Seasonally specific responses of the East Asian monsoon to deglacial climate changes

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ABSTRACT

The deglacial meltwater pulse in the North Atlantic that induced the Younger Dryas event also prompted climate cooling in East Asian monsoon regions such as Japan and coastal mid-latitude China. However, very little is understood about the mechanism that can transmit changes in the North Atlantic to the Far East. Here we show that the shutdown of the North Atlantic thermohaline circulation brought about significantly lower temperatures and higher precipitation in the Japanese winter, whereas the change in the Japanese summer climate was considerably smaller. The cooling of the Siberian air mass seems to have caused an increased pressure gradient between Siberia and the West Pacific in winter, intensifying the winter monsoon. The Mongolian high-pressure system and the westerly jet stream played an important role in the teleconnection. In contrast, the warming at the onset of the late glacial interstadial (GI-1; Bølling-Allerød) in the West Pacific did not have season-specific features, implying that the principal driving mechanism of this warming event may lie in a pan-hemispheric or global factor, such as insolation changes.

Keywords: monsoon, deglaciation, palynology, Younger Dryas, paleoclimatology, seasonal variability.

INTRODUCTION

The Asian monsoon front is an important geoclimatic boundary that divides coastal mid-latitude Asia into two distinct climatic regimes; the area to the northwest of the front is under a strong influence of the Siberian (continental) air mass, which is characterized by low humidity and large seasonal temperature variability, whereas the area to the southeast of the front is governed by the Pacific (oceanic) air mass, which, in contrast, is wet and characterized by smaller seasonal temperature variability. The climate of the West Pacific and coastal East Asia tends to be characterized by clear seasonality because the monsoon front seasonally migrates across these regions (Fukui, 1977) (Fig. 1). Because the seasonal temperature variability is bigger on the continent and smaller on the ocean, the temperature gradient between the two air masses seasonally flips. This generates a surface air-pressure gradient that seasonally changes its direction, which in turn is the driving engine of the NW and SE surface winds in winter and summer (the monsoon), respectively (Fig. 1).

It has been suggested that at least some of the late Pleistocene abrupt climate changes were triggered by the changes in the North Atlantic ocean circulation, which had its effect on a much broader area, including the monsoon regions (Sirocko et al., 1996; Broecker, 1987; Wang et al., 2001; Nakagawa et al., 2003). Studies on the Chinese Loess Plateau have suggested that the influence of the massive surge of icebergs in the North Atlantic (Heinrich Events) is restricted to the west of the monsoon front (An et al., 1991; Porter and An, 1995). As for the deglacial warming episode, attempts have been made to separate seasonal signals on the Chinese Loess Plateau (Zhou et al., 1996, 1999, 2001), as well as in the North Atlantic (Rochon and de Vernal, 1998; Björck et al., 2002; Lücke and Brauer, 2004), the Arabian Sea (Sirocko et al., 1996), and southern China (Sun and Li, 1999). These studies tend to reconstruct colder winter temperatures for the Younger Dryas chronozone, whereas summer precipitation only shows spiky oscillations, and summer temperatures show very weak or even no change. However, the nature and precise mechanism of this teleconnection have not yet been adequately explained.

Here we report quantified reconstructions of seasonal temperatures and precipitation for the Last Termination using pollen data from an-

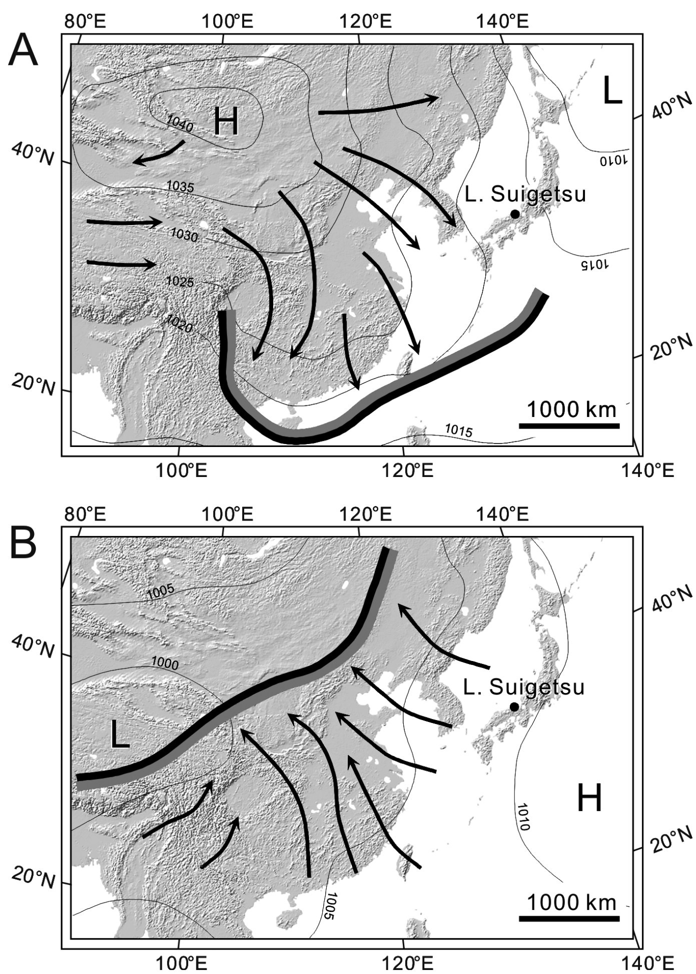

Figure 1. Location of Lake Suigetsu and seasonal change of wind system in East Asian monsoon area. A: January; B: July. Arrows show dominant wind vectors, and bold lines show average position of both winter (A) and summer (B) monsoon limits (modified from Porter and An, 1995).

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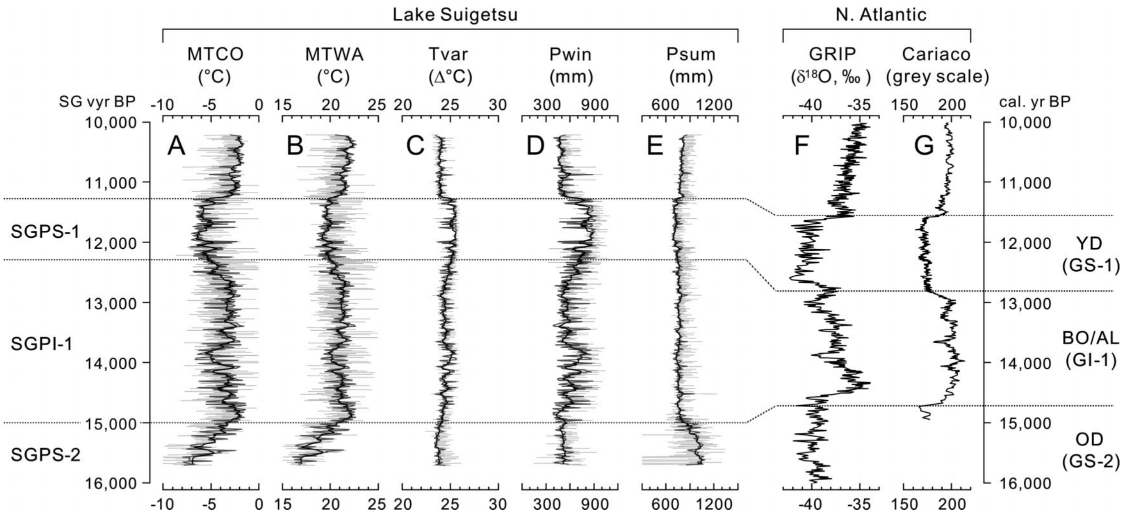

Figure 2. Seasonal climatic properties reconstructed for the Last Termination from the Lake Suigetsu pollen profile, and its correlation to the North Atlantic event stratigraphy (Björck et al., 1998). A: Mean temperature of the coldest month (MTCO). B: Mean temperature of the warmest month (MTWA). C: Seasonal temperature variability (*T*var: MTWA minus MTCO). D: Cumulative precipitation from October to March (*P*win). E: Cumulative precipitation from April to September (*P*sum). F: Variations in the stable oxygen isotope ratios of Greenland Ice Core Project (GRIP) ice core. G: Gray-scale variations in the marine record from the Cariaco basin. (SG vyr B.P. is Suigetsu varve yr B.P.: 0 = A.D. 1950) YD—Younger Dryas; BO/AL—Bølling-Allerød; OD—Older Dryas.

nually laminated Lake Suigetsu, Japan (35°35′N, 135°53′E, 0 m above sea level [asl]) (Fig. 1; GSA Data Repository[1]). Lake Suigetsu is ideally located for reconstructing the behavior of the Siberian air mass, the Pacific air mass, and the monsoon front for the following reasons: First, the lake is located to the north of the monsoon front in winter and to the south of the front in summer. Thus, the winter temperature around Lake Suigetsu represents the temperature of the Siberian air mass, whereas the summer temperature around the lake reflects the temperature of the Pacific air mass. Second, Lake Suigetsu is located on the Sea of Japan coast, which is directly exposed to the winter monsoon from the continent, which blows over the Sea of Japan before arriving at the Japanese archipelago (Fig. 1). Because the surface temperature of the Sea of Japan is relatively high, the cold and dry wind of the winter monsoon assumes a high humidity, and ultimately precipitation, when the monsoon wind arrives at Japan (Fukui, 1997). Unlike the Chinese Loess Plateau, therefore, the winter precipitation at Lake Suigetsu is considered to be the proxy of the winter monsoon intensity. Finally, the summer precipitation represents the summer monsoon intensity, simply because it brings humidity from the Pacific to Japan. In summary, we can use the winter temperature, the summer temperature, the winter precipitation, and the summer precipitation as proxies of the temperature of the Siberian air mass, the temperature of the Pacific air mass, the winter monsoon intensity, and the summer monsoon intensity, respectively.

MATERIAL AND METHODS

A total of 370 pollen sample counts is available from the part of the sequence spanning 15,701–10,217 SG vyr B.P. (Suigetsu varve yr B.P.: 0 = A.D. 1950). The sampling resolution is equivalent to 14.8 yr on average. The chronology of the core has been well established by varve counting and an intensive radiocarbon dating program (Kitagawa and van der Plicht, 1998a, 1998b, 2000). A complete pollen diagram and its description, as well as a full description of the basin and vegetation settings, are provided in a separate paper (Nakagawa et al., 2005). We applied the standard modern analogs technique (Guiot, 1990; Nakagawa et al., 2002) to our pollen data set and quantitatively reconstructed the mean temperature of the coldest month (MTCO), the mean temperature of the warmest month (MTWA), the winter precipitation (*P*win = cumulative precipitation from October to March), and the summer precipitation (*P*sum = cumulative precipitation from April to September). We also calculated the difference between MTWA and MTCO (*T*var) as an indicator of the seasonal temperature variability.

Each fossil pollen spectrum was assigned to the eight closest analogs in the Japanese surface pollen data set ($n = 285$). The similarity coefficient was calculated as the Euclidean metric in the space defined by the 32 taxa proportion that was previously determined to be suitable for biome reconstruction in Japan (Gotanda et al., 2002); i.e.,

$$S_{ij} = \sqrt{\sum_{k=1}^{32} (P_{ki} - P_{kj})^2} \quad \text{and} \tag{1}$$

$$\sum_{k=1}^{32} P_{ki} = 1, \tag{2}$$

where S_{ij} denotes the similarity coefficient between pollen spectra *i* and *j*, and P_{ki} denotes the percentage value of pollen taxa *k* in spectrum *i*. The climatic indices estimated at the eight analog sites were averaged using the reciprocal number of the similarity coefficient as the weight factor, then adopted as the reconstructed climate for the fossil pollen spectrum; i.e.,

$$CR_i = \left(\sum_{j=1}^{8} \frac{1}{S_{ij}} \right)^{-1} \sum_{j=1}^{8} \frac{CE_j}{S_{ij}}, \tag{3}$$

where CR_i denotes reconstructed climate for horizon *i*, S_{ij} denotes similarity coefficient between pollen spectra of fossil horizon *i* and surface site *j*, and CE_j denotes estimated climate at surface site *j* that was determined to be an analog of the fossil spectrum *i* using the similarity coefficient defined by equation 1. We also estimated the potential error range by calculating the variability of climate indices within the eight modern analogs assigned to each fossil spectrum (Guiot, 1990).

RESULTS

The reconstructed changes of MTCO, MTWA, *T*var, *P*win, and *P*sum at Lake Suigetsu from 15,701–10,217 SG vyr B.P. are presented in Figure 2. The results show different patterns of fluctuations for all the reconstructed parameters. Both MTCO and MTWA show cooling during the SGPS-1 biozone (Suigetsu Pollen Stadial-1: Japanese counterpart of the Younger Dryas; Nakagawa et al., 2003). However, the amplitude of the oscillation is different for summer and winter temperatures. The anomaly of MTCO between stadial and interstadial

[1]GSA Data Repository item 2006103, Lake Suigetsu pollen-based quantitative climate reconstruction results against varve age, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

phases in Lake Suigetsu (2–4 °C) is substantially bigger than that of MTWA (0–2 °C). Most of the MTWA oscillations did not exceed the range of the estimated reconstruction error.

Another characteristic of the deglacial climate change in Lake Suigetsu is the increase in *P*win during the stadial phase. *P*win during the stadial phase (SGPS-1) reaches 900 mm or even more, whereas the typical values for the interstadial phase (SGPI-1) are ~400 mm. In contrast, there is no significant change of *P*sum at Lake Suigetsu during the SGPS-1 biozone. It stays at around 700 mm, which is not different from (or even slightly lower than) the *P*sum during the SGPI-I biozone (between 700 and 800 mm).

At the onset of the interstadial phase at ca. 15,000 SG vyr B.P., both summer and winter temperatures rose at the same magnitude (~5 °C). *P*sum decreased, whereas *P*win did not change. These are both significantly different from climate changes at the onset of the cold reversal phase at ca. 12,250 SG vyr B.P.

DISCUSSION

The different amplitude of cooling between summer and winter temperatures during the late glacial cold reversal phase (SGPS-1) can be interpreted as meaning that the cooling of the Siberian air mass related to the North Atlantic Younger Dryas event was more severe than that of the Pacific air mass. This strongly implies that the monsoon front is one of the important paleogeoclimatic boundaries that divided the Northern Hemisphere into more than one block, each of which was characterized by different reactions to the rearrangement of ocean circulation. The supporting evidence for this hypothesis includes the records from the Chinese Loess Plateau (Zhou et al., 1996, 2001), the South China Sea (Rochon and de Vernal, 1998), the Arabian Sea (Sirocko et al., 1996), and Lake Victoria (East Africa) (Stager et al., 1997), which show that the Younger Dryas–like climatic oscillation is either missing or only represented by a short spike of humidity in the regions to the south of the monsoon front. It is also consistent with results of modeling, which suggest that shutdown of the thermohaline circulation results in more severe cooling in Siberia than in the Pacific (Ganopolski and Rahmstorf, 2001) and strengthens the advection of the Siberian air mass in winter (Mikolajewicz et al., 1997).

The seasonally differential fluctuation of precipitation during the late glacial stadial phase can also be explained by the different magnitude of cooling of the two air masses. More severe cooling of the winter Siberian air mass must have generated a stronger temperature gradient between the Eastern Eurasia and the Pacific during winter. This greater temperature gradient brought about a steeper surface air-pressure gradient, and resulted in the intensification of the winter monsoon, which was responsible for more active vapor transport from the Sea of Japan and higher winter precipitation around Lake Suigetsu.

In contrast, the land-ocean temperature gradient in summer was not enhanced by the cooling of the Siberian air mass, resulting in no change or even slight decrease of summer precipitation. This is in accordance with curves reported from the North Atlantic (Björck et al., 2002; Lücke and Brauer, 2004) and the Chinese Loess Plateau (Zhou et al., 2001), where summer temperature changes during the Younger Dryas period were not very significant, as well as in Lake Suigetsu. This does not agree with records from Inner Mongolia (Mikolajewicz, et al., 1997), the western part of the Chinese Loess Plateau (Fang et al., 1999; An et al., 1993), and Qinghai Lake (Kelts et al., 1989), which show oscillations of summer precipitation that correspond to the Younger Dryas. Given that these sites are very close to the present northeastern limit of the monsoon front migration, we assume that the summer precipitation signals in these sites are very sensitive to the change of the frequency of the years in which the monsoon front reaches the sites. When the Siberian air mass becomes cold during the Heinrich events, the Mongolian high-pressure system becomes stronger and pushes the monsoon front southward (Zhou et al., 1996, 1999), in which case these localities are more frequently out of the reach of the monsoon. This process was only important in the area close to the monsoon limit, but did not cause significant changes in the Japanese summer regime.

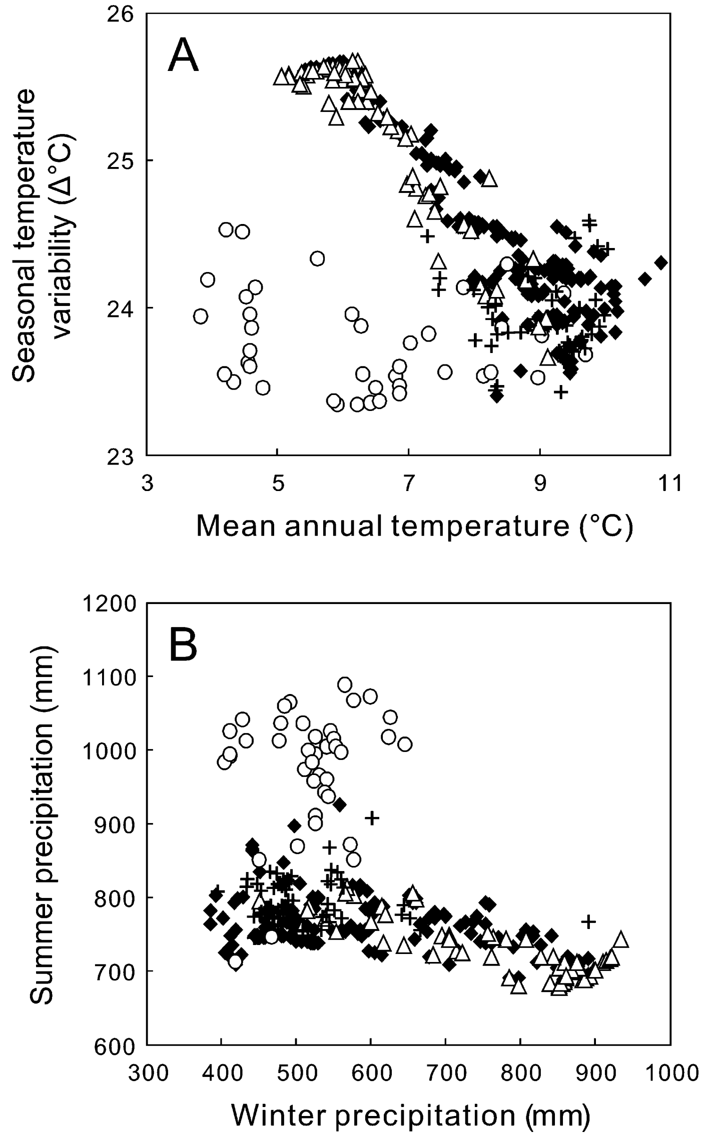

Figure 3. Relationships between typical climatic parameters reconstructed for the Lake Suigetsu profile. A: Seasonal temperature variability versus mean annual temperature. B: Summer precipitation versus winter precipitation. Open circles: earlier than 15,000 SG vyr B.P.; solid diamonds: 15,000–12,300 SG vyr B.P.; open triangles: 12,300–11,250 SG vyr B.P.; crosses: later than 11,250 SG vyr B.P. (SG vyr B.P. is Suigetsu varve yr B.P.: 0 = A.D. 1950).

The mechanism responsible for the climate changes toward the interstadial (ca. 15,000 SG vyr B.P.) was different from that of the cold reversal, as is clearly expressed by the change in the relationships between climatic parameters at this transition (Fig. 3). Probably the warming toward the interstadial was driven by a factor that is not specific to the circum-Atlantic area and the Siberian air mass, for example, insolation changes. Summer precipitation seems to have decreased at the stadial-interstadial transition. However, the peak of the summer precipitation before 15,000 SG vyr B.P. could have been a very short-lived one, as the study on the longer pollen profile from Japan shows that the general trend of the deglaciation was the change from the full-glacial drier condition to the Holocene-like wetter condition (Yasuda, 1982; Nakagawa et al., 2002). The mechanism for such a high-frequency change, if it exists, still remains unknown.

It has been suggested that El Niño–like sea-surface temperature

(SST) distribution patterns in the tropical Pacific may have been responsible for generally weaker monsoons and trade winds during the stadial phase (e.g., Zhou et al., 2001; Wang et al., 2001; Altabet et al., 2002). The behaviors of both tropical Pacific SST and the Pacific gyre are closely linked to orbital and solar forcing (Clement et al., 2000; Beaufort et al., 2001; Yamamoto et al., 2004), and may well have controlled the climate of the West Pacific through the heat transported by the Kuroshio Current (Jian et al., 2000; Yamamoto et al., 2004). Such a mechanism may explain the changes that we observe at ca. 15,000 SG vyr B.P. in the Lake Suigetsu profile. In contrast, the Younger Dryas episode has its origin in the North Atlantic and, according to our results, had stronger influence on the Siberian air mass than on the Pacific air mass. This implies that the teleconnection between the North Atlantic circulation and the Asian monsoon does not necessarily require the Pacific SST as the propagation mechanism. More likely, the Mongolian high-pressure system and the westerly jet played a more important role in connecting western and eastern margins of the Eurasian continent.

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