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Quantitative reconstruction of paleoclimate in central Japan for the past 158,000 years based on a modern analogue technique of pollen composition

Tomohiko Kigoshi [a], Fujio Kumon [b, *], Sayuri Kawai [c, 1], Atsuko Kanauchi [d, 1]

[a] Shimotakai Agricultural and Forestry High School, Hotaka 2975, Kijimadaira Village, Shimotakai County, Nagano Pref., 389-2301, Japan
[b] Center for Advanced Marine Core Research, Kochi University, Monobe B200, Nankoku City, Kochi Pref., 783-8502, Japan
[c] Institute of Mountain Science, Shinshu University, Asahi 3-1-1, Matsumoto City, Nagano Pref., 390-8621, Japan
[d] Center for Obsidian and Lithic Studies, Meiji University, Kanda-surugadai 1-1, Chiyoda Ward, Tokyo, 101-0064, Japan

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ABSTRACT

In this study, quantitative climate information for central Japan for the past 158 ka is reconstructed on the basis of pollen composition data of NJ88 core from Lake Nojiri and those of TKN-2004 core from the lacustrine Takano Formation using a modern analogue technique. Reconstructed values at the sites around 36.6°N and 700 m altitude are as follows.

In marine isotope stage (MIS) 6, the average annual mean temperature was about 2.1 °C, with a coldest month temperature of −11.8 °C, which suggest very cold climate conditions. The climates of MIS 4 and 2 were similarly cold, and the precipitation was low with ~1050 mm for mean annual precipitations during these cold periods. In contrast, the annual mean temperatures of MIS 5e and MIS 1, among the warmest periods, averaged about 5.5 °C and 9.1 °C, respectively. The annual mean temperature of MIS 5e was significantly lower than that of the Holocene. We estimate that an intensely cold winter controlled the vegetation, which resulted in the lower temperature reconstruction for MIS 5e. The annual mean temperatures of intermediately warm periods such as MIS 5c and 5a were a slightly high, with averages of 4.4 °C and 5.1 °C, respectively. Annual precipitations increased up to ~1400 mm on average in these warmer periods. Annual mean temperatures of MIS 5d and 5b were low with averages of about 3.0 °C.

Annual mean temperatures reconstructed for MIS 3 fluctuated over short periodicities that correspond to Dansgaard–Oeschger cycles. For example, the annual mean temperature of the interstadial GI-8 (Greenland Interstadial 8), 38–39 cal ka BP (calendar ka before 1950 CE) was about 4.0 °C, and that of the stadial HE 4 (Heinrich event 4) in 42–43 cal ka BP was about 2.6 °C. From 14 to 12 cal ka BP, annual mean temperature increased significantly in a relatively short period, from 1.3 to 9.5 °C, and annual precipitation also increased from 1040 to 1380 mm. A cool event corresponding to the Younger Dryas was identified in this deglaciation process, but its intensity was much weaker than that in the North Atlantic region. The climate in the Holocene (MIS 1) was warm, with an average annual mean temperature of 9.0 °C with wide variation, by a maximum of about 2 °C, which suggests temporal change of the Arctic polar front situated in mid-latitude regions.

1. Introduction

A great deal of progress has been made recently in the studies of paleoclimate and paleoenvironments in the East Asian Monsoon region. Paleoclimate archives reported from this region include loess–paleosol sequences in China (e.g., Xiao et al., 1995; Porter and An, 1995; Sun et al., 2006), lacustrine sediments such as those of Lake Biwa (e.g., Horie, 1984, 1991; Xiao et al., 1997; Kuwae et al., 2002; Hayashida et al., 2007; Nakagawa et al., 2009), Lake Baikal (e.g., Watanabe et al., 2004; Karavchinsky et al., 2007) and Lake Suigetsu (e.g., Nakagawa et al., 2005, 2006, 2012), Japan Sea sediments (e.g., Tada et al., 1999; Nagashima et al., 2004, 2007; Kido et al., 2007), open marine sediments of the NW Pacific Ocean

* Corresponding author.
E-mail address: fkumon@kochi-u.ac.jp (F. Kumon).
[1] Retired.

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(Oba et al., 2006; Igarashi and Oba, 2006), and stalagmites in China and Japan (e.g., Wang et al., 2001, 2005, 2008; Yuan et al., 2004; Sone et al., 2013).

Among these archives, the study of oxygen isotope records of stalagmites as detailed and long-term precipitation records for continental areas has greatly advanced recently. Stalagmite records have another advantage in that the age of the stalagmite can be measured by uranium-series disequilibrium methods. Wang et al. (2001, 2008) suggested that oxygen isotope ratios of stalagmites from China reflect the precipitation of the East Asian summer monsoon. Its temporal fluctuation corresponds well with the summer insolation curves for high-latitude regions of the Northern Hemisphere, and even to the frequent stadial and interstadial changes in oxygen isotopes detected in Greenland ice cores, known as Dansgaard–Oeschger (D–O) cycles (e.g., Bond et al., 1997).

Although many studies have been conducted for paleoclimate reconstruction, most research on the mid-latitude land areas in the Pleistocene has revealed only relative warmness and/or wetness. Quantitative paleoclimate information is generally scarce, especially in the mid-latitude East Asian monsoon regions.

Nakagawa et al. (2002) proposed an adaptable modern analogue technique for fossil pollen data in the Japanese islands. This technique is based on surface pollen spectra and modern meteorological observations in and around the Japanese islands (Gotanda et al., 2002). Furthermore, the modern pollen dataset was recently improved by adding new modern pollen data to include taxa from the southernmost Japanese islands (Kyushu and Okinawa) and the Russian Far East (Okuda et al., 2007; Tarasov et al., 2011). This method can provide quantitative climate parameters, such as temperature and precipitation, not only as annual means but also as seasonal averages.

This method has been used successfully in studies of sediments from Lake Mikata (Nakagawa et al., 2002, 2003), Lake Suigetsu (Nakagawa et al., 2005, 2006), Lake Biwa (Nakagawa et al., 2008, 2009; Tarasov et al., 2011; Kigoshi et al., 2014), and northern Sakhalin (Leipe et al., 2015). This method can contribute to reconstructing climate parameters and resolving the mechanisms of climate change, such as glacial–interglacial cycles and cooling events (Nakagawa et al., 2006, 2008, 2009). In a case study by Nakagawa et al. (2008), seasonal temperature variability between the coldest and warmest months was shown to be an important factor controlling monsoon strength. However, this modern analogue is based on a pollen dataset that includes eurythermal taxa such as *Pinus* and *Cryptomeria*. *Pinus* includes both the eurythermal *P.* subgenus *Diploxylon* and the subalpine *P.* subgenus *Haploxylon*. This mixture may result in failed reconstruction of climate parameters. Generally, the modern analogue method assumes constancy of physiological characteristics of the taxa used, but organisms frequently develop in and adapt to new environments.

In this contribution, we add two examples of quantitative climate reconstruction with high time resolutions covering the past 158 ka, on the basis of fossil pollen data from the sediment cores of Lake Nojiri and the lacustrine Takano Formation (Kumon et al., 2012; Kudo and Kumon, 2012; Kanauchi et al., 2015). The two sites are located at almost the same altitude and similar latitudes in the northern Japanese Alps, central Japan. In addition, the natural vegetation of both sites, presently a cool-temperate deciduous broad-leaved forest, has been very sensitive to climate change through glacial–interglacial cycles (Kumon et al., 2012; Kanauchi et al., 2015). The time resolution of the pollen data from Lake Nojiri is exceptionally high, less than 100 years on average. Based on these advantages, the objectives of the present study are the following: 1) reconstruction and compilation of a quantitative climate record for the past 158 ka, 2) detailed analysis of the abrupt climate changes known as D–O cycles, and 3) comparison of climate conditions between the Holocene and the Last Interglacial period.

2. Study sites

2.1. Lake Nojiri

Lake Nojiri is located at the northern margin of the Japanese Alps (N 36° 49.6′, E 138° 13.1′, altitude 654 m above sea level (asl)) with a surface area of 4.6 km^2 (Fig. 1). The present natural vegetation around Lake Nojiri is a cool-temperate deciduous broad-leaved forest (Miyawaki, 1985). The meteorological information measured at the Shinanomachi meteorological station (N 36° 48.5′, E 138° 11.5′, altitude 685 m asl) are as follows for 1981–2010 CE: annual mean temperature of 7.9–10.1 °C, with an average of 9.1 °C; mean temperatures of the warmest and coldest months of 22.1 °C and −3.2 °C, respectively; annual precipitation of 1268 mm; summer precipitation (April–September) of 708 mm; and winter precipitation (October–March) of 560 mm (Japanese Meteorological Agency: http://www.jma.go.jp/jma/index.html). The warm index (WI: annual sum of mean monthly temperatures above 5 °C) and the cold index (CI: annual sum of mean monthly temperatures below 5 °C) are 74.2 °C and −25.7 °C, respectively; these indices control forest type in Japan (Kira, 1949). The sediment core (NJ88 core) was drilled at the northeastern flank of the lake basin in 1988. It consists of homogenous silty clay with several intercalated marker tephra beds (Fig. 2). The depths and ages of the marker tephra beds are listed in Table 1 with ^{14}C dates.

2.2. Takano Formation

The Takano Formation, which consists of late Pleistocene lacustrine sediments, is distributed in a small intramountain basin (N 36° 32.9′, E 138° 2.1′; altitude 730 m asl) in southern Nagano City, central Japan (Fig. 1). The natural vegetation is a cool-temperate deciduous broad-leaved forest (Miyawaki, 1985). The climate during 1981–2010 CE, measured at the Shinshu-shinmachi meteorological station (N 36° 32.9′, E 137° 59.8′, altitude 509 m asl) is as follows: annual mean temperature of 10.7–12.9 °C with an average of 10.9 °C; mean temperatures of the warmest and coldest months of 24 °C and −1.4 °C, respectively; annual precipitation of 1120 mm; and summer and winter precipitation of 725 mm and 395 mm, respectively. The WI and CI indices are 88.8 °C and −19.9 °C, respectively. Although the WI at Shinshu-shinmachi is slightly above 85 °C, which indicates a warm-temperate zone, the CI is lower than −10 °C, which corresponds to cool-temperate deciduous broad-leaved forest. Additionally, because the Takano Basin is about 200 m higher than Shinshu-shinmachi, cool-temperate deciduous broad-leaved forest grew there in the Holocene.

TKN-2004 core was drilled at the center of Takano Basin in 2004 CE, and its recovery rate was about 99% (Tawara et al., 2006, Fig. 2). The undisturbed sediment core is 53.88 m in length and composed mainly of clayey silt intercalated with numerous widespread marker tephra beds. The depths and ages of the marker tephra beds in the core are listed in Table 2.

3. Materials and methods

3.1. Modern analogue technique based on pollen composition

Modern analogue techniques (MAT) of pollen composition can be used to reconstruct quantitative climate indices based on the statistic relationships between modern pollen compositions and meteorological observations (Overpeck et al., 1985; Guiot, 1990). In

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