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ORIGINAL ARTICLE

Reconstruction of millennial-scale variations in the East Asian summer monsoon over the past 300 ka based on the total carbon content of sediment from Lake Biwa, Japan

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Abstract The total carbon content analysis for Takashima-oki core extracted from Lake Biwa with time resolutions of approximately 150 years was used to reconstruct millennial-scale climate change in the East Asian monsoon region over the past 300 ka. The total carbon content of the Takashima-oki core is an indirect proxy for the East Asian summer monsoon, because the total carbon content reflects primary productivity within the lake, which is controlled by precipitation in the catchment area. Using these data, we clarify temporal variations in the East Asian summer monsoon prior to MIS 5, which were previously unresolved. The observed variations show a ~1,500-year cycle that is also recorded by paleoclimate indices in the North Atlantic region. We propose that the East Asian summer monsoon underwent abrupt millennium-scale changes during interglacial stages such as MIS 5 and 7.

Keywords Lake Biwa · East Asian summer monsoon · Dansgaard–Oeschger cycles · Total carbon content

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Introduction

The East Asian monsoon controls the climate of East Asia, and is itself simultaneously influenced by the high-latitude atmosphere of the northern hemisphere and the sea-surface temperature at low-latitudes (An 2000). The East Asian monsoon is also influenced by water circulation in the densely populated East Asian region. Accordingly, many studies have investigated the nature of the paleomonsoon (e.g. Zhang and Liu 1992; An 2000), as an understanding of historical changes in the East Asian monsoon is important in terms of evaluating climate change and changing trends in water supply to the region.

Since abrupt millennial-scale changes in climate were first discovered (D–O cycles) within Greenland ice cores (e.g. Dansgaard et al. 1984; Oeschger et al. 1984), variations associated with D–O cycles have been confirmed from paleoenvironmental indicators that record temporal changes in the Asian monsoon (e.g. Chen et al. 1997). In the North Atlantic, millennial-scale changes in climate have been confirmed for the past 500 ka, confirming that the amplitudes of climatic variations were greater during glacial than during interglacial stages (Oppo et al. 1998; McManus et al. 1999). However, studies of millennial-scale changes in climate within the Asian monsoon region have only demonstrated that the Asian monsoon was synchronized with D–O cycles during the last glacial stage; millennial-scale changes in the Asian monsoon prior to this period remain unresolved. In particular, the elucidation of millennial-scale changes in climatic conditions during interglacial stages is important for the accurate prediction of future changes in climate; such data are currently only available for the Holocene.

Lake Biwa, Japan, is one of just a few sites that provide a high-resolution and continuous record of climatic change in East Asia. Approximately 250 m of homogeneous silty clay sediment has been deposited in the lake during the last 400 ka (Horie 1984), indicating that sediments within the lake were deposited continuously under stable conditions. Recent studies of Lake Biwa have reconstructed climatic change over the past 400 ka (e.g. Kuwae et al. 1997, 2002; Miyoshi et al. 1999); however, these studies did not obtain sufficient time-resolution to facilitate a discussion of millennial-scale climate change. Studies of millennial-scale climate change (Kuwae et al. 2003, 2004; Yamada 2004) have yet to consider the period prior to MIS 6.

In the present study, we reconstruct millennial-scale changes in climate over the past 300 ka based on the total carbon (TC) content of sediment from the Takashima-oki core recovered from Lake Biwa. We use these data to reconstruct temporal variations in the East Asian summer monsoon prior to MIS 5, which remains unresolved.

Regional setting

Lake Biwa, Central Japan, is the largest freshwater lake in Japan (Fig. 1), with a surface area of 674 km^2, a catchment area of 3,850 km^2, and maximum water depth of 104 m. The sole outflow river is the Seta River, though there are 120 rivers that flow into the lake. The mean annual, mean summer (July and August), and mean winter (January and February) temperatures around the lake fall in the ranges of 12–15, 23–28 and 1–6°C, respectively (Hikone Meteorological Observatory 1993). Precipitation around Lake Biwa is mainly associated with frontal systems (seasonal rain fronts), tropical cyclones (typhoons), and extratropical cyclones. These weather systems are closely related to the Asian summer monsoon. Precipitation during winter (snow) is brought about by the winter monsoon in the northern area facing the Japan Sea. Annual precipitation ranges from 1,500 to 2,600 mm.

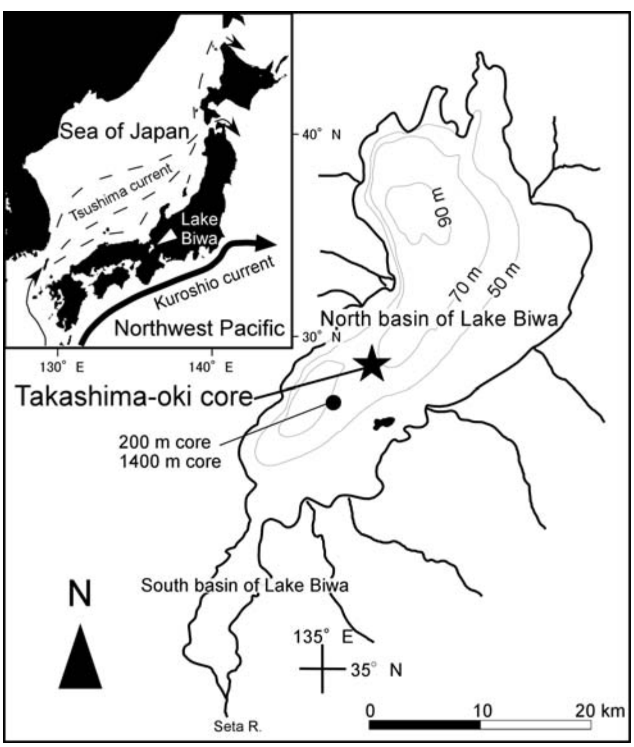

Fig. 1 Map of the Lake Biwa study area showing the sampling site of the Takashia-oki core analyzed in the present study. *Contours* show water depth within the lake

Materials

Takashima-oki core

The Takashima-oki core was drilled in 1987 in a water depth of about 63 m within Lake Biwa's north basin (35°14′23.46″N, 136°03′3.54″E). The total length of the core is about 150 m (Fig. 1), with a high rate of sediment recovery, in excess of 90%, throughout the core. The drilling site is on a ridge, located in the north basin of the lake. The site was chosen because the sedimentation rate is relatively low and the site contains almost no seismoturbidites derived from the lake margins. The site is located about 5 km northeast of a 200 m core drilled in 1971 and a 1,400 m core drilled in 1981.

The upper 137.28 m of the Takashima-oki core is composed of homogeneous lacustrine silty clay, with the lower part composed mainly of fine to medium sands (Fig. 2). Yoshikawa and Inouchi (1991) reported that 76 tephra layers are intercalated with the core sediments. Some of these ash layers can be correlated with widespread tephras (Yoshikawa and Inouchi 1991; Nagahashi et al. 2004).

Depositional age

The depositional ages of the sediments can be estimated from the ^{14}C ages of wood fragments (Kuwae et al. 2003) and the known ages of widespread tephras. The widespread tephras used to determine the chronology of the core include the Kawagodaira (Kg) (Okumura et al. 1999), K-Ah (Fukusawa 1995), U-Oki (Fukusawa 1995), AT (Tada et al. 1999), Sakate (Ashida et al. 2006), Aso-4 (Matsumoto et al. 1991; Machida and Arai 2003), K-Tz (Danhara 1995; Mach-

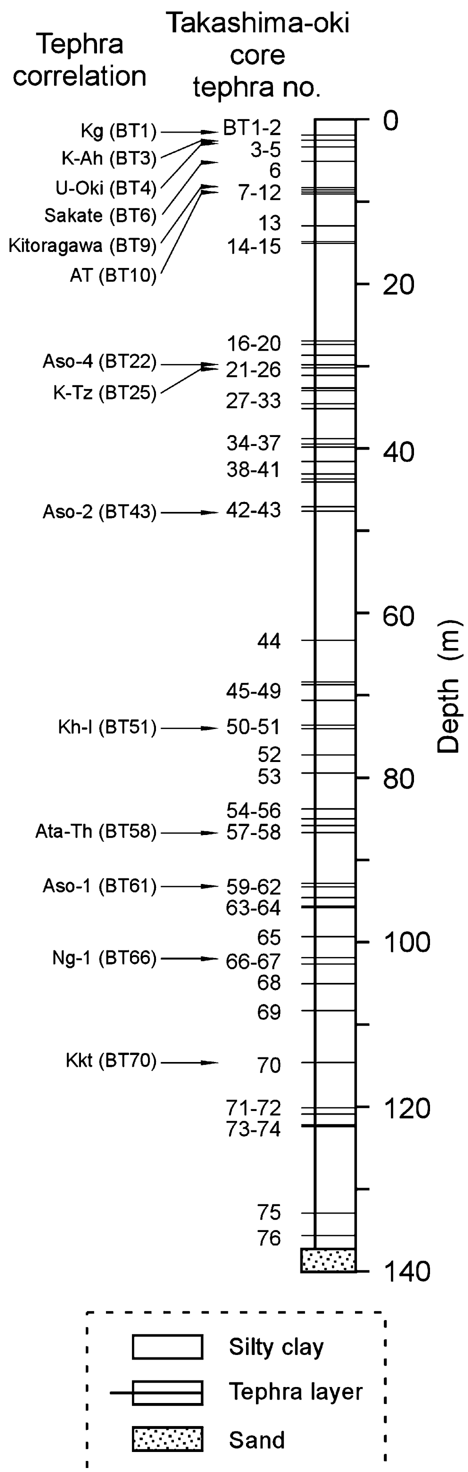

Fig. 2 Geologic column of the Takashima-oki core after Yoshikawa and Inouchi (1991)

ida and Arai 2003), Aso-2 (Matsumoto et al. 1991; Machida and Arai 2003), Ata-Th (Danhara 1995; Shirai 2000), Aso-1 (Watanabe 2001; Shirai et al. 1997), Ng-1 (Yamada et al. 1985; Machida and Arai 2003), and Kkt (Machida and Arai 2003) tephras (Table 1).

The BT51 volcanic ash layer in the Takashima-oki core is correlated with the Kh-I volcanic ash layer in the Koushienhama core and P7 in the Port Island core (Nagahashi et al. 2004). Kh-I and P7 underlie Ma 11(2) marine clay sediments of the Osaka Group that were deposited during MIS7.3; accordingly, the depositional age of BT51 is estimated to be 216 ka, during the early MIS7.3 (Nagahashi et al. 2004).

To compensate for the influence of compaction, we estimated the dry weight per bottom area (1 cm^2) from both the water content and specific gravity (assumed to be 2.65) of the sample. Moreover, the sedimentation rate (in terms of sediment weight) was estimated from both the length of time and accumulated weight in each of the intervals between the age -and depth control points. Depositional ages were calculated using an interpolation method, while depositional ages that predate the Kkt tephra were calculated using an extrapolation method (Fig. 3).

Analytical methods and results

The total carbon (TC) and total nitrogen (TN) contents of the samples were measured at 5 cm intervals using a CHN-Corder (Yanagimoto Co., Kyoto, Japan). The upper 137 m of the core, above the sand layer, provides a record of continuous deposition over the past ~400 ka. The TC content varies from 0.46–2.19 wt%, with an average of 0.93 wt%. The TC content is highest (in excess of 2 wt%) at the surface and at core depths of 0.5–2.0 m (Fig. 4). TN varies from 0.09–0.25 wt%, with an average of 0.15 wt%. The TN content is highest (in excess of 0.2 wt%) at core depths of 0–2.0 and ~37–40 m (Fig. 4). The C/N ratio varies within the range 2.71–12.15, with an average of 6.36. For the most part, C/N ratios are less than 10 (Fig. 4).

We analyzed biogenic silica content at 2 m intervals using the alkaline dissolution method of Conley et al. (2001). In this method, silica is dissolved within an alkaline solution, and the amount of dissolved silica is estimated using the molybdenum-yellow method. We measured the amount of dissolved silica using an AE-350 (ERMA Inc., Tokyo, Japan) spectrophotometer with an absorbance wavelength of 385 nm. To dissolve biogenic silica in the analyzed samples, 40 ml of 1 M Na_2CO_3 was added to a centrifugation tube containing dry samples. Thereafter, the tubes were placed in a shaking waterbath at 85°C and 60 rpm. Under these conditions, diatom valves dissolve completely after 90 min. The amount of dissolved silica was measured after 90, 120, 150, and 180 min. The intercept of the linear equation of dissolved silica, based on measure-

Table 1 Details of depth–age data for the Takashima-oki core

Takashima-oki tephra and sample no	Tephra code	Radiometric age (ka) and method	Oxygen isotope stage corresponding to tephras	Depth (m)	Cal. Kyr B.P	Reference
T1-2–30		1.764(14C)*		1.10	1.76*	*Kuwae et al. (2003)
BT1	Kg			1.52	3.1*	*Okumura et al. (1999)
BT3	K-Ah			2.23	7.3*	*Fukusawa (1995)
BT4	U-Oki			2.65	10.7*	*Fukusawa (1995)
BT6	Sakate	19.5(14C)*		4.76	19.5*	*Ashida et al. (2006)
BT10	AT			8.62	29.2*	*Tada et al. (1999)
T4-1-60		27.259(14C)*		9.92	31.3*	*Kuwae et al. (2003)
BT22	Aso-4	89 ± 7 (K-Ar)*	MIS 5.1–5.2**	29.61	87.5**	*Matsumoto et al. (1991) **Machida and Arai (2003)
BT25	K-Tz	98 ± 26 (FT)*		30.88	95**	*Danhara, (1995) **Machida and Arai (2003)
BT43	Aso-2	141 ± 5(K-Ar)*141 ± 50 (K-Ar)**		47.41	141*	*Machida and Arai, (2003) *Mastumoto et al. (1991)
BT51	Kh-I		MIS 7.3*	73.58	216*	*Nagahashi et al. (2004)
BT58	Ata-Th	240 ± 40 (FT)*	MIS 8.0**	86.49	240**	*Danhara (1995) **Shirai, 2000)
BT61	Aso-1	266 ± 14 (K-Ar)*	MIS 8.2**	94.37	255**	*Watanabe (2001) **Shirai et al. 1997)
BT66	Ng-1	340 ± 50 (FT)*	MIS 8.6–9.1**	101.68	295**	*Yamada et al. (1985) **Machida and Arai (2003)
BT70	Kkt	340 ± 10 (K-Ar)*	MIS 9.3*	114.63	335*	*Machida and Arai (2003)

* and ** indicate tephra age and corresponding reference in the respective tephras

ments at 90, 120, 150, and 180 min, is equivalent to the amount of biogenic silica, as the linear equation represents dissolved mineral silica once the diatom valves have been completely dissolved. Our results indicate biogenic silica contents in the range 1.1–15.4 wt% (Fig. 4).

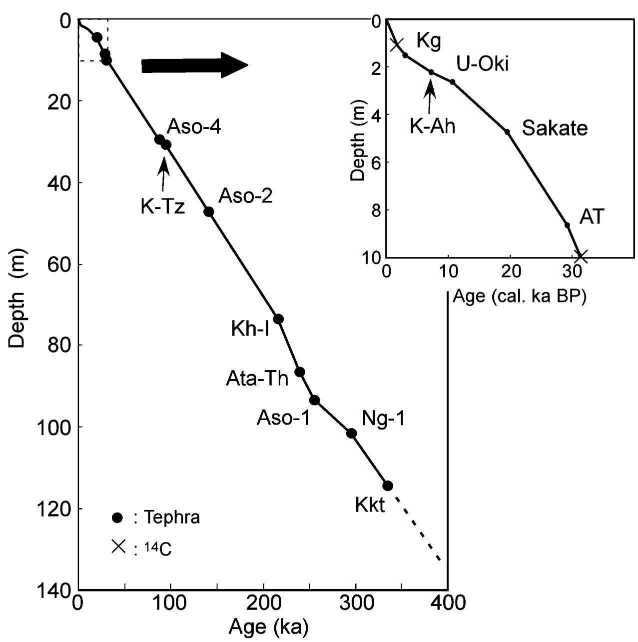

Fig. 3 Age model of the Takashima-oki core. The *solid line* represents the sedimentation rate deduced from widespread tephra layers and radiocarbon ages. *Broken line* represents the sedimentation rate calculated using an extrapolation method. An enlargement of the youngest data is shown to the *upper right*

Mineral grain sizes were measured using a SALD-2100 laser diffraction particle size analyzer (Shimadzu Co., Kyoto, Japan) at 5 cm intervals in the upper ~3 m, representing Holocene deposits. Pretreatment consisted of adding 40 ml of 5% Na_2CO_3 to ~50 mg of dry sample, which was then left in a shaking water bath at 85°C and 60 rpm for 90 min to remove diatom valves. Obtained mineral grain sizes within the Holocene sediments are 3.5–5.5 µm.

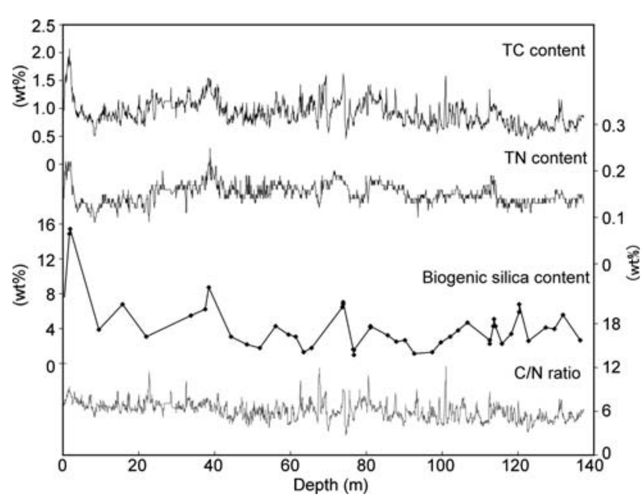

Fig. 4 Depth profiles of variations in total carbon content (TC), total nitrogen content (TN), biogenic silica content, and C/N ratio within the Takashima-oki core

Discussion

Factors that control TC concentration

The results of X-ray diffraction analysis demonstrate that sediments from the Takashima-oki core do not contain carbonate minerals such as calcite, dolomite, and aragonite. Meyers and Takemura (1997) stated that sediments within Lake Biwa contain less than 0.2% $CaCO_3$. These findings indicate that TC content generally corresponds to the total organic carbon (TOC) content.

The main formation mechanisms of organic matter in sediment are biological production in a lake and inflow from terrestrial regions. In general, the C/N ratio for sediment is a proxy for the relative contributions of exotic and authigenic organic matter (e.g. Sampei and Matsumoto 2001). Low C/N ratios (average 6.4) in the Takashima-oki core indicate that the contribution of exotic organic matter is only minor (Fig. 5). Therefore, variations in TC content within the Takashima-oki core mainly reflect the primary production of organic matter. TC content shows a strong positive correlation with biogenic silica content in the upper 100 m of the core (Fig. 6a). This trend provides support for the hypothesis that TC content reflects primary production.

The amount of organic matter in sediment varies greatly with water depth and the dissolved oxygen content of the water mass (Littke 1993), as the oxidation environment play an important role in the decomposition of organic matter while it is falling through the water column and when it lies on the surface of the lake floor. Organic matter within sediment is also slowly decomposed immediately following deposition; however, there is no systematic decrease in TC and TN contents in the lower part of the Takashima-oki core (Fig. 4). Organic matter decomposes from high polymers that contain nitrogen (Matsuda and Koyama 1977); however, the measured C/N ratios dont systematically increase in the lower part of the Takashima-oki core (Fig. 4). This indicates that the decomposition of organic matter in the analyzed samples is poorly advanced. Moreover, an investigation of sediments from Lake Kizaki (Kumon et al. 2005) indicates that organic matter within the sediment was only minimally decomposed following aggradation and the establishment of a reducing environment. These findings indicate that the TC content of the Takashima-oki core was not affected by the decomposition of organic matter, except for the surface part of the core and depths in excess of 100 m mentioned later.

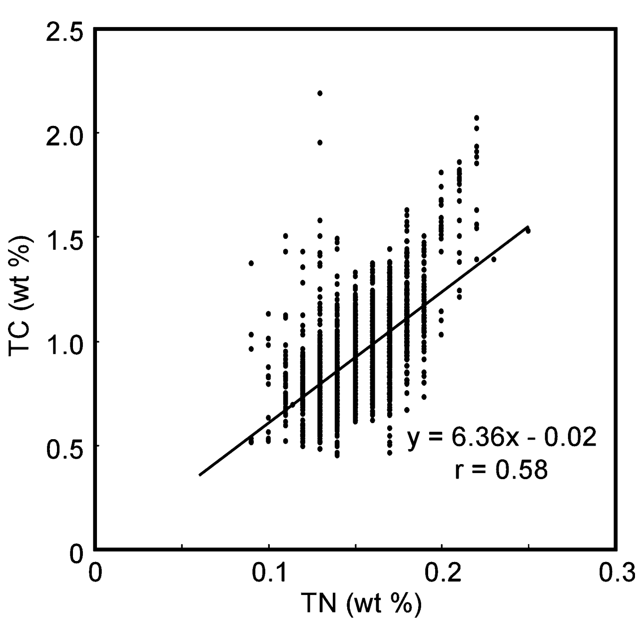

Fig. 5 Correlation between TN and TC

It is also important to note that the measured TC contents in sediments from depths in excess of 100 m may not reflect primary productions within the lake. As dissolution of diatom valves is not observed in the Takashima-oki core (Kuwae et al. 1997), the conditions of most of the diatom valves are the same as at the time of deposition. Therefore, it is likely that the amount of organic matter shows a good positive correlation with biogenic silica content. In the upper 100 m of the Takashima-oki core, a strong correlation exists between the amount of biogenic silica, which reflects the number of diatom valves, and the TC content ($r = 0.88$); however, correlation of these factors within the lower 100 m of the core is very poor ($r = -0.26$) (Fig. 6b). In addition, the C/N ratios of many samples from the lower ~100 m are less than 6 (Fig. 4). Meyers and Takemura (1997) stated that C/N ratios can be extremely low in the deeper parts of long cores because a portion of the organic carbon transforms to gas such as carbon dioxide and methane during continuing diagenesis of organic matter. While the gas may be emitted, organic nitrogen converted to ammonia nitrogen, is adsorbed and preserved by clay minerals. These observations indicate that within the lower 100 m of the Takashima-oki core, organic matter was decomposed or sedimentary environment was changed, and accordingly, TC contents may not constantly reflect the primary production of organic matter within the lake. Therefore, in the present study we only consider the upper 100 m of core (for the time period of the past 300 ka).

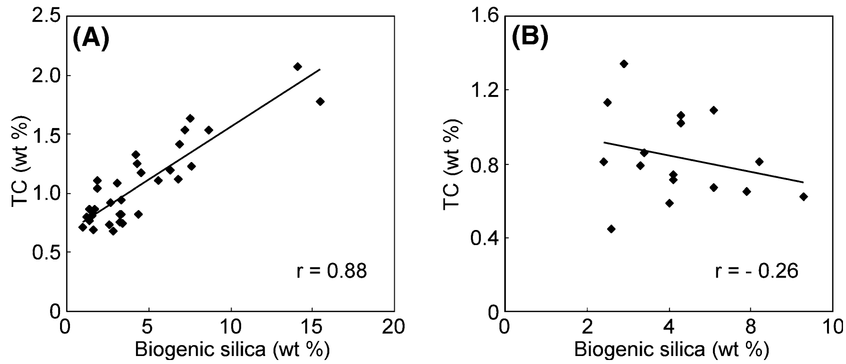

Fig. 6 Correlation between biogenic silica content and total carbon content for the depth intervals of 0–100 m **a** and 100–140 m **b**

Climatological factors that control TC content

In general, the grain size of a sediment is controlled by the hydraulic environment of the catchment area; however, Saito and Inouchi (2004) proposed that grain size within the Takashima-oki core is controlled by the proportion of diatom valves.

We analyzed the grain size of samples for which diatom valves had been dissolved in alkaline solution, as the mineral grain size is considered to directly reflect the hydraulic environment. The results show a positive correlation between mineral grain size and TC content, with the mineral grain size becoming coarser with increasing TC content (Fig. 7a). C/N ratios also show a strong positive correlation with TC content, and although the absolute values of C/N ratios are low (less than 10), C/N ratios increase with increasing TC content (Fig. 7b). These results indicate that the TC content increases during periods of high precipitation when the grain sizes of supplied mineral are coarse and when much terrigenous organic matter is supplied into the lake.

We propose that this actually happens, as river inflow from the catchment area brings nutrient salts into the lake. Within Lake Biwa, primary production is controlled by nutrient salts. In particular, phosphates are the limiting factor affecting phytoplankton in Lake Biwa during each year (Tezuka 1985), as well as a lack of surface nitrogen within the lake during summer (Somiya 2000). These nutrient salts are supplied by rainfall-related inflow from the catchment area. During times of heavy rain, adhering algae may flow into the lake from the catchment area. Consequently, TC content within the lake sediment is mainly controlled by precipitation. This hypothesis is supported by indications that past diatom production was related to precipitation (Meyers et al. 1993; Kuwae et al. 2003), the fact that annual diatom production in present-day Lake Biwa shows a strong positive correlation with summertime precipitation (Kuwae et al. 2004), and the indication that TOC content was related to precipitation (Yamada 2004).

A correlation between primary production and temperature has also been suggested. Kumon et al. (2005) proposed that wintertime temperature measured over the past 20 years at Lake Kizaki shows a correlation with TOC content. The authors proposed that primary production in the lake increases when the circulation period expands during times of elevated wintertime temperature. In an analysis of data from Lake Biwa for the past 100 years, Watanabe et al. (2005) demonstrated that temperature shows a correlation with particle density of sediment that a indicator of diatom production, especially during May. The concentration of nutrient salt in Lake Kizaki is higher than that in Lake Biwa, although the concentration of

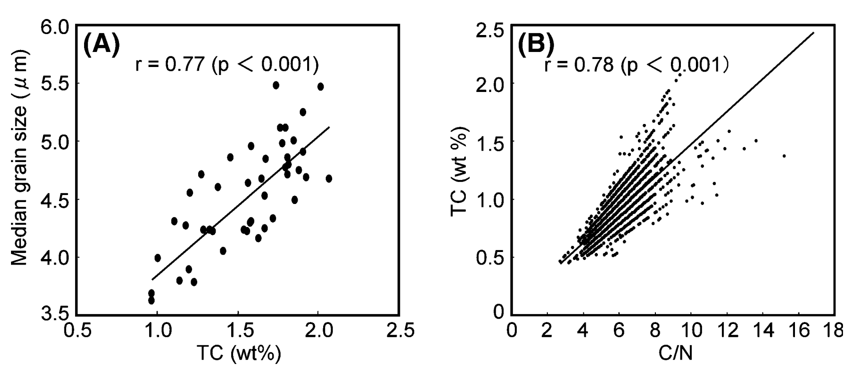

Fig. 7 Correlation between TC and median grain size of mineral grains **a** and correlation between C/N ratio and TC **b**

nutrient salt in Lake Biwa has increased since the 1940s. We therefore propose that the temperature also may regulate primary production within Lake Biwa, although the two lake conditions are not directly comparable with past Lake Biwa condition.

Precipitation in East Asia is mainly brought about by the summer monsoon. This involves cyclonic and frontal precipitation in the arctic frontal zone controlled by the principal axis of westerly winds (Fukusawa et al. 2003). Precipitation in Japan is also dependent on the summer monsoon, as well as snowfall related to the winter monsoon in areas facing the Japan Sea; however, meltwater in Lake Biwa represents only ~20% of total annual inflow volume (Okuda 1987). Moreover, snowfall decreased in the past during glacial stages with a weaker Tsushima Current, as snowfall related to the winter monsoon in areas facing the Japan Sea depends on the existence of the warm Tsushima Current (Ono and Naruse 1977). Accordingly, precipitation in the catchment area of Lake Biwa that is related to variations in TC content is mainly brought by the summer monsoon. Temperature variations that influence primary production in Lake Biwa are also considered to be related to the intensity of the summer monsoon. We therefore propose that variations in TC content within sediment in Lake Biwa are an indirect proxy for the East Asian summer monsoon.

Millennial-scale climate change over the past 300 ka

Figure 8 shows age profiles of TC and TN content within the Takashima-oki core over the past 300 ka. The thick line in the figure represents a 30-point moving average. TC and TN contents are high during the interglacial stages MIS 1, 5, and 7, but are low during the glacial stages MIS 2–4 and 6. These variations correspond to trends in the oxygen isotopic ratio curve (e.g. Bassinot et al. 1994) that indicates changes in global paleoclimate. This result shows in a gross sense that primary production and participation increased during interglacial stages and decreased during glacial stages. Detailed analysis of variations in TC and TN contents reveal variations on a millennial scale. This suggests that the summer monsoon, which controls the primary production of the lake, varied at the millennial scale over the past 300 ka.

During the Holocene, TC contents have increased since ~8 ka, and were highest during 2–6 ka. It is therefore apparent that the East Asian summer monsoon was strongest during the period 2–6 ka.

During the last glacial stage (MIS2-4), TC content varied from 0.8–1.2 wt%, with most values being less

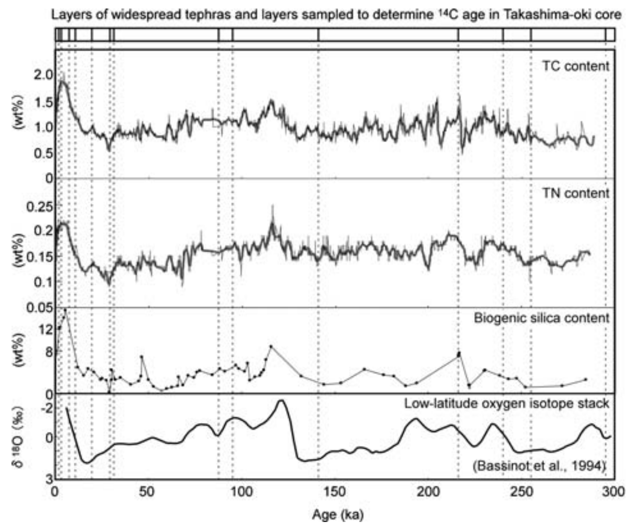

Fig. 8 Variations in the TC, TN and biogenic silica contents of the Takashima-oki core and low-latitude oxygen isotope stack over the past 300 ka (Bassinot et al. 1994). The *thick lines* in the TC and TN plots represent 10-point moving averages

than 1.0 wt%. This result indicates that the East Asian summer monsoon during periods of the last glacial stage was not as strong as during the Holocene. Figure 9 shows oxygen isotopic ratios for the GRIP2 ice core and TC and TN contents for the Takashima-oki core during the last glacial stage. The TC and TN contents vary according to long-duration warm and

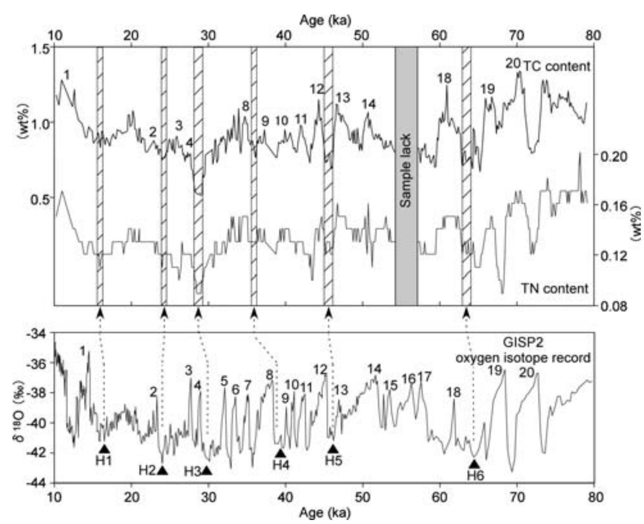

Fig. 9 Correlation between the TC and TN contents of the Takashima-oki core and the oxygen isotope record of the Greenland GISP2 ice core (Meese et al. 1994) for the period MIS 2–4. *Solid triangles* (H1–H6) indicate Heinrich Events (HEs) in the North Atlantic. *Hatched areas* indicate a decrease in TC content within the Takashima-oki core associated with HEs. *Numbers* in the figure indicate interstadial numbers of the DO cycle

cold stages of D–O cycles, except for short interstadial stages of D–O cycles such as IS (Interstadial number) 3 and 4. In particular, variations in TC and TN contents show decreasing periods that correspond to cold events that occurred simultaneously with Heinrich events (HEs). These findings suggest that enhancement of the summer monsoon in Japan is synchronized with warming in Greenland, resulting in an increase in primary production within Lake Biwa at such times. In contrast, weakening of the summer monsoon in Japan is synchronized with cooling in Greenland and a decrease in primary production within Lake Biwa. These observations are consistent with reports of the Asian monsoon based on loess and palaeosol sequences on the Chinese inland (e.g. Fang et al.1999), the color of sedimentary layers related to variations in fresh water inflow from the Chinese continent to the Japan Sea (Tada et al.1999), and the flux of diatom valves within the Takashima-oki core (Kuwae et al. 2003, 2004).

One of the characteristics of D–O cycles is rapid warming, with a 10°C increase in temperature recorded over several decades (e.g. Dansgaard et al. 1984); however, the increase in TC and TN contents associated with this warming is not as rapid as that of D–O cycles. This observation indicates that enhancement of the East Asian monsoon associated with the warming of D–O cycles may be slower than the rise in temperature of D–O cycles.

TC contents were high during MIS 5, and were generally more than 1 wt% during MIS 5.2 and 5.4. This indicates that for a period of tens of thousands of years, the East Asian summer monsoon was strong, as was primary production in Lake Biwa.

In MIS 6 and 8, TC contents varied from 0.8–1.2 wt%, with most values being less than 1.0 wt%. This indicates that the East Asian summer monsoon was weak at this time, as well as during the last glacial stage.

In MIS 7, TC contents were high during MIS 7.1, 7.3, and 7.5, being greater than 1.5 wt% during MIS 7.3 and 7.5; however, TC contents were extremely low (~0.5 wt%) during MIS 7.2 and 7.4. These trends indicate that MIS7 had a large amplitude in variations, with an ~20 ky cycle (precession cycle) of the East Asian summer monsoon.

Periodicity prior to MIS5

Millennial-scale changes in the Asian monsoon prior to the last glacial stage are rarely discussed. Here, to clarify millennial-scale changes in Lake Biwa prior to MIS5, we carried out a spectral analysis of the TC contents of the Takashima-oki core for the periods MIS 5–8. The spectral power and red-noise background were estimated using REDFIT (Schulz and Mudelsee 2002). Spectral analysis of TC contents shows periodicities (significance levels greater than 95%) of 1,715 years during MIS 5, 2,941 and 1,239 years during MIS6, 3,717 and 1,312–1,175 years during MIS 7, and 3,773 and 1,883 years during MIS 8. All periods had periodicities of 1,500 ± 400 years (Fig. 10). Periodicities in climate change of about 1,500 years, similar to the periodicities of D–O cycles, have been confirmed from Greenland ice cores from the last glacial stage (e.g. Schulz 2002). In addition, Bond et al. (1997) proposed that climate change associated with iceberg-discharge events in the North Atlantic had periodicities of 1,470 ± 500 years during the Holocene and the last glacial stage.

D–O cycles have been confirmed all over the world for the last glacial stage (e.g. Leuschner and Sirocko 2000; Voelker and workshop participants 2002). Recently, the existence of 1,500-year cycles of climate change during the Holocene has been clarified (e.g. Bond et al. 1997, 2001; Wang et al. 2005). In the North Atlantic, millennial-scale climate change prior to the last glacial stage has been confirmed for the past 500 ka (Oppo et al. 1998; McManus et al. 1999), and iceberg discharge events occurred more than 1 million years ago (Raymo et al. 1998). The amplitude of millennial-scale changes is smaller during interglacial stages and greater during glacial stages (McManus et al. 1999);

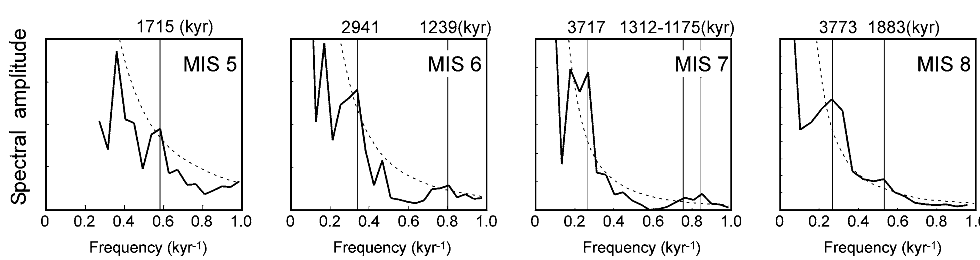

Fig. 10 Frequency analysis of the TC record for the periods MIS 5–8. The spectral power and red-noise background were estimated using REDFIT (Schulz and Mudelsee 2002). The number of overlapping (50%) segments is four, and the spectral window is a Welch-type. *Broken lines* indicate the red-noise background (upper 95% false-alarm level)

however, millennial-scale changes in the Asian monsoon prior to MIS 5 have barely been discussed. Here, we propose that the East Asian summer monsoon had an ~1,500-year cycle during both glacial and interglacial stages. This result indicates that millennial-scale small-amplitude climate changes that occurred during interglacial stages affected the East Asian monsoon.

Conclusions

The TC content of the Takashima-oki core extracted from Lake Biwa reflects primary productivity within the lake, and is controlled by precipitation in the catchment area. This finding indicates that variations in TC content provide an indirect measure of changes in the East Asian summer monsoon. The East Asian summer monsoon in Japan, as reconstructed on the basis of TC content, shows variations during the last glacial stage that correspond to D–O cycles. Frequency analysis of TC content indicate that the East Asian summer monsoon had a cycle of 1,500 years over the past 300 ka that was associated with iceberg discharge events in the North Atlantic and D–O cycles. Although the amplitude of changes in the North Atlantic during interglacial stages is small, millennial-scale changes in the East Asian summer monsoon occurred during interglacial stages.

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