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Late Pleistocene vegetation change in Korea and its possible link to East Asian monsoon and Dansgaard–Oeschger (D–O) cycles

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ABSTRACT

Late Pleistocene carbon isotope ($\delta^{13}C$) records from a paleolithic sedimentary sequence collected from Baeki, Hongcheon, central Korea, show long-term changes with superimposed short-term isotopic excursions. The $\delta^{13}C$ value of the sedimentary organic matter, a proxy for past vegetation change, varied from −26‰ to −23‰ for the period between 30 and 90 ka, with a long-term variation similar to insolation changes. High-amplitude (−1‰ to approximately −1.5‰) fluctuations superimposed on the long-term changes in the $\delta^{13}C$ values decreased during stronger summer monsoon intervals but increased during the weakened summer monsoon. This millennial-scale pattern is generally similar to Greenland Dansgaard–Oeschger (D–O) cycles. The possible connection between the Hongcheon area, Korea and high latitudes may be explained by atmospheric circulation changing in response to the D–O oscillations in the Northern Hemisphere.

Introduction

Multi-millennial-scale climate changes in East Asia during the last glacial period have been identified from studies of speleothem (Wang et al., 2001, 2008) and loess sediments (Fang et al., 1999; Sun et al., 2012) in China. The fluctuations corresponding to intensified summer/winter monsoons in East Asia have been understood in terms of a remote link to warm/cold periods in Greenland known as Dansgaard–Oeschger (D–O) cycles (Wang et al., 2001, 2008). These cycles are characterized by climatic warming periods (D–O interstadials) and cooling periods (D–O stadials) represented by higher/lower $\delta^{18}O$ values in Greenland ice cores (Dansgaard et al., 1993). Such climatic connections have been attributed to northward/southward shifts of the westerlies (Porter and An, 1995; Fang et al., 1999; Ijiri et al., 2005; Nagashima et al., 2011). A recent study of changes in the strength of the winter monsoon over the past 60,000 years suggests that Atlantic meridional overturning circulation drove abrupt changes and that the northern westerlies played a role in transmitting this signal from the North Atlantic to the Asian monsoon regions (Sun et al., 2012). For stable natural resource (e.g., food and forest resources) attainment and sustainable economic development, a key question is whether and how terrestrial ecosystems in temperate regions in East Asia responded to these rapid millennial-scale climate changes.

To trace terrestrial responses to past climate changes, carbon isotopic ratios of organic matter in sediments, a proxy for the vegetation changes, have been used because (1) deposited plant organic matter preserves its original carbon isotopic composition with little or no isotopic fractionation during burial, and (2) carbon isotopic ratios of terrestrial plants are affected by environmental conditions including climate changes (Cerling et al., 1997; Meyers, 1997; Boutton et al., 1998; Huang et al., 2001; Nordt et al., 2002; An et al., 2005; Lim et al., 2010). In general, terrestrial plants can be divided into two groups (C_3 and C_4 plants) according to their carbon fixation processes. The $\delta^{13}C$ values of C_3 plants that use a C_3 photosynthetic pathway, including all trees and cold-season grasses/sedges, typically range between −32‰ and −21‰, with a mean value of −27‰. In contrast, the $\delta^{13}C$ values of C_4 plants such as warm-season grasses/sedges, range between −17‰ and −9‰, with a mean value of −13‰ (O`Leary, 1981, 1988; Tieszen, 1991). Seven families and 92 species of C_4-type herbaceous plants in Korea (Chang and Lee, 1983a) have been reported.

The present distribution of C_3 and C_4 plants is related to plant habitat. C_4 plants are dominantly found in human-disturbed forest areas, cultivated areas, and seashore areas. Arid areas contain a high proportion of C_4 flora, whereas well-developed woody forests and humid areas contain a lower proportion of C_4 plants (Chang and Lee, 1983b). Recently, Lim et al. (2010) suggested that the East Asian monsoonal changes linked to continental ice volume (or glaciation level) are the primary determinants of suborbital vegetation change in the Cheollipo area on the western coast of Korea. The increase in the estimated proportion of C_4 plants during Marine Isotope Stage (MIS) 3, between 60 and 30 ka, corresponded to an increase in continental ice volume, with an intensification of the winter monsoon coupled with a weakening of the summer monsoon. This past study, however, focused only on vegetation changes during MIS 3.

In the present study we expanded the record of vegetation change in Korea by assessing MIS 3, MIS 4 and MIS 5a (30–90 ka) using

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optically stimulated luminescence (OSL) dating techniques and analyses of the carbon isotope of sedimentary organic matter from Hongcheon area, central Korea. We then consider the possible influence of D–O events on millennial-scale vegetation changes.

Study site

The Hongcheon area (Fig. 1) is located in the mountainous interior of the central part of the Korean Peninsula and is characterized mostly (85% of the total area) by steep mountainous terrain with elevations of 150–1000 m. Its vegetation is dominated by C_3 plant communities including species such as *Quercus variabilis*, *Quercus mongolica*, and *Pinus densiflora*. Chang and Lee (1983b) observed that a grassland in the Hongcheon area consisted of approximately 24% C_4 plants such as *Arundinella hirta*, *Andropogon brevifolius*, *Cymbopogon tortillis*, *Spodipogon sibiricus*, *Themada japonica*, and *Zoysia japonica*. The Baeki site is located in the middle portion of the Hongcheon River (Fig. 1). The basement rocks in the catchment of the river are composed of both Precambrian garnet-bearing granitic gneiss and Precambrian banded gneiss. It has been reported that there are several river terraces along the both sides of midstream of the Hongcheon River (Lee and Yoon, 2003; Shin et al., 2005). These terraces are generally situated on the gravel beds with different elevations and have been suggested to consist of loess–paleosol deposits that are similar to the Chinese loess sequences (Shin et al., 2005). The study area receives approximately 1200 mm in mean annual precipitation, 65% of which falls during the summer in association with the East Asian summer monsoon.

Material and methods

Trenched samples 5 m long were collected from a representative sedimentary profile at the summit of the northwestern part of a hill and were divided into 212 subsamples. Magnetic susceptibility (MS) was measured using a Bartington MS2 system (Bartington Instruments, Ltd., UK). Total organic carbon (TOC) analyses were performed on small quantities of homogenized subsamples. Approximately 5 mg of subsample treated by 1 N HCl at around 100°C for 1 h was loaded into tin combustion cups. TOC was determined using a FlashEA-1112 (Thermo Finnigan S.p.A., Milan, Italy). Stable carbon isotope analyses of the HCl-treated subsamples ($n = 97$) were performed using a continuous-flow isotope-ratio mass spectrometer (Isoprime; GV Instrument, UK) coupled with a CHN elemental analyzer (Euro EA 3000-D, Italy). The results were expressed in δ-notation relative to the Vienna Pee Dee belemnite (V-PDB) standard. The reference material was International Atomic Energy Agency (IAEA) CH6 (sucrose, $\delta^{13}C = -10.45 \pm 0.033$‰). Replicated analyses had a precision >0.2‰. The grain size of lithogenic minerals was analyzed using the laser diffraction method with a Mastersizer 2000 (Malvern Instruments, Ltd., Worcestershire, UK) after treatment with 35% H_2O_2 and 1 N HCl at approximately 100°C for 1 h to remove organic matter and carbonate minerals, respectively.

Results

The OSL age-dating results ($n = 4$) from the Baeki sedimentary sequence provided a depositional chronology (Kim, 2006; Song and Kim, 2009) (Table 1 and Fig. 2). The age increased steadily with depth, which may indicate that sediment deposition took place progressively and without reworking between 90 and 30 ka. The sedimentation rate between 86 and 64 ka, corresponding to MIS 4–MIS 5a, was 2.3 cm/ka. Significant changes in the sedimentation rate during MIS 3 were found. Compared with the 5.5-cm/ka sedimentation rate in early MIS 3 (64–44 ka), the sedimentation rate during the middle to late MIS 3 (44–36 ka) increased significantly, reaching 17.27 cm/ka. This indicates a gradual increase in sediment supply to the Baeki site during the late Pleistocene. If we assume the same sedimentation rate between MIS 4 and MIS 5 and between late MIS 3 and middle MIS 3, as indicated by dashed lines in the depth–age curve (Fig. 2), the Baeki sedimentary sequence may provide past environmental information for the period between 130 and 28 ka.

The MS results show long-term variation (Fig. 2). Values are low through MIS 5 and MIS 4. Significant increase in MS is found during MIS 3 but MS decrease during MIS2. The results of the grain-size analysis indicated different long-term variations in the clay, silt, and sand components (Fig. 2). For example, the sand content abruptly decreases through MIS 5 and MIS 4 but remains relatively stable throughout MIS 3. The $\delta^{13}C$ value of TOC, which varied between −26‰ and −23‰, was characterized by long-term change different from those of MS and sand content,

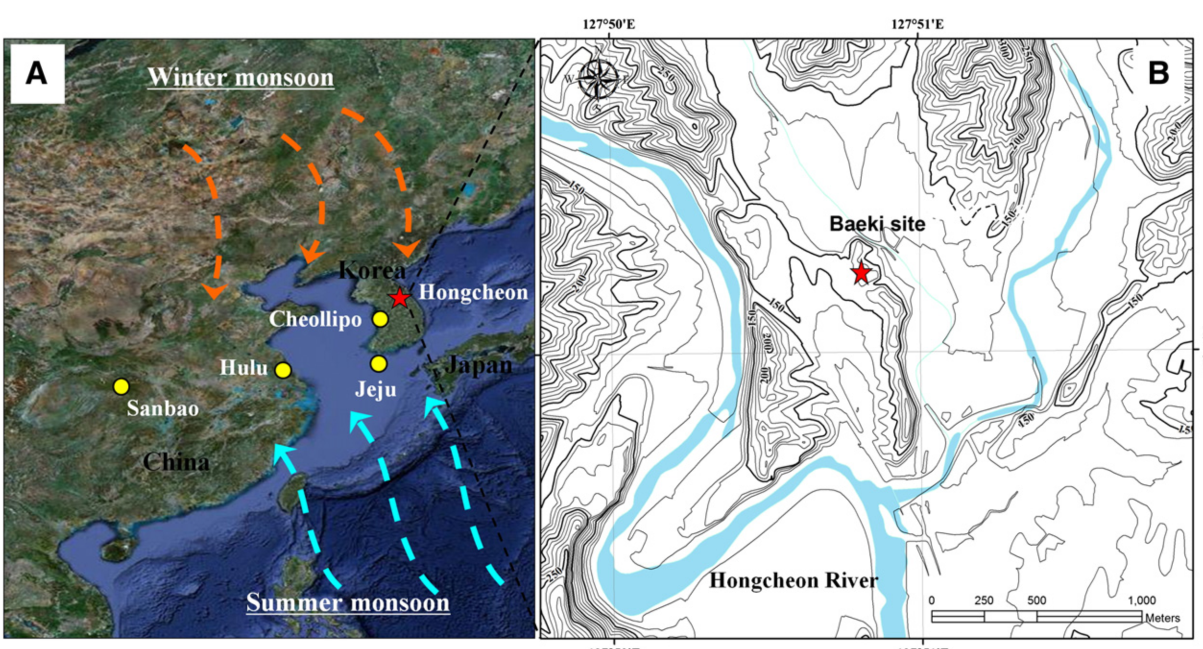

Figure 1. (A) Map of the climatic system in East Asia, with the East Asian summer and winter monsoons. The red star indicates the location of the sampling site (Hongcheon area, Korea). (B) Map of the sample site in the Hongcheon area, Korea.

Table 1
Results of OSL age dating in a paleolithic sedimentary sequence collected from Baeki, Hongcheon, central Korea.
Modified from Song and Kim (2009).

Sample code	Dose rate (Gy/ka)	Equivalent dose (Gy)	OSL age (ka, 1σSE)
KMY-BY-1	3.25 ± 0.04	117 ± 4	36.0 ± 1.3
KMY-BY-2	3.25 ± 0.04	144 ± 8	44.3 ± 2.5
KMY-BY-3	3.10 ± 0.04	199 ± 10	64.2 ± 3.3
KMY-BY-4	2.86 ± 0.04	246 ± 17	86.0 ± 6.1

For OSL age dating, 125–250 μm diameter quartz was extracted through chemical separation from the sediment samples. OSL dating was then performed on the purified quartz using a Risø TL/OSL-DA-20 automated system (Bøtter-Jensen et al., 2000; Song and Kim, 2009).

with short-term variability corresponding to approximately 1.5‰ superimposed on the long-term change. TOC values varying from 0.3 to 0.6% seem to be negatively correlated with the $\delta^{13}C$ value of the TOC during MIS 4 and MIS 5, but this relation is not clear during MIS 3 (Fig. 2). The average resolution for the $\delta^{13}C$ of TOC analysis during the period between 30 and 90 ka is 750 yr per sample, sufficient to indicate possible millennial-scale variability.

Discussion

The comparison of age-dating results and grain-size analyses may provide preliminary information on the formation of Baeki sedimentary sequence during the late Pleistocene. The sequence is laid on the basal layer dominated by coarse sand, gravel, and pebbles, which probably originated from weathered bedrock. The sand % decreased through MIS 5 and MIS 4, leading to increase in clay and silt components. Since MIS 3, the grain size remains nearly stable as shown from the median grain-size change. These grain-size features are quite different from the long-term MS variation (Fig. 2). Temporal MS change seems to be coupled with well-known loess–paleosol sequences that have been suggested from the observation of the several river terraces around the Hongcheon River (Shin et al., 2005). MS values are low during MIS 4 and MIS 2 but high during MIS 3, though MS values are very low during MIS 5. Furthermore change in the grain-size distribution (Fig. 3) gives further information on the evolution of the sedimentary sequence. Grain-size distributions during MIS 5 and MIS 4 are mainly bimodal, showing two components (silt-sized and sand-sized components) but during MIS 3 mainly unimodal with clay- and silt-sized grains. This suggests that the sand component, probably transported from the river basin by wind, decreased with time. Direct input of river basin material by fluvial processes would have been impossible because the sampling site is located at the summit of the northwestern part of a hill about 500 m away from the river. Based on the physical characteristics mentioned above, the Baeki sedimentary sequence seems to have been affected by the local and remote eolian deposition during the late Pleistocene. Each individual influence on the study site needs to be discussed in detail with more spatial data.

It is interesting that the organic components appeared to have little relationship with the physical sedimentary components. For example, the difference in the $\delta^{13}C$ and TOC values was quite different from that for the median grain size (Fig. 2). This suggests that vegetation change was relatively unaffected by the process responsible for supplying sediment (probably eolian deposition) to the hill where the study site is located. Thus, we focused on the vegetation with long-term and superimposed short-term changes rather than on the stable physical components.

The $\delta^{13}C$ values in the Baeki sediments may preserve information about past terrestrial vegetation changes (Cerling et al., 1997; Huang et al., 2001; Nordt et al., 2002; An et al., 2005). The $\delta^{13}C$ values of TOC in the Baeki sediments varied between −23 and −26‰ and are characterized by significant millennial-scale fluctuations of −1‰ to around −1.5‰. This relatively narrow $\delta^{13}C$ value range in central South Korea during the late Pleistocene is quite different from that of the $\delta^{13}C$ value of TOC (−18‰ and −26‰) reconstructed from the western coastal area of Korea during MIS 3 (Lim et al., 2010); nonetheless, the long-term changes were similar. From comparison of the Asian monsoon index and sea-level changes, Lim et al. (2010) suggested that long-term sub-orbital East Asian monsoonal change linked to continental ice volume (or glaciation level) was the main factor controlling vegetation changes in the Cheollipo area of Korea, indicating global links.

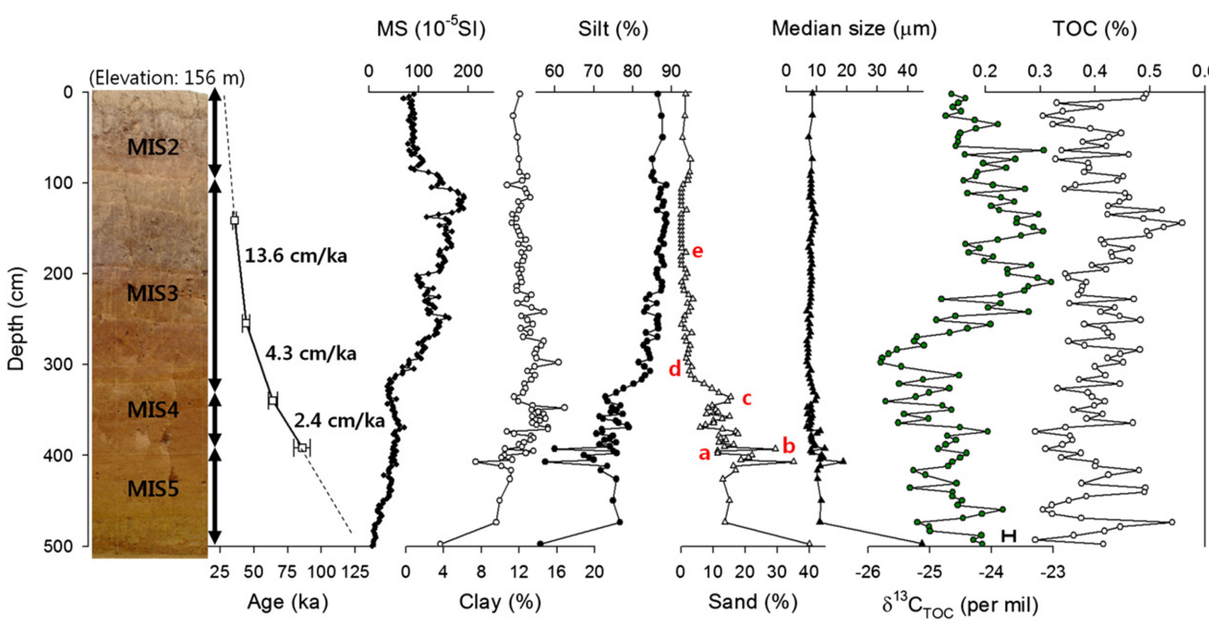

Figure 2. Results of OSL age-dating and multi-proxy analyses of the sedimentary sequence from the Hongcheon (Baeki site), Korea: OSL age-dating results (Kim, 2006; Song and Kim, 2009) and calculated sedimentation rate between OSL dating depths ($n = 4$) (assuming the same sedimentation rate between MIS 4 and MIS 5 and between late MIS 3 and middle MIS 3, as indicated by dashed lines in the depth–age curve); magnetic susceptibility (MS); results of grain-size analyses; $\delta^{13}C$ values of total organic carbon (TOC); TOC content (%). A standard error bar (~0.2‰) for the $\delta^{13}C$ value is shown in lower-right corner of the panel to test short-term variability (~1.5‰) corresponding to millennial-scale climate changes. Examples of grain-size distribution in the sediments (a–e) are shown in Fig. 3.

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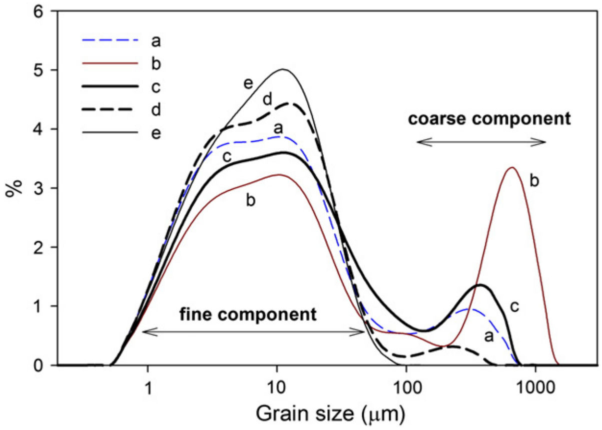

Figure 3. Representative grain-size distributions in the sedimentary sequence of the Baeki site in Hongcheon, Korea (refer to letters a–e in Fig. 2).

To test possible links to regional and global climate change, the vegetation records of the Baeki site have been compared with changes in the East Asian monsoon, as inferred from the δ^{18}O values of stalagmites from the Chinese Caves (Wang et al., 2001, 2008), as well as high-latitude climate change as inferred from δ^{18}O values obtained from Greenland ice cores (Dansgaard et al., 1993; Grootes and Stuiver, 1997) (Fig. 4). They show some similarity, which is rather surprising because the time series of the Baeki sediment sequence was calculated by assuming a constant sediment accumulation rate between OSL dating depths ($n = 4$), resulting in a rough age control. Many previous studies of long-term climate change in East Asia (e.g., Wang et al., 2001, 2008) have suggested that the Asian monsoon generally changes in accordance with orbital insolation changes. This can be confirmed in the present study. During MIS 5a–MIS 3 in the late Pleistocene, the long-term changes in the δ^{13}C values are generally consistent with insolation changes. This is true even during MIS 5, for which there is very poor age resolution (Fig. 4).

Furthermore, millennial-scale variability in the δ^{13}C values from the Baeki site seems to have been synchronous with that of East Asian summer monsoon strength and remote air temperature in Greenland (D–O oscillations). A possible linkage between vegetation changes on East Asian islands and D–O oscillations during the last glacial period has been found from pollen records showing several biome shifts, such as from temperate deciduous/conifer forest to cold/cool conifer forest in Japan, and from subtropical forest to temperate deciduous/conifer forest in Taiwan (Takahara et al., 2010). Around Lake Biwa in western Japan, millennial-scale increases in the abundance of *Cryptomera japonica* during the last 40,000 yr are correlated with D–O 8 to 5 and have been attributed to changes in summer monsoon strength or winter snowfall (Hyashi et al., 2010). These suggest that the millennial-scale variability in the δ^{13}C values may reflect climatic responses in Korea to D–O oscillations in the Northern Hemisphere.

The connection between the Hongcheon area and high latitudes may be explained by the two atmospheric responses to the D–O oscillations in the Northern Hemisphere (Rohling et al., 2003; Sun et al., 2012). The first was tropical/monsoon-mode dominated summer-type conditions during the D–O interstadials, which showed weakening and contraction of the polar vortex and enhanced summer monsoon intensities. The second was polar/westerly-mode dominated winter-type conditions during the D–O stadials, which showed intensification and expansion of the polar vortex in higher latitudes, with enhanced winter monsoon intensities.

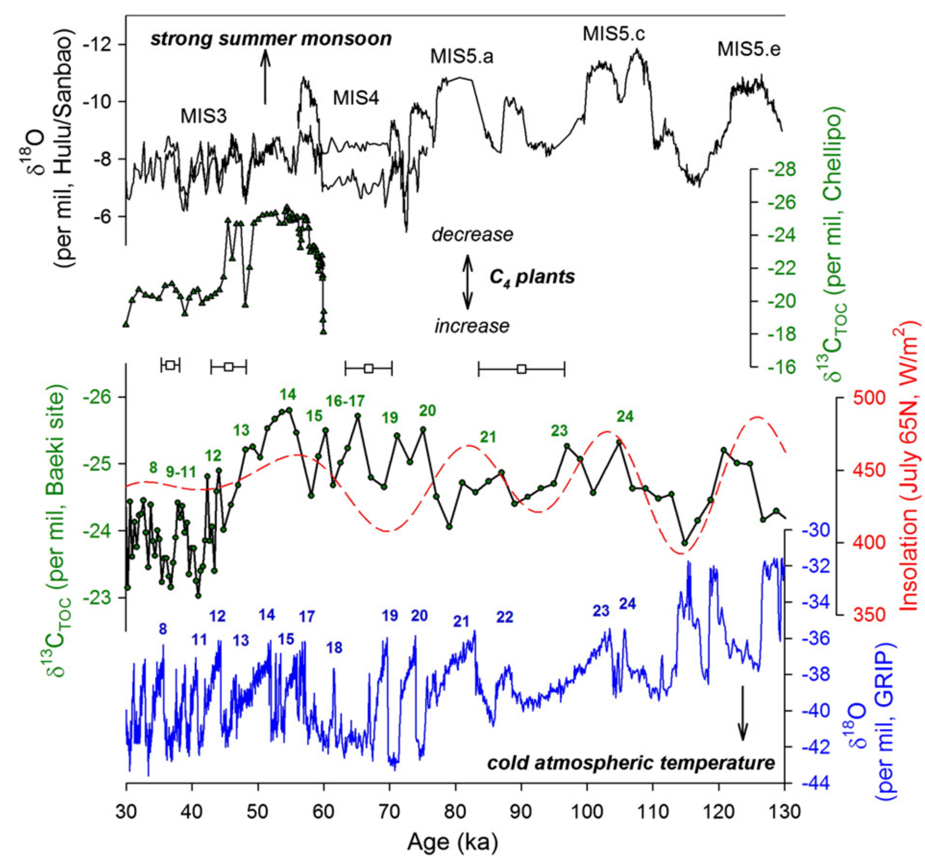

Figure 4. Comparison of vegetation signals in the Hongcheon ($\delta^{13}C_{TOC}$) and Cheollipo areas ($\delta^{13}C_{TOC}$) (Lim et al., 2010), Korea, with the East Asian monsoon proxy (Wang et al., 2001, 2008), the Northern Hemisphere summer insolation changes (Berger, 1978), and high-latitude climate change inferred from δ^{18}O values in Greenland ice cores (Dansgaard et al., 1993). To facilitate comparison of the variability on millennial time scales, we assigned numbers from 8 to 24 for δ^{13}C values of total organic carbon for the Hongcheon area, indicating the possible influence of D–O cycles. Squares with error ranges represent OSL age dating points in the sedimentary sequence of the Baeki site in Hongcheon, Korea.

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From the viewpoint of global atmospheric circulation, the fine component of eolian dust deposited on a maar of Jeju Island, Korea, during the last 6500 yr has been used to test the possible climatic linkage between Korea and Greenland (Lim and Matsumoto, 2006, 2008). The results indicated that the variability of the fine quartz flux in Jeju Island on centennial to millennial time scales correspond to the warm/cold atmospheric temperature record from Greenland ice cores, suggesting climatic and atmospheric links to Greenland through the pathway change of the westerlies. Furthermore, Sun et al. (2012) suggest that Atlantic meridional overturning circulation was a driver of the abrupt changes and that the northern westerlies played a role in transmitting this signal from the North Atlantic to the Asian monsoon regions. Thus, the past millennial-scale vegetation changes in the Baeki area of central South Korea during the last glacial period represent the alternation between the stadials and interstadials in Korea, as shown in Figure 4.

During the D–O interstadials the climate in East Asia, including Korea, was dominated by summer-like conditions. The $\delta^{13}C$ values reflecting the vegetational response to regional climate changes during these intervals can be understood in the contexts of competitive responses and C_3 plant-dominated response.

First, it seems that warm and wet climate conditions favor an increase in C_3 plants, and a reduction in the relative abundance of C_4 plants is suggestive of a competitive response between the two plant types. Various areas could respond differently to environmental conditions (e.g., pCO_2, temperature, precipitation, and aridity) (e.g., Cerling et al., 1997; Sage et al., 1999; Huang et al., 2001; Schefuß et al., 2003; Zhang et al., 2003; Huang et al., 2006). Among these, temperature is a particularly critical factor for the growth of C_4 plants (Zhang et al., 2003; Rao et al., 2007). When growing season temperature was higher than 13–15°C, lower pCO_2 and arid conditions favored C_4 expansion, as seen in Africa (Street-Perrott et al., 1997) and Quexil, Mesoamerica (Huang et al., 2001). In contrast, below this temperature threshold, it is likely that C_4 plants were outcompeted by C_3 plants despite lower pCO_2 and increased aridity, as seen in areas of the Chinese Loess Plateau (Zhang et al., 2003) and Lake Baikal (Brincat et al., 2000). Lim et al. (2010) demonstrated that C_4 plants in the Cheollipo area, located on the western coast of Korea during MIS 3, may have responded more sensitively to the intensity of the summer monsoon and suggest that C_4 plants may have been controlled by aridity changes driven by summer monsoon changes. This differs from the high-latitude regions, where low growing-season temperatures may have suppressed the aridity influences. This present study, performed in the Hongcheon area located in the inner part of central Korea, confirms the results of previous studies showing that the relative abundance of C_4 plants in Korea during MIS 3 was generally negatively correlated with summer monsoon strength, further suggesting possible links to the millennial-time scale D–O cycles during MIS 5–MIS 3.

Secondly, physiological responses of C_3 plants should be considered. Yamamoto et al. (2010) found significant changes in carbon isotope values in plant wax biomarkers since 16 ka in the Hani peat sequence of northeast China. The $\delta^{13}C$ values of *n*-alkanes varied from −36.6 to −30.7‰, indicating that organic-matter delivery to this peatland was almost certainly dominated by C_3 vegetation despite significant paleoclimatic changes. Furthermore, this study has attributed changes in $\delta^{13}C$ values of *n*-alkanes to changes in the composition of the plant community forming the *n*-alkanes in response to climate change (e.g., summer monsoon strength). This suggests that the possible impact of different assemblages of C_3 plants in East Asia should be considered when the carbon isotope values vary within the isotopic range of C_3 plants.

In some areas (e.g., northwestern Europe), the $\delta^{13}C$ values of sedimentary organic matter in loess sequences changed between −26‰ and −23‰ during the last climatic cycle, suggesting that vegetation predominantly followed a C_3 photosynthetic pathway (Hatté et al., 2001; Hatté and Guiot, 2005). This variability has been noted to be very similar and contemporaneous to some D–O cycles as recorded in Greenland ice cores. Furthermore, $\delta^{13}C$ of loess organic matter has been used as a proxy for paleoprecipitation, and atmospheric connections with the behavior of the Greenland ice sheet have been demonstrated by matching D–O events with precipitation increases of around 100–200 mm/yr (Hatté et al., 2001; Hatté and Guiot, 2005).

Consequently, it is likely (1) that the $\delta^{13}C$ values of −26‰ to approximately −23‰ from the Baeki site can be attributed to a result of the relative contribution of C_3 and C_4 plants and/or the physiological responses of C_3 plants in response to past climate changes; and (2) that C_3 plants (e.g., forest and steppe ecosystems) dominated the Baeki site throughout the history recorded in its sediment sequence. Superimposed on the long-term variation in the $\delta^{13}C$ values was a high-amplitude fluctuation (−1‰ to approximately −1.5‰), suggesting possible significant extrinsic variability as a response to millennial-scale atmospheric circulation changes (D–O events) in the Northern Hemisphere.

Lastly, from the viewpoint of the long-term climate/environment change, the $\delta^{13}C$ values in MIS 4 indicate similar or higher than those in MIS 5, suggesting smaller amount of C_4 plants and warmer and/or wetter climate in the Hongcheon area. This variation is different from the previous vegetation and climate changes in East Asia and should be tested in other sites in Korea to determine its specific meaning. Regarding to the short-term change, further studies with higher sampling resolution and more OSL dating points are necessary to test the possible synchronicity and elucidate extrinsic millennial-scale variability in the context of possible Atlantic meridional overturning circulation and resultant atmospheric circulation changes (Fang et al., 1999; Rohling et al., 2003; Ijiri et al., 2005; Sun et al., 2012).

Conclusions

Our results suggest that East Asian monsoonal changes linked to D–O events are the main factors controlling the millennial-scale vegetation changes at the Baeki site, Hongcheon, central Korea, for the period between 30 and 90 ka. As shown from the comparison, the millennial-scale increases/decreases in the $\delta^{13}C$ values during the weakened/intensified summer monsoon periods generally corresponded to the D–O stadials/interstadials. Results of this study support previous studies performed in the western coastal area of Korea. The two data sets suggest that long-term vegetation change in west and central Korea was controlled by insolation changes coupled with sea-level changes and continental ice volume in the Northern Hemisphere. More specifically, this study suggests the possibility of synchronous climate change on millennial time scales between Korea and Greenland during the late Pleistocene.

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