PALEOINTENSITY OF THE ASIAN WINTER MONSOON AND THE WESTERLIES SINCE THE LAST GLACIAL PERIOD, RECONSTRUCTED BY EOLIAN DUST FLUX IN LACUSTRINE SEDIMENTS OF LAKE BIWA AND LAKE SUIGETSU, CENTRAL JAPAN

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Abstract Lacustrine sediments of Japan contain a lot of eolian dusts transported from Chinese Loess Plateau by the Asian winter monsoon and the westerlies. Sequential changes of eolian dust concentrations in lacustrine sediments since the last glacial period would be useful as a proxy record for reconstructing paleointensity of the Asian winter monsoon and the westerlies. In this paper, it is clarified that the changes of eolian dust flux during the last 38,000 years in the lacustrine sediments of Lake Biwa and Lake Suigetsu, central part of Japan. Sedimentological observations and calculation of sedimentary flux in lacustrine sediment cores of both lakes show that most of illite and quartz minerals in lacustrine sediments originate in eolian dusts from the inland of China, and that the intensity of the Asian winter monsoon and the westerlies has strengthened when eolian quartz flux was higher and has weakened when flux was lower. These changes of the intensity of the Asian winter monsoon and the westerlies have been closely related to the global climatic changes. In the Lake Biwa sediments during the last 38,000 years, it can be recognized such global climate coolings as Heinrich events 1-4, Younger Dryas and 8.2 ka cooling event. In the Lake Suigetsu sediments, Younger Dryas and Older Dryas cooling periods can be recognized. Also, our investigations suggest that the changes of the intensity of the Asian monsoon and the westerlies might be one of the triggers of the global environmental changes.

Key words: eolian dust flux, the Asian monsoon, the westerlies, lacustrine sediments, the last glacial period

1. Introduction

The Asian monsoon, which have fluctuated with glacial/interglacial cycle, have controlled dry-wet climatic changes in the inland of East Asia (Prell and Kutzbach 1987). The arid/semi-arid areas such as Takla Makan Desert and Gobi Desert widely exist in the inland of East Asia. Clastic particles on the surface of these areas are blown up in the air by sand storms (Inoue and Naruse 1990). These particles, known as 'eolian dust', are transported and deposited in and around Japan by the Asian winter monsoon and the westeries (*e.g.* Uematsu *et al.* 1985; Institute for Hydrospheric-Atmospheric Sciences, Nagoya University 1991). The amount of clastic particles, blown up from arid areas in the inland of China, increases under cool and dry climate conditions because arid areas are expanded by progression of aridity. The amount of eolian dusts, deposited in the Japanese Islands, increases also because the Asian winter monsoon and the westerlies are intensified by activated Hadley circulation according to progression of coldness. In the opposite side, the amount of eolian dusts decreases under warm and wet climate condition because the vegetation is rapidly recovered by the intensified Asian summer monsoon which transports water vapor into the inland of China, and by the weakened Asian winter monsoon. In short, the variation of eolian dust flux might result from the variations of 1) the extent of vegetation covered areas, and 2) the intensity of the Asian monsoon and the westerlies (Ono and Naruse 1997).

Eolian dusts are composed of fine quartz and illite as known by meteorological observations as present (Institute for Hydrospheric-Atmospheric Sciences, Nagoya University 1991). Based on the mineralogical and sedimentological studies of deep-sea sediment core (795A) in the Sea of Japan which was collected by the Ocean Drilling Program, Leg 127 cruise, Fukusawa and Koizumi (1994) clarified the relationship betweeen the fluxes of quartz and illites in mg cm^{-2} yr^{-1} and illite crystallinity, which indicates dry-wet climatic condition in origin area (Chamley 1989), over the last 780,000 years (Fig. 1). The result shows that variations of the quartz and illite fluxes as eolian dusts are quite similar tendency. When the illite crystallinity is well, the fluxes of quartz and illite increase. Conversely, when the crystallinity is poor, the fluxes decrease. This indicates that the eolian dust flux deposited in deep-sea floor of the Sea of Japan increased in glacial periods when the inland of China was drier, while the flux decreased in interglacial periods when the inland of China was wetter.

The long-term variations of eolian dust fluxes in many areas which are situated downward from East Asia show the very similar tendency with glacial/interglacial cycles, and the eolian dust flux is useful as a proxy record of the long-term paleointensity of the Asian winter monsoon and the westerlies (*e.g.* Rea and Leinen 1988). The main topic of the conventional paleoclimatological studies have focused on the long-term climatic changes such as glacial/interglacial cycles controlled by the Milankovitch forcing. In addition, the millennial-scale abrupt climatic changes have occurred in the last glacial period were revealed by recent studies of ice cores in Greenland and deep-sea sediments in the North Atlantic (Bond *et al.* 1993; Dansgaard *et al.* 1993). Until now, however, there are a few studies focused on the relation between Asian monsoon activities and the millennial-scale abrupt climate changes in the last glacial period. Though some studies have performed by using loess-paleosol sequences (An and Porter 1997; Chen *et al.* 1997) and marsh sediments (Suzuki *et al.* 1997), it has not been yet clarified enough to compare of Asian monsoon activities with the global millennial-scale abrupt climatic changes such as Dansgaard-Oeschger cycles because of the lack of detailed chronology and low sample resolution for paleoenvironmental analyses.

The lacustrine sediments record high-resolution environmental changes of coastal and terrestrial areas (Beer and Strum 1995). In the lacustrine sediments, there are often non-glacial varved sequences which can be recognized as annual layers, and they provide advantages to enable accurate and high-resolution analysis because the periodicity and higher rates of sedimentation.

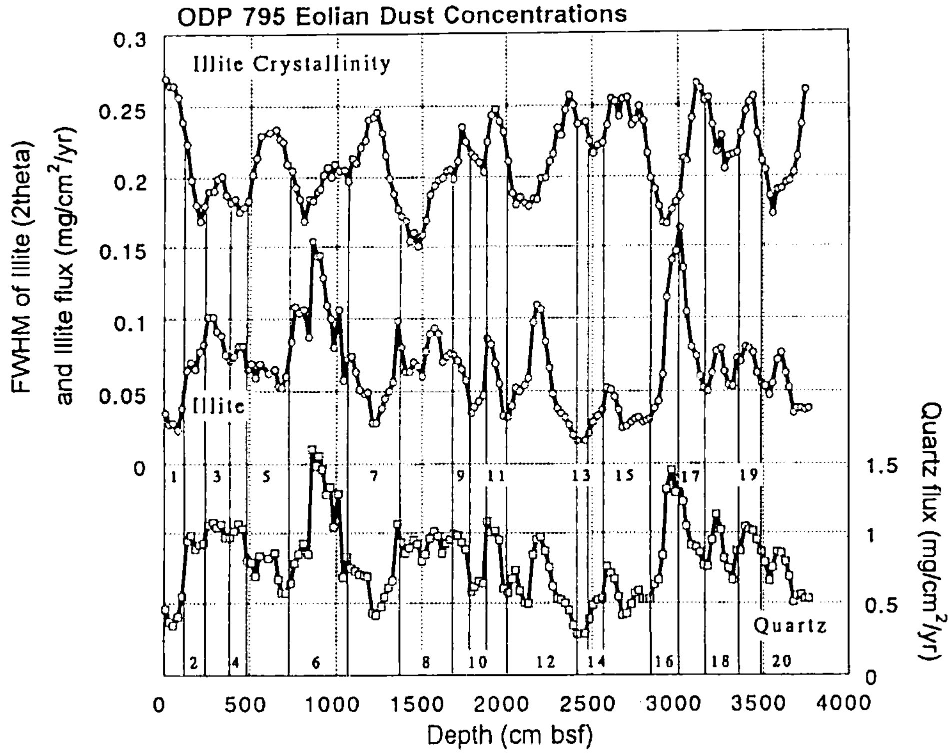

Fig. 1 The last 780 ka variations of the quartz flux, the illite fluxes and illite crystallinity in deep-sea sediments at ODP site 795 (Fukusawa and Koizumi 1994).

Non-glacial varved sequences over the last 100,000 years are recognized in bottom sediments of Lake Suigetsu, central Japan, and analyzed by Kitagawa *et al.* (1995) and Fukusawa (1995). Based on varve chronological and geochemical investigations, Kitagawa and van der Plicht (1998a) suggests that the changes of ^{14}C concentrations in large orgaic remains of varves have shown decadal to centennial changes of atmospheric circulations during the last 45,000 years. Also, continuous sequences of non-glacial varves during Holocene have been recognized in Lake Tougou-ike, southwestern Japan. Lake Tougou-ike is a brackish water lake where sea-water invasion occurs. Based on the changes of iron mineral fluxes in varves of Lake Tougou-ike, Fukusawa (1998) has clarified annual to decadal changes of sea-levels during Holocene.

In this paper, on the basis of illite and quartz flux changes in lacustrine sediments, we will clarify millennial-scale variation of the intensity of the Asian winter monsoon and the westerlies for the past 38,000 years using the Lake Biwa lacustrine sediment, and annual to decadal variation during the last deglaciation using the Lake Suigetsu lacustrine sediment. In particular, we focus on detecting a short-term variation of the intensity of the Asian winter monsoon and the westerlies by using the variations of illite and quartz fluxes in the lacustrine sediments.

2. Lake Biwa Sediments

Lithology, chronology, sampling and method

Lake Biwa is located in the central part of Honshu Island. It is the largest lake in Japan occupying 674 km^2 with a maximum water depth of 104 m. The lake has two basins, the northern one being larger and deeper than the southern one. The northern basin has two depressions more than 70 m deep and an average depth of 48 m, making much of the basin deep enough that bottom sediments are not easily disturbed by wave turbulence (Meyers *et al.* 1993).

Seven sediment cores of 12-16 m long were collected at three sites by a piston core sampler in the summer of 1995. The details of the coring operation and initial core descriptions are reported elsewhere (Takemura *et al.* 1999). BIW95-4 core (14.45 m long) was recovered at BIW95 Site-2, which located in 35° 15'N, 136° 03'E and 67 meter below surface level (m.b.s.l.) (Fig. 2). The core consists of homogeneous grey to dark grey slity clay with nine thin visible volcanic ash layers (Fig. 3). Seven volcanic ashes are identified as followings: Kawagodaira (Kg: 3.000 calendar year [cal.yr] B.P.), Kikai-Akahoya (K-Ah: 7.300 cal.yr B.P.), Ulleung-Oki (U-Oki: 10,750 cal.yr B.P.), Sakate ash, Daisen-Higashidaisen (DHg), Daisen-Sasagodaira (DSs) and Aira-Tn (AT) (Takemura *et al.* 1999). The three layers of Kg, K-Ah and U-Oki ashes serve as important markers for age estimation. Eight AMS ^{14}C datings were also measured by using leaves and organic carbon in sediments (Kitagawa, personal com.) (Fig. 3). As the radiocarbon ages of these ashes and AMS ^{14}C data are converted to calendar ages by using age calibration curve (Kitagawa and van der Plicht 1998b) (Table 1), it is found that the sediment of BIW95-4 core has continuously deposited for the past 38,000 years with a stable

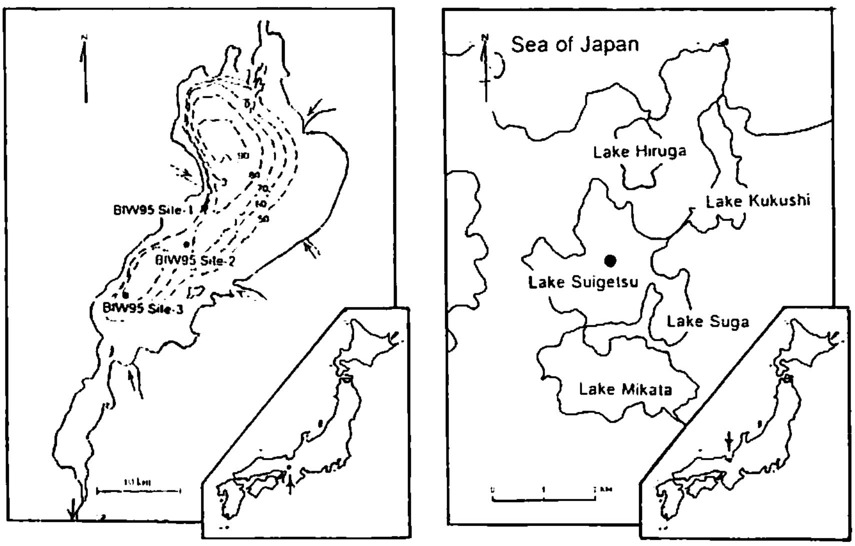

Fig. 2 Index maps of Lake Biwa (left) and Lake Suigetsu (right) and sampling positions. Solid circles show the sampling positions: BIW95-4 core investigated in this study is from BIW95 Site-2 in 1995 (left); SGP3 core in 1993 (right).

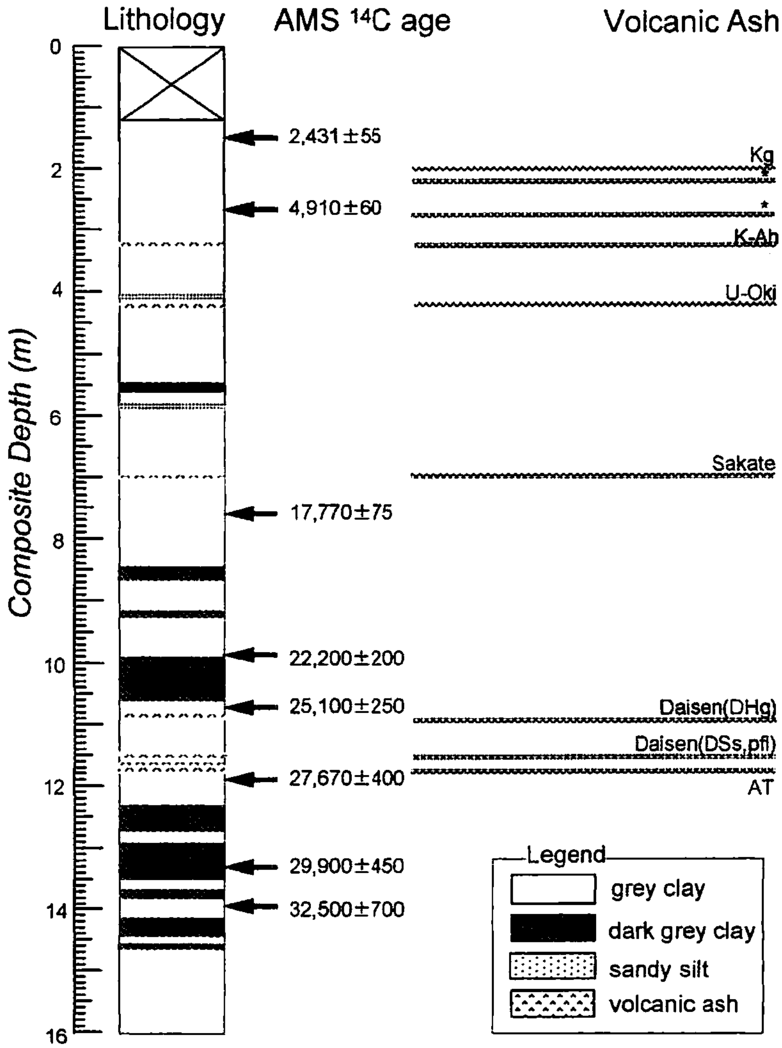

Fig. 3 Lithology of BIW 95-4 core sediments. Lines show the volcanic ash layers which are identical with the widespread volcanic ashes (shown above lines) in Japan (Takemura *et al.* 1999). Arrows show the horizons where AMS ^{14}C dating ages (Kitagawa, personal com.) were gotten.

sedimentation rate.

In BIW95-4, it is known that the surface part (1.227 m corresponding to 2,000 years) of the sediment is missing because of the problem of sample collection, based on stratigraphic correlations with other piston cores collected at the same site (Takemura *et al.* 1999).

A total of 627 discrete samples was obtained through continuous sub-sampling at 2.25 cm intervals using 7 cm^3 plastic cubes. The sample resolution range between 10 and 70 years,

Table 1 Calendar ages and ^{14}C ages in BIW95-4

Sample Depth (m)	Sample description	Method	14C age (yr.B.P.)	Calender age (cal yr B.P.)
1.643	Leaf	AMS	2,431±55	2,450
1.851	Ash(Kg)	-	-	3,000
1.803	Leaf	AMS	4,910±60	5,650
3.183	Ash(K-Ah)	-	-	7,300
4.117	Ash(U-Oki)	-	-	10,750
6.823	Ash(Sakate)	-	-	15,420
7.703	Leaf	AMS	17,770±75	20,550
9.943-9.993	TOC	AMS	22,200±200	24,920
10.873-10.923	TOC	AMS	25,100±250	27,810
11.973-12.023	TOC	AMS	27,670±400	31,200
13.463	Leaf	AMS	29,900±450	32,200
14.003	Leaf	AMS	32,500±700	33,930

Notes: the age calibration is based on Kitagawa and van der Plicht (1998b).
AMS ^{14}C ages are measured by Dr. H. Kitagawa.

dependent on the linear sedimentation rate. Samples were prepared for X-ray diffraction (XRD) analysis after measurement of the weight, following the methods of Yamada *et al.* (1998). The quantity in wt% of quartz illite was determined by the internal standard method of XRD analysis (Shimoda 1985).

Results in BIW95-4

The quartz (or illite) flux in mg cm^{-2} yr^{-1} is deduced from quartz (or illite) concentration in wt%, the dry bulk density in mg cm^{-3}, and the linear sedimentation rate in cm yr^{-1} of the lacustrine sediments. The quartz (or illite) concentration is deduced from XRD analysis in a sample. Dry bulk density was determined by the weight of original samples collected by 7 cm^3 plastic cubes which had been dried at ca. 80 degrees Celsius for 48 hours. Linear sedimentation rates were calculated by interpolating between calendar ages of volcanic ashes and AMS ^{14}C data, and sampled horizons.

Figure 4 shows the variations of quartz and illite fluxes for the past 38,000 years in BIW95-4. The variations of quartz and illite fluxes for the past 38,000 years show the similar tendency. The variation of quartz (as well as illite) flux tends to divide into two background levels at ca. 8,000 cal.yr B.P.: one is a low flux value which ranges around 3 mg cm^{-2} yr^{-1} during Holocene, and the other is a high flux value which ranges from 5 to 8 mg cm^{-2} yr^{-1} during the last glacial period, except at ca. 33,000 cal.yr B.P. showing 10-20 mg cm^{-2} yr^{-1}. The average value of quartz flux for the past 38,000 years is 6.4 mg cm^{-2} yr^{-1}. In the last glacial period, quartz flux tends to oscillate by the millennial-scale frequency, and increase in 37,000, 34,000-31,000, 29,500-28,000, 26,000-24,500, 17,000, 16,000-14,500, 14,000-12,000 and 10,000-8,000 cal.yr B.P. Particularly, two spikes in 34,000-31,000 and 29,500-28,000 cal.yr B.P.

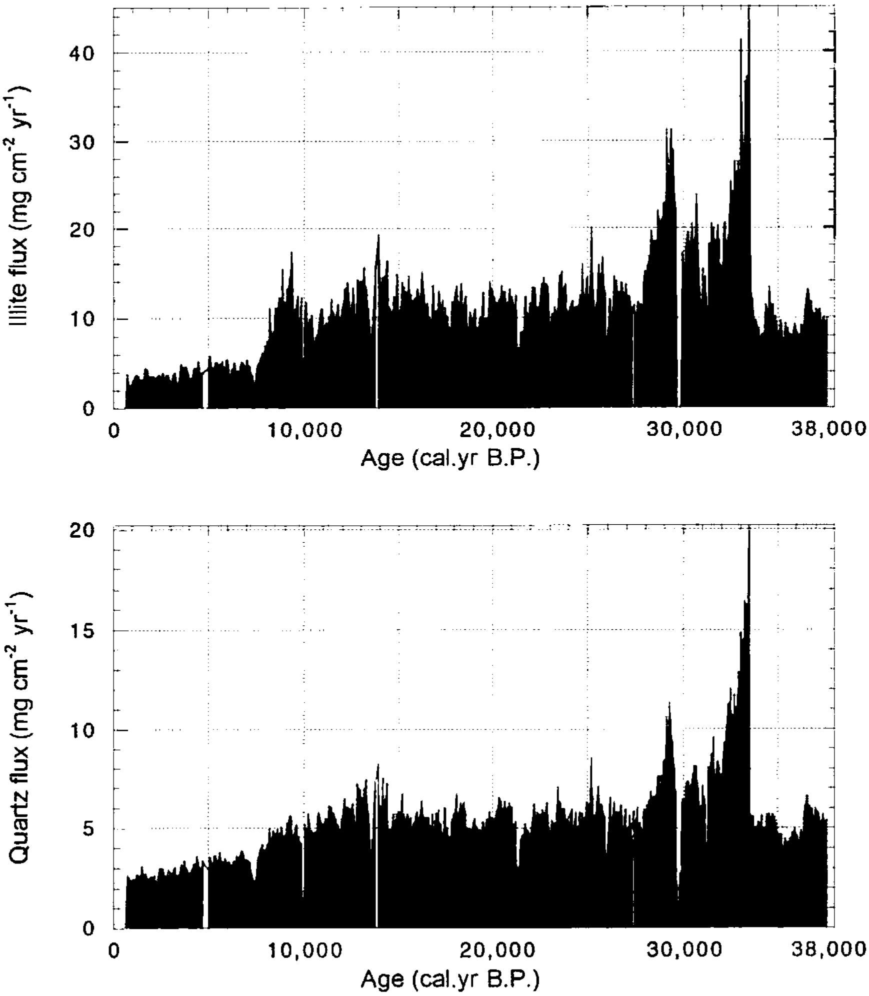

Fig. 4 The variations of the illite flux (upper) and the quartz flux (lower) in BIW 95-4 during the last 38,000 years.

are more than 10 mg cm^{-2} yr^{-1} and show a serrate shaped oscillation pattern. In Holocene, quartz flux is stable around 3 mg cm^{-2} yr^{-1}.

3. Lake Suigetsu Sediments

Lithology, chronology, sampling and method

Lake Suigetsu is located near coast of the Sea of Japan (Fig. 2). It is the biggest one of Mikata five lakes (Lake Suga, Mikata, Hiruga, Suigetsu, Kukushi) occupying 4.16 km^2 with a maximum water depth of 33.7 m. The lake is a kettle-type basin, nearly flat at the center. At present. Lake Suigetsu is a brackish water lake where sea-water invasion occurs. Also, the hydrological condition is unique in Lake Suigetsu. A large fraction of water coming into the lake is supplied from only one small river (the Hasu River) through Lake Mikata. Since Lake Suigetsu is connected to Lake Mikata by a narrow natual waterway, the most of detritus supplied from the Hasu River is expected to be deposited in Lake Mitata. Therefore, the major source of detritus into Lake Suigetsu is wind-transported materials such as eolian dust and valcanic ash.

Three sediment cores of 12-16 m long were collected from the center of the lake by a piston core sampler during two coring campaigns in 1991 and 1993. The continuous composite profiles were compiled by Fukusawa (1995). SGP3 core is 16 m long and was recovered at 35° 34' 57"N, 135° 53' 7.5"E and 33 m.b.s.l. (Fig. 2). The sedimentological feature of the lower 8 m part of SGP3 core is dominated by silty clay with annual laminations (non-glacial varves) covering a time span from ca. 6,300-15,500 cal.yr B.P. with three thin volcanic ash layers (Yamada 1999) (Fig. 5). Volcanic ashes are identified as K-Ah, U-Oki and Sakate ash respectively (Fukusawa 1995). The three kinds of the varve strucure are confirmed as biogenic, clastic and ferrogenic varves by microscopic observation of thin sections (Yamada 1999). As the result of comparing AMS ^{14}C ages with varve counting ages, there should exist a sedimentary break (hiatus) between ca. 8,500-10,150 cal.yr B.P. (Kitagawa *et al.* 1995) (Fig. 5).

A total of 331 discrete samples were obtained through continuous sub-sampling at 2.25 cm intervals using 7 cm^3 plastic cubes. The sample resolution ranges between 5 and 35 years, dependent on sedimentation rate by microscopic varve counting. Samples were prepared with the same methods in BIW95-4.

Microscopic varve counting and thickness measurements were carried out on 184 pieces of thin section covering all of sediment in SGP3. These result in construction of precise varve chronology. The error of varve counting is within 0.3%, compared with AMS ^{14}C dating ages (Kitagawa and van der Plicht 1998b).

Results in SGP3

The quartz (or illite) flux in mg cm^{-2} yr^{-1} is deduced from the quartz (or illite) concentration in wt%, the dry bulk density in mg cm^{-3}, and the sedimentation rate by varve counting in cm yr^{-1} of the lacustrine sediments. The quartz (or illite) concentration is deduced from XRD analysis in a sample. Dry bulk density was determined by the weight of original samples collected by 7 cm^3 plastic cubes which had been dried at ca. 80 degrees Celsius for 48 hours. Sedimentation rate in SGP3 is decided by continuous varve counting of the studied section, which resulted in a floating chronology of 9,133 varve years that linked to an absolute time scale using the K-Ah and the U-Oki as chronomarkers. As the result, sedimentation rates between ca. 6,300-15,500 cal.yr B.P. range from 0.03 to 0.32 cm yr^{-1}, and average 0.09 cm yr^{-1} (Fig. 6). Thus, for sedimentation rate in SGP3 is more precise than that in BIW95-4, it is possible to detect annual to decadal scale quartz and illite flux changes from SGP3.

Figure 6 shows the variations of quartz flux, illite flux and sedimentation rate from 15,500 to 6,300 cal.yr B.P. in SGP3. The variations of quartz and illite fluxes from the last deglaciation to early Holocene show the similar tendency. Quartz flux increases in each

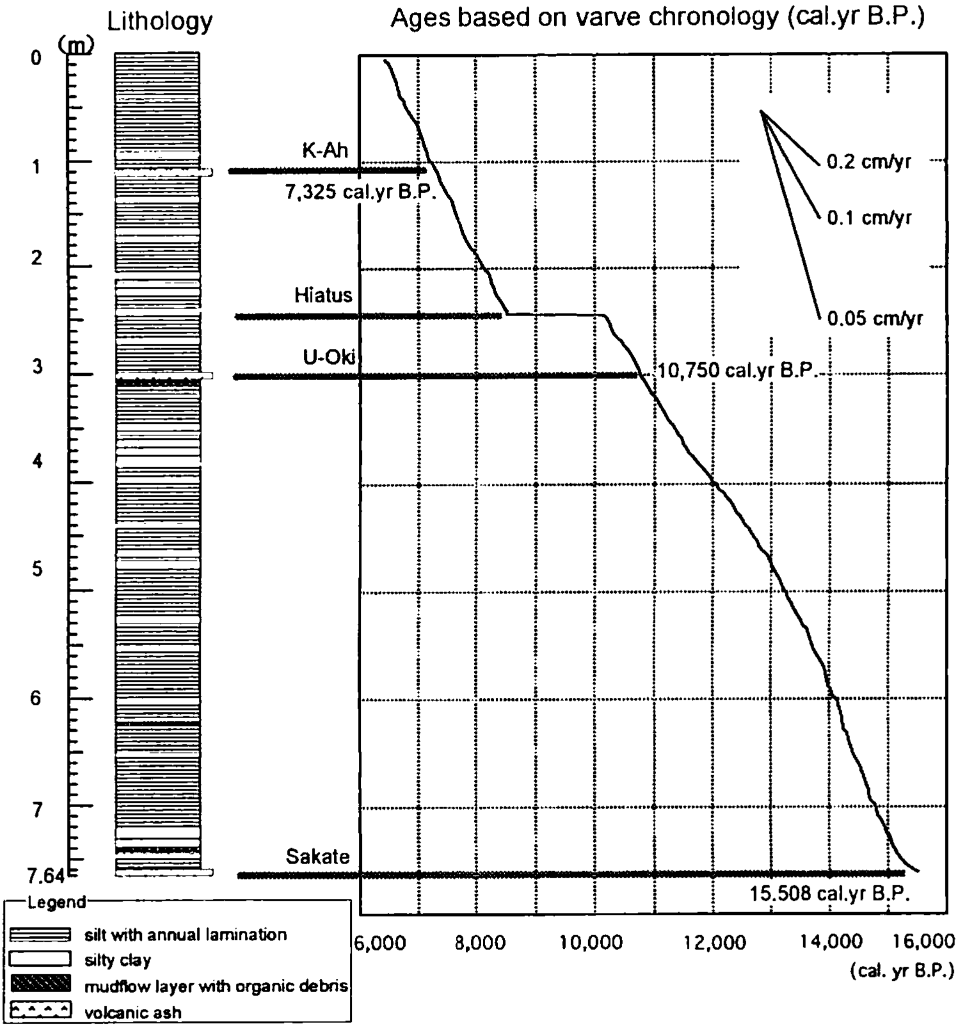

Fig. 5 Lithology of SGP3 core sediments (the lower 8 m part), and calendar age curve based on varve chronology against depth. Lines show the volcanic ash layers which are identical with the widespread volcanic ashes (shown above lines) in Japan (Fukusawa 1995), and the horizon of hiatus.

interval of 15,500-13,600, 13,300-12,500, 11,600-11,000, 8,500-8,100, 7,950-7,500 and 7,100 cal.yr B.P. The high quartz flux values in these intervals show 6-13, 2.5-6, 2-7, 2.5-3.5, 3-7 and 4 mg $cm^{-2} yr^{-1}$, respectively. Most of quartz spikes have a uni-modal pattern. The low quartz flux value is stable with ca. 1.5 mg $cm^{-2} yr^{-1}$, identified as the background value. Also, the average value of quartz flux for the past 15,500 years is 3.4 mg $cm^{-2} yr^{-1}$.

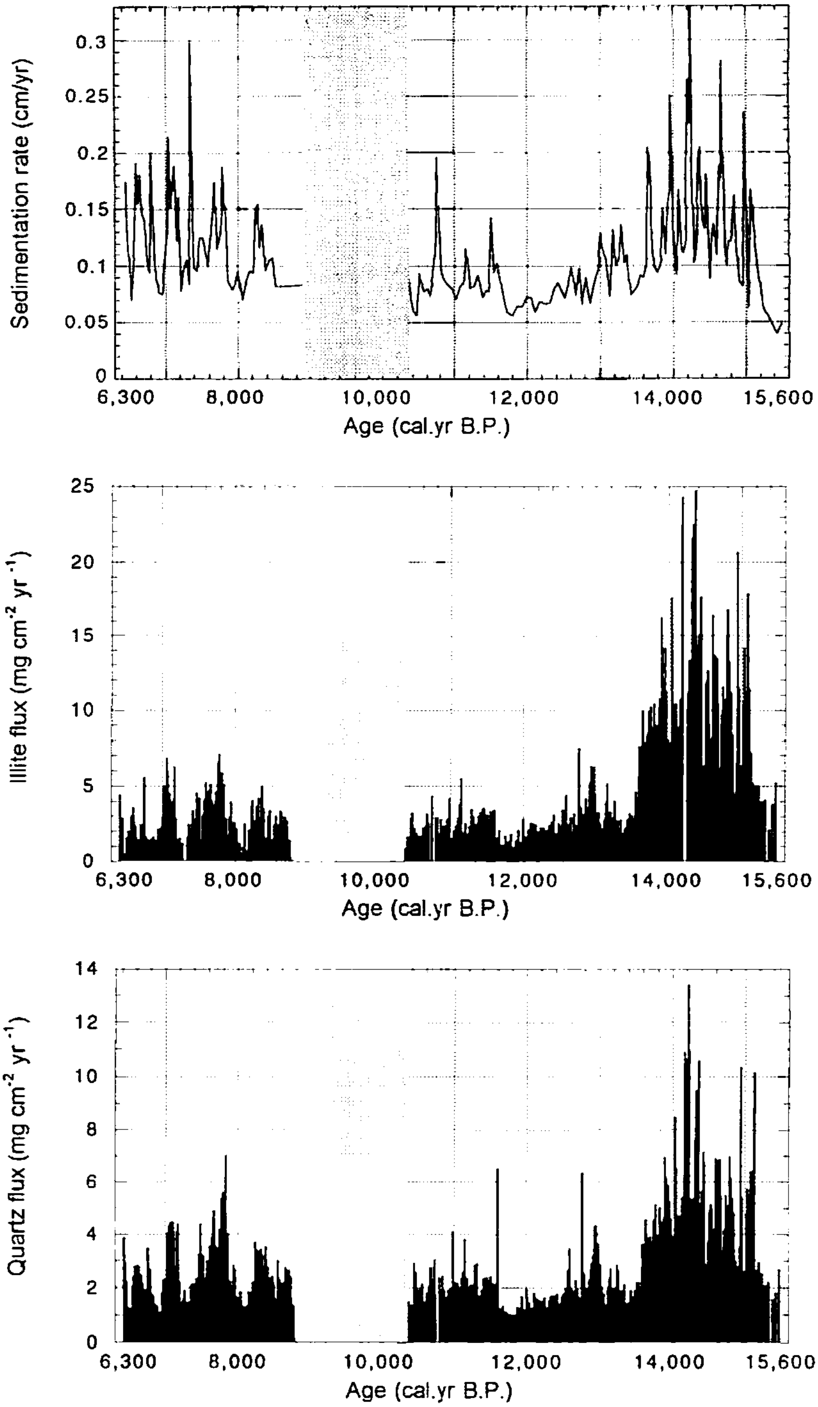

Fig. 6 The variations of sedimentation rate (upper), the illite flux (middle) and the quartz flux (lower) in SGP3 from 15,500 to 6,300 cal.yr B.P.

4. Discussion and Interpretation

Verification of the quartz flux in lacustrine sediment as a proxy record of paleointensity of the Asian winter monsoon and the westerlies

The increase of eolian dust is caused by the expansion of arid areas in China and/or the strengthening of the Asian winter monsoon and the westerlies (Ono and Naruse 1997). Therefore, the variation of the quartz flux as a eolian dust indicates the changes of the intensity of the Asian winter monsoon and the westerlies, which control climate in East Asia. Based on many studies in terrestrial sequences, deep-sea sediments and lacustrine sediments concerned with eolian dust, it is clarified that the variation of the quartz flux accords with glacial/interglacial cycles (*e.g.* Fukusawa and Koizumi 1994; Yoshinaga 1996; Xiao *et al.* 1997a). But, there are few studies to reconstruct the millennial-scale climatic changes as detected by the variation of the quartz flux. Particularly in lacustrine sediments, Xiao *et al.* (1997a) points out that the parameter of the eolian quartz flux to lakes is not so sensitive to rapid and short-timescaled fluctuations in the intensity of the Asian winter monsoon activities due to the dilution resulted from fluvial deposits entering the lake from the surrounding areas.

Table 2 shows quartz flux values of some sequences of Japan. While quartz flux values in terrestrial sequences and deep-sea sediments range from ca. 0.1 to ca. 1 mg cm^{-2} yr^{-1}, the value in lacustrine sediments ranges from ca. 3 to ca. 10 mg cm^{-2} yr^{-1}. The quartz flux in lacustrine sediments is about ten times as large as in terrestrial sequences and deep-sea sediments. The reason of this difference is thought to be short-timescaled secondary input to lacustrine sediments (Yoshinaga 1998), and the long-timescaled denudation in surface layer of terrestrial sequences. Quartz grains entering into lakes through rivers can be devided into two main sources: One is eolian dusts deposited at the surrounding areas. The other is fluvial detritus originated from the surrounding areas by the weathering of parent rocks. It is not

Table 2 Eolian quartz flux value in various sequences of Japan

sample source	observation area	interval	Eolian quartz flux (mg cm^{-2} yr^{-1})
1: terrestrial (Loam)	Tokachi,Hokkaido	since MIS 5	0.1 - 0.8
2: terrestrial (paleosols)	the Sea of Japan coast	since MIS 3	0.1 - 0.55
3: deep-sea	the Sea of Japan	since MIS 18	0.3 - 1.6
4: deep-sea	the Sea of Japan	since MIS 6	0.3 - 0.6
5: lacustrine	Lake Biwa	since MIS 6	4.5 - 8
6: lacustrine	Lake Biwa	since 38 ka	2.5 - 20
7: lacustrine	Lake Suigetsu	since 15 ka	0.6 - 13

Data sources

1: Yoshinaga (1996) 2: Inoue and Naruse (1990) 3: Fukusawa and Koizumi (1994)
4: Tada (1997) 5: Xiao et al. (1997a) 6 and 7: our results

easy to distinguish the two sources. In this study, we attempt distinguishing the source of quartz grains by using the geological features of illite mineral.

Most of surface soils in Japan tend to be acid because of the existence of volcanoes. Under these acid environments, illite changes into kaolinite by weathering process (Chamley 1989). If illite deposists on surface soils in Japan, the crystals of illite decompose easily. Based on K-Ar dating ages of illite in lacustrine layers of Hokkaido, northern Japan, the origin of illite is determined to be eolian dusts transported from the inlands of China (Yahata *et al.* 1997). Hence, illite deposited in lacustrine sediments is eolian dusts, which fall directly into lakes.

On the basis of results of Fig. 4 and Fig. 6, quartz and illite fluxes tend to have the similar tendency. That relation shows that the quartz flux in lacustrine sediments also consists of eolian dusts which not only fall directly into lakes but also enter the lakes through rivers from drainage area covered by fallen eolian dusts. Though Xiao *et al.* (1997b) indicates that quartz particles more than 20 μm are fluvial quartz originated from the surrounding areas, most of quartz particles are within 20 μm based on microscopic observation of thin sections in SGP3.

As mentioned above, it is confirmed that the surplus quartz flux in lacustrine sediment as shown in Table 2 is not fluvial quartz originated from the surrounding areas but eolian quartz deposited in the drainage areas and then transported through rivers. This is supported by the result that the average value of the quartz flux in BIW95-4 is larger than that in SGP3, because the drainage area of Lake Biwa is bigger than that of Lake Suigetsu. However, it is urgent by necessary to establish the method of separation of sources of quartz in lacustrine sediments by ESR, $\delta^{18}O$, and size distribution.

Short-timescaled paleointensity of the Asian winter monsoon and the westerlies

We attempt detecting the short-timescaled variation of the intensity of the Asian winter monsoon and the westerlies by using the eolian dust flux in lacustrine sediments.

We could detect the centennial to millennial variations for the past 38,000 years in BIW95-4. As shown in Fig. 7, the Asian winter monsoon and the westerlies were strengthened in 37,000, 34,000-31,000, 29,500-28,000, 26,000-24,500, 17,000, 16,000-14,500, 14,000-12,000 and 10,000-8,000 cal.yr B.P. Yamada *et al.* (1999) estimated the Asian monsoon activities for the past 75,000 years, based on the carbonate carbon content of the loess-paleosol sequence in Lanzhou, China. The result shows that the carbonate carbon content rapidly increased in 30,000, 25,000, 21,000, 16,000 yr B.P., Younger Dryas and 8.2 ka cooling event, and interpreted that the eolian dust inputs from Takla Makan Desert were increased by the strengthening of the Asian winter monsoon activities (Fig. 7). Comparison with the carbonate carbon content in Lanzhou (Yamada *et al.* 1999) and the quartz flux in Lake Biwa, the periods of increasing dust flux agree with the intervals of the carbonate carbon content peak (Fig. 7). It is indicated that the Asian winter monsoon and the westerlies activities occur almost simultaneously between the inland of China and the Japanese Islands.

Also, we compared the eolian dust flux in Lake Biwa and $\delta^{18}O$ curve of the Greenland ice core (GISP2) to examine the linkage with global climatic changes (Fig. 7). As the result, the strengthening of the Asian winter monsoon and the westerlies always occur in the periods

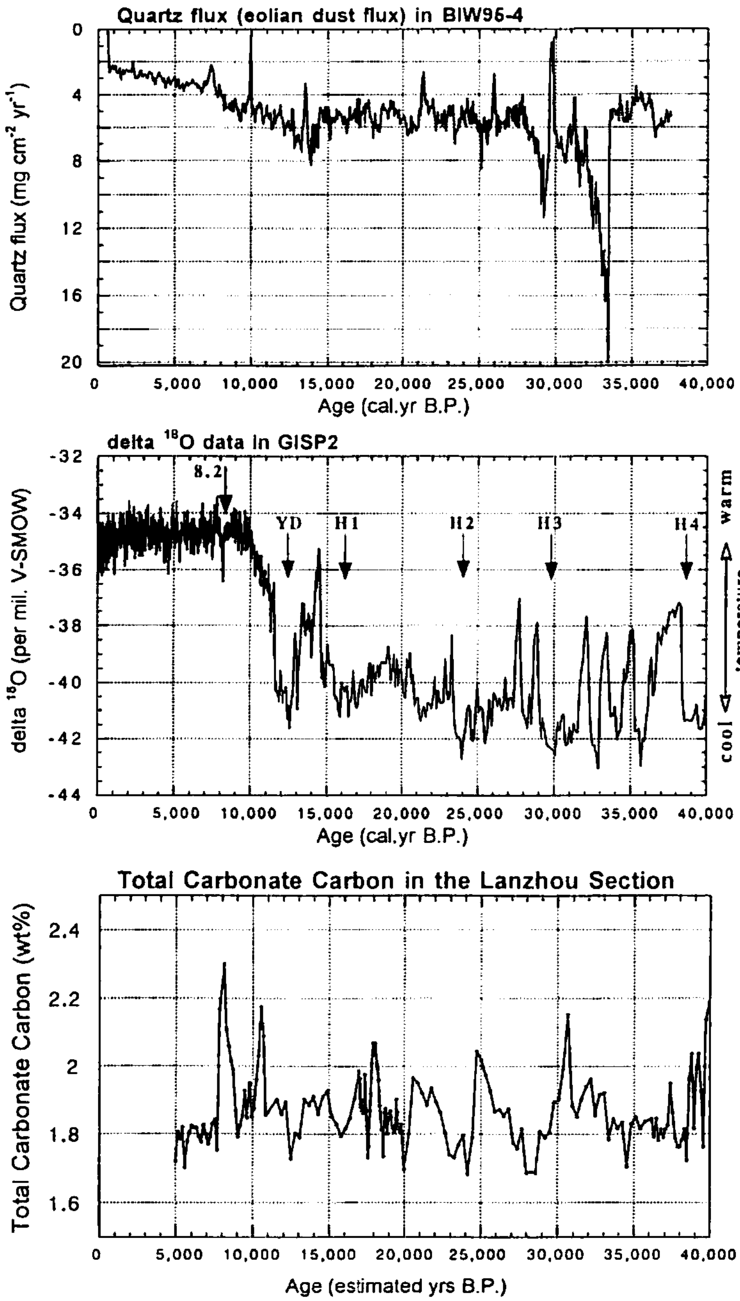

Fig. 7 The last 40 ka variations of the quartz flux in Lake Biwa (upper) compared with $\delta^{18}O$ in GISP2 (Dansgaard *et al.* 1993) (middle) and the carbonate carbon content from the Lanzhou loess section, China (Yamada *et al.* 1999) (lower). Arrows of middle diagrams show the periods of global climatic coolings: 8.2 ka cooling event (shown as 8.2), Younger Dryas (YD) and Heinlich events 1-4 (H1-4) (Stuiver *et al.* 1995 ; Vidal *et al.* 1997).

(Stuiver *et al.* 1995; Vidal *et al.* 1997) that are Heinrich events 1-4 (Heinrich 1988), Younger Dryas and 8.2 ka cooling event recognized as global coolings in the North Atlantic and Europe. In other words, whenever cooling occurs in the North Atlantic and Europe, the intensity of the Asian winter monsoon and the westerlies are strengthened, and the teleconnection by atmospheric circulation between East Asia and the North Atlantic region exists for the past 38,000 years.

Then, we could detect the annual to decadal variation during the last deglaciation in SGP3. As shown in Fig. 8, the Asian winter monsoon and the westerlies were strengthened

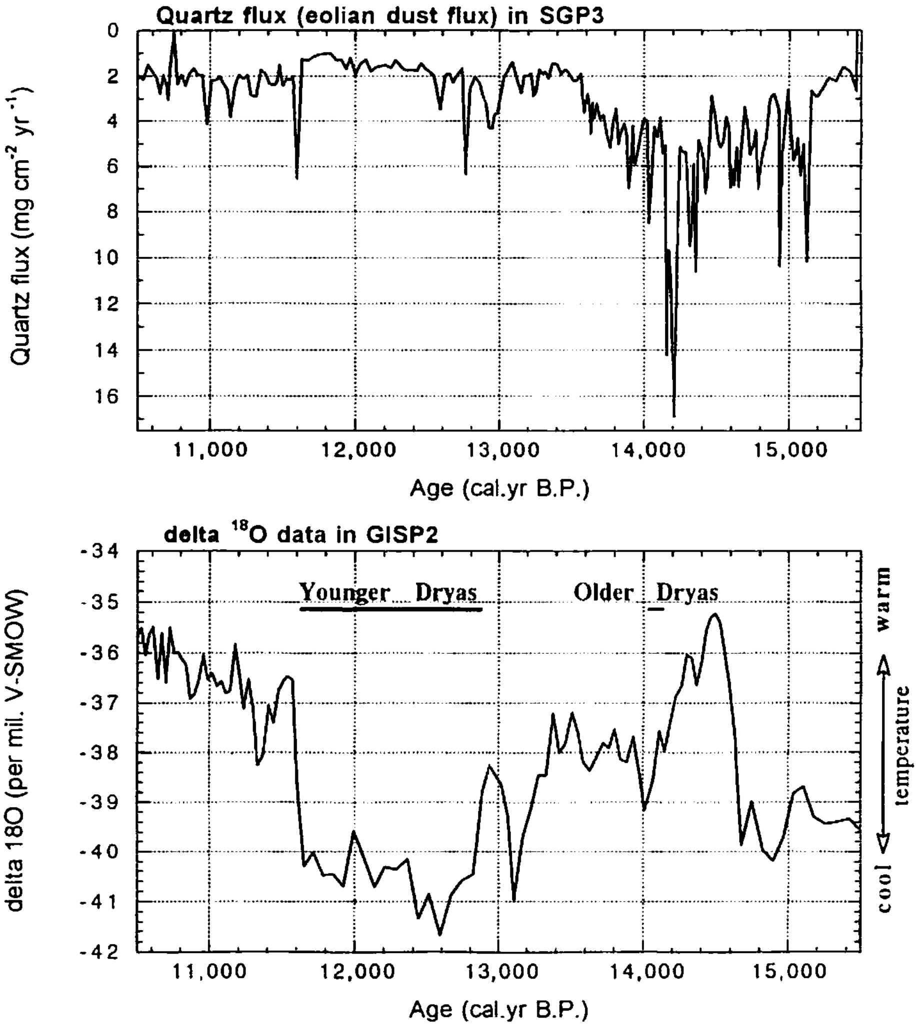

Fig. 8 The variations in the quartz flux in Lake Suigetsu (upper) compared with $\delta^{18}O$ from Greenland ice core (Dansgaard *et al.* 1993) (lower) during the last deglaciation. Solid lines show the periods of Younger Dryas and Older Dryas (Stuiver *et al.* 1995).

in 15,000-13,600, 13,300-12,500 and 11,600-11,000 cal.yr B.P.

The large and abrupt climate deterioration known as Older Dryas and Younger Dyas is recognized during the last deglaciation in high latitude of the North Hemisphere, and such as event is recorded in the variation of atmospheric ^{14}C concentration ($\Delta^{14}C$) (Stuiver *et al.* 1995). As the reason for the appearance of the cooling during the last deglaciation, it is indicated that the formation of the North Atlantic deep water (NADW) was suppressed by the large amount of meltwater rapidly flowed in the North Atlantic Ocean, and that thermohaline circulation (THC) which supplies the high latitude region with heat (Broecker and Denton 1989) was stopped.

The THC oscillation can be linked to atmospheric $\Delta^{14}C$ as follows: $\Delta^{14}C$ increases when formation of NADW is reduced abruptly and THC decreases, after the climatic cooling; in contrast, $\Delta^{14}C$ decreases when THC northward heat advection and deep water production resume after climatic warming (Charles and Fairbanks 1992; Kitagawa and van der Plicht 1998a).

Kitagawa and van der Plicht (1998a) indicated that the short-timescaled abrupt climate coolings (with suppression of NADW and weakening of THC) existed three to four times in East Asia, based on the variation of atmospheric $\Delta^{14}C$ using large plant residues in varved sediments of Lake Suigetsu. These onset times of climate cooling were 15,000, 12,800 and 10,900 cal.yr B.P., respectively (Fig. 9). As the result of comparison of the eolian dust flux in Lake Suigetsu with atmospheric $\Delta^{14}C$ (Kitagawa and van der Plicht 1998b) (Fig. 8), the

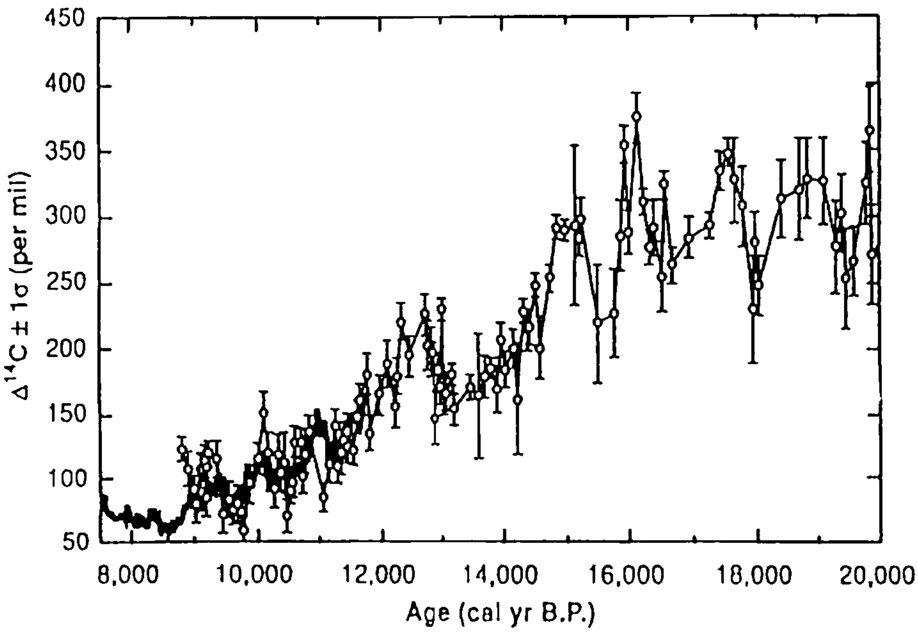

Fig. 9 Atmospheric ^{14}C variations during the last deglaciation, normalized to the present value and given in $\Delta^{14}C$ in per mil, reconstructed from varves in Lake Suigetsu (Kitagawa and van der Plicht 1998a).

periods at which eolian dust flux increases rapidly agrees with the onset times of climatic cooling. Therefore, the two climatic cooling periods of 15.000-13,600 and 13,100-12,500 cal.yr B.P. (the strength of the intensity of the Asian winter monsoon and the westerlies) correspond to Older Dryas and Younger Dryas, respectively.

We clarify the temporal relationships between the high latitude climate and middle to low latitude one during the last deglaciation on the basis of the comparison of the eolian dust flux in SGP3 with $\delta^{18}O$ in GISP2 (Fig. 8). The onset times of Older Dryas and Younger Dryas are 14,090 and 12,890 cal.yr B.P. in high latitude from the record of GISP2 (Stuiver *et al.* 1995), while these are 15,000 and 13,100 cal.yr B.P. in middle to low latitudes from the record of SGP3. This result indicates that the environmental changes in middle to low latitude might go ahead of that in high latitude, and might agree with the view that the trigger of the short-timescaled abrupt environmental changes during the last deglaciation depends on the variation of atmospheric circulation pattern in middle to low latitudes (Tada 1997, 1998).

5. Concluding Remarks

Illite and quartz fluxes in the lacustrine sediments of Japan are very useful as a proxy record for reconstructing high-resolution paleointensity of the Asian winter monsoon and the westerlies since the last glacial. Higher fluxes of eolian dusts including illite and quartz minerals show strengthening of the Asian winter monsoon and the westerlies, while lower fluxes show weakening. Changes of atmospheric circulation pattern of East Asia relating to global climate changes caused intensity changes of the Asian winter monsoon and the westerlies reconstructed by the eolian dust flux.

Based on eolian dust flux records during the last 38,000 years in lacustrine sediments of Lake Biwa, global cooling events such as Heinrich events 1-4, Younger Dryas and 8.2 ka cooling event can be found. By investigation on high resolution changes of the eolian dust flux during the deglaciation period including Younger Dryas and Older Dryas cooling periods in varved lacustrine sediment of Lake Suigetsu, oscillations of paleointensity of the Asian winter monsoon and the westerlies might be one of triggers on the global environmental changes.

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