Journal of Asian Earth Sciences 40 (2011) 1214–1220

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Millennial-scale oscillations of the westerly jet path during the last glacial period

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ARTICLE INFO

Article history:
Received 30 October 2009
Received in revised form 25 August 2010
Accepted 31 August 2010
Available online 9 September 2010

Keywords:
Dansgaard–Oeschger cycles
Aeolian dust
Westerly jet
East Asian summer monsoon
Japan Sea
ESR

ABSTRACT

It has been established that East Asian summer monsoon intensity varies with Dansgaard–Oeschger cycles, suggesting a connection between the climates of East Asia and the North Atlantic on a millennial timescale. However, the dynamics of such a connection are still unsolved. Here we demonstrate that temporal changes in the provenance of aeolian dust in Japan Sea sediments, which we interpret to reflect changes in the westerly jet path over East Asia, exhibit variations in harmony with Dansgaard–Oeschger cycles. The dominance of dust with a Mongolian Gobi provenance during stadials suggests a westerly jet axis located to the south of the Himalaya–Tibetan Plateau throughout most of the year, whereas the co-dominance of dust from both the Taklimakan Desert and the Mongolian Gobi during interstadials suggests that the westerly jet axis jumped to the north of the Tibetan Plateau at latest in summer. As the shift of the westerly jet axis to the north of the Tibetan Plateau is closely related to the onset of the East Asian summer monsoon, changes of the westerly jet path apparently critically affect the teleconnection between the climates of Asia and North Atlantic on a millennial timescale.

1. Introduction

Abrupt changes in the East Asian summer monsoon (EASM) intensity in association with Dansgaard–Oeschger (D–O) cycles have been well demonstrated by variations in the oxygen isotope ratio of stalagmites in southern China (Wang et al., 2001) and the grayscale profile of hemipelagic sediments from the Japan Sea (Tada et al., 1999; Tada, 2004). Recently, an ultra-high-resolution study of a Greenland ice core has suggested that decreases in the aeolian dust flux from mid-latitude Asian deserts may have approximately coincided with the temperature shifts at the onsets of the Bølling–Allerød, the Pre-Boreal, and a prominent D–O interstadial, or may even have preceded them by several to 10 years (Steffensen et al., 2008; Thomas et al., 2009). These findings suggest the presence of a direct linkage of millennial-scale climate changes between Asia and the North Atlantic. Thus, it is important to clarify the dynamics of that climate linkage.

At present, the westerly jet (WJ) path over East Asia may be a dominant factor determining the position of the EASM rain band (Liang and Wang, 1998; Sung et al., 2006; Sampe and Xie, 2010). Because of the topographic barrier of the Himalaya–Tibetan Plateau, the 500-hPa WJ axis passes to the south of the Himalayas in spring, and then jumps to the north of the Tibetan Plateau in early summer (Schiemann et al., 2009) (Fig. 1). Sampe and Xie (2010) recently demonstrated clearly a relationship between the WJ and the EASM rain band: the emergence of the latter is triggered by the jump of the westerly jet axis to the north of the Tibetan Plateau, and the rain band migrates northward and then disappears as a result of the northward migration of the westerly jet axis during summer. Moreover, the WJ path over the North Atlantic is closely linked to the North Atlantic climate; the WJ causes a front to develop that brings high precipitation, and the WJ path is largely controlled by the sea-ice extent and the meridional gradient of sea surface temperature (Laîné et al., 2009).

By analogy with the present close linkage of the WJ path with both the position of the EASM rain band (Liang and Wang, 1998; Sung et al., 2006; Sampe and Xie, 2010) and the climate of the North Atlantic region (Laîné et al., 2009), it can be inferred that dynamic changes of the WJ path may have played a critical role in linking the millennial-scale climate changes of East Asia and the North Atlantic in the past (Tada, 2004). This possibility is supported by the $\delta^{13}C$ and $\delta^{18}O$ records of benthic foraminifers from the Mediterranean Sea (Cacho et al., 2000; Moreno et al., 2002), which suggest that the WJ path over the North Atlantic region

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doi:10.1016/j.jseaes.2010.08.010

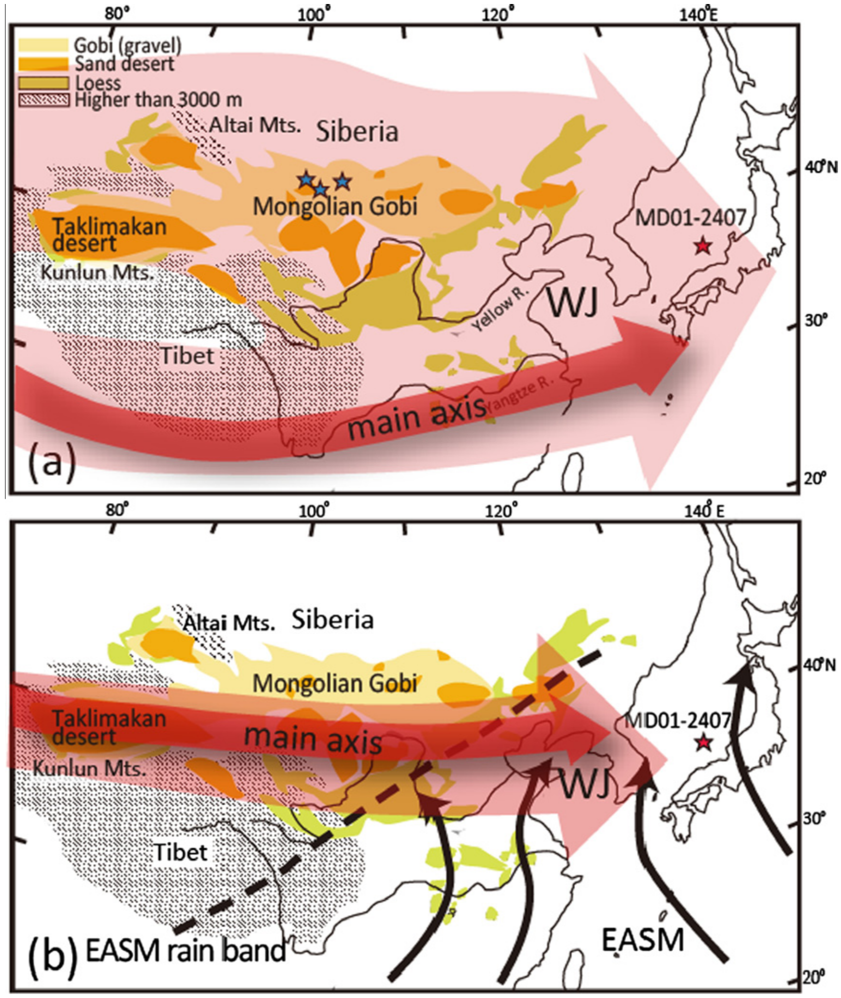

Fig. 1. Maps showing atmospheric circulation patterns over East Asia in (a) spring and (b) summer associated with the WJ (light pink arrows; areas where jet occurs frequently. Dark pink arrows; areas where jet occurs most frequently. Both are modified after Schiemann et al. (2009), of its data from 40-year ECMWK re-analysis data), surface winds of the EASM (black arrows), and the EASM rain band (dotted line). Also shown are the location of core MD01-2407 (red star), sampling sites in the Mongolian Gobi (blue star in a), and the distributions of loess and major deserts in central and eastern Asia, adapted from Sun et al. (2007).

varied in association with D–O cycles. However, millennial-scale changes of the WJ path over East Asia have not yet been demonstrated. Thus, we reconstructed variations in the WJ path over East Asia during the last glacial period by examining the provenance and grain size of aeolian dust in a sediment core obtained from the Japan Sea and investigated the possible role of the WJ path in linking millennial-scale climate changes between East Asia and the North Atlantic.

At present, a substantial amount of aeolian dust is emitted from the extensive dry areas of East Asia: along the northern margin of the Tibetan Plateau, in particular, the Taklimakan Desert; and in the higher latitude area of Siberia–Mongolia–Northeast China, in particular, the Gobi Desert in southern Mongolia (hereafter, Mongolian Gobi) (Sun et al., 2001; Zhao et al., 2006). Dust emission from both the Mongolian Gobi and the Taklimakan Desert is most frequent in spring owing to the weakening of the Siberian High and the large temperature gradient that develops between high and middle latitudes, which permit the vertical displacement of the air mass (Roe, 2009). In this season, the WJ most frequently appears to the south of the Himalayas but meridional dispersion of the jet is so strong that the WJ also frequently appears to the north of the Tibetan Plateau attains to 50°N, which exerting a broad influence at high latitude (Fig. 1a) (Schiemann et al., 2009). This northward extent of the WJ is an additional important prerequisite for dust emission at the Mongolian Gobi and the Taklimakan Desert in spring because the high-latitude WJ is closely related with the polar front, with its associated wave activities (Machalett et al., 2008), and trough of the wave brings cold, dry air from Siberia to these deserts, causing large-scale windstorms (Roe, 2009). Dust emitted from the Mongolian Gobi is dominantly transported to proximal to intermediate regions by near-surface northwesterly winds (Sun et al., 2001; Zhao et al., 2006), although sometimes the dust is lifted up to the high altitude of the WJ and transported for longer distances (Sun et al., 2001; Zhao et al., 2006). In contrast, dust from the Taklimakan Desert is typically lifted up to altitudes exceeding 5 km by the northeasterly surface winds blowing against the northern margin of the Tibetan Plateau and transported long distances via the WJ (Sun et al., 2001; Seino et al., 2005).

During summer, on the other hand, the frequency of dust emission from the Mongolian Gobi is low because the atmosphere at high latitudes has warmed up and the resulting small temperature gradient between high and middle latitudes diminishes the frequency of the windstorms (Roe, 2009). Moreover, in this season, the WJ axis jumps to the north of the Tibetan Plateau and the WJ meridional distribution is concentrated within a narrow band at the northern edge of the Tibetan Plateau (Schiemann et al., 2009), which suppresses the entrainment of cyclonic activity from high latitudes to the Gobi Desert. However, the frequency of dust