomass (Chen et al. 2003). Since 1990, algae blooms have occurred in each summer, affecting drinking water extraction as well as fish culture (Qin et al. 2004). Meanwhile, more pollution-resistant species of cladocera, copepods, annelids and arthropods have appeared. Aquatic macrophytes have also experienced a pronounced decline in diversity, with a shift from 66 species (dominated by *Potamogeton malaianus*) in 1950–1960 to 17 species (dominated by *Vallisneria spiralis*) after 1990 (Fan 1996).

The north part of Taihu Lake is the most nutrient-enriched area. In order to track the eutrophication history of the lake, three bays were selected for coring in this area: Meiliang, Mashan and Gonghu. Meiliang and Mashan Bay have high nutrient status, with water quality in the Mashan bay being greatly affected by the Meiliang bay and the open lake area. Algal blooms have often been observed in the two bays in recent years, with few *Phragmites communis* stands in the littoral zones. However Gonghu Bay is macrophyte-dominated and has low TP relative to the other two bays (Table 1). An aquatic plant survey in 2002 reported occurrence of *Nymphoides peltata*, *Potamogeton malaianus*, *Myriophyllum spicatum* and *P. crispus* across almost the whole bay. Annual water quality data from the three stations (the station in Mashan Bay is much closer to the lake center than the coring site) from spring 2001 to winter 2002 (Table 1) in the three bays, demonstrates large spatial heterogeneity in water quality in Taihu Lake. All three coring sites in this study were selected in the areas where sediment accumulation has been recorded and which were, therefore, considered to be suitable for palaeolimnological research. Owing to the barrier effect of the Mashan Hill, the sediment depth of Mashan Bay is much greater than in the other bays.

Materials and methods

Sampling

A single core was taken using a gravity corer from each of the three bays and sectioned in the field as follows: (i) Meiliang Bay (Meiliang core, N31°29′20″, E120°12′09″), a 0.5 m core in a water depth of 2 m on June 2001, sectioned at 0.25 cm intervals; (ii) Mashan Bay (Mashan core, N31°22′56″, E120°07′56″), a 0.5 m core in a depth of 2.5 m on November 2002, sectioned at 0.5 cm intervals; (iii) Gonghu Bay (Gonghu Core,

Table 1 Selected physical and chemical data based on seasonal samples (2001–2002) for the three bays

	Meiliang Bay	Mashan Bay	Gonghu Bay
Location	E120.192, N31.475	E120.179, N31.343	E120.2955, N31.3865
Surface area (km^2)	123.8	–	169.7
Depth (m)	2.4	2.6	2.43
Secchi depth (m)	0.51	0.58	0.52
Cond. (μS/cm^2)	471.8	424.9	405.6
pH	8.62 (7.70–9.67)	8.3 (7.95–8.67)	8.27 (8.08–8.62)
COD$_{Mn}$ (mg/l)	7.99 (4.13–11.71)	5.12 (2.88–6.15)	4.57 (3.51–6.03)
Chlorophyll-*a* (μg/l)	17.45 (7.63–22.53)	7.89 (2.70–12.84)	7.26 (2.08–15.05)
DO (mg/l)	11.14 (9.74–16.30)	10.53 (8.23–13.60)	9.46 (7.52–11.39)
Total nitrogen (mg/l)	2.654 (1.037–5.444)	1.771 (0.797–2.395)	1.695 (0.771–2.930)
Total phosphorus (μg/l)	172 (106–395)	108 (59–210)	66 (28–100)
SiO$_2$ (mg/l)	7.29 (6.47–8.59)	4.67 (4.06–5.63)	3.44 (1.54–6.66)

Maximum and minimum measured values are given in parentheses for the chemical variables

N31°25′05″, E120°20′27″), a 0.3 m core taken in a water depth of 1 m on November 2005, sectioned at 0.5 cm intervals for the top 10 cm and 1 cm intervals thereafter. Additionally six short cores were taken on November 2005 using a gravity corer (two sites in each bay), and surface samples (about 0.5 cm) were sub-sampled from the top of these cores.

Plankton samples were collected on a monthly basis between November 2005 and October 2006 (February and May were missed) at the surface (0.1 m), at sites located in Gonghu Bay and Meiliang Bay (Fig. 1). In the field, aliquots (0.2 L) were fixed with Lugol's solution and were subsequently settled in the laboratory for 24 h and concentrated into ca. 5 ml for further diatom treatment.

Dating

Due to the superior diatom preservation in the core from Mashan Bay (see below), only the Mashan core was dated. Sediment samples were analyzed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Bloomsbury Environmental Isotope Facility (BEIF) at University College London, using an ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector (Appleby et al. 1986). Lead-210 was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 and 352 keV gamma rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs and ^{241}Am were measured by their emissions at 662 and 59.5 keV. The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample.

Diatom analysis

Preparation of diatom samples followed standard techniques (Battarbee 1986). To quantify planktonic diatom concentration, a known amount of glass microspheres was added to the concentrated phytoplankton samples before treatment (Battarbee and Kneen 1982). Diatom concentrations in Taihu Lake were relatively low, and therefore ca. 350 valves were counted per slide when possible. When preservation was poor only 100–200 valves could be identified, and for dissolved diatoms, only those whose main parts remained could be counted. Counts were made using a Leica microscope (DC-300 Type) with oil immersion objective (magnification 1,000×). The main taxonomic sources were Krammer and Lange-Bertalot (1986, 1988, 1991a, b). Species abundances were expressed as percentages.

For rapid assessment of diatom preservation, a three-scale description was used. This comprised: good preservation (assemblages almost pristine: almost whole community preserved well without signs of dissolution or only slight physical fragmentation of a few taxa); medium preservation (assemblages partially dissolved: most species were well preserved while few species were dissolved); poor preservation (most species were dissolved, and only robust species remain often with the valve rim missing or central area only preserved). Diatom zones in the core were identified using the constrained incremental sum of squares (CONISS) facility within the computer programs TILIA and TILIAGRAPH (Grimm 1987, 1991).

TP reconstruction

The reconstruction of historical TP concentrations was based on the diatom-TP transfer function established from 45 lakes in the middle and lower reaches of the Yangtze River (Yang et al. in revision). TP was selected because it was the key measured environmental factor affecting the variation of diatom distributions in the surface samples according to canonical correspondence analysis (CCA, ter Braak 1987). The inverse deshrinking weighted averaging regression and calibration method was employed to generate the transfer function. The final formula was expressed as follows: $\log_{10} \mathrm{TP} = -1.22 + 1.64\, x_i$, in which x_i represents the initial inferred TP for the i sample. The transfer function model had a high correlation coefficient between inferred and observed TP ($R^2_{\mathrm{jack}} = 0.82$) and a low inference error ($\mathrm{RMSEP}_{\mathrm{jack}} = 0.12$ $\log_{10}\mathrm{TP}$). The reconstruction was implemented with the program C2 (Juggins 2003).

Two approaches were used to validate the reconstruction. First the analogue matching technique was used to evaluate how well the calibration set of modern samples provided analogs for the fossil core samples. Every fossil sample was compared to the calibration set by using a squared chord distance as a dissimilarity measure (Overpeck et al. 1985) using the program C2. A critical value with which to compare the fossil samples was determined by calculating the mean minimum dissimilarity coefficient (DC). Any fossil samples with minimum DCs in the extreme 10% dissimilarity of the modern calibration set were deemed to have a poor modern analogue (Birks et al. 1990).

Second, the accuracy of diatom-inferred TP concentrations was assessed by comparison with measured water chemistry data from 1988 to 2004. The surface sample from Mashan Bay (on October 2005) was also compared with the monitoring data from 2002 to 2004 because it could be taken to represent the last 3 years of sediment accumulation, based on a sedimention rate of about 0.17–0.18 cm/year. The annual average TP concentration from Meiliang Bay was used for comparison purpose, since the core location was near to the mouth of Meiliang Bay, and has similar water quality to that in Mashan Bay, especially in the littoral area (Huang et al. 2001).

Results

Chronology

Due to the non-monotonic variation in unsupported ^{210}Pb activity, the dates were calculated using the constant rate of supply (CRS) model (Appleby and Oldfield 1978; Appleby 2001). The CRS model places the 1963/1964 layer just above 4 cm (Fig. 2a), which is in the section 0.5–4 cm of the core with relatively high ^{137}Cs values (Fig. 2b). ^{137}Cs concentrations are low throughout the core. However, a peak in ^{137}Cs activity around the depth of 4 cm, was used to roughly identify the fallout maximum from the atmospheric testing of nuclear weapons in 1963. The sedimentation rates varied from the beginning of the 20th century to the 1950s, followed by an increase from 0.032 g cm^{-2} yr^{-1} in the 1950s to about 0.135 g cm^{-2} yr^{-1} in the present day.

Comparison of planktonic and surface sediment diatom assemblages

The monthly planktonic diatom assemblages exhibited high seasonal variability (Fig. 3). The total planktonic diatom populations in both bays showed similar patterns, with population size decreasing from winter to summer, then increasing in the autumn (highest population in winter while lowest in summer). There were more epiphytic diatoms in Gonghu Bay than Meiliang Bay during each season. In Meiliang Bay, *Stephanodiscus minutulus* occurred in higher percentages in autumn and winter and decreased dramatically in summer, whilst in contrast

Fig. 2 ^{210}Pb CRS depth-age model and the sedimentation rates vs. time calculated using the CRS model

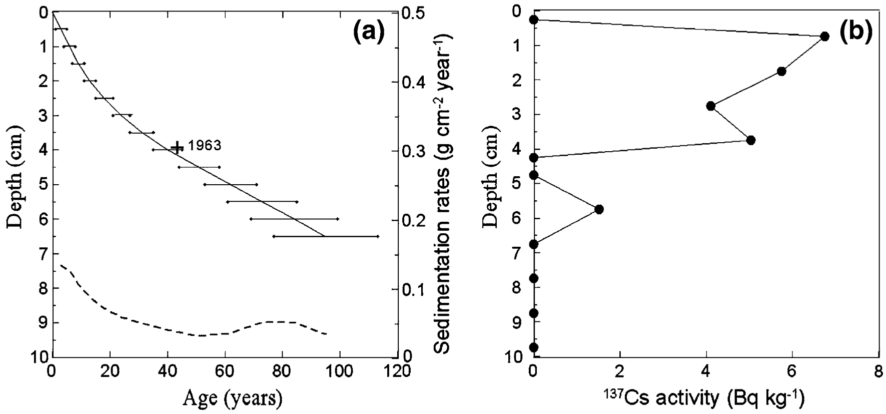
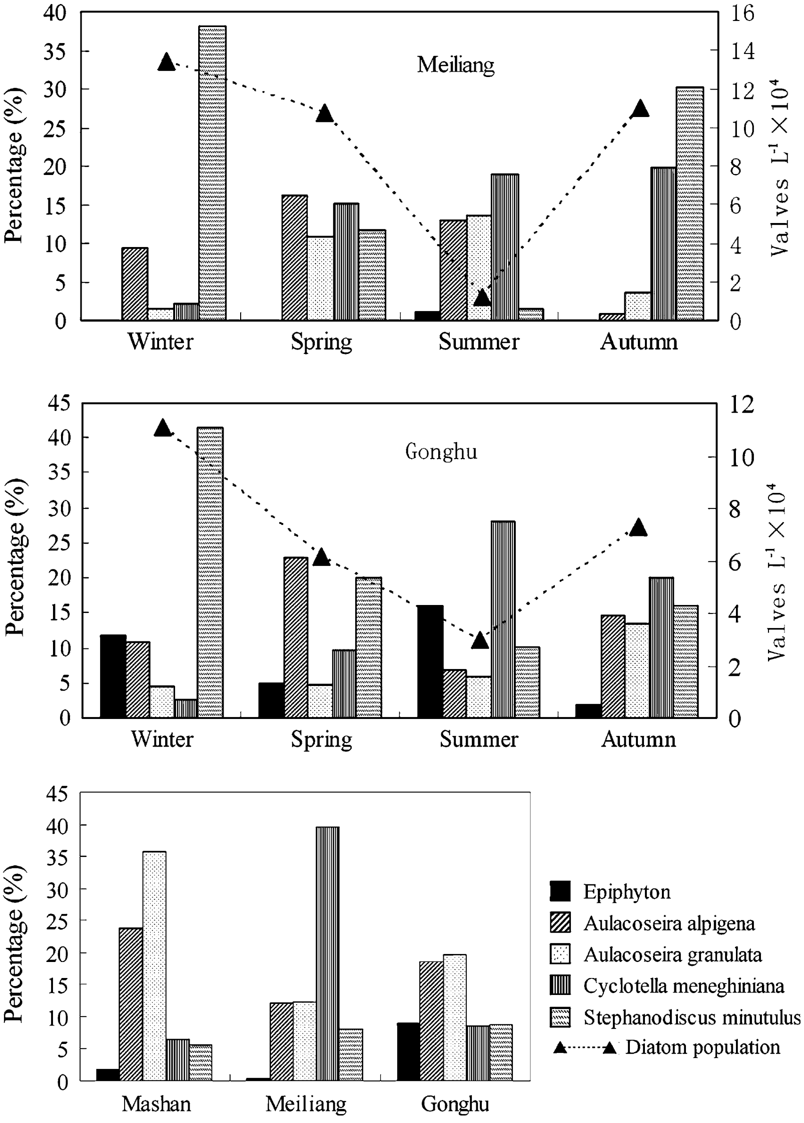


Fig. 3 Percentages of dominant diatom taxa in seasonal water column (top two figures) and surface sediment (bottom figure). The seasonal diatom populations are expressed as the highest monthly value within each season



the percentage of *Cyclotella meneghiniana* increased gradually from spring to autumn then decreased in winter. Similarly in Gonghu Bay, *Stephanodiscus minutulus* occurred in higher percentages in spring, autumn and winter than in summer, and *Cyclotella meneghiniana* was observed in its lowest percentage in winter.

In the surface samples, *Cyclotella meneghiniana* occurred in higher abundance in Meiliang Bay than in the other two bays, while more epiphytic species (reaching about 10%) were observed in Gonghu Bay and more *Aulacoseira granulata* (reaching 36.5%) occurred in Mashan Bay (Fig. 3). *Aulacoseira* taxa, such as *Aulacoseira granulata*, and *Aulacoseira alpigena*, were the sub-dominant species in the surface sediment samples of all three bays.

A comparison of the surface sediment and the planktonic diatom assemblages showed that all of the dominant planktonic taxa were found in the surface sediment samples. Furthermore, their percentages in the surface sediments were in the same range as that of the seasonal monitoring data, with the exception that *Cyclotella meneghiniana* in Meiliang Bay and *Aulacoseira granulata* in Gonghu Bay occurred in higher amounts in the sediments than in the plankton counts.

Diatom stratigraphy and preservation

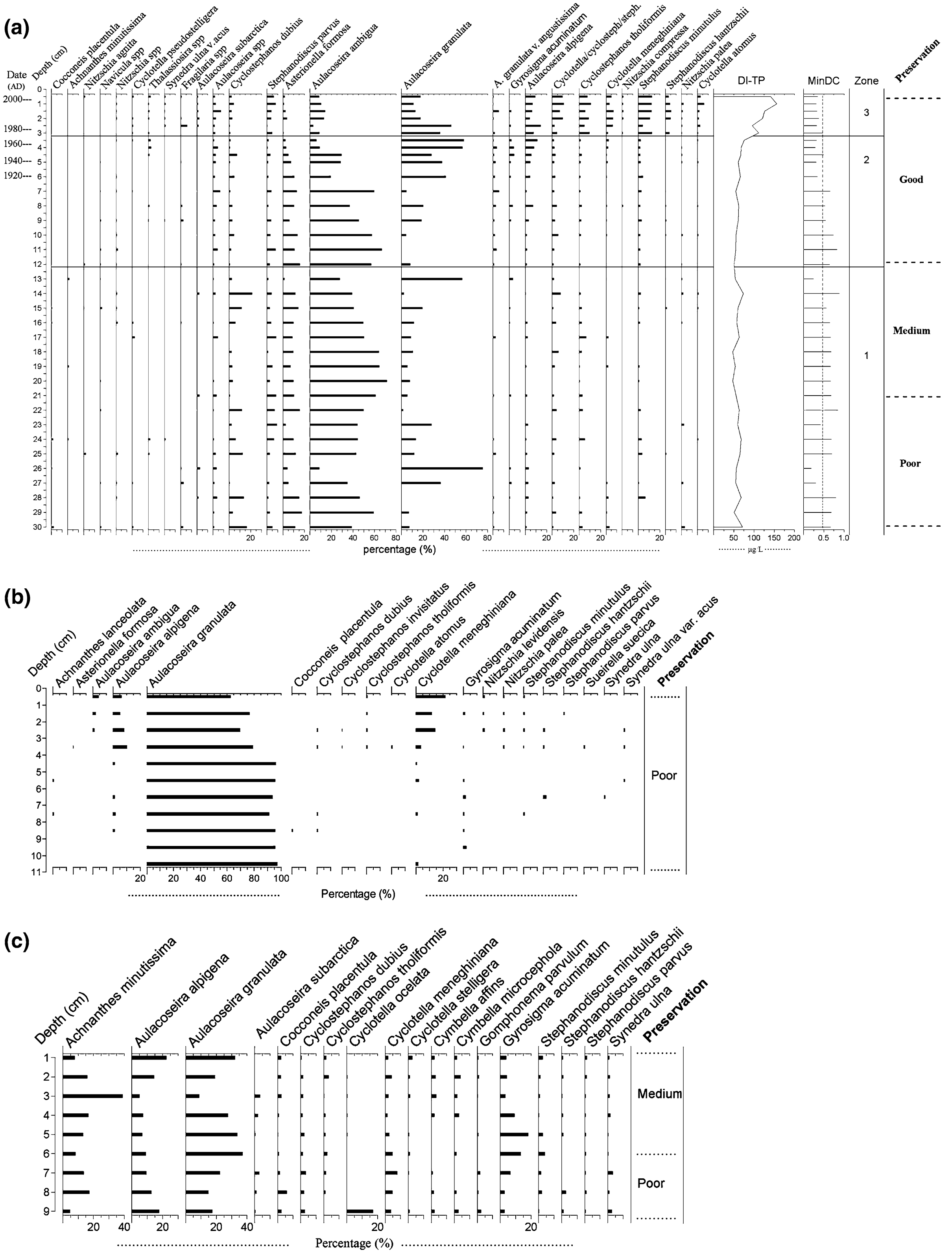
The diatom records of the three cores differed from one another (Fig. 4), although a number of the centric planktonic diatoms, namely *Aulacoseira*, *Cyclotella*, *Cyclostephanos* and *Stephanodiscus* were found in all three cores. In the Meiliang and Mashan Bay cores, the diatom assemblages were mainly dominated by planktonic species; while in the Gonghu core, more epiphytic species were present. Diatom preservation among the cores also varied. There was poor preservation in the Meiliang Bay core, intermediate preservation in the Gonghu Bay core and relatively good preservation in the Mashan Bay core. In each core the preservation deteriorated with increasing depth.

A total of 81 diatom taxa were identified in the Mashan core (Fig. 4a). The whole core was dominated by planktonic diatoms such as *Aulacoseira ambigua*, *A. granulata*, *Asterionella formosa*, *Cyclostephanos* spp. and *Stephanodiscus* spp. with few epiphytic or benthic species. In the top 12 cm all the species were well preserved but below 12 cm preservation deteriorated. Most of the dissolved species were *Aulacoseira granulata.* Small centric diatoms, such as *Cyclostephanos* spp. and *Stephanodiscus* spp., were relatively well preserved. Cluster analysis identified three major zones in the diatom record, indicating a clear change in the diatom species composition over time. Zone 1 (30–12 cm) was characterized by *Aulacoseira ambigua* and *Asterionella formosa*, with high percentages of *Aulacoseira granulata*, *Cyclostephanos dubius* and *Stephanodiscus parvus* in a few samples. Zone 2 (12–3 cm) was characterized by a gradual increase in *A. granulata* and *A. alpigena* and a decrease in *A. ambigua* and *Asterionella formosa.* In this zone the species of *Gyrosigma acuminatum* reached its peak values in the whole core. Zone 3 (3–0 cm) was markedly different with an expansion in small centric diatoms, namely *Stephanodiscus minutulus*, *Cyclostephanos tholiformis*, *Cyclotella atomus*, *C. meneghiniana* and *S. hantzschii.*

In the Meiliang core (Fig. 4b) the dominant species was *Aulacoseira granulata. Cyclotella meneghiniana* and *A. alpigena* were relatively abundant in the top 3 cm. Only a few very poorly preserved valves of *Aulacoseira granulata* remained below 3 cm and very few specimens were found below 11 cm. The preservation status in the whole core was poor with most diatom valves showing significant signs of breakage and evidence of dissolution.

In the Gonghu core (Fig. 4c) more epiphytic diatoms were present than in the other two cores with percentages greater than 20% in all samples. *Aulacoseira granulata* was still one of the dominant species. Other centric planktonic species occurred in relatively low percentages. The preservation status in this core was poor but was better than that in the Meiliang core. The epiphytic species, such as *Achnanthes minutissima* and *Gyrosigma acuminatum*, showed no evidence of dissolution although some of the *Gyrosigma acuminatum* valves were physically broken. As for the Mashan core, *Aulacoseira granulata* was the major species displaying signs of dissolution.

Fig. 4 Summary diatom stratigraphies (percentage relative abundance) of the cores from Mashan Bay (**a**), Meiliang Bay (**b**), Gonghu Bay (**c**); their preservation status is shown. In (**a**) the curve of reconstructed TP and results of analog analyses are shown (the vertical dash line represents the extreme 10% dissimilarity for training set samples) ▶


(a)
Date (AD)
Depth (cm)
Cocconeis placentula
Achnanthes minutissima
Nitzschia agnita
Navicula spp
Nitzschia spp
Cyclotella pseudostelligera
Thalassiosira spp
Synedra ulna v. acus
Fragilaria spp
Aulacoseira subarctica
Aulacoseira spp
Cyclostephanos dubius
Stephanodiscus parvus
Asterionella formosa
Aulacoseira ambigua
Aulacoseira granulata
A. granulata v. angustissima
Gyrosigma acuminatum
Aulacoseira alpigena
Cyclotella/cyclosteph/steph.
Cyclostephanos tholiformis
Cyclotella meneghiniana
Nitzschia compressa
Stephanodiscus minutulus
Stephanodiscus hantzschii
Nitzschia palea
Cyclotella atomus
DI-TP
MinDC
Zone
Preservation
2000
1980
1960
1940
1920
3
2
1
Good
Medium
Poor
percentage (%)
µg/L
(b)
Depth (cm)
Achnanthes lanceolata
Asterionella formosa
Aulacoseira ambigua
Aulacoseira alpigena
Aulacoseira granulata
Cocconeis placentula
Cyclostephanos dubius
Cyclostephanos invisitatus
Cyclostephanos tholiformis
Cyclotella atomus
Cyclotella meneghiniana
Gyrosigma acuminatum
Nitzschia levidensis
Nitzschia palea
Stephanodiscus minutulus
Stephanodiscus hantzschii
Stephanodiscus parvus
Sueirella suecica
Synedra ulna
Synedra ulna var. acus
Preservation
Poor
Percentage (%)
(c)
Depth (cm)
Achnanthes minutissima
Aulacoseira alpigena
Aulacoseira granulata
Aulacoseira subarctica
Cocconeis placentula
Cyclostephanos dubius
Cyclostephanos tholiformis
Cyclotella ocelata
Cyclotella meneghiniana
Cyclotella stelligera
Cymbella affins
Cymbella microcephola
Gomphonema parvulum
Gyrosigma acuminatum
Stephanodiscus minutulus
Stephanodiscus hantzschii
Stephanodiscus parvus
Synedra ulna
Preservation
Medium
Poor
Percentage (%)

Nutrient reconstruction and validation

Given the poor standard of diatom preservation in the Meiliang and Gonghu Bay cores, the past epilimnetic TP concentrations were reconstructed based on the fossil diatoms in the Mashan core only (Fig. 4a). All of the species found in the core were present in the calibration dataset. The effective number of occurrences and maximum relative abundance (Max) of selected species (whose maximum abundances were more than 2% in the sediment core), are shown in Table 2. Additionally their TP-optima and tolerances used in the reconstruction are given (Yang et al. in revision).

The results show that prior to 1980 (about 3 cm) there was little change in TP concentration, with values always around 50 µg/l. Around the depth of 3 cm, there is a marked increase in DI-TP from 75 to 115 µg/l. In the upper part of the core TP levels remain high (>100 µg/l), with the highest value of 157 µg/l occurring at 1 cm.

Analogue matching analysis indicated that most of the fossil samples in the top 6 cm had a good analogue with the modern calibration samples, except for samples at the depths of 3 and 4.5 cm. However, samples below 6 cm generally had poor analogues, with only four samples classified as good (Fig. 5). Notably, most of the poor analogue samples contained high percentages of *Aulacoseira ambigua* and *Asterionella formosa*.

Diatom assemblages in lake sediments represent an integrated time-averaged view. Consequently for comparative purpose the monitoring data were smoothed using a 3-point-running average (Fig. 5). Comparisons of measured annual mean TP concentrations from Meiliang Bay and DI-TP indicated that the DI-TP values were close to the monitored data, with the latter falling into the error range of the inferred values, except in 1987 and 1991. Therefore the reconstruction appears to be sufficiently reliable to describe dominant trends in TP concentrations over time.

Discussion

Comparison of surface sediment and planktonic diatom assemblages

Similar patterns in the seasonal changes of the planktonic diatom communities and total population were observed in Gonghu and Meiliang bays, suggesting a close relationship with changes in environmental conditions. However, epiphytic species were more abundant in the water column samples in Gonghu Bay, reflecting different ecological structures

Table 2 Summary statistics for key species in the Mashan core

Taxa	Effective occurrence	Max (%)	TP optimum (µg/l)	TP tolerance (log µg/l)
Asterionella formosa Hassall	25.21	17.5	51.11	0.26
Aulacoseira alpigena (Grunow) Krammer	14.15	34.01	134.03	0.19
Aulacoseira ambigua (Grunow) Simonsen	27.03	71.43	58.45	0.36
Aulacoseira granulata (Ehrenberg) Simonsen	18.87	75.46	70.57	0.28
Aulacoseira italica v. *tenuissima* (Grunow) Simonsen	14.00	5.61	82.78	0.27
Cocconeis placentula Ehrenberg	3.28	2.04	58.67	0.2
Cyclostephanos dubius (Fricke) Round	15.32	21.28	138.04	0.21
Cyclostephanos tholiformis Stoermer Theriot	16.95	10.72	148.56	0.23
Cyclotella atomus Hustedt	5.97	5.84	254.86	0.31
Cyclotella meneghiniana Skvortzow	12.71	6.97	195.66	0.26
Cyclotella pseudostelligera Hustedt	6.80	2.17	57.52	0.17
Gyrosigma acuminatum (Kützing)	12.77	4.65	58.59	0.2
Nitzschia palea (Kützing) W. Smith	10.53	3.06	104.52	0.33
Stephanodiscus minutulus (Kützing) Cleve & Moller	13.65	12.56	258.05	0.27
Stephanodiscus hantzschii Grunow	7.23	5.39	144.61	0.25
Stephanodiscus parvus Stoermer & Hakansson	23.89	9.38	191.56	0.23

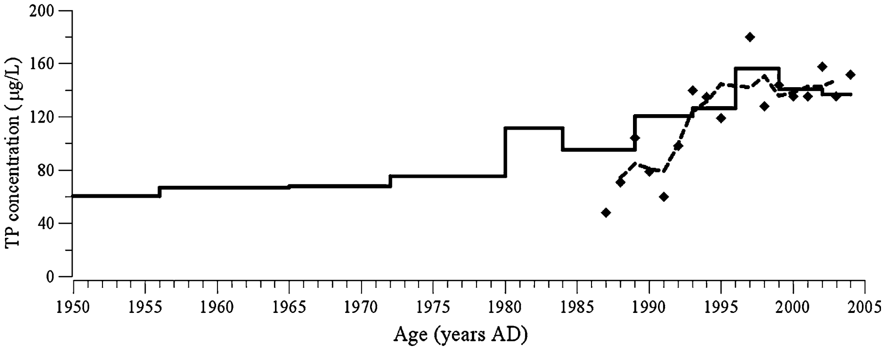


Fig. 5 Comparison of measured annual mean TP and DI-TP. Horizontal bars indicated the predicted TP in period of each sample covered. Filled diamonds indicate the annual average TP measured from the six monthly-monitoring stations in Meiliang Bay [Data of 1987–1999 were from Zhang and Qin 2001; 2000–2004 were from Taihu Laboratory for Lake Ecosystem Research (TLLER)]

in the two bays as there are more floating-leaved macrophytes in Gonghu Bay, which provide habitats for epiphytic diatoms (Karst and Smol 2000). The epiphytic diatoms were suspended in the water column because of strong wave effect. The 1-year dataset revealed distinct seasonal patterns related to changes in the water environment. As seen in most lakes, diatom populations initially peaked in spring and then decreased in summer, reaching the lowest values of the year (Talling 1993; Winder and Schindler 2004). After the autumn bloom, diatom populations continued to increase through the winter, which is inconsistent with the situation in deep lakes. In fact phytoplankton seasonal dynamics in shallow lakes are often difficult to describe. Unexpected peaks in population dynamics of the dominant species and sudden species replacements frequently characterize their temporal behavior or are superimposed on ‘regular’ seasonal patterns (Reynolds 1994; Tryphon and Moustaka 1997).

The comparison between diatom assemblages in the surface sediments and those in the phytoplankton samples from Meiliang Bay and Gonghu Bay revealed that the sediment record may be used to supplement the monitoring data. General agreement between the sediment and the plankton data was reasonably good both in terms of floristic composition and pattern of dominance (Battarbee 1981). The only differences between the water column and surface sediment samples in Meiliang Bay were the higher relative abundances of *Cyclotella meneghiniana* in the sediment and higher amount of *Stephanodiscus minutulus* in the water column. In Gonghu Bay a much higher percentage of *Aulacoseira granulata* was observed in the sediment samples than in the plankton. Since preservation in the surface sediment appears to be good, these discrepancies are probably due to sediment mixing and dilution by the influx of other, more abundant taxa (Battarbee 1981). For example, *Stephanodiscus minutulus*, a small centric species (with a diameter about 4–8 μm) has a slow sinking rate and is easily resuspended, and therefore its abundance varies considerably in the short term as a combined effect of growth/loss, transport by horizontal water currents and periodic resuspension from the sediment surface (Padisak and Dokulil 1994). In Taihu Lake, due to the prevalence of strong north–west winds in winter (Luo et al. 2004), great numbers of *Stephanodiscus minutulus* can survive in the water column, leading to higher abundances in winter. Alternatively the observed differences might be caused by inter-annual variability in the diatom populations because the surface samples represent the last few years, whilst the plankton were monitored over only 1 year. Further collection of planktonic diatom samples would be useful for testing the repeatability of our results.

Diatom preservation

The preservation status of diatoms in the fossil assemblages of all cores from Taihu Lake was generally poor. Only diatoms in the top 12 cm of the Mashan Bay core were almost pristine. Comparably poor preservation was reported in several cores from the lake by Rose et al. (2004). It is well recognized that diatom preservation declines with increasing pH, temperature, coarseness of sediment, grazing and bioturbation, water depth and exposure (Flower 1993; Barker et al. 1994). Taihu Lake has a number of characteristics that may contribute to the observed poor diatom preservation. First the lake is large and shallow (average depth less than 2 m), which facilitates wind-induced resuspension as well as provides more oxygen for the sediment. Frequent resuspension of diatoms in the water column increases the possibility of dissolution (Beyens and Denys 1982). In oxygen-rich sediments, biological activity is high and thus invertebrate grazing and bioturbation can exacerbate dissolution by promoting breakage and diffusion of dissolved silica (Rippey 1983). Second the water is highly alkaline and relatively warm for almost the whole year, conditions under which the opaline silica of diatom valves is susceptible to dissolution (Lawson et al. 1978). Third the lake is directly connected to several large rivers, resulting in a retention time of approximately 360 days which is short for a lake of such great volume (about 44.3×10^8 m^3). The short retention time will accelerate the recycling of Si or other ion concentrations, which may affect silicon dissolution (Marshall and Warakomski 1980).

Despite the diatom preservation problems, the upper part of the Mashan Bay core was sufficiently well preserved for further palaeolimnological study. Both the average water depth and sediment depth were greater in Mashan Bay than in the other two coring locations and the adjacent Mashan Hill provides some shelter from wind disturbance, reducing mixing and likely enhancing preservation. However, the present study does not provide a full explanation of the causes of diatom preservation and a more systematic study is required.

The dissolution rates of the diatom taxa were species specific. Some of the best preserved taxa were fine epiphytic forms, such as *Achnanthes minutissima*, *Cocconeis placentula* and *Gyrosigma acuminatum*. Additionally the centric species of *Cyclotella/Cyclostephanos/Stephanodiscus* appeared to be resistant to dissolution and were relatively well preserved in the cores. The worst preserved species was *Aulacoseira granulata*, although this species was recorded as one of the most abundant taxa in all three cores (Fig. 4). This phenomenon may be due to the overwhelming abundance of *Aulacoseira* spp. prior to the lake's nutrient enrichment and the filter-grazing effect of zooplankton. In a study of grazing effect on diatoms, grazers were more successful at ingesting large, high-profile diatom taxa and less able to remove small, adnate forms (Peterson 1987). Such 'selectivity' may be one explanation for the bad preservation of *Aulacoseira granulata*, since small centric diatoms could escape grazing while much bigger *Aulacoseira granulata* could not.

Diatom stratigraphy

Given the poor diatom preservation in cores from Meiliang and Gonghu Bay, only the Mashan core is discussed here (Fig. 4). As expected for an alkaline eutrophic lake, the diatom assemblages are dominated by planktonic taxa (average 91.6%, range 80.1–98.3%) and a typical succession indicating enrichment has been observed in other sediment records (Bennion et al. 2000; Sayer 2001; Schönfelder et al. 2002; Bradshaw et al. 2005; Taylor et al. 2006).

Before 1980 the diatom assemblages were dominated by species of *Aulacoseira ambigua*, *A. granulata* and *Asterionella formosa*, consisting of over 90% of the total percentage in each sample. The three species had relatively low TP optima and DI-TP prior to 1980 was ~45–80 μg/l. Thereafter the eutrophic planktonic species of *Cyclostephanos tholiformis*, *Cyclotella atomus*, *C. meneghiniana*, *Stephanodiscus minutulus* and *S. hantzschii* increased rapidly. These taxa are commonly associated with higher nutrient status in lakes from the Yangtze River catchment and elsewhere (Bradshaw et al. 2002; Schönfelder et al. 2002; Dong et al. 2006). Consequently DI-TP increased, reaching over 100 μg/l after 1980.

The genus *Aulacoseira* was dominant in all the zones. It has heavy silicified cells with a high sinking rate, and it requires turbulence to maintain its presence in the water column (Bradbury 1975). Increasing turbulence (sometimes corresponding to nutrient increases) in a lake can favor this genus over other planktonic species. Owen and Crossley (1992) reported that frequent upwelling conditions in southern Lake Malawi favored *Aulacoseria* filaments. Additional studies by Pilskaln and Johnson (1991) in Lake Malawi found that *Aulacoseira* dominated the assemblages during dry-windy periods where it took advantage of the high-turbulence conditions. Taihu Lake is a typical shallow lake with strong wind-driven current circulation, which may explain the high percentages of *Aulacoseira* spp. in the sediment cores.

Asterionella formosa was the second most abundant taxon (25.21% in effective occurrence, slightly lower than the highest value of 27.03% for *Aulacoseira ambigua*) in the sediment core. It maintained relatively stable percentages (~10%) before 1980 and subsequently decreased dramatically. The growth of *Asterionella formosa* was stimulated with N amendments [both $Ca(NO_3)_2$ and HNO_3] in in situ incubations in an eastern side lake in Rocky Mountain National Park (McKnight et al. 1990). In Taihu Lake water chemistry records show that before 1980 there were increases in TN and COD_{Mn}, while after 1980 TN increased more slowly and greater increases were seen in TP and chlorophyll-*a* concentration (Qin et al. 2004). The change in *Asterionella formosa* in the core may be due to the decrease of N:P ratios. *Asterionella formosa* has been reported to be a pioneer species occurring when the first agricultural activities began, and has been among the first diatoms to follow catchment settlement and agriculture in European lakes in the 12th and 13th centuries (Lotter 1998), and North American settlements in the 18th and 19th centuries (Hall et al. 1999). Similarly its appearance seems to mirror early agricultural activity in the Taihu Lake catchment, as the timing is consistent with the long-term record of agricultural activity in the Yangtze River catchment (Sun et al. 1981).

Throughout the Mashan core the percentages of epiphytic species such as *Cocconeis placentula* and *Gyrosigma acuminatum*, as well as the benthic species such as *Fragilaria* spp. and *Navicula* spp. were low. *Gyrosigma acuminatum* is typically found in lakes with abundant aquatic plants in the middle and lower reaches of the Yangtze River (Yang et al. 2005). Given that epiphytic species are commonly found growing on the stems of emergent plants (Sayer et al. 1999; Karst and Smol 2000), their low numbers are indicative of the lack of aquatic vegetation in Mashan Bay. This conclusion is supported by surveys carried out in recent decades, which recorded low aquatic plant cover in Mashan Bay (Qin et al. 2004). Benthic *Fragilaria* spp. and *Navicula* spp. seldom appeared in the core, most likely because of the low light availability and the high degree of wind-induced turbidity.

Potential error sources

The diatoms preserved in the Mashan sediment core appear to provide a record of nutrient enrichment. Nevertheless there are a number of potential error sources in this study which should be considered when interpreting the sediment record.

First, fossil diatom representativity is likely to be a major error source. In Taihu Lake the variable preservation status in the three cores, and the comparison between planktonic and surface diatom assemblages indicates that the fossil diatom record could be representative of the algal communities in the lake. However, the percentage discrepancies of some species still exist. The quality of the fossil diatom record in the sediment varies from lake to lake and is controlled by a variety of processes including mixing, transport, sedimentation, resuspension, bioturbation and diagenesis (Anderson et al. 1994). Taihu is a shallow lake and wave flume experiments showed that the critical shear stress (0.03–0.04 N m^{-2}) that leads to extensive sediment resuspension in Taihu Lake could be induced by a 4–6 m s^{-1} wind event (Qin et al. 2004). Thus strong sediment resuspension effects are likely to result in mixing of the diatom assemblages. Nevertheless, even a smoothed record is valuable for management purposes as the major trends can still be detected (Anderson 1993).

A second error source probably results from the inherent limitation of the transfer function. The diatom-TP model is heavily dependent on the estimated species' optima, which in turn are influenced by the length of the TP gradient in the modern training set. In the training set the TP gradient (from 38 to 568 µg/l) is reasonably long but it is lacking in samples from nutrient-poor sites (only five sites with TP concentration <50 µg/l), as there are few oligotrophic lakes in the Yangtze River catchment at present. From the analogue analysis, it was apparent that the fossil samples with high percentages of *Aulacoseira ambigua* are lacking good analogues with the modern samples (Fig. 4a). This also indicates that whilst the training set is good for high nutrient status reconstruction, it is likely to result in overestimations for the pre-enrichment period (Anderson 1995). To overcome such problems, larger data sets are required, covering a longer TP gradient.

Third, the model is only able to provide an estimate of annual mean TP concentrations, whereas it is well documented that TP can be highly variable both intra-annually and inter-annually and thus it is a difficult parameter for a simple model to predict (e.g., Gibson et al. 1996). In Taihu Lake the epilimnetic TP varies spatially and temporally with a typical seasonal range in the northern part of 28–395 μg/l (2001–2002, Table 1).

Recent nutrient history of Taihu Lake

The diatom shifts and inferred increase in TP in the Mashan Core indicate that this area of Taihu Lake has become enriched since the early 1980s. It is well established that 1980 marks the time when water quality deteriorated in Taihu Lake as a whole. According to the Environmental Quality Standard for Surface Water of China, water quality is assigned to five classes, from the best (I) to the worst (V). The water quality of the lake was ranked as class I or II until the 1970s. In the early 1980s, it deteriorated to class II or III. In the late 1980s, the average water quality fell to class III, while in some parts it was class IV or V. In the early 1990s, the average water quality declined still further and was ranked as class IV, while approximately one-third of the lake was class V. In the late 1990s, the water quality was degraded to the worst class V (State Environmental Protection Administration 2000). The timing of the shifts in the diatom assemblages in the core agree with the historical data. DI-TP concentrations increased from 75 μg/l in ca. 1970s to 115 μg/l in ca. 1980s, then increased to 121–157 μg/l in ca. 1990s. These three nutrient enrichment phases, especially the recent enrichment since the 1990s, were also observed in a recent multi-proxy palaeolimnological study of the lake including phosphorus, pigments, δ^{15}N, δ^{13}C and TOC/TN (Wu et al. 2007). It is important to note, however, that our core was taken from the north part of Taihu Lake, where the water quality is poorer than in other parts of the lake (Qin et al. 2004). This explains why the diatoms yield inferences suggesting greater enrichment in recent decades than those that have been described in reports which focus on Taihu Lake as a whole (Qin et al. 2004).

The diatom record provides evidence of relatively high background nutrient concentrations. Below the depth of 3.5 cm (pre-1980), *Cyclostephanos dubius* and *Stephanodiscus parvus*, taxa associated with nutrient-rich waters were present, suggesting that the lake has been nutrient-rich for a long time. Early agriculture or natural factors such as climate, floods or fires could have resulted in eutrophication (Webster et al. 1996). Historically the Yangtze River catchment was a densely populated area and early human impact certainly included agricultural activities (e.g., ploughing of fields) which led to an increase in land erosion and consequently enhanced nutrient supply. The subtropical climate of the region with plenty of rainfall may have enhanced soil erosion, hence nutrient load increased. Similar results have been reported from the palaeolimnological study of Taibai Lake, also located in the Yangtze catchment (Dong et al. 2006), where *Cyclostephanos dubius* was observed prior to 200 B.P. The diatom inference model indicates that baseline TP concentration in Taibai Lake was about 50 μg/l, and therefore this value can be used as a restoration target to guide management of the lake.

Potential and problems of using diatoms as a palaeolimnological tool in Taihu Lake

The good agreement between inferred and measured total phosphorus concentration suggests that sedimentary diatoms can be used to track the eutrophication process in Taihu Lake. Palaeolimnological studies, therefore, have the potential to provide historical information on the evolution of trophic status in the lake, including baseline conditions and degree of ecological change. The good preservation of epiphytic species in the cores provides potential for further work on this group, perhaps allowing shifts in macrophyte cover to be inferred. Unfortunately, the wider use of diatoms for palaeolimnological studies in Taihu Lake is somewhat restricted owing to the preservation problems. Dissolution can severely affect diatom composition and the ability to make reliable and accurate palaeoecological or palaeoenvironmental inferences from them. The modern diatom ecology and the interplay between biotic and abiotic factors in Taihu Lake are not yet completely understood, and it is difficult, therefore, to identify the environmental changes responsible for the observed shifts in the diatom assemblages. Consequently further work concerning modern diatom distribution and mechanisms of diatom dissolution in Taihu Lake are required.

Conclusions

(1) The diatom study of three sediment cores from the northern part of Taihu Lake illustrates that there is considerable spatial and temporal variation in diatom distribution and quality of preservation. The quality of preservation increases in the order Meiliang Bay, Gonghu Bay, Mashan Bay. The relatively good preservation in Mashan Bay is most likely due to the lower wave-disturbance in this area as a result of the barrier effect of Mashan Hill. However, at present the mechanisms and processes causing the differential dissolution across Taihu Lake remain unclear.

(2) Fossil diatom assemblages in the dated sediment core from Mashan Bay exhibit a shift at 3.5 cm (~1980) from *Aulacoseira ambigua*, *A. granulata* and *Asterionella formosa* to taxa associated with highly nutrient-rich waters (*Cyclostephanos tholiformis*, *Cyclotella atomus*, *C. meneghiniana*, *Stephanodiscus minutulus* and *S. hantzschii*). Diatom-inferred TP concentrations indicate that prior to 1980 TP concentrations were stable, with values of 40–50 μg/l. Since 1980 a marked increase in DI-TP occurred with values increasing from 75 to 157 μg/l in the late 1990s.

(3) The close agreement between measured TP and diatom-inferred TP values indicates that the reconstruction is suitable for describing the changes in lake trophic status in the northern part of Taihu Lake. The present investigation clearly illustrates the potential of using diatoms as a palaeolimnological indicator. However due to the complex hydrological, sedimentological and biological conditions in Taihu Lake, further work is required to understand the mechanisms of diatom distribution, evolution and preservation.

Acknowledgements We wish to thank Zhang Enlou, Ji Jiang and Wang Rong from Nanjing Institute of Geography and Limnology (NIGLAS) for their help in the field. We are also grateful to Carl Sayer, Simon Turner, Gavin Simpson, Wang Luo, Yang Hong from Environmental Change Research Centre (ECRC), Wang Sumin, Gao Guang, Zhang Yunlin from NIGLAS and anonymous reviewers for their helpful comments and suggestions on the manuscript. This study was supported by the Key Project of Chinese Academy of Sciences (kzcx2-yw-319), the UK Royal Society/Chinese Academy of Sciences joint project on Shallow Lake Ecosystems, the National Natural Science Fund of China (40572177). Dong Xuhui was also supported by a scholarship under the UK/CSC Excellence programme.

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