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Diatom-based inference of variations in the strength of Asian winter monsoon winds between 17,500 and 6000 calendar years B.P.

Luo Wang,[1] Houyuan Lu,[1] Jiaqi Liu,[1] Zhaoyan Gu,[1] Jens Mingram,[2] Guoqiang Chu,[1] Jingjing Li,[3] Patrick Rioual,[1] Jörg F. W. Negendank,[2] Jingtai Han,[1] and Tungsheng Liu[1,4]

[1] We present a continuous record of fossil diatoms from Huguang Maar Lake (HML) in southeastern China, spanning the time interval 17,500 to 6000 calendar years (cal years) B.P. The seasonal change in relative abundance of the dominant diatom taxa, *Aulacoseira* and *Cyclotella* species, can be used as a proxy of the strength of winter monsoon winds (WMW), which is supported by the results of a sediment trap experiment in HML and by an extensive review of the literature on the autoecologies of these species. In the sediment, high *C. stelligera* abundance and high-diatom concentration, which indicate warm conditions and low wind-driven turbulence of the water column, characterize an interval equivalent to the Greenland Interstadial 1. This is followed by an interval with low-diatom concentration and with assemblages dominated by *Aulacoseira* species, which suggests high wind-driven turbulence and therefore strong WMW. This interval corresponds with the Greenland Stadial 1. During the early and middle Holocene, another two episodes with strong WMW are evident from the data between 10,000 and 8500 and between 7000 and 6000 cal years B.P. The diatom record implies that strong winter monsoon episodes not only occurred during the last glacial-Holocene transition but also during the Holocene "thermal maximum."

1. Introduction

[2] The Asian-Australian monsoon is an important component of the Earth's climate system that influences the societal and economic activity of roughly half the world's population. The Asian monsoon consists of summer monsoon and winter monsoon. The summer monsoon transport moisture and heat northward from the north of Australia across the Warm Pool to northern China. The winter monsoon is characterized by cold, dry Siberian airflowing southward across eastern China, ultimately contributing to the Australian summer monsoon [*An*, 2000]. In addition, the Asian monsoon may affect climate globally, through interactions with ENSO [*Z. Y. Liu et al.*, 2000]. Recently, several studies focused on the relationship between the Asian winter monsoon and El Nino [*Wang et al.*, 2000; *W. Zhou et al.*, 2007]. Archives such as cave deposits have been used successfully to reconstruct changes in the past strength of the rain-bearing East Asian summer monsoon. Such records show that on a millennial scale the monsoon is controlled by changes in oceanic and atmospheric circulation patterns in addition to those forced by solar changes [*Wang et al.*, 2001; *Yuan et al.*, 2004; *Dykoski et al.*, 2005]. However, in most high-resolution studies, reconstruction of the winter monsoon is rarely offered because of the lack of suitable proxie records, especially during the Holocene. Therefore, there is a clear need to develop high-resolution-independent proxies records suitable for the reconstruction of the strength of winter monsoon winds.

[3] The high-resolution records of Huguang Maar Lake (HML) represent a potential archive to investigate past changes in the intensity of the Asian monsoon. In recent years, several studies tried to reconstruct the Asian monsoon from this site [*J. Q. Liu et al.*, 2000; *Chu et al.*, 2002; *Fuhrmann et al.*, 2003; *Mingram et al.*, 2004; *Liu et al.*, 2005; *Wang et al.*, 2007; *Yancheva et al.*, 2007]. So far, however, only titanium (Ti) content has been used as a proxy record of past variations in WMW [*Yancheva et al.*, 2007]. *H. Y. Zhou et al.* [2007], however, have argued that instead of being transported by winds, as proposed by *Yancheva et al.* [2007], Ti is likely to have come mainly from the catchment of HML and so that the Ti content may be more related to the hydrology of the lake than to the strength of the WMW.

[4] Diatoms are unicellular algae and are used extensively in palaeoecological studies because they are excellent indicators of past environmental conditions [*Battarbee et al.*, 2001]. Diatoms have been widely used as proxy indicators to reconstruct Holocene climate variability

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[1]Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China.
[2]GeoForschungsZentrum, Potsdam, Germany.
[3]School of Geosciences and Resources, China University of Geosciences, Beijing, China.
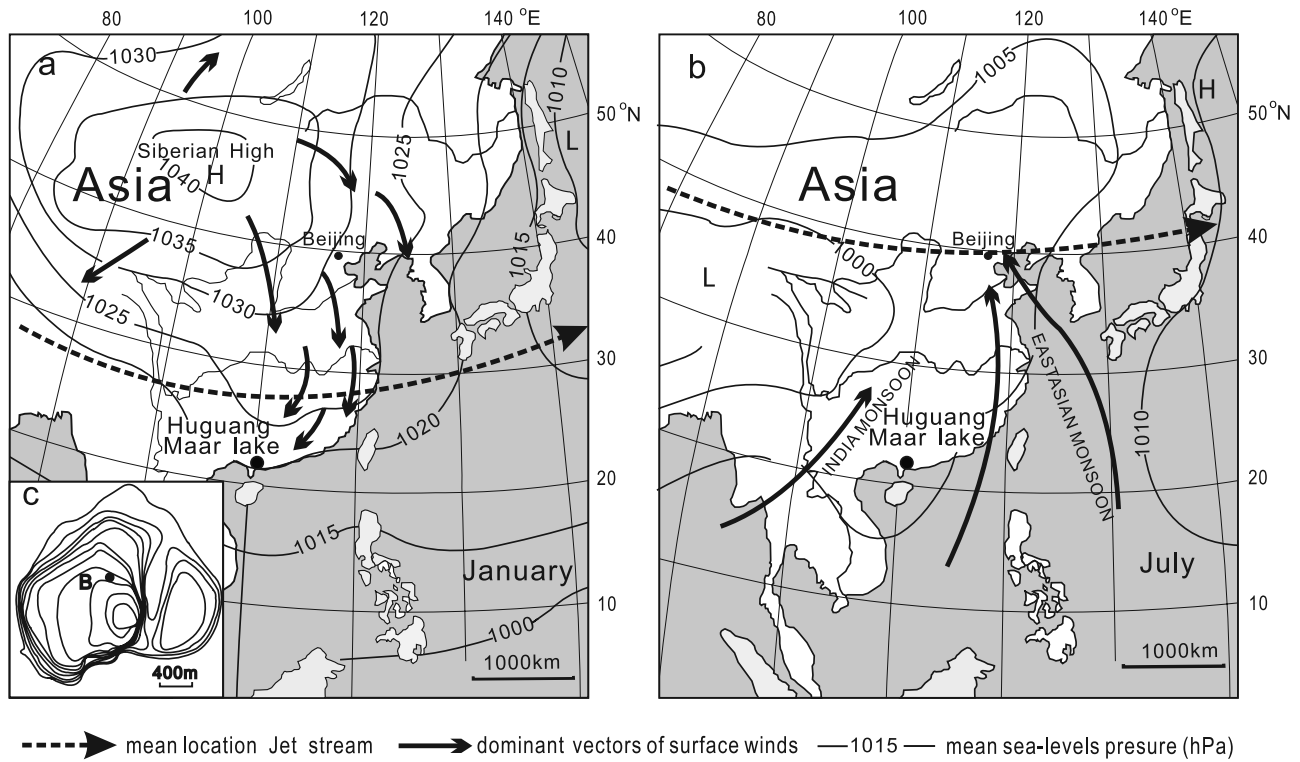[4]Deceased 6 March 2008.

Figure 1. Southeast Asian meteorological features in (a) January and (b) July and the (c) location of the HML (modified from *Mingram et al.* [2004]). Reprinted with permission from Elsevier.

[*Smol and Cumming*, 2000; *Mackay et al.*, 2003b]. The majority of recent studies use quantitative multivariate techniques to reconstruct past climatic variables either directly, such as surface water temperature [*Pienitz et al.*, 1995; *Vyverman and Sabbe*, 1995; *Rosén et al.*, 2000; *Bigler et al.*, 2002] and air temperature [*Korhola et al.*, 2000], or indirectly by reconstructing, for example, salinity [*Fritz et al.*, 1991; *Laird et al.*, 1996; *Gasse et al.*, 1997; *Verschuren et al.*, 2000; *Yang et al.*, 2004], DOC [*Pienitz et al.*, 1999], and conductivity [*Davies et al.*, 2002]. Furthermore, numerous studies on lake systems have shown that seasonal changes in the composition, production and diversity of diatom assemblages are related to variations of limnological variables such as the duration and timing of ice cover, the stability of the water column thermal stratification usually in summer and the turbulence of the water column because of strong wind in winter, and snow thickness [*Pilskaln and Johnson*, 1991; *Weyhenmeyer et al.*, 1999; *Lotter and Bigler*, 2000; *Mackay et al.*, 2003a; *Tolotti et al.*, 2007]. So far only a few studies have used such relationships for interpreting sedimentary diatom sequences. Among the most remarkable ones are studies focused on recent global warming [*Smol et al.*, 2005; *Rühland et al.*, 2008], shifts in ITCZ [*Pilskaln and Johnson*, 1991] and the African monsoon [*Stager et al.*, 2003].

[5] Here we use seasonal changes in diatom composition from the HML as a proxy for tracking changes in the intensity of WMW. Our data (sediment trap experiments,
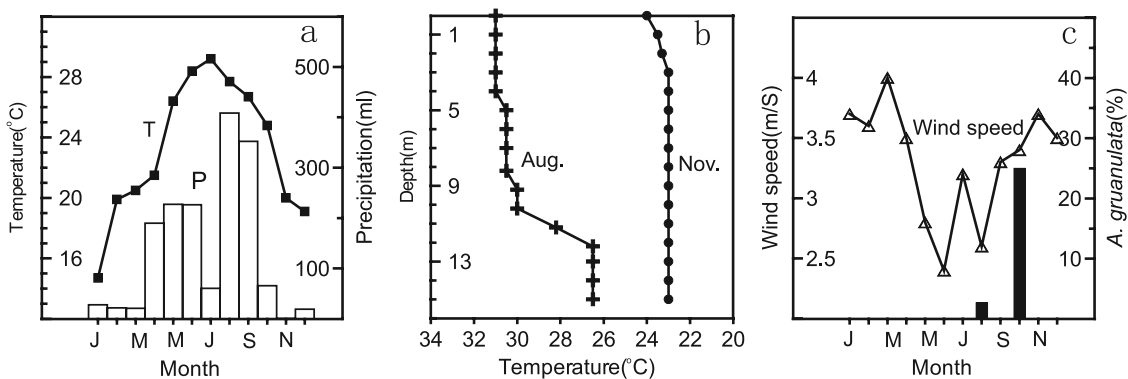

Figure 2. (a) Ombrothermic diagram for Zhanjiang weather station in 2007, (b) thermal stratification of the HML on 9 August and 9 November 2007, and (c) wind speed record at Zhanjiang in 2007 and percentage of *A. granulata* in the sediment traps in August and October.

meteorological and lake hydrology physical data) suggest that, over the time interval 17,500 to 6000 calendar years (cal years) B.P., shifts in the relative abundances of the dominant diatom taxa in this lake (heavily silicified, meroplanktonic, species of *Aulacoseira* against small euplanktonic *Cyclotella* species) are mainly controlled by changes in seasonal windiness.

[6] The HML (21°9′N, 110°17′E, Figure 1) is located in Guangdong province, near the South China Sea coast. This lake is very sensitive to hydrological and atmospheric cycles, because it is situated in a zone with seasonal climate, influenced by both the Asian summer and winter monsoons (Figures 1a and 1b). The mean annual temperature in Zhanjiang (15 km from the HML) is 23.1°C and the mean annual precipitation is 1440 mm (Figure 2a). The natural vegetation is that of a tropical semievergreen seasonal rain forest [*Zheng and Lei*, 1999]. The areas of the lake and its catchment are 2.3 km^2 and 3.5 km^2, respectively. The lake has no surface inflow or outflow. It has a maximum depth of 22 m, and is warm monomictic, being stratified from March to October. Human impact on the lake is small as only two small temples, built during the Sui (between A.D. 581 and 618) and Song dynasties (between A.D. 960 and 1200), are located within the catchment of HML. Moreover, agricultural activities have been stopped since the year 2000, when HML became part of a protected natural reserve.

2. Material and Methods

[7] In 1997, seven sediment cores (HUG-A to HUG-G) from three different sites in HML were drilled with a high-precision piston coring system [*Mingram et al.*, 2007] (Figure 1). The Core HUG-B used for this study has a length of 24.28 m and was recovered from a water depth of 13.4 m [*Mingram et al.*, 2004] (Figure 1c). The age model is based on 9 AMS (accelerator mass spectrometry) ^{14}C dates, 5 of leaves and 4 of bulk sediment. Details of the age model are given in [*Yancheva et al.*, 2007], and all the ages given here are calibrated ages. The events identified in the HML diatom sequence are compared with the GRIP isotope stratotype [*Lowe et al.*, 2008], now recognized as a template for climatic events during the Last Termination. For the readership convenience we also refer to the widely use terms such as "Younger Dryas," "Bølling," "Allerød," and "Preboreal." Trend in magnetic susceptibility and titanium content, which were derived from the same core and interpreted as proxy records for aeolian input [*Yancheva et al.*, 2007], will be compared to our diatom data. The wind speed data come from the China Meteorological Data Sharing Service System.

[8] In order to investigate the autoecology of the diatom species that dominate the present-day assemblages as well as the core samples, sediment traps were deployed in the lake in 2007. Cylindrical sediment traps were built according to the recommendations of *Blomqvist and Hakanson* [1981]. The traps were deployed for one month between 9 August and 9 September and between 9 October and 9 November at about 16 m water depth in the center of the lake, respectively. The solid material together with water in the cups was transported to the laboratory for diatom analysis. Lake water temperature profiles were measured at 1-m intervals

in the field using a water collector equipped with a thermometer.

[9] Diatom slides were prepared in test tubes from about 0.05 g of dry sediment using hot H_2O_2 followed by HCl to remove organic matters and carbonates, respectively [*Battarbee et al.*, 2001]. The 300 to 600 diatom valves were counted from almost all samples, except for 4 samples with low-diatom concentration for which only 200 valves could be counted. Diatom taxonomy followed the guidelines of *Krammer and Lange-Bertalot* [1991] and valves were identified to the lowest taxonomic level possible. The diatom data are shown as relative abundance. The S/G ratio (S/G stands for *Cyclotella stelligera/Aulacoseira granulat*) and *a*, two most abundant species in the diatom sequence, is a (nonlinear) estimate of the abundance of *C. stelligera* to that of *A. granulata*. In the HML, a low S/G ratio indicates strong WMW (see below for explanations). Diatom concentration (diatom valve number per gram) was estimated in each section by adding divinyl benzene microspheres to the cleaned suspension [*Battarbee and Kneen*, 1982]. The stratigraphical data were divided into diatom assemblage zones (DAZ) using the program ZONE (A. F. Lotter and S. Juggins, unpublished data, 1994), on the basis of a numerically optimal sum-of-squares partitioning with stratigraphical constraints [*Birks and Gordon*, 1985]. The resulting zonation was compared with the "broken stick" model [*Bennett*, 1996], and four statistically significant zones were established using the unpublished program BSTICK. In addition, we also distinguished nonsignificant subzones within DAZ 1 and 4.

3. Results

3.1. Sediment Trap and Thermal Stratification

[10] Sediment trap samples were collected and water temperature profiles were recorded twice in August and November 2007. Our data show that thermal stratification was developed in August with the temperature of the upper mixed layer reaching 31°C, while the bottom water temperature was 26°C (Figure 2b). This difference in temperature may seem small but because it occurs at high temperature, it causes large difference in water density and strong stratification [*Wetzel and Likens*, 2000]. In contrast, in November with higher wind speed inducing turbulent mixing, the water column was nearly isothermal (Figure 2b), at 23–24°C.

[11] The diatom assemblage composition of the two trap samples of August and November is significantly different. In August, *C. stelligera* dominated (91%), the relative abundance of *A. granulata* was very low (only 2.7%). In October, *C. stelligera* relative abundance decreased to 70% while that of *A. granulata* increased to 25%.

3.2. Diatom Stratigraphy

[12] 135 diatom taxa were recorded in the studied sediment core HUG-B. Figure 3 shows the most common diatom taxa, expressed as percent relative abundances.

[13] DAZ 1 (between 17,500 and 16,800 cal years B.P.) is dominated by heavily silicified, meroplanktonic *Aulacoseira* species (*A. ambigua, A. granulata*) and planktonic *Cyclotella radiosa* and small, planktonic *C. stelligera*. The most common benthic diatoms are *Achnanthes lanceolata, Fragilaria*
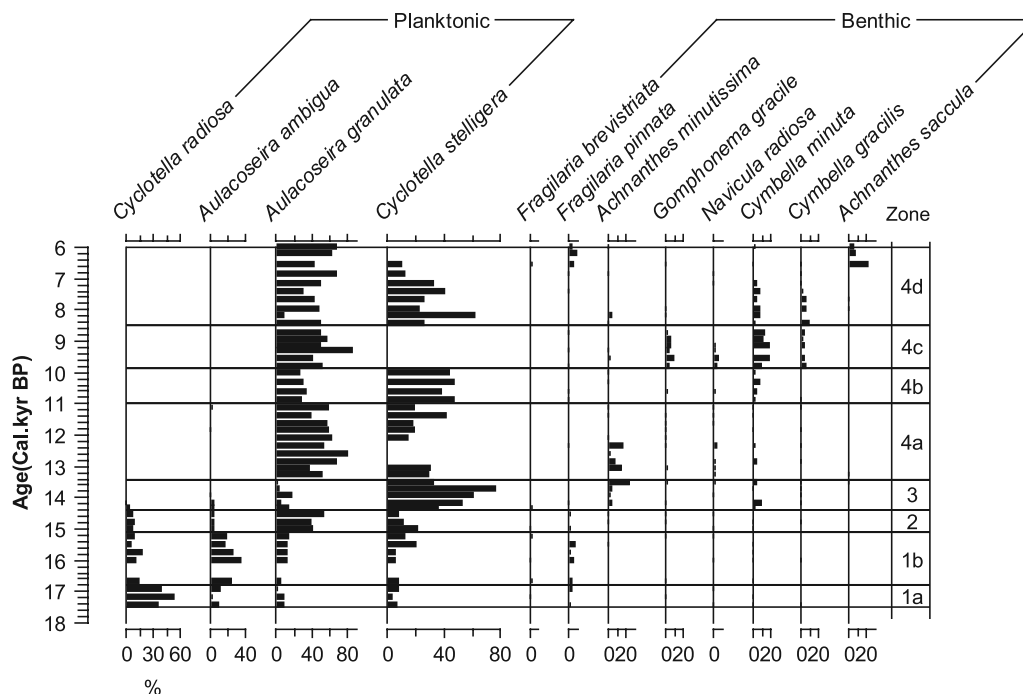
Figure 3. Diatom stratigraphy, expressed as relative percentages (only the most abundant taxa are shown), for Core HUG-B of the HML. The age model is after *Yancheva et al.* [2007].

brevistriata, *Fragilaria construens* var. *venter*, and *Fragilaria pinnata*. Within this zone, two subzones can be distinguished. DAZ 1a characterized by dominant *C. radiosa* and DAZ 1b characterized by dominant *A. ambigua*.

[14] In DAZ 2 (between 15,100 and 14,400 cal years B.P.) *A. granulata* dominates while *C. radiosa* decreases.

[15] In DAZ 3 (between 14,400 and 13,400 cal years B.P.) *C. stelligera* dominates while *A. granulata*, *A. ambigua*, and *C. radiosa* virtually disappear from the assemblages.

[16] In DAZ 4 (between 13,400 and 6,000 cal years B.P.) four subzones were identified according to the alternating dominance of *A. granulata* and *C. stelligera*. *A. granulata* is most abundant in DAZ 4a and 4c (i.e., between 13,400 to 11,000 and 10,000 to 8,500 cal years B.P., respectively) while *C. stelligera* dominates DAZ 4b and 4d (i.e., between 11, 00 and 10,000 and between 8500 to 6000 year ago, respectively). Benthic diatoms are particularly abundant in DAZ 4c and are mainly represented by *Cymbella gracilis*, *Cymbella minuta* and *Gomphanema gracile*. Additionally, a short interval at the top of DAZ 4d could also be distinguished although not identified as statistically significant by the program ZONE (probably because it includes too few samples). In this interval, *C. stelligera* decreases significantly while *A. granulata* increases, and the benthic component of the assemblages also changed, being dominated by *Achnanthes saccula* and *F. pinnata*.

4. Discussion

4.1. Relationship Between *Aulacoseira* and *Cyclotella* Species and Wind Strength

[17] Previous studies on diatom ecology have shown that many *Aulacoseira* species are meroplanktonic species. Meroplanktonic organisms enter the plankton when mixing

conditions are such that they can be suspended and maintained in the water column [*Kilham*, 1990]. *Aulacoseira* species can adapt to low-light levels that cells experience in a well-mixed water column by increasing the amount of chlorophyll per cell and thus their light-harvesting capacity [*Talling*, 1957]. These species also have resting stages that allow them to survive in the dark when they sink to the sediment surface at the lake bottom [*Schelske et al.*, 1995]. *Aulacoseira* species, such as *A. ambigua* and *A. granulata*, also appear to have rather high nutrient requirements [*Kilham and Kilham*, 1975]. During periods of strong wind, the lake thermal stratification breaks down, causing nutrient concentrations to increase and therefore offering conditions for meroplanktonic diatoms to thrive in abundance. Therefore, the abundance of *Aulacoseira* species, such as *A. granulata* and *A. ambigua*, is an indirect paleoenvironmental indicator of the persistence of strong, seasonal wind stress and resultant turbulent water column mixing and nutrient upwelling conditions [*Pilskaln and Johnson*, 1991].

[18] By contrast, euplanktonic species such as *Cyclotella* more commonly occur when lakes are thermally stratified during warm periods with weak wind [*Battarbee et al.*, 2002; *Sorvari et al.*, 2002; *Rühland et al.*, 2003]. *C. stelligera*, in particular, has been found to be the dominant algae in the deep chlorophyll layer that develops at the bottom of the epilimnion during thermal stratification in summer in Lake Superior [*Fahnenstiel and Glime*, 1983]. Euplanktonic species occur when lakes nutrients are more likely to be limiting [*Tilman et al.*, 1982]. *Cyclotella* species are also commonly observed in higher abundances in lakes with low nutrients (i.e., oligotrophic) [*Rühland et al.*, 2003]. During warm periods with weak wind, lakes stratify, causing nutrients (P, N and Si) to become depleted in the epilimnion [*Petrova*, 1986], as euplanktonic diatoms compete for

limiting resources among each other and with other algae [*Tilman et al.*, 1982].

[19] In our sediment trap, *A. granulata* and *C. stelligera* are the main species. The water column temperature (Figure 2b) and the diatom assemblages found in sediment trap samples from the HML support previous findings on the ecology of *Aulacoseira* species and *C. stelligera*. In August, *C. stelligera* dominates the trap samples, but in October, the relative abundance of *C. stelligera* decreased and that of *A. granulata* significantly increased.

[20] It is well established that the stability of thermal stratification in lakes is greatly affected by wind speed. In particular, when wind speed exceeds a threshold of roughly 3 m s^{-1}, Langmuir cells circulation can develop, which has a strong effect on the vertical distribution in the epilimnion of nonmotile planktonic organisms such as diatoms [*Reynolds*, 2006].

[21] The meteorological data for the Zhanjiang area in 2007 show that in November the daily mean wind speed often exceeded 3 m s^{-1} (70% of the daily mean), and in October the daily mean wind speed often exceeded 3 m s^{-1} (54% of the daily mean). In contrast in August the daily mean wind speed seldom exceeds 3 m s^{-1} (26% of the daily mean) (Figure 2c). Over the whole period covered by the meteorological data (1954–2007), there is still a significant difference between the daily mean wind speed of winter months (December, January, and February) and summer months (June, July, and August), although it is less pronounced (58 and 35% exceeding 3 m s^{-1}, respectively). The data suggests that *C. stelligera* dominates during summer because of well-developed lake thermal stratification and decreases with increasing wind strength, while *A. granulata* has opposite requirements (Figure 2c). Therefore, these data suggest that wind speed is an important factor in the mixing regime of this lake and is consistent with the diatom shifts recorded in the trap, indicating that relative abundance of *A. granulata* and *C. stelligera* is a good indicator of WMW and thermal stratification.

4.2. Interpretation of the Diatom Sequence

[22] DAZ 1b and 2, covering 16,800–14,400 cal years B.P., is most likely equivalent to the cold period defined in the Greenland ice core δ^{18}O record as Greenland Stadial (GS) 2a [*Lowe et al.*, 2008]. *A. granulata*, and *A. ambigua* dominate (Figure 3). In zone 4a (between 13,400 and 11,000 cal years B.P.), that includes the GS 1 cold period [*Lowe et al.*, 2008] (still widely referred to as the Younger Dryas), the relative abundance of *A. granulata* in the sediments is high, while that of *C. stelligera* is low. Therefore, these diatom data indicate that the WMW was strong during the GS 2a and GS 1cold periods.

[23] In contrast, during 14,400 and 13,400 cal years B.P. (DAZ3), equivalent to the warm Greenland Interstadial (GI) 1 (widely known as the Bølling Allerød), and between 11,000 and 10,000 cal years B.P. (DAZ 4b), an interval equivalent to the Preboreal [*Lowe et al.*, 2008], the relative abundance of *C. stelligera* in the sediments is high, while that of *A. granulata* is low and *A. ambigua* disappear (Figure 3). The diatom data from these zone suggested that strength of WMW was reduced during these warm periods.

[24] Following GS 1, another two intervals with relatively strong WMW occurred between 10,000 to 8500 and

between 7000 to 6000 cal years B.P., as evident from the curve of *A. granulata* abundance (Figure 3). Although we cannot quantify how strong the WMW were during these two intervals, high relative abundances of *A. granulata* suggest that the WMW was quite strong.

[25] As indicated by the zonation, the most significant shift in diatom composition occurred at about 14, 400 cal years B.P. with *A. ambigua* and *C. radiosa* disappearing from the assemblages as *A. granulata* and *C. stelligera* become the dominant species. *A. ambigua* has similar ecological requirements to *A. granulata*, as these species often cooccur [*Bradbury*, 1975]. However, by contrast with *A. ambigua* that is commonly found in temperate and high-latitude regions [e.g., *Siver and Kling*, 1997; *Trifonova and Genkal*, 2001; *Kauppila et al.*, 2002], *A. granulata* is considered as a thermophilic diatom [*Shear et al.*, 1976; *Poulíčková*, 1993]. *A. granulata* is often found in tropical and subtropical lakes [e.g., *Levis*, 1978; *Kilham et al.*, 1986; *Torgan et al.*, 2002; *Davies et al.*, 2004] while in the temperate regions its occurrences are restricted to the warm season [e.g., *Stoermer and Ladewski*, 1976; *Simola et al.*, 1990; *Poulíčková*, 1993]. *C. radiosa*, like *A. ambigua*, is also a species commonly found in lakes of the temperate and northern regions, where it blooms preferentially during the spring and autumn circulation periods [e.g., *Kiss and Padisák*, 1990; *Chu et al.*, 2005; *Kienel et al.*, 2005]. *C. stelligera*, unlike *C. radiosa*, is frequently reported in tropical lakes [*Bradbury*, 2000; *Dam et al.*, 2001]. This suggests that the temperature during the interval 17500 and 15,000 cal years B.P., which was dominated by *C. radiosa* and *A. ambigua*, was colder than the following period. The Mg/Ca and alkenones (UK37) records from the tropical South China Sea also show that the temperature of sea surface during the Greenland Stadial (GS) 2a was colder than in the following period, including GI1, GS1 and the Holocene [*Steinke et al.*, 2008].

[26] An alternative interpretation for the variations in diatom relative abundance observed in the HML sediment sequence would be to consider changes in precipitation instead of the WMW. It is generally assumed that increased precipitation during summer could bring more nutrients to the lake from its surrounding catchment because of increased runoff and groundwater supply. Such catchment-mediated process would favor the development of *A. granulata*, which is an eutrophic species [*Kilham and Kilham*, 1975], instead of *Cyclotella*, which is considered as oligotrophic species. However, our trap data show that the dominant diatom species is not *A. granulata* but *C. stelligera* in summer. This indicates that the physical process, especially windiness and its effect on the stability of the water column in the case of HML, is likely to be more important here for explaining the dynamic shifts between these two diatoms than changes in nutrient concentrations. Indeed, *Aulacoseira* taxa are thickly silicified and form filamentous colonies which make them relatively heavy and more likely to sink out of the photic zone as stratification develops unless turbulent conditions help them to remain in suspension [*Kilham et al.*, 1996; *Pannard et al.*, 2008]. On the other hand, *Cyclotella* species such as *C. stelligera* are small-sized diatoms that do not form colonies and have therefore much lower sinking rates compared with *Aulacoseira* which allow them to remain in suspension in the lake column
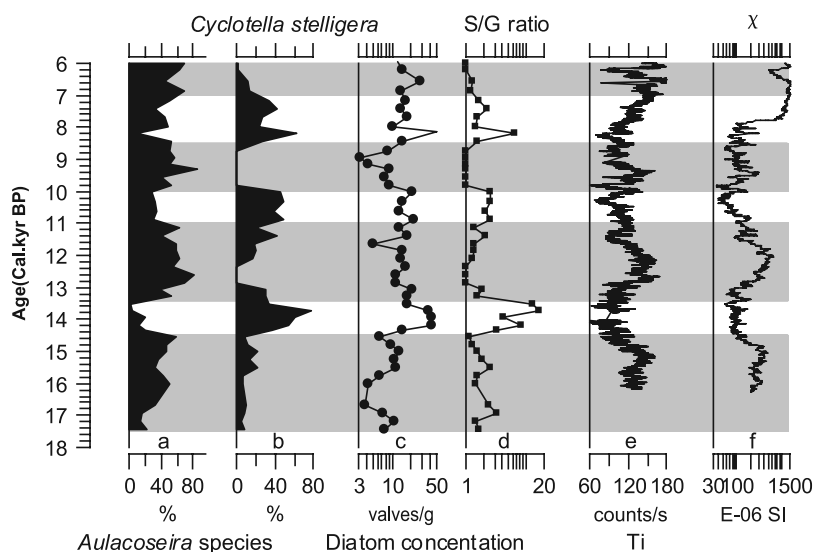
Figure 4. Comparison of the diatom data with other proxy records from HML. (a−e) Data from core HUG-B and (f) data from cores HUG-A and HUG-C. Relative percentages of *Aulacoseira granulata + ambigua* (Figure 4a) and *Cyclotella stelligera* (Figure 4b); diatom concentration ($\times 10^7$ valves g^{-1} dry matter) (Figure 4c); the ratio between *C. stelligera* and *A. granulata* (Figure 4d); Ti content [*Yancheva et al.*, 2007] (Figure 4e); and magnetic susceptibility χ [*Yancheva et al.*, 2007] (Figure 4f).

much longer [*Rühland et al.*, 2008]. *Cyclotella* are also known to tolerate high-light conditions and to be able to regulate their buoyancy to prevent sinking [*Saros et al.*, 2003]. Interestingly, similar shifts between *Cyclotella* and *Aulacoseira*, linked to thermal stratification, have been observed elsewhere [*Pannard et al.*, 2008; *Rühland et al.*, 2008]. In a lake system such as HML, with a small and forested catchment, surface runoff from precipitation would bring only little nutrients to the lake water. By contrast, wind-driven turbulence, disturbing the sediment at least in the littoral zone of the lake (Figure 1c), can cause large release of nutrients. Therefore, if nutrient still plays a role in the diatom succession at HML, it is most likely controlled by wind-driven turbulence and has the same effect on the composition of the assemblages (i.e., increased relative abundance of *A. granulata*).

4.3. Comparison of the Diatom Data With Other Paleoclimatic Records

[27] Our interpretation of the diatom record as a proxy for the variations in WMW is supported by independent paleoclimatic data. Changes in the magnetic susceptibility (χ) and titanium content of the sediment from the HML (Figure 4) are interpreted as a measure for dust input and lake mixing, which are both intensified in times of stronger winter monsoon winds [*Yancheva et al.*, 2007]. During cold climates, before 14.400 cal years B.P. and during GS 1, *Aulacoseira* species (*granulata* and *ambigua*) are abundant and S/G ratio is low while Ti content and χ are high (Figure 4). Pollen analysis from this same core also supports our interpretation of the diatom results as it shows that subtropical and temperate trees were dominant during GS 1, indicating a relatively cool climate. In contrast, during GI 1 and Preboreal, tropical evergreen trees dominated [*Wang et al.*, 2007].

[28] During the time interval 10,000 to 8500 cal years B.P. although Ti content and χ fluctuations are not as significant as during GS 1 (Figure 4), the diatom data and S/G ratio indicating strong WMW (Figure 4). The increasees in benthic diatoms in zone 4c (Figure 3) are also consistent with strong WMW, as wind-induced turbulence would bring more benthic diatom from the littoral zone where they grow into the center of the lake where the sediment core was retrieved (Figure 1c). At high latitudes in the Northern hemisphere, the atmospheric circulation over the North Atlantic and Siberia strengthened during the interval between 9000 and 8000 cal years B.P. [*Mayewski et al.*, 2004]. At least one large pulse of glacier meltwater into the North Atlantic probably enhanced production of sea ice, providing an additional positive feedback on climate cooling. In low latitudes, this is a period of widespread aridity [*Mayewski et al.*, 2004]. In the arid regions of northern China, the temporal distribution of calibrated ^{14}C dates of palaeosol units from numerous stratigraphic sections investigated can be used to distinguish episodes of soil formation (mild and moist climate) and episodes of loess and sand deposition (under a cold and dry climate, when no soil was formed and therefore from which no radiocarbon dates were yielded). Within the Holocene, one of the dry periods identified in this way occurred between 9,000 and 8500 years B.P. [*Guo et al.*, 2000]. However, some records from southern China indicated that the summer monsoon was also strong during the early Holocene (usually in the literature, this interval has been referred as the "early Holocene optimum" or the Holocene "thermal maximum") [*Wang et al.*, 2005; *Wang et al.*, 2007]. A possible explanation for this apparent discrepancy is that both winter and summer monsoons were strong during the early Holocene, as high summer insolation enhanced the seasonal contrast [*Kutzbach*, 1981]. It is worth mentioning that particularly strong storminess in summer would also

benefit the development of *A. granulata* [*Miyajima et al.*, 1994] while being detrimental to taxa adapted to a more stable water column such as *C. stelligera*.

[29] Between 7000 to 6000 years B.P., the abundance of *A. granulata*, the S/G ratio and high percentages of benthic species all suggest that WMW was strong. This is consistent with the Ti and χ records (Figure 4). In the paleosol records of northern China, the sparsity of ^{14}C dates for this time interval also suggests that the interval was characterized by severe dry events [*Guo et al.*, 2000]. Lake geomorphological and lithological evidence from the Alashan Plateau indicates strong lake desiccation during the mid-Holocene around 5000 to 7000 cal years B.P. [*Chen et al.*, 2003]. We should also consider that a stronger winter monsoon might not have been the only cause of the dry events recorded in North China. These events may have been caused by lower precipitation (weaker summer monsoon), or a combination of both a strengthening of the winter monsoon and a weakening of the summer monsoon.

[30] The results of this study highlight the overall good correspondence we observed between the geochemical and diatom data. This suggests that the diatom S/G ratio and the HML titanium content are a reliable proxy record of the strength of the winter monsoon over the time interval studied.

5. Conclusions

[31] The relative diatom abundance of *Aulacoseira* species and *Cyclotella* species from the HML can be used as a proxy of the strength of winter monsoon winds. The HML sedimentary diatom record shows dramatic changes implying four episodes with strong WMW over the time interval from 17,500 to 6000 cal years B.P. Remarkably, diatom assemblages imply that strong winter monsoon episode not only occurred during the last glacial-Holocene transition, but also during the Holocene thermal maximum.

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G. Chu, Z. Gu, J. Han, J. Liu, H. Lu, P. Rioual, and L. Wang, Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, 52 Sanlihe Road, 100864 Beijing, China. (wangluo@mail.igcas.ac.cn)

J. Li, School of Geosciences and Resources, China University of Geosciences, Xuanyuan Road 29, 100083 Beijing, China.

J. Mingram and J. F. W. Negendank, GeoForschungsZentrum, Telegrafenberg, D-14473 Potsdam, Germany.