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Ecological variations in diatom assemblages in the Paleo-Kathmandu Lake linked with global and Indian monsoon climate changes for the last 600,000 years

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ABSTRACT

Variations in fossil diatom assemblages and their relationship with global and Indian monsoon climate changes for the last 600,000 yr were investigated using a core of ancient lake (Paleo-Kathmandu Lake) sediments drilled at the Kathmandu Basin, Nepal Himalaya. Chronological scales of the core were constructed by tuning pollen wet and dry index records to the SPECMAP $\delta^{18}O$ stack record. Examinations of biogenic silica contents and fossil diatom assemblages revealed that variations in productivity and compositions of diatom assemblages were closely linked with global and Indian monsoon climate changes on glacial and interglacial time scales. When summer monsoonal rainfall increased during interglacials (interstadials), diatom productivity increased because of increased inputs of terrestrial nutrients into the lake. When summer monsoonal rainfall reduced and/or winter monsoonal aridification enhanced during glacials (stadials), productivity of the diatoms decreased and lake-level falling brought about changes in compositions of diatom assemblages. Monospecific assemblages by unique *Cyclotella kathmanduensis* and *Puncticulata versiformis* appeared during about 590 to 390 ka. This might be attributed to evolutionary fine-tuning of diatom assemblages to specific lake environmental conditions. Additionally, low-amplitude precessional variations in monsoon climate and less lake-level changes may have also allowed both species to dominate over the long periods.

Introduction

The Indian monsoon is a dominant climate system controlling environmental conditions in South Asia. Knowledge concerning Indian monsoonal activity and associated environmental changes during the Pleistocene has increased by investigations of marine sediments at the northern Indian Ocean, especially the northwest Arabian Sea (e.g., Clemens and Prell, 1990, 1991, 2003; Clemens et al., 1991, 1996; Prell et al., 1992; Anderson and Prell, 1993). In contrast, such knowledge obtained from the continental interior is extremely limited. In this point, basin-fill sediments of an ancient lake, named the Paleo-Kathmandu Lake, in the Kathmandu Valley on the southern slope of the Nepal Himalaya are expected to record history of changes in the Indian monsoon climate and in associated lake environment over the middle to late Pleistocene (Sakai, 2001a). Therefore, we undertook core-drillings in the Kathmandu Basin and retrieved a 218-m-long core, called Rabibhawan (RB) core (Sakai et al., 2001).

Preliminary studies revealed that sediments of the RB core are abundant in fossil diatom valves (Hayashi et al., 2002; Hayashi, 2007). Interestingly, the fossil diatom assemblages appear to be characterized by periodical changes in abundance and compositions. Fossil diatom assemblages preserved in sediments in large lakes are known to be potential indicators of climatic and environmental changes (Bradbury, 1999). Thus, the fossil diatom assemblages in the RB core sediments are expected to record changes in the Indian monsoon climate and the associated lake environment.

A goal of this study is to reveal variations in productivity and compositions of the diatom assemblages in the RB core sediments and to examine their relationship with global and Indian monsoon climate changes. For these objectives, however, an age model of the RB core is needed. Although it is known that the history of the Paleo-Kathmandu Lake dates back to ca. 1 Ma (Sakai et al., 2006), a preliminary paleomagnetic study revealed that the bottom of the RB core does not reach the Brunhes-Matuyama polarity boundary at about 780 ka, and

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intensity of remanent magnetization of the RB core sediments is too weak to identify geomagnetic events and excursions and to use them for dating (Yahagi and Hideo Sakai, unpublished data). In addition, it is generally difficult to employ radiometric dating methods except AMS ^{14}C for lake sediments during the Brunhes Chron. For those reasons, most of the chronology of the RB core has remained uncertain, and this has prevented the detailed examination of relationship of changes in fossil diatom assemblages in RB core sediments with global and Indian monsoon climate changes. Therefore, we construct the age model of the RB core based on pollen climate records reconstructed by Fujii (2002) and Maki (2005) before discussing the variations in the diatom assemblages.

Materials and methods

The Kathmandu Basin is an intermontane basin surrounded by mountains of more than 2000 m above the sea level: the Shivapuri Lekh to the north and the Mahabharat Lekh to the south (Fig. 1). The average elevation of the basin floor is approximately 1340 m above sea level. The catchment area of rivers is confined within the inside slope of the valley, and the sedimentary system in the valley is virtually closed. Only the Bagmati River cuts the Mahabharat Lekh to the south of the valley and flows out to the Gangetic Plain.

The RB core was drilled at Rabibhawan in the west-central part of the Kathmandu Basin (27°49′N, 85°29′E, 1303 m above sea level) (Fig. 1). The RB core is lithostratigraphically divided into the Patan and Kalimati Formations (Sakai et al., 2001) (Fig. 2). The Patan Formation, the uppermost 12-m-thick sequence, mainly consists of medium- to very coarse-grained micaceous granitic sands that were derived from the Shivapuri Lekh. This formation is believed to reflect the fact that the lake water started to drain at around 17 ka, and the majority of the Paleo-Kathmandu Lake disappeared by 15 ka (Sakai, 2001b; Hayashi, 2007). The Kalimati Formation, the lower 206-m-thick sequence, is composed of lacustrine sediments in which clayey silt predominates. The lowermost part of the Kalimati Formation, a 38-m-thick sequence below 180 m depth of the RB core, comprises shallow to marginal lacustrine sediments and pebbly mud interbeds, but the core recovery of this part is very poor.

In 83–89.5 m depth of the RB core, a sand bed is interbedded in the lacustrine mud beds of the Kalimati Formation. The sand bed is not observed in the other cores drilled at northern and southern sites of the Kathmandu Basin (see Fig. 5 in Sakai, 2001c). This means that the sand bed is not extensively distributed and the lacustrine clayey sequence continues in the subsurface of the Kathmandu Basin. Thus, the sand bed is considered to have deposited in a short period by a local event, such as gravity flow (Sakai, 2001c; Sakai et al., 2001; Hayashi, 2007). In addition, immediately above and beneath the sand bed, significant changes are not observed in fossil diatom assemblages in the RB core that are sensitive to environmental changes (Hayashi, 2007).

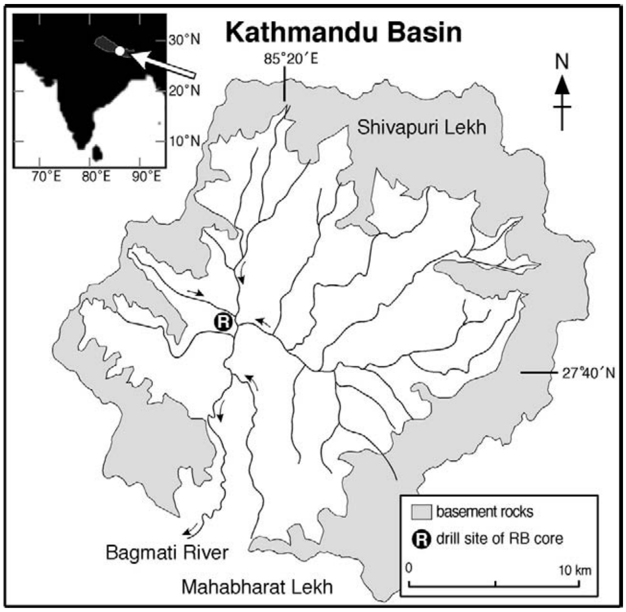

Figure 1. Locations of the Kathmandu Basin and the drill-site of the RB core (27°49′N, 85°29′E, 1303 m above sea level).

For the analysis of biogenic silica (Bio-Si) contents, samples were collected from the RB core at 50-cm intervals from 10.0 to 181.0 m in depth. Organic matter in all Bio-Si samples was removed by 5 ml of 10% H_2O_2 solution, and carbonates and iron oxides were removed by 5 ml of 10% HCl solution. Dissolved Bio-Si contents were extracted by the alkaline extraction method of Mortlock and Froelich (1989) with 0.5 M Na_2CO_3 solution at 85°C, and then Bio-Si values were determined by molybdate-blue spectrophotometry (Strickland and Parsons, 1968).

For the analysis of valve concentrations, dry weights of duplicate samples used for the Bio-Si analysis were measured, and then 10-ml suspensions were created. The 1-ml suspensions were concentrated on membrane filters (0.45-μm pore size) by the Millipore® filter transfer method. At least 300 valves in individual samples were counted along radiuses of the filters under scanning electron microscope (SEM) observation, and numbers of valves per 1 μg were calculated. Then, relative abundances of total planktonic diatoms, total benthic diatoms and individual species were calculated. Degree of overlap of diatom assemblages was calculated using the α index by Pianka (1973):

$$\alpha_{\mathrm{jk}} = \sum p_j p_k \Big/ \left(\sum p_j^2 \sum p_k^2\right)^{1/2}$$

where p_j and p_k are relative abundances of individual species between adjacent core samples.

In Figure 2, we plot the analytical results of Bio-Si contents and diatom valve concentrations with pollen wet and dry index records reconstructed by analyses of RB core samples at 10-cm intervals from 7.1 to 37.0 m depth, and at 100-cm intervals from 37.5 to 180.5 m depth by Fujii (2002) and Maki (2005). The wet index is defined as total pollen of *Alnus*, *Betula* and *Carpinus* per arboreal pollen, and the dry index is defined as total pollen of *Artemisia*, *Chenopodiaceae*, *Compositae* and *Gramineae* per arboreal and nonarboreal pollen, on the basis of relationship among pollen assemblages of the RB core, present vegetation distribution, and vertical climatic zones in the valley and surrounded mountains (Fujii, 2002; Maki, 2005). Since the wet (dry) index record lacks obvious fluctuation when the dry (wet) index shows high averages, e.g., 127.5–116.5 and 69.5–63.5 m in depth (Fig. 2), a composite wet–dry (CWD) index was calculated by subtracting standardized dry index from standardized wet index in order to examine relative changes between wet and dry conditions. The increase in CWD index value, namely the increase in wet index value and/or the decrease in dry index value, indicates wetter condition.

Spectral analyses (Blackman–Tukey cross-spectral analyses; Jenkins and Watts, 1968) on the time-series pollen CWD index, Bio-Si content, and diatom valve concentration records were performed using the AnalySeries software (Paillard et al., 1996).

Results

Biogenic silica contents

The Bio-Si record of the RB core is characterized by two kinds of fluctuation patterns (Fig. 2). One is large-scale fluctuations repeated at intervals of several tens of meters. There are five major peaks at depths of 52.5 m (16.7 wt.%), 92.0 m (17.5 wt.%), 105.0 m (19.2 wt.%), 136.5 m (21.1 wt.%) and 159.5 m (17.4 wt.%). The large-scale fluctuations are further composed of small-scale fluctuations repeated at 4–6 m intervals. The small-scale fluctuations are pronounced especially at 41.5–54.0, 74.0–119.0 and 134.5–142.5 m depth, with amplitude of 10–

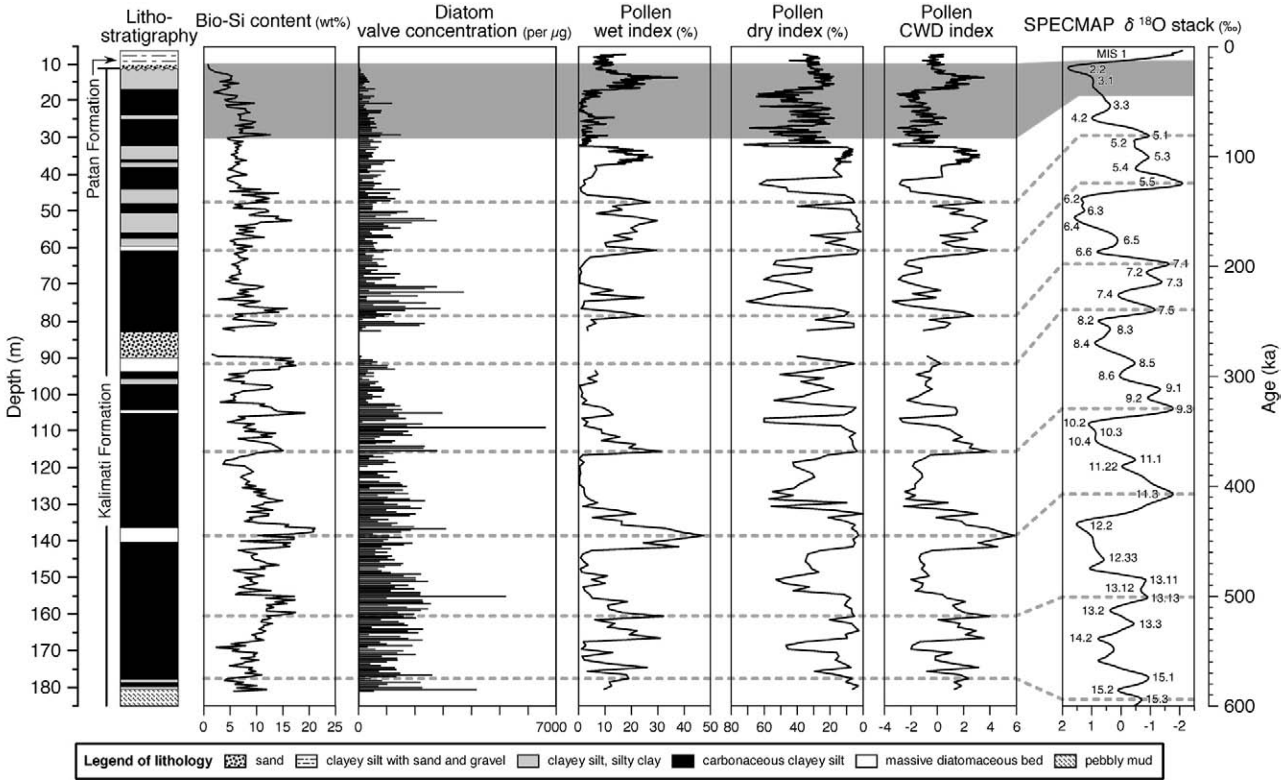

Figure 2. Records of Bio-Si contents, diatom valve concentrations, the pollen wet index, the pollen dry index and the pollen CWD index (modified from Fujii, 2002 and Maki, 2005) plotted along depth of the RB core, compared with the SPECMAP $\delta^{18}O$ stack record (Imbrie et al., 1984) with the LR04 age model (Lisiecki and Raymo, 2005). The transverse axis of the dry index record is reversed for comparison with the other records in the same sense. Ages in the gray area in 9.75–30.1 m depth of the RB core were calculated by the AMS ^{14}C dating method (Table 1). Gray dotted lines denote tie points used for the construction of the pilot age–depth model (Fig. 3; Table 2). Lithostratigraphy of the RB core is shown in the left. MIS numbering beside the SPECMAP $\delta^{18}O$ stack curve follows the scheme by Bassinot et al. (1994).

15 wt.%. At 155.0–167.5 m depth, Bio-Si contents keep a relatively high average of 12.4 wt.%, but the small-scale fluctuation is absent.

In general, Bio-Si contents in lacustrine sediments are derived from diatom valves; chrysophycean scales; and cysts, sponges and phytoliths (Conley and Schelske, 2001). SEM observation revealed that diatom valves are the most abundant throughout the RB core, followed by smaller chrysophycean cysts. Since one chrysophycean cyst is found against several hundreds diatom valves, most of the Bio-Si contents are derived from the diatom valves.

Fossil diatom assemblages

Changes in valve concentrations of fossil diatoms are basically synchronous with those in Bio-Si contents regarding both the large- and small-scale fluctuations (Fig. 2). The valve concentration record, however, is different from the Bio-Si record in the following two points. At 89.5–102.0 m depth, the valve concentrations are kept relatively low in contrast to great changes in Bio-Si contents, because of the appearance of *Aulacoseira ambigua* (Fig. 3) whose valves are thicker and larger than the other dominant diatom species in RB core sediments. In addition, the valve concentration record is characterized by some spikes (Fig. 2) attributed to events of explosively increasing small species. As an example, very small (less than 10 μm) *Cyclostephanos delicatus* and *Stephanodiscus minutulus* explosively increase at the depth of 109.0 m where the valve concentration shows the largest value and the amount of Bio-Si content shows a relatively small value.

Fossil diatom assemblages in RB core sediments consist of about twenty planktonic taxa and ninety benthic taxa. Valve concentrations of total planktonic diatoms generally overwhelm those of total benthic diatoms (Fig. 3); an average relative abundance of the total planktonic diatoms is 75.2% between 10.0 and 181.0 m in depth. Degree of overlap of diatom assemblages fluctuates every a few meter above 110 m depth, while it is virtually constant, with values of approximately 1, below that depth. In the lower section, exceptionally sharp decreases in degree of overlap occur at 133.0–135.0 m and 148.0–148.5 m depth. The degree of overlap depends largely on relative abundances of seven major planktonic species: *Aulacoseira ambigua*, *A. granulata*, *Cyclostephanos dubius*, *Cyclostephanos* sp.1, *Cyclotella ocellata* complex, *Cyclotella kathmanduensis* and *Puncticulata versiformis*. At 13.0–19.0 m depth, *Cyclostephanos dubius* dominates and averages 79.6%, though its valve concentrations are relatively low. Between 19.0 m and 110.0 m depth, *C. ocellata* complex and *A. granulata* dominate repeatedly, while *Cyclostephanos* sp.1 and *A. ambigua* dominate only in 62.0–79.0 m and 90.0–105.0 m depth, respectively.

In contrast to 13.0–110.0 m in depth, where valve concentrations and relative abundances of the five major planktonic species fluctuate every several meters, almost monospecific planktonic assemblages appear for long intervals between 110.5 m and 176.5 m in depth. At 110.5–133.0 m and 148.5–176.5 m depth, *C. kathmanduensis* continues to be very abundant, and relative abundances are very high: in particular, 90.3% at 113.0–128.5 m depth and 91.4% at 153.0–162.0 m depth. At 135.0–148.0 m depth, where *C. kathmanduensis* is temporarily absent, *P. versiformis* becomes very abundant and dominates with an average relative abundance of 88.6%. At 177.0–181.0 m depth, *Cyclostephanos dubius* is abundant and dominates with an average relative abundance of 73.1%.

Discussion

Age–depth model of the RB core based on AMS ^{14}C dates and pollen climate records

Comparison of pollen wet and dry index records with the SPECMAP $\delta^{18}O$ stack record

Middle to late Pleistocene global climate changes represented by the SPECMAP $\delta^{18}O$ stack record (Imbrie et al., 1984) are expressed as

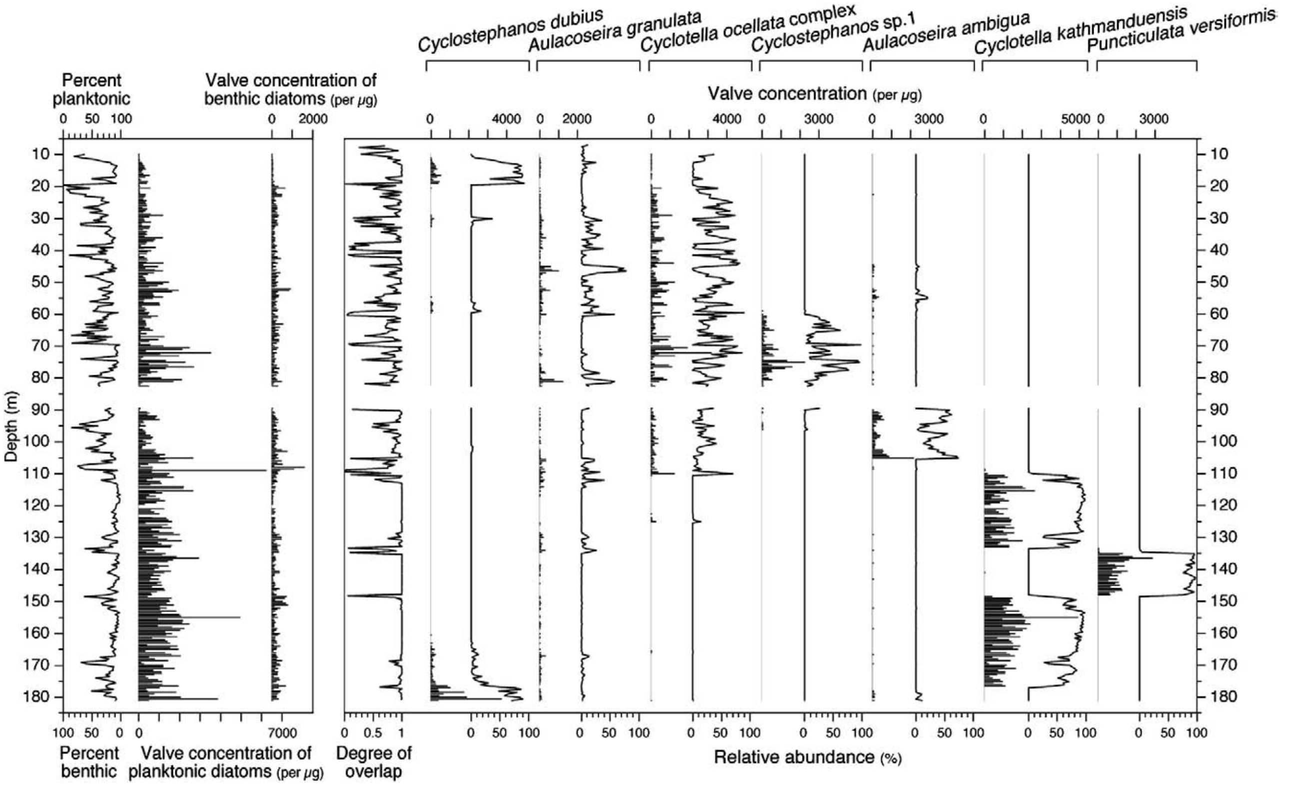

Figure 3. Summary of records of fossil diatom assemblages in RB core sediments: relative abundances of planktonic diatoms (percent planktonic), valve concentrations of planktonic and benthic diatoms, degree of overlap of diatom assemblages and valve concentrations and relative abundances of seven major planktonic species. All the records are plotted along the depth of the RB core.

asymmetrical “saw-tooth-like oscillations”, which are gradual (about 90,000 yr) ice growths followed by rapid (about 10,000 yr) deglaciations (Broecker and van Donk, 1970; Broecker, 1984). Additionally, each glacial–interglacial cycle is composed of four to five precessional stadial–interstadial cycles (Raymo, 1997). In these points, fluctuation curves of pollen wet and dry index records of the RB core (Fujii, 2002; Maki, 2005) closely resemble that of the SPECMAP stack record from Marine Isotope Stage (MIS) 1 to MIS 15.3 (Fig. 2). In this section, we make detailed comparisons between the pollen wet and dry index records and the SPECMAP stack record with the LR04 age model modified by Lisiecki and Raymo (2005); the discussion of the age–depth model of the RB core will be given in the next section.

A series of AMS ^{14}C dates from 12,900 to 44,280 cal yr BP are calibrated from 9.75 to 30.13 m depth (gray area in Fig. 2; Table 1). Within the constraint of the AMS ^{14}C dates, a large-scale wet event above about 17.0 m depth (ca. 19,000 cal yr BP) and a small-scale wet event around 24.5 m depth (ca. 33,500 cal yr BP) clearly correspond to the early MIS 1 interglacial period and the MIS 3.1 interstadial period, respectively. In addition, a wet event recognized around 35.0 m depth would correspond to the MIS 3.3 interstadial period, considering continuity with the small-scale wet event around 24.5 m depth.

Between 46.5 and 61.5 m depth, the wet index keeps a relatively high average of 18.8%, with three peaks at depths of 47.5 m (26.8%), 52.5 m (29.8%) and 60.5 m (29.6%), while the dry index shows a low average of 10.2% with two relatively high peaks at depths of 48.5 m (39.9%) and 56.5 m (31.6%). These appear to represent features of the oscillation curve of the SPECMAP stack record during MIS 5 characterized by three interglacial and interstadial periods and two stadial periods.

Between 62.5 and 75.5 m depth, the wet index record is characterized by a single significant peak of 24.7% at the depth of 73.5 m. This peak probably corresponds to the MIS 6.5 interstadial period. On the other hand, the dry index shows a high average of 47.6% in this interval, and three peaks occur at depths of 63.5–64.5 m (53.5%), 68.5 m (60.2%) and 74.5 m (70.7%). The three dry peaks appear to represent features of the MIS 6.2, 6.4 and 6.6 glacial (stadial) periods well.

Between 76.5 and 92.5 m depth, the wet index shows a peak of 24.7% at the depth of 78.5 m, corresponding to the MIS 7.1 interstadial period. Additionally, the dry index significantly decreases into 5.6% and 5.3% at 81.5 and 91.5 m depth, respectively, though pollen of the wet index is absent there. The low values of the dry index are approximately equal to other interglacial (interstadial) values, for example 5.2% at 47.5 m depth corresponding to the MIS 5.1 interglacial period. Therefore, they probably correspond to the MIS 7.3 and 7.5 interglacial (interstadial) periods.

Between 93.5 and 142.5 m depth, the wet index record shows apparent saw-tooth-like fluctuations. In ascending order, the wet index increases more than 30% in 1 m and then gradually decreases over about 15 m. This is very similar to the fluctuation patterns of the

Table 1
AMS ^{14}C dates of the RB core.

Depth (m)	^{14}C age (yr BP)	One σ error (yr)	Calibrated age (yr BP)
9.75	10,960	130	12,900
17.10	15,890	120	19,040
19.10	17,090	80	20,220
20.40	18,670	90	22,240
22.05	24,010	120	28,220
23.20	27,410	160	32,080
24.57	28,800	410	33,640
26.13	33,100	230	38,380
28.13	35,000	260	40,440
30.13	38,600	360	44,280

AMS ^{14}C dates were calculated using CALIB 5.0.1 (Stuiver and Reimer, 1993) and the calibration curve IntCal04 (Reimer et al., 2004).

SPECMAP stack record from MIS 8.2 to 12.2. The wet peak of 47.4% at 138.5 m depth is the largest one in the record of the RB core, indicating that unusually wet condition prevailed at that time (Maki, 2005). This would reflect the unusually warm interglacial period during MIS 11.3 (Droxler and Farrell, 2000; Droxler et al., 2003). In this interval, the dry index record is characterized by major six peaks at depths of 94.5 m (50.4%), 101.5 m (53.9%), 106.5–107.5 m (60.0%), 118.5–119.5 m (42.2%), 126.5–128.5 m (51.5%) and 130.5 m (55.6%), corresponding to the MIS 8.2, 8.4, 8.6, 10.2, 10.4 and 11.22 glacial (stadial) periods.

Between 142.5 and 154.5 m depth, the wet index record is characterized by a relatively high peak of 8.6% at 149.5–151.5 m depth. On the other hand, the dry index shows a high average of 34.4% through this interval. These appear to be consistent with features of MIS 12 glacial period with the MIS 12.33 interstadial period.

Between 155.5 and 180.5 m depth, the wet index shows a relatively high average of 12.8%. There are five wet peaks at depths of 156.5 m (18.5%), 160.5 m (32.1%), 166.5 m (30.9%), 174.5 m (26.0%) and 177.5 m (19.0%), corresponding to the MIS 13.11, 13.13, 13.3, 15.1 and 15.3 interglacial (interstadial) periods. Additionally, a relatively high wet index peak (12.9%) is detected at the depth of 170.5 m. This is also represented in the SPECMAP stack record as an interstadial-like event at around 550 ka, though a MIS number is not assigned in the scheme by Bassinot et al. (1994). The dry index shows three peaks at depths of 161.5 m (20.3%), 168.5–169.5 m (46.1%) and 175.5 m (29.5%), corresponding to the MIS 13.2, 14.2 and 15.2 glacial (stadial) periods.

Construction of pilot age–depth model

It is well known that fluctuations in the Indian summer monsoon were synchronous with global climate changes, and weakened summer monsoon resulted in the reduction in rainfall during the MIS 2 glacial and MIS 3.1 interstadial periods compared to the MIS 1 interglacial period (e.g., Van Campo et al., 1982; Thompson et al., 1997; Goodbred and Kuehl, 2000; Finkel et al., 2003; Goodbred, 2003; Juyal et al., 2006). Pollen wet and dry index records of the RB core are consistent with this interpretation within the constraint of AMS ^{14}C dates (gray area in Fig. 2; Table 1). Additionally, both the pollen records also delineate global climate (SPECMAP δ^{18}O) changes from MIS 3.3 to MIS 15.3 well, as mentioned in the previous section. Therefore, in order to construct a pilot age model of the RB core between 13 and 594 ka, we adopted eight peaks of the wet index corresponding to the MIS 5.1, 5.5, 7.1, 7.5, 9.3, 11.3, 13.13 and 15.3 interglacial (interstadial) periods as tie points (see gray dotted lines in Fig. 2). Detailed information about depths and converted ages of the tie points is given in Table 2.

In the age–depth model, sedimentation rates are assumed to be constant among individual tie points and AMS ^{14}C dates gradually decrease with depth (Fig. 4). This is consistent with the increase in consolidation of sediments with depth. The sedimentation rate of 0.29 mm/yr between 115.5 and 138.5 m depth (329–407 ka; MIS 9.3–11.3) is higher than that of 0.27 mm/yr in the upper interval between 91.5 and 115.5 m depth (239–329 ka; MIS 7.5–9.3). This is probably attributed to high accumulation of diatom valves, expressed by the highest value of the Bio-Si content and the most developed diatomaceous bed around 140 m depth (MIS11) (Fig. 2).

Table 2
Tie points between the pollen wet and dry index records and the SPECMAP δ^{18}O stack record.

Depth (m)	Corresponding MIS stage	Age (ka)
47.5	5.1	81
60.5	5.5	125
78.5	7.1	198
91.5	7.5	239
115.5	9.3	329
138.5	11.3	407
160.5	13.13	501
177.5	15.3	594

The chronology of the SPECMAP δ^{18}O stack record follows Lisiecki and Raymo (2005). MIS numbers follow Bassinot et al. (1994).

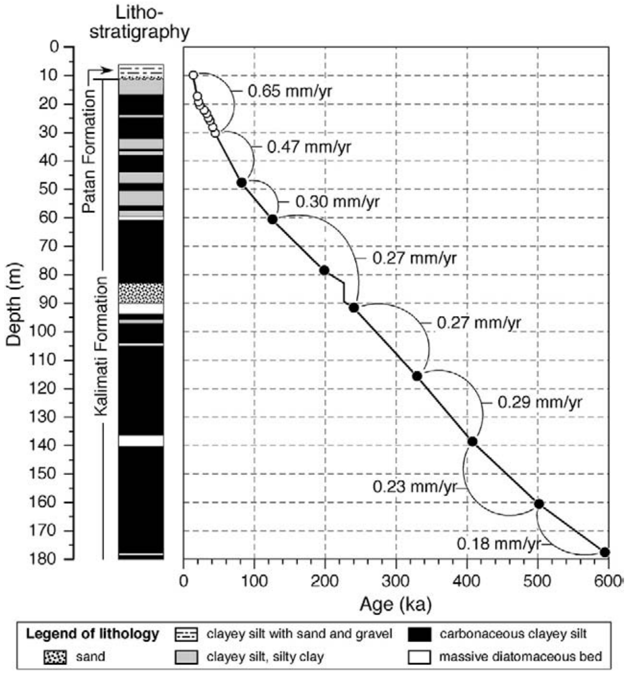

Figure 4. Age–depth model of the RB core based on ten AMS ^{14}C dates in the range 9.75–30.13 m depth (white circles; Table 1) and eight tie points in 47.5–177.5 m depth range (black circles; Table 2). Lithostratigraphy of the RB core is shown in the left. The length of time that the event sand bed in 83.0–89.5 m depth deposited is assumed to be zero. Sedimentation rates linearly calculated among AMS ^{14}C dates (Table 1) and tie points (Table 2) are shown beside the age–depth curve.

Reconstructed time-series wet and dry index records faithfully represent not only features of the fluctuation curve of the SPECMAP stack record but also those of a planktonic foraminiferal δ^{18}O record from the equatorial Indian Ocean, reflecting salinity changes in the surface water controlled by the monsoonal rainfall (Rostek et al., 1993; Bassinot et al., 1994) (Fig. 5). In order to examine the accuracy of the constructed age–depth model on orbital time scales, spectral analysis on the time-series pollen CWD index record was performed (Fig. 6A). The CWD index record is characterized by dominant 100,000-yr, 41,000-yr obliquity and the 23,000-yr and 19,000-yr precession variances as well as global climate (SPECMAP δ^{18}O) changes. Furthermore, Blackman–Tukey cross-spectral analysis between the CWD index record and the SPECMAP stack record demonstrates high coherence in the 100,000-yr and 41,000-yr obliquity bands, and a significant coherence level of 0.92 is detected in the 23,000-yr precession band (Fig. 6B).

Leuschner and Sirocko (2003) proposed an Indian summer monsoon index (ISMI), insolation difference between 30°N and 30°S for 1 August, based on the fact that the modern Indian summer monsoon is mainly driven by low pressure over the Himalaya–Tibetan Plateau and high pressure over the southern subtropical Indian Ocean (Clemens et al., 1991). Since the original ISMI is based on the old insolation model by Laskar (1990), we recalculated a modified ISMI based on the new insolation model by Laskar et al. (2004). The pollen CWD record is coherent with the modified ISMI record in the 41,000-yr obliquity and the 23,000-yr and 19,000-yr precession bands (Fig. 6C). Especially, both records show a significant coherence level of 0.92 in the 23,000-yr precession band known as the most important component of monsoon changes (e.g., Kutzbach, 1981; Kutzbach and Street-Perrott, 1985; Kutzbach and Guetter, 1986; Prell and Kutzbach, 1987).

Huybers and Wunsch (2004) pointed out the possibility that the orbital tuning method has the ability to suppress nonlinearities

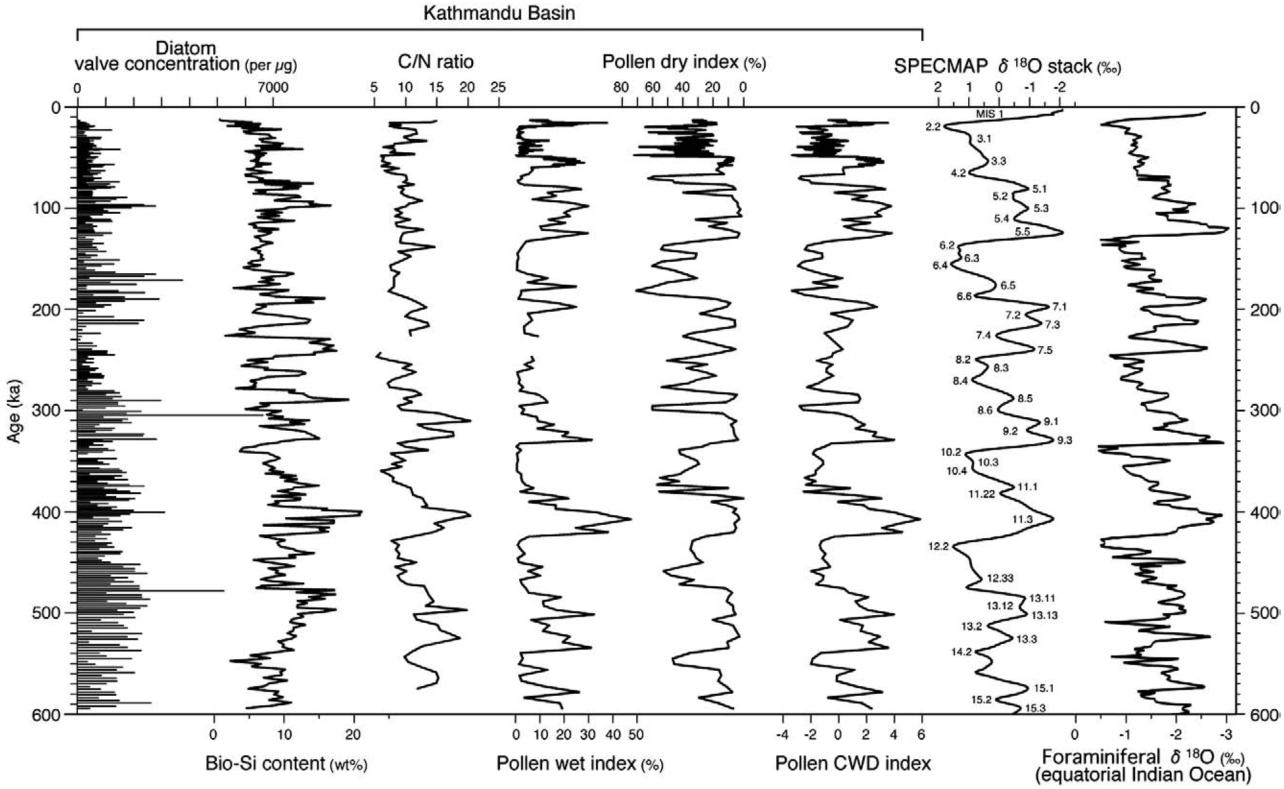

Figure 5. Time-series records of valve concentrations, Bio-Si contents, ratios of total organic carbon to total nitrogen (C/M ratio: modified from Mampuku et al., 2004) and the pollen wet, dry and CWD index (modified from Fujii, 2002 and Maki, 2005) reconstructed from the RB core, compared with the SPECMAP δ^{18}O stack record (Imbrie et al., 1984) with the LR04 age model (Lisiecki and Raymo, 2005) and the planktonic foraminiferal δ^{18}O record from the equatorial Indian Ocean (Rostek et al., 1993; Bassinot et al., 1994). MIS numbering beside the SPECMAP δ^{18}O stack curve follows the scheme by Bassinot et al. (1994).

inherent within climate systems and to linearly produce orbital periodicity. It is important to note that only eight tie points are used over the last 600,000 yr in our age–depth model of the RB core, in contrast to the usual orbital tuning method that uses many tie points attributable to peaks, midpoints and bottoms in obliquity and precession cycles. Additionally, six tie points, except the two

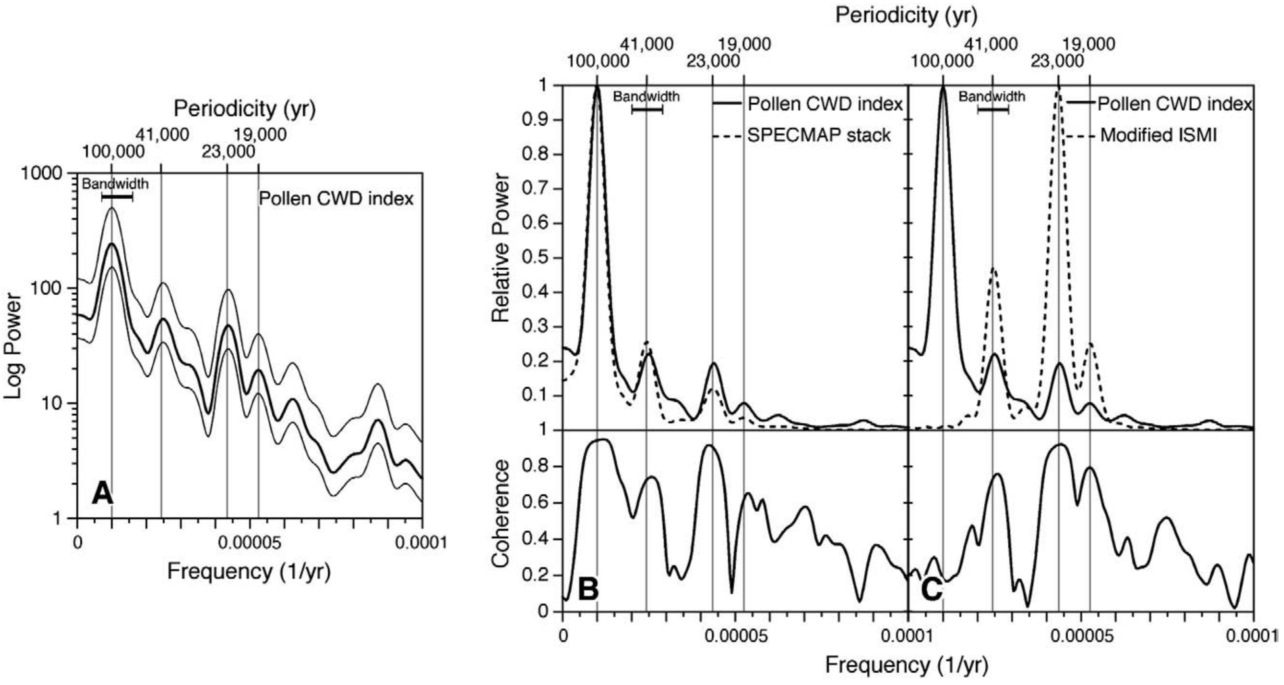

Figure 6. Power spectrum of the time-series record of the pollen CWD index (A), and results of Blackman–Tukey cross-spectral analyses on the pollen CWD index record with the SPECMAP δ^{18}O stack record (Imbrie et al., 1984) based on the LR04 age model (Lisiecki and Raymo, 2005) (B) and with the modified ISMI record (Leuschner and Sirocko, 2003) recalculated using the insolation model by Laskar et al. (2004) (C). In A, upper and lower thin curves indicate 80% confidence interval. Bandwidth of each plot is 0.009.

corresponding to MIS 5.1 and 7.1, are separated by 78,000 to 114,000 yr. These suggest that our age–depth model minimizes the suppression of the nonlinearities, and tuning-derived bias is mostly free as regarding short variances (especially obliquity and precession). Therefore, the presence of the prominent obliquity and precession variances in the CWD index record indicates the validity of the age–depth model on orbital time scales.

Relationship of diatom productivity with climate changes

Based on the age–depth model constructed in the previous section, it is clear that increases in Bio-Si contents and diatom valve concentrations in RB core sediments occur at interglacial and interstadial periods (Fig. 5). This is supported by the fact that both the Bio-Si content and valve concentration records are dominated by the 100,000, 41,000, 23,000 and 19,000-yr variances that are coherent with orbital variances in the SPECMAP stack record (Figs. 7A–D). These facts suggest that fluctuations in diatom productivity in the Paleo-Kathmandu Lake were closely related to global climate changes. Similar relationships between diatom productivity and global climate changes were reported from Lake Biwa and Lake Baikal during the middle Pleistocene to the Holocene (Colman et al., 1995; Williams et al., 1997; Xiao et al., 1997; Prokopenko et al., 2001; Kuwae et al., 2002). This seems to be important considering that regional climatic and environmental backgrounds are different among the Paleo-Kathmandu Lake at low-latitude South Asia, Lake Biwa at middle-latitude East Asia and Lake Baikal at high-latitude Siberia. The agreement suggests that global climate changes may have played a critical role controlling diatom productivity in large lakes over Asia, regardless of differences in regional climatic and environmental backgrounds.

In the case of the Paleo-Kathmandu Lake, one of the more direct factors controlling the diatom productivity would be changes in Indian summer monsoonal rainfall, because the majority of nutrients for diatoms, such as phosphorus content, are generally transported from land to a lake through rivers. Indeed, increases in Bio-Si contents and valve concentrations are synchronous with increases in the pollen wet index and decreases in the pollen dry index (Fig. 5), and variances in both the diatom productivity records are coherent with variances in the modified ISMI record in the obliquity and precession bands (Figs. 7E, F). Furthermore, the increases in Bio-Si contents and valve concentrations are synchronous also with increases in ratios of total organic carbon to total nitrogen of RB core sediments (Fig. 5), suggesting that inputs of terrestrial matter including nutrients for diatoms into the lake increased during interglacial and interstadial periods (Mampuku et al., 2004).

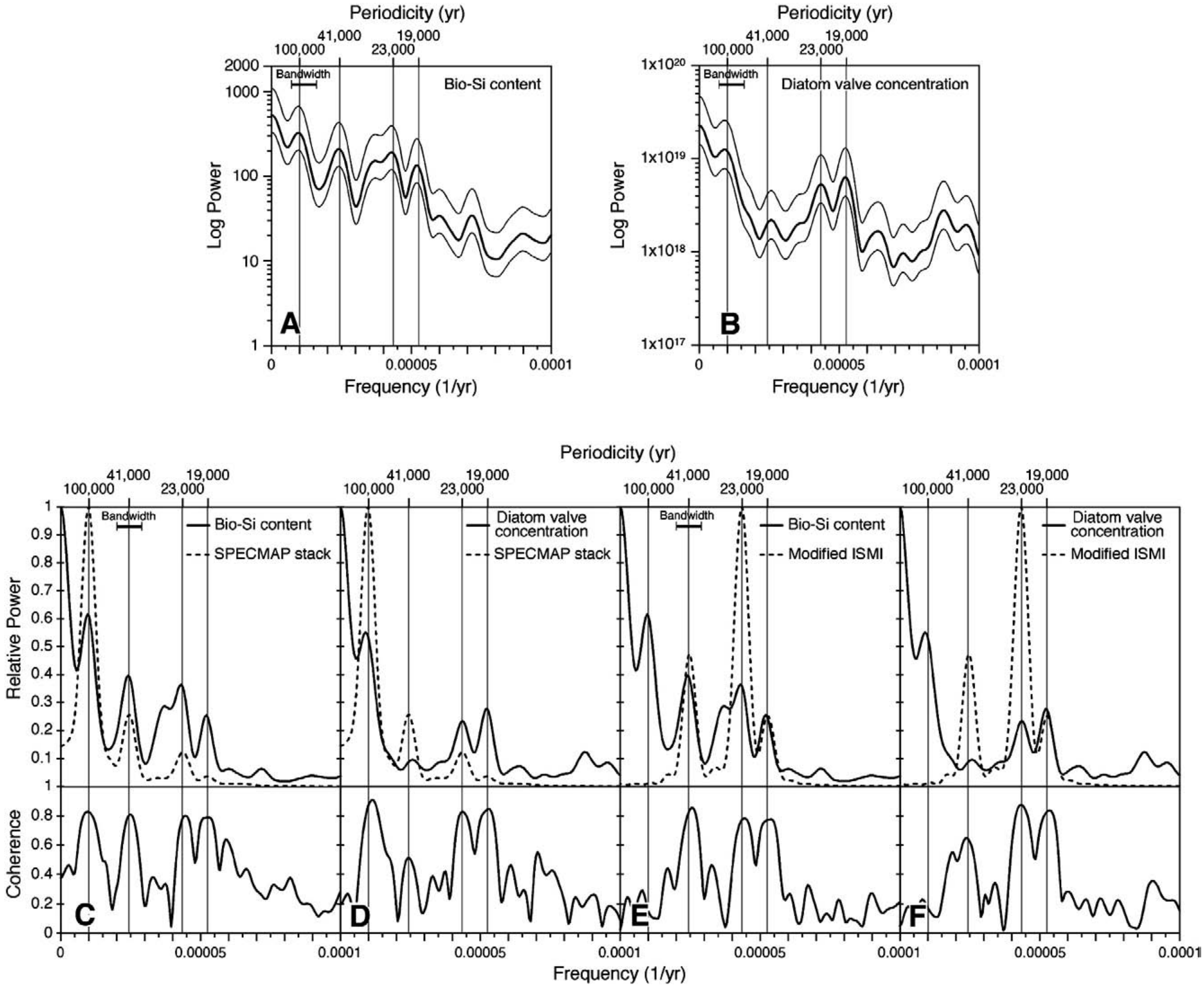

Figure 7. Power spectra of time-series records of Bio-Si contents (A) and diatom valve concentrations (B), and results of Blackman–Tukey cross-spectral analyses on the Bio-Si content and diatom valve concentration records with the SPECMAP δ^{18}O stack record (Imbrie et al., 1984) based on the LR04 age model (Lisiecki and Raymo, 2005) (C and D) and with the modified ISMI record (Leuschner and Sirocko, 2003) recalculated using the insolation model by Laskar et al. (2004) (E and F). In A and B, upper and lower thin curves indicate 80% confidence interval. Bandwidth of each plot is 0.009.

Contrary to the case of the whole diatoms, however, only valve concentrations of benthic diatoms tend to increase with values of pollen dry index (Fig. 8). At the same time, values of percent benthic diatoms also abruptly increase by over 50%, synchronous with the increases in the pollen dry index (Fig. 8), suggesting that significant lake-level drops occurred and were accompanied by aridification in the basin. Much of the monsoon climate changes between interglacial (interstadial) wet conditions and glacial (stadial) dry conditions are expressed as the lake-level changes, shown by the percent benthic diatoms (Fig. 8). As water-level falls, habitats for benthic diatoms at a lake bottom generally diversify, and this should increase productivity of benthic diatoms. Therefore, the observed variations in valve concentrations of the benthic diatoms probably reflect degree of diversification of habitats for the benthic diatoms caused by lake-level changes on glacial and interglacial time scales, more than changes in the amount of nutrient inputs.

Relationship of compositions of diatom assemblages with climate changes

The global and Indian monsoon climates may have exerted an influence over the whole ecology of diatom assemblages in the Paleo-Kathmandu Lake, considering their strong influence over the diatom productivity. Here, we focus on composition (degree of overlap) of diatom assemblages in RB core sediments. For the last 300,000 yr, sharp decreases in degree of overlap occur periodically, mainly reflecting frequent alternations of dominant planktonic species among *A. ambigua*, *A. granulata*, *Cyclostephanos dubius*, *Cyclostephanos* sp.1 and *C. ocellata* complex (Fig. 9). It is important that most of the decreases in degree of overlap correspond to peaks in the pollen dry index record and lowest points in precessional cycles in the modified ISMI record (Fig. 8), suggesting reduced summer monsoonal rainfall and/or strengthened winter monsoonal aridification. Furthermore, the decreases in degree of overlap are also accompanied by increases in percent and valve concentrations of benthic diatoms (Fig. 8), suggesting lake-level falling. It is well known that compositions of diatom assemblages are sensitive to water-level changes and associated environmental changes (e.g., Wolin and Duthie, 1999). Especially, it would be easy to suppose that compositions of diatom assemblages vary greatly between much diversified near-littoral environments under much seasonal variations in nutrient, light, temperature and turbulence (Stoermer, 1975), and more homogeneous pelagic environments (Hutchinson, 1961). Therefore, it is likely in the Kathmandu basin that weakened summer monsoon (reduced rainfall) and/or strengthened winter monsoon (enhanced aridification) during the glacial and stadial periods resulted in lake-level falling, and as a result that, compositions of diatom assemblages (especially dominant planktonic diatoms) dramatically changed. Additionally, the records of degree of overlap and relative abundance also indicate the important fact that in the last 300,000 yr, a few planktonic species could adapt to and eventually dominate pelagic environments created by water-level raising after the shallow lake periods, and decline or disappear following the significant lake-level drops that occurred within every a few tens of thousands of years (Figs. 8 and 9).

On the other hand, in most periods from 590 to 300 ka, degree of overlap is kept approximately 1, indicating that compositions of diatom assemblages changed little over long periods of more than

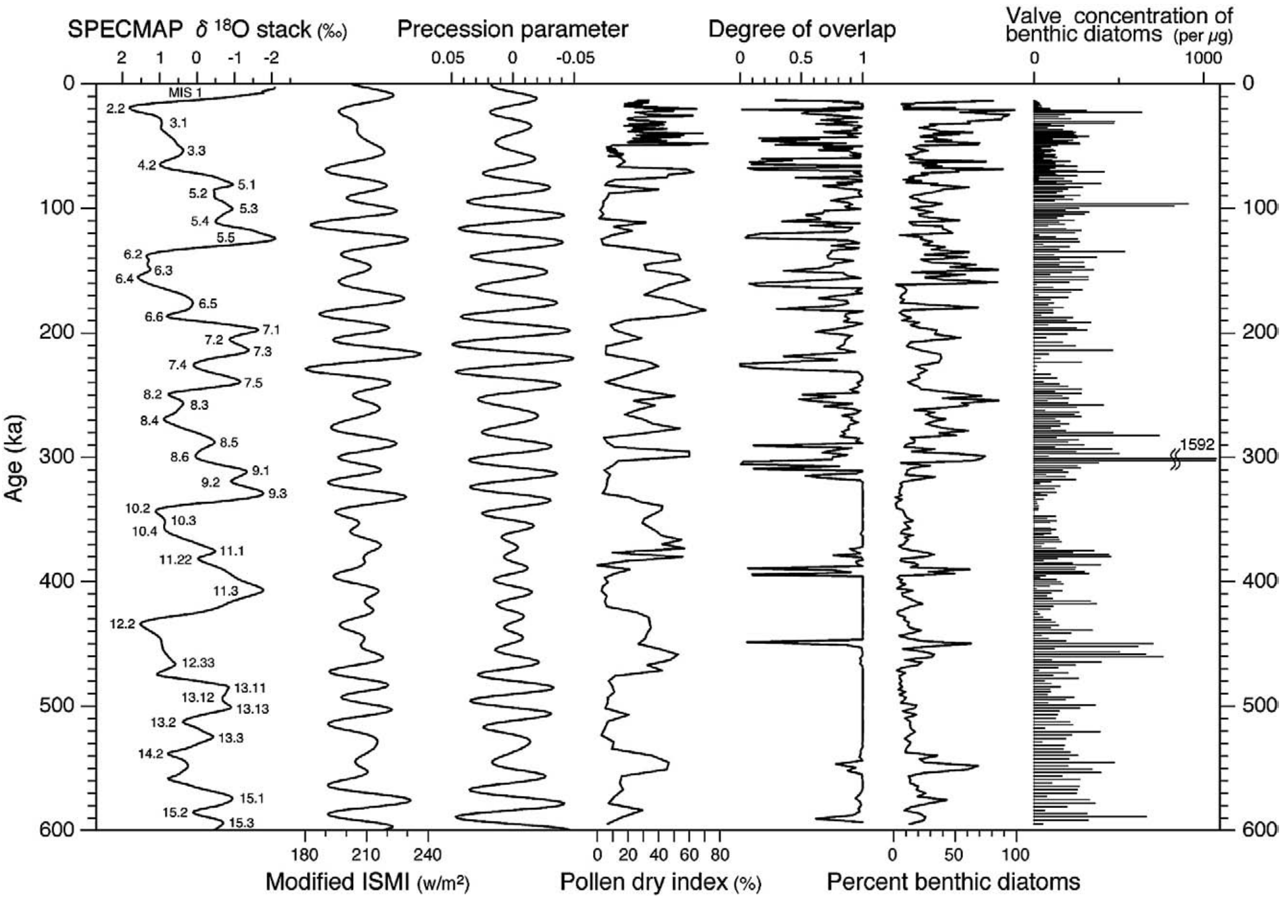

Figure 8. Comparison of time-series records of the SPECMAP δ^{18}O stack (Imbrie et al., 1984) based on the LR04 age model (Lisiecki and Raymo, 2005), the modified ISMI (Leuschner and Sirocko, 2003) recalculated using the insolation model by Laskar et al. (2004), the precession parameter (Laskar et al., 2004), the pollen dry index (Fujii, 2002; Maki, 2005), degree of overlap of diatom assemblages, percent and valve concentrations of benthic diatoms. MIS numbering follows the scheme by Bassinot et al. (1994).

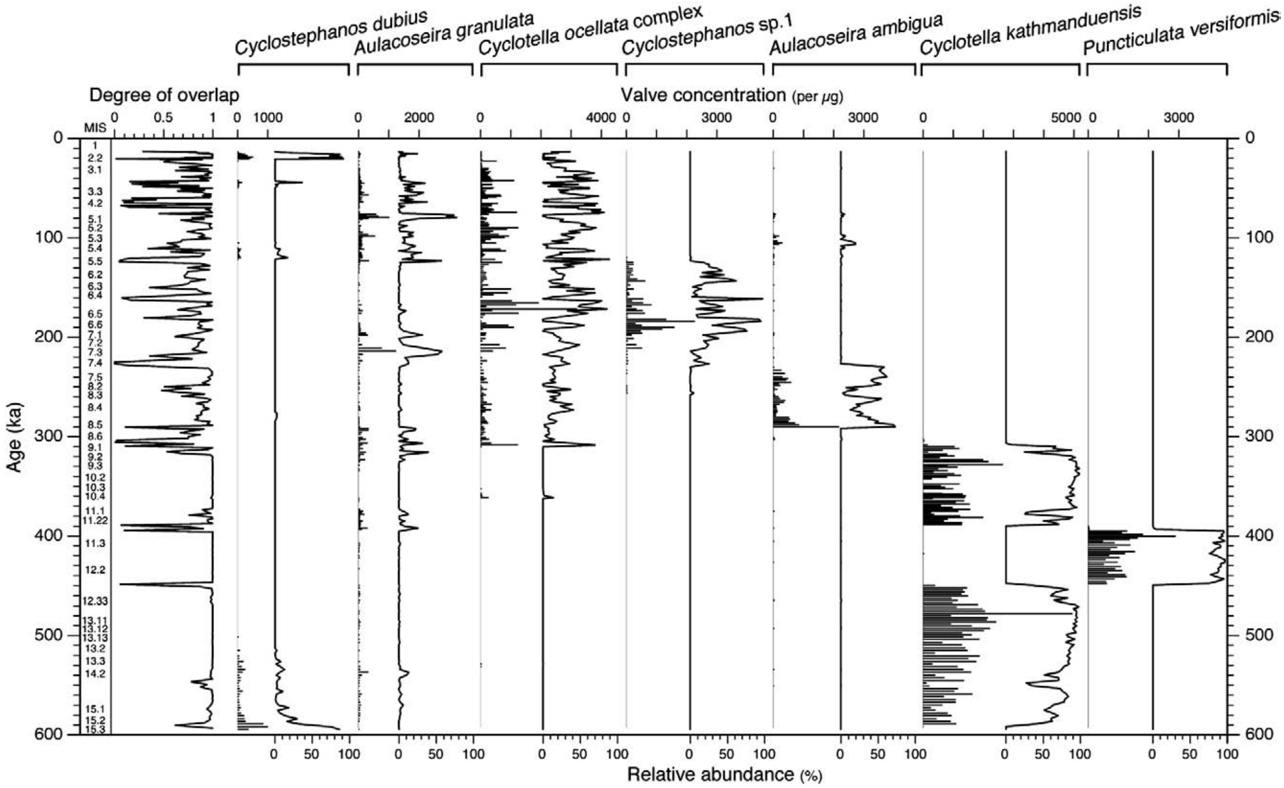

Figure 9. Time-series records of degree of overlap of diatom assemblages and valve concentrations and relative abundances of seven major planktonic species in RB core sediments. MIS numbering follows the scheme by Bassinot et al. (1994).

several tens of thousands of years (Fig. 9). This reflects appearances of almost monospecific assemblages by *C. kathmanduensis* during about 590–450 ka and 390–300 ka, and *P. versiformis* during about 450–390 ka (Fig. 9). Valve concentrations of *C. kathmanduensis* and *P. versiformis* are much higher than the other diatom species in the RB core sediments. Furthermore, they have quite unique morphological features, and progressive changes in some morphological features are observed (Hayashi et al., 2007; unpublished data). Thus, Hayashi et al. (2007) described *C. kathmanduensis* and *P. versiformis* as new fossil species from the Paleo-Kathmandu Lake deposits. From these viewpoints, the appearances of *C. kathmanduensis* and *P. versiformis* seem to be the oddest events in the diatom flora in the Paleo-Kathmandu Lake. It is interesting that the period from 590 to 390 ka, when the first population of *C. kathmanduensis* and the following population of *P. versiformis* appeared, is comparable to the period from about 590 to 370 ka when high productive and almost monospecific diatom assemblages of *Stephanodiscus distinctus* with varieties appeared in Lake Baikal under exceptionally warm climatic conditions (Khursevich et al., 2001; Prokopenko et al., 2002).

Although the presence of monospecific planktonic diatom assemblages has been sometimes reported from Pleistocene lake sediments, this may be an unlikely event considering recent diversified lake ecosystems. Hutchinson (1961) first questioned “how it is possible for a number of phytoplankton species to coexist in a relatively isotropic or unstructured environment all competing for the same sorts of materials?” He further stated that according to the competitive exclusion principle, one species alone would outcompete all the others so that in a final equilibrium situation the assemblage would reduce to a population of a single species. Recently, phycologists have doubted that possibility, for instance from the perspective of patch dynamics and environmental factors excepting species competition (e.g., Brönmark and Hansson, 1998).

On the other hand, Stoermer and Edlund (1999) pointed out the possibility that in large ancient lakes that have existed continuously for periods greater than 10,000 to 100,000 yr, an evolutionary process similar to competitive exclusion operates, and this results in the development of very non-diverse planktonic diatom assemblages composed of species uniquely adapted to each lake's specific physical and chemical conditions (evolutionary fine-tuning). If so, it may be that such evolutionary fine-tuning operated in the Paleo-Kathmandu Lake, which existed continuously over at least 600,000 yr, and consequently developed almost monospecific (i.e., very low evenness) assemblages of unique *C. kathmanduensis* and *P. versiformis*. To verify this possibility, however, further synecological investigation, especially regarding species diversity and the evolution of assemblages, will be required.

Climatic and lake environmental stability during the middle Pleistocene may have also contributed to the appearances of *C. kathmanduensis* and *P. versiformis*. Around the same time when the monospecific diatom assemblages of *C. kathmanduensis* and *P. versiformis* appeared in the Paleo-Kathmandu Lake, amplitudes of precessional cycles in the modified ISMI record are kept relatively low (Fig. 8). This agrees with the fact that there are less precessional variations in the pollen dry index record in this period, as compared to the last 300,000 yr (Fig. 8). Because Indian monsoon changes are largely controlled by precession cycles (e.g., Kutzbach, 1981; Kutzbach and Street-Perrott, 1985; Kutzbach and Guetter, 1986; Prell and Kutzbach, 1987), the low-amplitude precessional changes in the monsoon climate may have kept lake environmental conditions more stable. In particular, extremely low values of percent benthic diatoms in those periods suggest the absence of the significant level falling events that dramatically changed the diatom ecosystem (Fig. 8). These may have allowed *C. kathmanduensis* and *P. versiformis* to dominate over unusually long periods. Additionally, alternations of dominant species between *C. kathmanduensis* and *P. versiformis* at about 450 and 390 ka are accompanied with increases in dry index values, and sharp increases in percent and valve concentrations of benthic diatoms (Fig. 8). Therefore, lake-level drops and associated environmental changes caused by weakened Indian summer monsoon and/or strengthened winter monsoon probably largely contributed to the appearances and disappearances of *C. kathmanduensis* and *P. versiformis*.

Conclusions

We have examined variations in productivity and compositions of diatom assemblages in the Paleo-Kathmandu Lake with the use of the RB core drilled at the Kathmandu Basin, Nepal Himalaya. We revealed that the variations in productivity and compositions of the diatom assemblages were closely related with global and Indian monsoon climate changes over the last 600,000 yr. The results of this study are summarized as follows.

1. The age model of the RB core was constructed based on AMS ^{14}C dates and by tuning the pollen CWD index record to the SPECMAP δ^{18}O stack record with the LR04 age model. The tuned CWD index record is dominated by 100,000-yr, 41,000-yr, 23,000-yr and 19,000-yr variances that are coherent with orbital variances in the SPECMAP δ^{18}O stack record and the modified ISMI record, indicating the accuracy of the constructed age model on orbital time scales.

2. Both Bio-Si contents and valve concentrations of whole diatoms show increasing trends during wet interglacial and interstadial periods with dominant variances of 100,000, 41,000, 23,000 and 19,000 yr that are coherent with orbital variances in the SPECMAP δ^{18}O stack and modified ISMI records. Furthermore, the increases in the Bio-Si contents and valve concentrations are synchronous with increases in ratios of total organic carbon to total nitrogen of the RB core sediments. These results suggest that increased summer monsoonal rainfall accelerated inputs of terrestrial nutrients for the diatoms into the lake during interglacial and interstadial periods. In contrast, percent and valve concentrations of only benthic diatoms increase during dry glacial and stadial periods. This probably reflects degree of diversification of habitats for the benthic diatoms caused by lake-level changes more than by the amount of nutrient inputs.

3. For the last 300,000 yr, degree of overlap of diatom assemblages changes within every a few tens of thousands of years, mainly reflecting alternations of dominant planktonic species among *A. ambigua*, *A. granulata*, *Cyclostephanos dubius*, *Cyclostephanos* sp.1 and *C. ocellata* complex. The decreases in degree of overlap correspond to peaks in the pollen dry index record, lowest points in precessional cycles in the modified ISMI record, and increases in percent and valve concentrations of benthic diatoms. This suggests that the changes in compositions of diatom assemblages were brought about by significant lake-level falling resulting from reduced summer monsoonal rainfall and/or strengthened winter monsoonal aridification during glacial and stadial periods.

4. Before 300 ka, degree of overlap of diatom assemblages is kept approximately 1, reflecting appearances of almost monospecific assemblages of unique planktonic *C. kathmanduensis* and *P. versiformis*. Since *C. kathmanduensis* and *P. versiformis* are characterized by much higher valve concentrations than the other diatom species and quite unique morphological features, their appearances are the oddest events in the diatom flora in the Paleo-Kathmandu Lake. One possible explanation for the events might be the evolutionary fine-tuning of diatoms to specific environmental conditions of the Paleo-Kathmandu Lake, which existed continuously for at least about 600,000 yr. Additionally, the long domination of diatom assemblages by *C. kathmanduensis* and *P. versiformis* may have been attributed to less variations in precessional monsoon climate and environments, especially the absence of the significant lake-level drops that dramatically changed the diatom ecosystem.

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