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Middle Holocene environmental change in central Korea and its linkage to summer and winter monsoon changes

Jaesoo Lim [a], Dong-Yoon Yang [a,*], Jin-Young Lee [a], Sei-Sun Hong [a], In Kwon Um [b]

[a] Geological Research Division, Korea Institute of Geoscience and Mineral Resources, Daejeon 305-350, Republic of Korea
[b] Petroleum & Marine Research Division, Korea Institute of Geoscience and Mineral Resources, Daejeon 305-350, Republic of Korea

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ABSTRACT

To trace the surficial responses of lowlands to past climate change, we investigated $\delta^{13}C$ in total organic carbon (TOC), C/N ratios, magnetic susceptibility (MS), and silicon (Si) intensity (directly proportional to concentration) in wetland sediments collected from the Gimpo area of central Korea, covering 6600–4600 cal yr BP. Two organic layers with high TOC%, negatively depleted $\delta^{13}C_{TOC}$ values (−27 to −29‰), low MS values, and low Si intensities were found at 6200–5900 and 5200–4800 cal yr BP, respectively. These middle Holocene wet periods corresponded to relatively intensified summer monsoon and solar activity periods. The intervening dry period (5900–5200 cal yr BP) with high MS, high Si, and low TOC% corresponded to an intensified dust-activity interval and stronger winter monsoon. This multi-centennial climatic fluctuation of wet periods (6200–5900 cal yr BP and 5200–4800 cal yr BP) and an intervening dry period (5900–5200 cal yr BP) in central Korea was more synchronous with climate change in the arid inner part of China than with that in South China, suggesting possible strong high-latitude-driven climatic influences (e.g., North Atlantic cooling events) during the middle Holocene.

Introduction

The Korean Peninsula is located in a transitional climate zone characterized by both oceanic and continental climate influences, a moist subtropical climate in southern Korea and a moist continental climate in northern Korea, and distinctive seasonal temperature and precipitation controlled by the East Asian summer and winter monsoons. In summer, humid and warm southwest winds driven by the North Pacific High flow over Korea. In winter, dry and cold northeast winds generated by the Siberian High are dominant. These monsoons are considered the main factors controlling landscape evolution, including geomorphological and vegetational change in East Asia (An, 2000). To trace the relationship between climate change and environmental change in East Asia, previous studies have used various proxies including pollen (e.g., Xiao et al., 2004; Yi et al., 2008; Jun et al., 2010), oxygen/carbon isotopes of stalagmites from caves (e.g., Dykoski et al., 2005; Wang et al., 2005; Jo et al., 2011, 2014), carbon isotopes of sedimentary organic matter (e.g., Zhong et al., 2010; Lim et al., 2012; Xue et al., 2014), eolian dust (e.g., An et al., 1991a; Porter and An, 1995; Xiao et al., 1995, 1997; An and Porter, 1997; Lim et al., 2005; Porter and Zhou, 2006), and total organic carbon content (TOC%) and grain size in lake/wetland sediments (e.g., Xiao et al., 2006, 2008, 2009; Yang et al., 2008; Nahm et al., 2011, 2013). Such studies have suggested that changes in the East Asian monsoon at centennial to millennial timescales during the Holocene were significantly influenced by high-latitude climates and low-latitude ocean–atmosphere teleconnections. However, previous studies of central Korea have provided little information about centennial- to millennial-scale variability in natural responses to Holocene climatic changes.

In central Korea, organic (or peat) layers formed intermittently during the Holocene have been reported in various riverside and coastal areas, implying remarkable surficial changes in lowland areas (Hwang et al., 1997; Hwang, 1998; Yang et al., 2008; Yi et al., 2008; Jun et al., 2010; Nahm et al., 2011, 2013). The presence of these organic layers is indicative of environmental/vegetational changes influenced by climatic and hydrological changes and sea-level transgression/regression. The cited studies confirmed the existence of the organic layers, but the details of their formation and the related local/regional climatic changes at multi-centennial timescales have yet to be investigated.

The formation of organic layers and accompanying environmental changes can be traced by environmental proxies. Coupled $\delta^{13}C$ of TOC and C/N ratios provide organic source information, which is usually linked to photosynthetic pathways and habitat conditions (e.g., aquatic or terrestrial) (Meyers, 1994, 1997; Aucour et al., 1999; Huang et al., 2001; Nordt et al., 2002; Lamb et al., 2006; Lim et al., 2010, 2012; Xue et al., 2014). According to their carbon fixation pathways, terrestrial plants are divided into two groups, C_3 and C_4 plants. All trees and cold-season grasses/sedges use the C_3 pathway, whereas warm-season grasses/sedges use the C_4 pathway. These C_3 and C_4 plants can be distinguished clearly by their carbon isotope ratios ($^{13}C/^{12}C$). C_3 plants have mean $\delta^{13}C$ values of -27 ± 2.0‰, and C_4 plants have mean values of

* Corresponding authors. Fax: +82 42 868 3037.
E-mail addresses: limjs@kigam.re.kr (J. Lim), ydy@kigam.re.kr (D.-Y. Yang).

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−13 ± 1.2‰ (O'Leary, 1981, 1988; Tieszen, 1991). However, because the δ^{13}C values of freshwater plants and C_3 plants are within the same range, C/N ratios must be used to distinguish these types of plants. Freshwater plants predominantly have atomic C/N ratios between 4 and 10, whereas terrestrial plants have relatively high C/N ratios of more than 20 because they are composed mainly of lignin and cellulose, which are nitrogen poor, though in the geologic record, C/N values may be partly dependent on the degree of preservation (Meyers, 1997; Lamb et al., 2006 and references therein).

The δ^{13}C values of organic matter in sediments have been used to reconstruct past local or regional plant communities in various areas because of their unique physiological responses to climate change (Sukumar et al., 1993; Cerling et al., 1997; Huang et al., 2001; Nordt et al., 2002; Vidic and Montañez, 2004; An et al., 2005; Lim et al., 2012; Xue et al., 2014). For example, Sukumar et al. (1993) studied vegetation changes during the past 20 ka in low-latitude tropical areas. They found that the δ^{13}C of peat sediments in southern India fluctuated between −12.8‰ and −24.2‰ and inferred that increased C_3 vegetation corresponded to an intensified summer monsoon and that C_4 vegetation increased under more arid and low-moisture conditions. Recently, similar results were reported from a peat sequence in the tropical Leizhou Peninsula, South China (Xue et al., 2014). Lower δ^{13}C values indicating more C_3 plants generally occurred during Marine Oxygen Isotope Stage 3 (MIS 3), whereas C_4 plants with higher δ^{13}C values dominated during MIS2. Furthermore, Xue et al. (2014) showed several short positive excursions of δ^{13}C values, suggesting short-term expansion of C_4 plants during cold events (the Younger Dryas and Heinrich events 1–4). At Jeju Island, Korea, Lim and Fujiki (2011) found significant changes in δ^{13}C values of wetland sediments through the past 6500 yr and suggested that changes in humidity on the island linked to regional climate change were the main factors controlling the isotopic value.

The goal of this study was to specify the formation process of organic layers in wetland sediments in central Korea using environmental proxies (e.g., δ^{13}C, C/N ratio, MS, and Si intensity), investigate their linkage to regional climate on a multi-centennial timescale, and describe climatic features of central Korea in terms of regional climatic changes and solar activity.

Sampling site and methods

The Gimpo area, located in central Korea (Fig. 1), has annual precipitation of ~1450 mm, half of which occurs during a rainy season known as the Jangma season (July to August) (Fig. 2). The catchment of the Gulpo River, a small tributary of the Han River, central Korea (Figs. 1 and 2), is underlain by various rock types, including Precambrian metasedimentary rock, mica gneiss, biotite gneiss, quartz schist, and Jurassic granites. Quaternary alluvial deposits are present widely along the river. Topographically, the study area is situated in a small basin surrounded by low mountains and the coring site is located on a distant floodplain including wetlands in the lower part of the Gulpo River. Recently the floodplain has been leveled and cultivated, and the near-surface sediments in the area have been disturbed.

The present lowland vegetation in the Gimpo area and its surrounding areas is characterized by different species at different sites (Chang and Lee, 1983a,b). For example, herbaceous C_3 plants (especially *Phragmites longivalvis*) is dominant along rivers, but the abundance of C_4 flora, dominantly herbaceous plants including *Miscanthus sinensis* and *Arundinella hirta*, is 23–26% in grasslands. In farmlands, the percentage of C_4 flora is 60%, with *Setaria viridis* being the dominant species (Chang and Lee, 1983a,b). As shown in Figure 1, the sampling site (Osei wetland; 37°32′ N, 126°48′ E) at an elevation of 7 m was located in an area of lowland that has included floodplain and swamp areas in the past.

Sediment cores 2 m in length were recovered using a peat core sampler, and the cores were subsampled at 1-cm intervals. We performed ^{14}C dating on plant fragments and humic materials at the accelerator mass spectrometry (AMS) facility of the Korea Institute of Geoscience and Mineral Resources (KIGAM). Magnetic susceptibility (MS) was measured using a Bartington MS2 system (Bartington Instruments, Ltd., UK).

To obtain semi-quantitative elemental information, X-ray fluorescence (XRF) analyses of the cores were performed using an ITRAX core scanner (Cox Analytical Systems, Sweden) at KIGAM. This device allows non-destructive extraction of near-continuous records of variations in elemental concentrations from sediment cores (Croudace et al., 2006; Löwemark et al., 2011). Measurement was performed at 35 kV and 35–40 mA with a Mo-tube using a scanning time of 10 s and a resolution of 2 mm. The peak intensity of different elements (e.g., Fe, Si, and Zr) was expressed as counts per second (cps).

For grain-size analysis of lithogenic minerals, about 300 mg of dry sample was treated with 35% H_2O_2 to decompose organic matter and then boiled in 1N HCl for 1 h to remove carbonates and iron oxides. After rinsing with distilled water, the samples were treated with an ultrasonic vibrator for 15 s to keep them in suspension and facilitate dispersion. Grain-size analysis was then performed using a Mastersizer 2000 laser analyzer (Malvern Instruments, UK).

For TOC and total nitrogen (TN) analyses, ~0.3 g of bulk subsample was treated with 1N HCl at ~100°C for 1 h and then rinsed with distilled water. Approximately 3–5 mg of the HCl-treated subsample was then loaded into a tin combustion cup. TOC and TN were determined using a CHN elemental analyzer (vario Micro cube; Elementar, Germany). Stable carbon isotope (δ^{13}C) analyses of the HCl-treated subsamples were performed using a continuous-flow isotope ratio mass spectrometer (Isoprime100; G. V. Instruments, Manchester, UK) coupled with a CHN elemental analyzer (vario Micro cube). The results are expressed in delta (δ) notation relative to the Vienna Pee Dee Belemnite standard (V-PDB). The reference material used was IAEA-CH6 sucrose (δ^{13}C = −10.45 ± 0.033‰) obtained from the International Atomic Energy Agency (IAEA). Replicated analyses had better than 0.2‰ precision.

Results

Dating results

The ~2-m-long core from the wetland consisted of three units (Fig. 3). The bottom part (Unit 1) of the core extending from ~193 to 140 cm depth consisted of grayish-yellow silty sediments. The middle part of the core (Unit 2) extending from ~140 to 40 cm was dark-gray silty sediments with abundant plant remains, and the upper part (Unit 3) from ~40 to 0 cm was mostly dark-brown silty sediments disturbed by reclamation. Units 1 and 2 of this sediment core were deposited during the late Pleistocene and middle Holocene, as shown by the AMS ^{14}C dating results (Table 1, Fig. 3). To test possible old carbon influence, plants and bulk sediments from the same depth (110 cm) were prepared (Table 1). The difference between the two dating results was ~10 yr, suggesting negligible old carbon effect in this core. The age at the bottom of the core (193 cm depth) was 22,240 cal yr BP, and the sediments at 158 cm depth were deposited around 19,910 cal yr BP, giving an average sedimentation rate of 0.15 mm/yr in the period between these two dates. A hiatus, marked by a significant leap in age, was observed between the late Pleistocene and early Holocene sediments. The uppermost age acquired in this study was 4600 cal yr BP at 44.5 cm depth. The sedimentation rate during the middle Holocene (7000–4600 cal yr BP) was estimated to be 0.447 mm/yr using data of three dates (6060, 5080, and 4600 cal yr BP). The time series shown in Figure 4 covering the middle Holocene (7000–4600 cal yr BP) was established based on this sedimentation rate. The bottom deposits formed in the late Pleistocene were relatively thin, less than 20 cm, and were followed by a hiatus related to past erosion-dominated

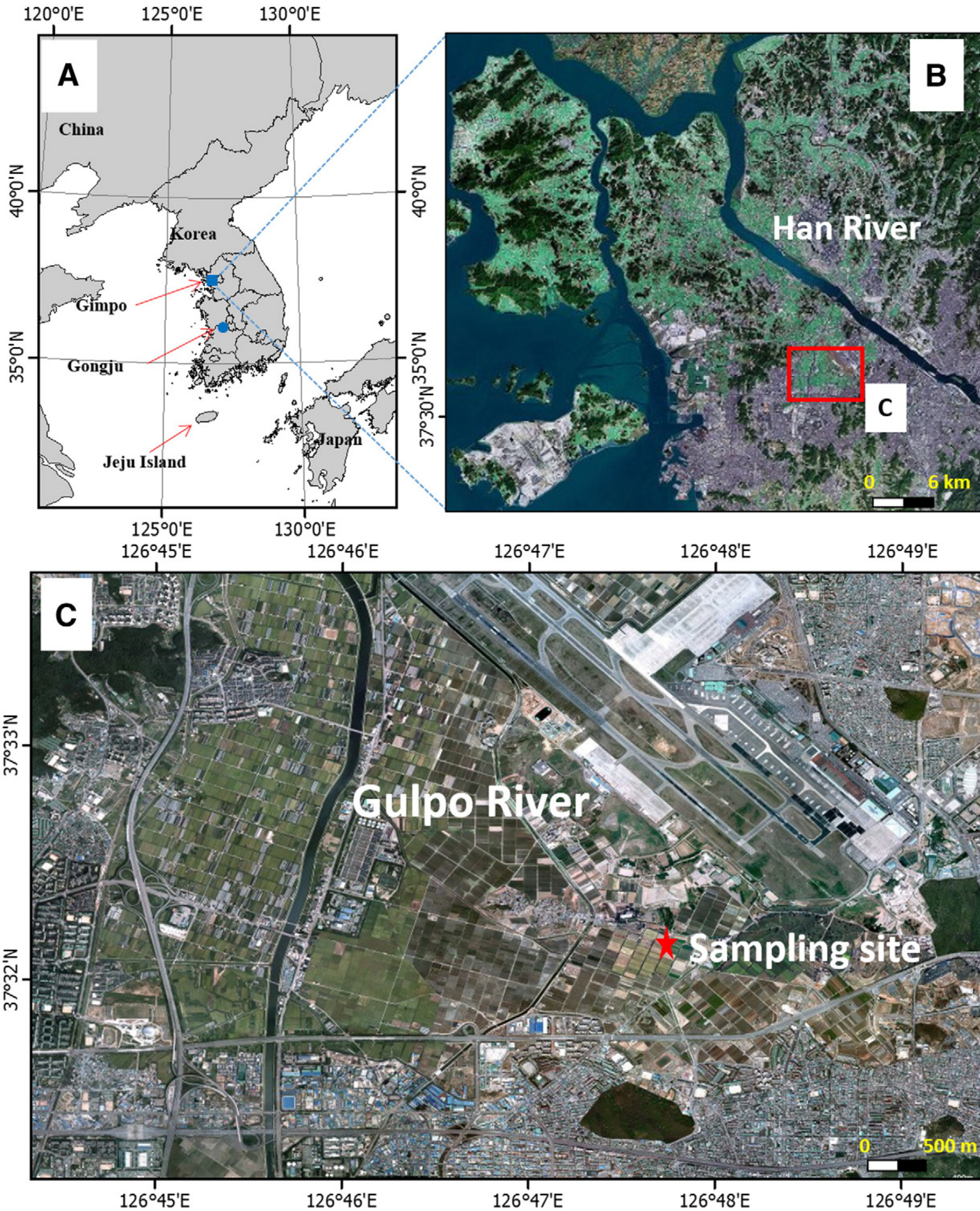

Figure 1. Map showing the study area and the location of the sampling site (Osei wetland) in the Gimpo area of central Korea (B and C, aerial views. Source: Naver Map).

environments. This topic is beyond the focus of this study, so detailed discussion of the bottom deposits (Unit 1) and the hiatus are not included.

Results of biogenic and lithogenic component analyses

As shown in Figures 3 and 4, TOC% in the cores fluctuated significantly, with two large peaks representing two organic layers formed during the middle Holocene. The first peak (organic layer 1) of up to 10% TOC was observed at a depth of about 110 cm, corresponding to ca. 6120 cal yr BP; the second peak (organic layer 2) was observed at a depth of 64 cm, corresponding to ca. 5050 cal yr BP. This pattern of fluctuation was also found in the depth profile of $\delta^{13}C_{TOC}$ values. During the period between 22,240 and 19,910 cal yr BP, the $\delta^{13}C_{TOC}$ value remained stable at between −25‰ and −26‰, except for one peak of −24‰. However, during the middle Holocene, the $\delta^{13}C_{TOC}$ value varied between −29‰ and −23.5‰, with two significant clusters having negatively enriched values of −29‰ to −27‰ at 6200–5900 cal yr BP and 5200–4800 cal yr BP (Figs. 3, 4). C/N ratios in the lower part of the core were more variable and had relatively high values (>20).

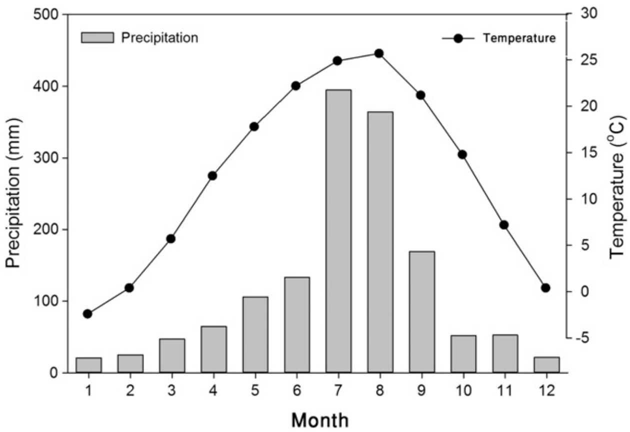

Figure 2. Monthly temperature and precipitation data for the interval 1981–2010, Incheon City (~20 km from the study site), South Korea.

Lower C/N ratios (16–30) occurred in organic layer 1 at a depth of 126–100 cm. These were followed by a rapid increase to a value of 50 in the lithogenic layer with relatively low TOC%. In organic layer 2, C/N ratios were relatively low at 20–34.

The MS values in the sedimentary cores varied between 0 and 100 μSI, and the long-term trend in MS was negatively correlated with TOC%: when MS increased, TOC% decreased, and vice versa (Fig. 3). The changes in the median grain size (MGS) of the lithogenic minerals of the cores were similar to those of MS in Unit 2, but different from those of MS in Unit 3, which was disturbed by reclamation. As a proxy for the lithogenic component (e.g., Liang et al., 2012), X-ray fluorescence (XRF) core scanning results in this study were reported with Fe, Si, and Zr. Although XRF core scanning is affected by several factors, e.g., grain size, density, water content, surface roughness, and gaps or cracks in samples (Croudace et al., 2006; Löwemark et al., 2011), change in the high-resolution dataset (Fe, Si, and Zr) was similar to that of MS. Elemental counts of Si and Zr were relatively very low in the organic layers, but were high in the intervening layer, similar to the trend of MS. Furthermore, this lithogenic layer corresponded to the coarsest mineral interval in the sediments, as shown from the median grain-size data.

Discussion

Significance of the middle Holocene organic layers

In this study, two organic layers, dated at 6250–5900 and 5200–4800 cal yr BP, respectively, were identified (Figs. 3, 4). The formation of the organic layers and the controlling factors can be traced by examining the meaning of the environmental proxies: $\delta^{13}C$ values, C/N ratios, MS values, and Si intensity.

The C/N ratios during the middle Holocene in this study varied between 20 and 60. Based on previous studies showing that the C/N ratios of freshwater plants range between 4 and 10 and that terrestrial plants have relatively high C/N ratios >20 (Meyers, 1997; Lamb et al., 2006 and references therein), it is clear that the two organic layers and intervening lithogenic layer were formed mainly with terrestrial plants and that the input of aquatic plants was very limited.

The $\delta^{13}C_{TOC}$ values provided detailed information about the terrestrial plants. By comparing the mean values of terrestrial C_3 plants (-27 ± 2.0‰) and C_4 plants (-13 ± 1.2‰) (O'Leary, 1981, 1988; Tieszen, 1991), the range of $\delta^{13}C$ values from this study, which varied between -29‰ and -23‰, suggests that the organic matter in the wetland sediments was derived mainly from C_3 plants, with only a minor contribution from C_4 plants. For example, the organic layer 1 formed at 6250–5900 cal yr BP had $\delta^{13}C$ values of -28‰ to -26‰, suggesting a predominant input from C_3 plants. In contrast, the sediments formed between 7000 and 6400 cal yr BP displayed higher $\delta^{13}C$ values of -25‰ to -23‰, which may indicate a slightly higher abundance of C_4 plants and a slightly lower abundance of C_3 plants.

These competitive responses of C_3 and C_4 plants have been driven by climate change (e.g., Sukumar et al., 1993; Zhong et al., 2010; Lim and Fujiki, 2011; Xue et al., 2014). Xue et al. (2014) reported several short positive excursions of sedimentary organic $\delta^{13}C_{TOC}$ values in South China and suggested short-term expansion of C_4 plants during cold events (e.g., the Younger Dryas and Heinrich events). Lim et al. (2012) reconstructed the Holocene record of floodplain vegetation change in the Gongju area of central South Korea using $\delta^{13}C_{TOC}$ values and pollen data and suggested that negative/positive excursions of sedimentary organic $\delta^{13}C$ values at millennial timescales were linked to wet/dry intervals. Thus it is likely that the organic layers observed in this study were formed during the period of increased C_3 vegetation corresponding to an intensified summer monsoon and the intervening lithogenic

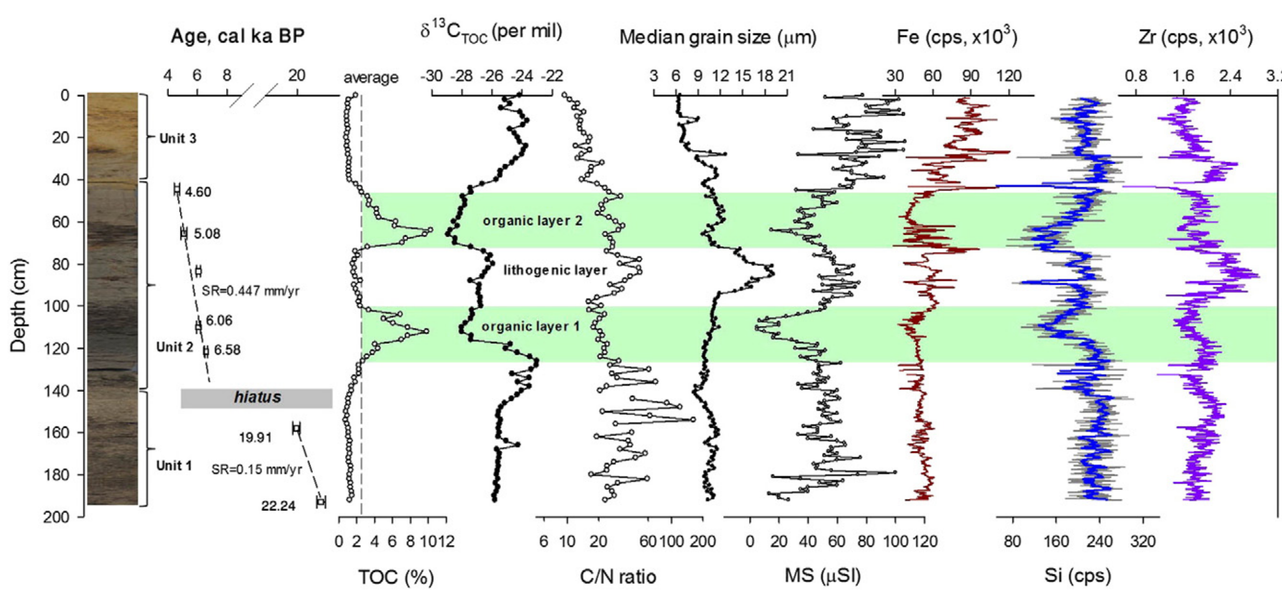

Figure 3. Results of dating and geochemical analyses of wetland sediments in the Gimpo area of central Korea including TOC (%), $\delta^{13}C$ of TOC, C/N ratios, MS, median grain size, XRF core scanning results. (SR—sedimentation rate; TOC—total organic carbon; C/N—carbon/nitrogen; MS—magnetic susceptibility; cps—counts per second).

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Table 1
Results of AMS ^{14}C dating and calibrated dates for Osei wetland sediments in the Gimpo area of central Korea.

Core depth (cm)	^{14}C age ($\pm1\ \sigma$) (^{14}C yr BP)	Calibrated age ($\pm2\ \sigma$) (cal yr BP)[a]	$\delta^{13}C$ (‰)	Lab. code	Dated material
44.5	4030 ± 40	4600 ± 185	−26.7 ± 0.1	ITg120318	Humic
65.5	4440 ± 40	5050 ± 205	−28.4 ± 0.6	ITg120319	Humic
83.5	5280 ± 10	6060 ± 120	−27.8 ± 1.0	ITg120321	Humic
110	5290 ± 40	6065 ± 125	−23.9 ± 0.1	ITg120316	Humic
110	5260 ± 40	6055 ± 130	−28.0 ± 0.3	ITg120317	plants
121	5780 ± 40	6580 ± 100	−24.4 ± 0.8	ITg120320	Humic
158	16770 ± 90	19910 ± 330	−28.8 ± 0.8	ITg120353	Humic
193	18690 ± 110	22240 ± 400	−29.5 ± 1.6	ITg120352	Humic

[a] Calibrated with Radiocarbon Calibration Program (CalPal) (http://c14.arch.ox.ac.uk/embed.php?File=oxcal.html).

layer was formed during the increased C_4 vegetation under low-temperature and low-moisture conditions.

It is worth noting that the $\delta^{13}C$ values in this study (−29‰ and −23‰) are generally within the isotopic range of C_3 plants (−32‰ to −20‰); thus, physiological responses of C_3 plants should be considered. Based on a theoretical viewpoint, humidity conditions can be a main factor controlling the $\delta^{13}C$ values in C_3 plants (Farquhar et al., 1982). For example, increased humidity can induce stomata open longer, increasing the conductance of the leaf stomata, resulting in a drop $\delta^{13}C$ values. Liu et al. (2005) investigated present $\delta^{13}C$ variation of C_3 and C_4 plant in arid northwestern China and showed a negative correlation between $\delta^{13}C$ values of C_3 plants (e.g., *Stipa bungeana*, *Lespedeza* sp. *and Heteropappus less*) and the mean annual precipitation, suggesting a total change of 5‰ and sensitivity of −1.1‰/100 mm. $\delta^{13}C$ values varying between −26‰ and −23‰ in loess organic matter sequences in northwestern Europe were considered to have been derived predominantly from C_3 plants and were tested as a proxy for paleoprecipitation (Hatté et al., 2001; Hatté and Guiot, 2005).

In this study, it is difficult to distinguish clearly between competitive responses and C_3 plant-dominated physiological responses to interpret the meaning of the $\delta^{13}C$ values. However, it is evident in both cases of organic layer that the $\delta^{13}C$ values relate to a similar wetter climatic condition. Therefore, the two organic layers and the intervening lithogenic layer indicate relatively wetter and drier intervals, respectively.

This interpretation for the formation of the two organic layers is supported by previous studies in Korea. At Jeju Island, Korea, Lim and Fujiki (2011) found significant changes in $\delta^{13}C$ values from wetland sediments formed during the past 6500 yr. The $\delta^{13}C$ values in the wetland in the island were compared with pollen data, and an increase/decrease in the $\delta^{13}C$ values was suggested to indicate dryer/wetter climate. As shown in Figure 4, the periods of the organic layers (6250–5900 and 5200–4800 cal yr BP, respectively) observed in this study are consistent with relatively lower $\delta^{13}C$ values in the wetland sediments of Jeju Island. Organic layer 2 corresponds especially with lower $\delta^{13}C$ values in the island, suggesting synchronous wetter climate in the two areas. Furthermore, a long-term decreasing trend in the $\delta^{13}C_{TOC}$ values in the Gimpo area also can be observed in the wetland sediments from Jeju Island. Although clear multi-centennial fluctuations in $\delta^{13}C$ values were not found at Gimpo and Jeju, a similar long-term trend appeared in $\delta^{13}C$ values from the Gongju area. This increasing wetness between 7000 and 4300 cal yr BP in the Gongju area was supported by an increase in aquatic plants as determined from pollen analysis. Based on these facts, the two organic layers formed under a relatively wet climatic condition in central Korea.

The MS signal and Si intensity provided additional information pertaining to the environments responsible for formation of the organic layers. The MS signal was positively correlated with Si intensity but negatively correlated with TOC%. MS has been used as a summer monsoon index because high values are considered to be produced by pedogenesis (An et al., 1991b; Maher, 1998; An, 2000; Hao and Guo, 2005). However, as discussed above, the organic layers with low MS formed under a relatively wet environment, probably linked to an increase in precipitation at that time. Thus, the MS signal could not be related to the summer monsoon at that time. Instead, MS, along with Si and Zr intensity, was high in the intervening lithogenic layer, suggesting that high MS was correlated with a dry climatic condition. Consequently, it is likely that the high signals of MS and Si intensity formed as a result of intensified dustiness rather than by wet conditions. This possible linkage between the lithogenic layer and high dust input is discussed in detail in the following section.

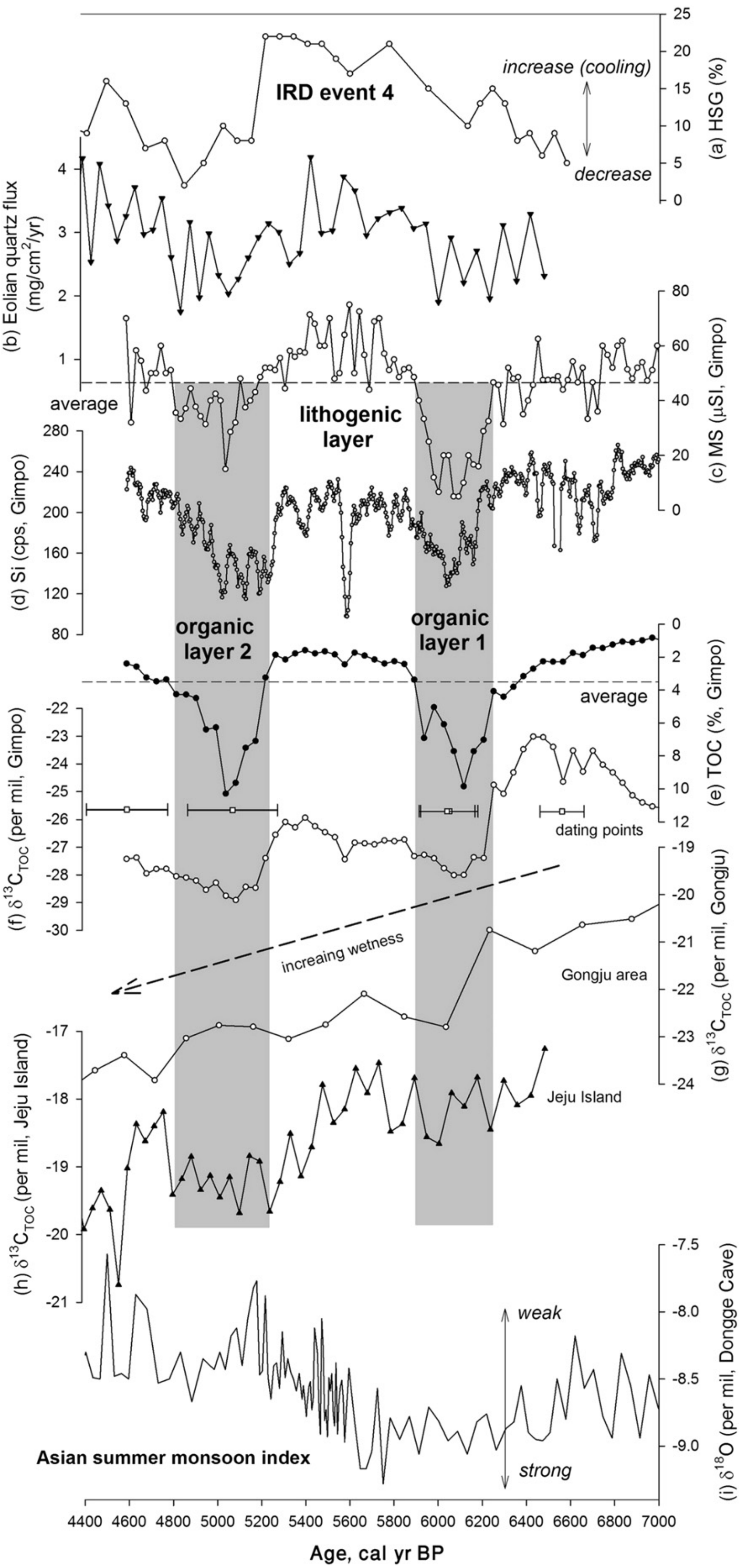
Environmental change in Gimpo during the middle Holocene and its links to summer monsoon change

To examine the behavior of MS, Si intensity, and $\delta^{13}C$ during the middle Holocene in terms of their responses to regional climate change, we compared our datasets with a regional climate index (an aridity index in the inner part of China and the Asian summer monsoon index from South China).

The long-term decreasing trend in the time series of the $\delta^{13}C$ values from central Korea during the period between 7000 and 4400 cal yr BP is different from that of Asian monsoonal precipitation changes inferred from the $\delta^{18}O$ record of stalagmites in Dongge Cave, South China (Dykoski et al., 2005). It is clear that some differences are due to different age control, but this long-term trend cannot be explained in terms of different age control. The difference between the two regions can be attributed partly to the different meanings of the proxies. It is considered that the $\delta^{18}O$ values of speleothems can be influenced not only by the rainfall amount effect but also by changes in moisture source, total vapor flux to the continent, moisture recycling, and temperature (Maher, 2008; LeGrande and Schmidt, 2009; Cai et al., 2010). In the case of the $\delta^{13}C$ of TOC (or reconstructed vegetation change) in this study, vegetation responded to past effective moisture determined by both temperature and precipitation changes. Lastly this difference may partly relate to systematic differences between the East Asian summer monsoon in Korea and possible Indian summer monsoon in South China (e.g., Hong et al., 2005).

Compared with previous studies, the long-term decreasing trend of $\delta^{13}C_{TOC}$ found in the Gimpo area in this study seems to reflect responses to the southward retreat of the East Asian summer monsoon rain belt in a time-transgressive manner (e.g., Lim et al., 2012).

An et al. (2000) traced the spatial and temporal distribution of summer monsoon precipitation in China during the Holocene using geological records including lake levels, pollen, and loess/paleosol and numerical modeling experiments. This study showed that summer solar radiation in the Northern Hemisphere reached a maximum at 11,000–10,000 cal yr BP and this amplified the seasonal contrast, resulting in northward advance of rain belt of summer monsoon into the present arid and semi-arid regions. As Northern Hemisphere seasonality weakened during the Holocene, the northernmost rain belt retreated southward due to resultant weakening of the summer monsoon. Based on this southward shift and geological evidences, they suggested an asynchronous Holocene optimum with maximum precipitation at different times in different regions: 10,000–8000 cal yr BP in northeastern


IRD event 4
increase (cooling)
decrease
(a) HSG (%)
(b) Eolian quartz flux (mg/cm2/yr)
average
lithogenic layer
(c) MS (μSI, Gimpo)
(d) Si (cps, Gimpo)
organic layer 2
organic layer 1
(e) TOC (%, Gimpo)
average
dating points
(f) δ13CTOC (per mil, Gimpo)
increaing wetness
Gongju area
(g) δ13CTOC (per mil, Gongju)
Jeju Island
(h) δ13CTOC (per mil, Jeju Island)
weak
strong
Asian summer monsoon index
(i) δ18O (per mil, Dongge Cave)
Age, cal yr BP

China, 7000–5000 cal yr BP in the middle and lower reaches of the Yangtze River, and 3000 cal yr BP in southern China.

In Korea, the possibility of a latitudinal shift of maximum precipitation and the asynchronous Holocene optimum have been tested very little. In a previous study of the Gongju area, this topic was tested by using $\delta^{13}C_{TOC}$ as a proxy for change in humidity (or aridity) (Lim et al., 2012). Based on a comparison of the environmental stages in the Yugu floodplain in the Gongju area during the Holocene with other climatic reconstruction datasets including summer monsoon intensity in South China (Dykoski et al., 2005), pollen data from the middle and lower reaches of the Yangtze River (Yi et al., 2003), and aridity changes in arid inner parts of China (Lim and Matsumoto, 2006). We hypothesized that vegetation change (or aridity change) in Korea may have been linked weakly to regional climate change during the early to middle Holocene compared with the late Holocene (Lim et al., 2012). This study suggest that the long-term increasing wetness (or effective moisture) in central Korea during the middle Holocene (Fig. 4) was probably the result of southward retreat of the East Asian summer monsoon rainbelt from northern Korea to southern Korea and was different from that in South China. This difference may be attributed to different responses to changing seasonality related to orbital forcing and progressive weakening of the summer monsoon (An et al., 2000).

Unlike the long-term climate change on multi-millennial timescales, relatively short-term multi-centennial fluctuations seem to be correlated with one another. The relatively lower $\delta^{13}C$ values during the formation of organic layer 1 (6250–5900 cal yr BP) were associated with a strong summer monsoon period, which supports the interpretation of a relative increase in C_3 plants and decrease in C_4 plants or a physiological response of C_3 plants in the study area under a wetter climate at that time. In contrast, during the period between 5800 and 5300 cal yr BP, the gradual increases in $\delta^{13}C$ values and MS values are consistent with a gradually weakening summer monsoon, suggesting that the sampling site was dry during this time, resulting in higher MS values and Si intensity, probably caused by increased dust input from local and/or remote areas. Once again, organic layer 2 (5200–4800 cal yr BP), which showed lower MS values, occurred during an interval with an intensified summer monsoon, suggesting wetland expansion.

Environmental change in Gimpo during the middle Holocene and its links to winter monsoon change

It is interesting that the two organic layers at 6200–5900 and 5200–4800 cal yr BP generally correspond to periods of lower eolian quartz flux (EQF) on Jeju Island, Korea (Lim et al., 2005; Lim and Matsumoto, 2006). Based on a comparison of the EQF signal with climatic changes in dust-source areas, it has been suggested that the EQF was influenced by changes in aridity in the dust-source areas. It has been reported that recent frequent dust events have a strong positive correlation with the surface wind velocity (Kurosaki and Mikami, 2003). Liu et al. (2004) suggested that dust activity is negatively correlated with the antecedent summer and annual precipitation and soil moisture anomalies. Thus, the organic layers observed in this study seem to have formed during periods of less dry conditions in the inner part of China, suggesting climatic linkages between central Korea and dust-source areas in China under simultaneous monsoonal circulation changes.

The change in the signal of the lithogenic component (e.g., MS and Si intensity) in this study is similar to that of dust flux on Jeju Island (Fig. 4), supporting a strong climatic connection between the two areas. The higher MS and Si intensity during the period between 5900 and 5300 cal yr BP in this study seem to be related to intensified eolian dust activity in China. A close correspondence between Chinese eolian climate-proxy records and North Atlantic deep-sea records during the Holocene was reported by Porter and Zhou (2006). They showed that the strengthened winter monsoon intervals of enhanced eolian dust activity that resulted in the deposition of loess and eolian sand in the arid to semi-arid transition zone of north-central China were correlated with millennial-scale variations in ice-rafted debris (IRD) in the North Atlantic (Bond et al., 1997, 2001), and suggested that changes in the physical oceanography of the North Atlantic Ocean affect the climate downwind through atmospheric teleconnection or the westerly wind system that passes over the Chinese desert and loess regions (Porter and An, 1995; Porter and Zhou, 2006). Qiang et al. (2014) showed similar results from grain-size data from Genggahai Lake on the northeastern Qiangai–Tibetan Plateau, suggesting intensified eolian activity during weakened summer monsoon periods and its link to cooling events in millennial-scale IRD events in the North Atlantic Ocean. These studies clearly indicated strong dust activity during the period of 6300–5400 cal yr BP.

As shown in Figure 4, the higher MS and increased EQF in Korea during the period between 5900 and 5300 cal yr BP correspond to intensified eolian dust activity in China and IRD event 4 in the North Atlantic Ocean. Thus, based on this dust–climate relationship in China, the climatic change in central Korea characterized by the similarity between the MS and EQF signals was likely significantly influenced by winter monsoon activity coupled with high-latitude climate change. Additionally, the high MS during the period of 5900–5300 cal yr BP, corresponding to the strong dust activity period in China (e.g., Porter and Zhou, 2006; Qiang et al., 2014), was likely influenced by increased dust mineral input to Korea from the inner part of China, and this input could have intensified the MS and Si values.

Therefore, the comparison of the environmental shifts described by variations in $\delta^{13}C$ values, MS, and Si signals in central Korea during the middle Holocene with summer monsoon change in South China and climate change in the inner part of China suggests that climatic variability at centennial to millennial timescales in central Korea during the middle Holocene was strongly coupled to the Asian monsoon systems. This study demonstrated that there were multi-centennial climatic fluctuations of wet periods (6200–5900 cal yr BP and 5200–4800 cal yr BP) and an intervening dry period (5900–5200 cal yr BP) in central Korea and that these periods were more synchronous with climate change in the arid inner part of China than in South China, suggesting possible strong high-latitude-driven climatic influences during the middle Holocene.

Conclusions

This study demonstrated that the observed organic layers formed during the middle Holocene were surficial responses to past regional climate changes. This assertion was supported by good correlations between the environmental proxies (e.g., $\delta^{13}C$ value, MS, and Si intensity) used in this study and changes in summer/winter monsoon activity. Two organic layers with negatively depleted $\delta^{13}C$ values (-27 to -29‰) and low MS values were found at 6200–5900 and 5200–4800 cal yr BP. These periods corresponded to periods of relatively weakened dust activity, intensified summer monsoon, revealing that wetland expansion and organic layer formation in the study area were influenced by regionally wet climate. This result suggests that the centennial-to-millennial climate changes in central Korea, South China, and the inner part of China during the middle Holocene (e.g., 7000–4400 cal yr BP) were strongly coupled.

The reconstructed wet periods (6200–5900 cal yr BP and 5200–4800 cal yr BP) and intervening dry period (5900–5200 cal yr BP) in

Figure 4. Comparison of the time-series of TOC (%), $\delta^{13}C_{TOC}$, MS, and Si intensity in Osei wetland sediments in the Gimpo area of central Korea (c–f) with other climate data: (a) the hematite-stained grains (HSG), expressed as percentages of lithic grains (ice-rafted debris) (Bond et al., 1997, 2001), (b) eolian quartz flux (aridity/winter monsoon index for Asian dust-source areas in arid China) (Lim et al., 2005; Lim and Matsumoto, 2006), (g) $\delta^{13}C_{TOC}$ of floodplain sediments in Gongju area, central South Korea (Lim et al., 2012), (h) $\delta^{13}C_{TOC}$ of wetland sediments in Jeju Island, south coast of Korea (Lim and Fujiki, 2011), (i) the Asian summer monsoon index (Dykoski et al., 2005).

central Korea were more synchronous with climate change in the arid inner part of China than with that in South China, suggesting possible strong high-latitude-driven climatic influences during the middle Holocene. Lastly, this study suggests that past wetland sediments in Korea, including organic layers and eolian dust deposits, provide a suitable archive for understanding past local climate change, which is linked to regional and global climate change, and that these sediments provide a useful opportunity to determine the real climate system over Korea and Asia.

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