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Research paper

Ice core record of ^{10}Be over the past millennium from Dome Fuji, Antarctica: A new proxy record of past solar activity and a powerful tool for stratigraphic dating

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Abstract

The cosmogenic nuclide ^{10}Be was analyzed by using accelerator mass spectrometry on an ice core drilled at the Dome Fuji station, inland Antarctica, for 700–1900 yr CE. The measured concentration of ^{10}Be in the Dome Fuji ice core and the derived ^{10}Be flux show similar fluctuations, with both increasing at known solar-activity minima over the last millennium in agreement with earlier observations of ^{10}Be and ^{14}C. Based on the similar nature of the ^{10}Be flux to the reconstructed ^{14}C production rate patterns, a ^{10}Be–^{14}C correlation age model for the Dome Fuji ice core was successfully constructed. This age model agrees well with the initial version of the tephrochronology of the core. The ^{10}Be-flux record contains information on variability in the amount of cosmic radiation incident on the atmosphere, which is mainly attributable to high-frequency change in solar activity and low-frequency background intensity adjustment of the geomagnetic field. High-resolution ^{10}Be analyses of the Dome Fuji ice cores promise to provide potentially important information on the history of cosmic radiation intensity over the past several hundred thousand years.

Keywords: Beryllium 10; Carbon 14; Past solar activity; Chronology; Cosmogenic nuclide; Cosmic ray intensity

1. Introduction

The cosmogenic nuclide ^{10}Be is produced in the earth's atmosphere by the spallation reaction of galactic cosmic ray particles with oxygen and nitrogen atoms. The atmospheric production of ^{10}Be and other cosmogenic nuclides such as ^{14}C and ^{36}Cl is controlled by a modulation effect caused by variation in solar activity and the geomagnetic field intensity affecting the cosmic radiation (Lal and Peters, 1967; Masarik and Beer, 1999). Production in the polar regions is less affected by the geomagnetic field. Concentrations in polar ice sheets are determined not only by factors affecting ^{10}Be production rate, but also by the processes of transport and deposition, which may be broadly described as "meteorological". Assuming that the high-frequency $>\sim 1/500\,yr^{-1}$ changes in solar activity may be distinguished from low-frequency variation $<\sim 1/500\,yr^{-1}$ of the background geomagnetic field intensity, both the ^{10}Be ice core record and the ^{14}C tree-ring record are thought to be the most promising proxies of past solar activity, at least for the Holocene epoch (e.g., Beer et al., 1988; Stuiver et al., 1991; Bard et al., 1997; Solanki et al., 2004; Vonmoos et al., 2006).

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A few long-term ^{10}Be records covering the entire Holocene have been obtained from Greenland ice cores (Beer et al., 1988; Finkel and Nishiizumi, 1997; Yiou et al., 1997; Vonmoos et al., 2006). These ^{10}Be records show a fairly good agreement with the ^{14}C tree-ring record (Beer et al., 1988; Finkel and Nishiizumi, 1997; Vonmoos et al., 2006). Recently, Muscheler et al. (2007) made a ^{10}Be stack of the past millennium using several ice core records from Greenland and Antarctica for a reconstruction of previous solar activity. However, the ^{10}Be variation in these records shows some significant discrepancy between Greenland and Antarctica (Bard et al., 1997; Muscheler et al., 2007), and a quantitative comparison between ^{10}Be and ^{14}C implies that local meteoric disturbance of the production signal in Greenland is higher than that in inland Antarctica (Bard et al., 1997; Marchal, 2005). Moreover, even if global stacks are a powerful tool for counterbalancing local effects, these must reduce fine structures, which may be attributable to changes in ^{10}Be production. Obtaining good quality records from inland Antarctica and stacking them must be another promising way of ascertaining past solar activity.

Inland Antarctica has a significant location advantage for studies on the variation in ^{10}Be production. After formation in the atmosphere ^{10}Be quickly attaches to aerosols and most of them fall to the earth's surface through wet and/or dry deposition within 1 or 2 yr (McHargue and Damon, 1991). Wet deposition of the nuclide is predominant in Greenland (Vonmoos et al., 2006). Because snow may not work as a simple diluent in the case of wet deposition, ^{10}Be deposition is susceptible to the snow accumulation rate (SAR) as compared with dry deposition. The ^{10}Be record from coastal Antarctica also shows a significant wet influence (Steig et al., 1998; Smith et al., 2000; Pedro et al., 2006) ranging through about 0–40% of total flux of the nuclide in the Holocene epoch (Steig et al., 1998). However, in inland Antarctica, dry nuclide and other metal ions deposition appears to predominate (Wolff et al., 2006; Raisbeck et al., 2006; Horiuchi et al., 2007b).

By assuming a constant SAR, earlier workers (Bard et al., 1997) show a profile of the ^{10}Be concentration (not the ^{10}Be flux) obtained from the South Pole ice core as a proxy record of the solar modulation over the past millennium. This record is frequently used as a solar proxy standard of ^{10}Be to investigate and discuss past solar changes (e.g., Bard et al., 2000; Pang and Yau, 2002; Usoskin et al., 2004; Muscheler et al., 2007). Nevertheless, it is evident that the acquisition of a further ^{10}Be record from inland Antarctica is extremely useful for more detailed studies such as in the identification of global production variation and local meteorological fluctuations (Bard et al., 1997, 2000; Horiuchi et al., 2007b).

We have analyzed ^{10}Be in ice cores drilled beneath the Dome Fuji station, eastern inland Antarctica (e.g., Horiuchi et al., 2007b). The annual net water equivalent accumulation at this station is estimated to be 25–30 mm yr^{-1} throughout the Holocene epoch (Watanabe et al., 2003; Parrenin et al., 2007; Kameda et al., 2008). This low SAR may limit meteorological disturbance of the cosmogenic ^{10}Be signal.

In this paper, we present a record of ^{10}Be over the past millennium (700–1900 yr CE) obtained from a Dome Fuji ice core. One purpose of this paper is to compare our ^{10}Be record with other cosmogenic nuclide records such as ^{14}C production and the South Pole ^{10}Be record, to verify that it is an indicator of past solar activity. Our preliminary study (Horiuchi et al., 2007b) has already shown an excellent agreement for ^{10}Be from the Dome Fuji ice core with comparable material from the South Pole, Δ^{14}C record from tree rings, and group sunspot number. However, the record therein presented is for ^{10}Be concentration only (without flux), it is inadequately short (between 1500 and 1810 yr CE), and it was not compared with the ^{14}C production record.

Reconstruction of the cosmogenic ^{14}C production from the tree-ring ^{14}C record is not simple because of uncertainty in the global carbon cycle (e.g., Stuiver and Quay, 1980; Usoskin and Kromer, 2005). After its production ^{14}C oxidizes to CO_2 gas and is then rapidly mixed in the hemispheric atmosphere. However, the global carbon cycle within the atmosphere, biosphere, geosphere, and the ocean affects the production signal preserved in the ^{14}C record. It is well known that the global carbon cycle delays the ^{14}C production signal, dampens those amplitudes, and may mask its nature as seen in the tree-ring ^{14}C records (e.g., Siegenthaler et al., 1980) if the status of the cycle has significantly changed.

Advantages of the tree-ring ^{14}C record are: (1) unlike the ^{10}Be signature it is virtually unaffected by local effects and (2) the time scale is based on robust dendrochronology. Reconstruction of the ^{14}C production rate for the entire Holocene has been attempted by using an "inverse method" (Usoskin and Kromer, 2005; Marchal, 2005) and it is possible to directly compare this result with the ^{10}Be record obtained from inland Antarctica.

A further aim of this paper is to construct a ^{10}Be–^{14}C age model for the Dome Fuji ice core, the basic concept of which was presented in a study of the Vostok ice core (Raisbeck et al., 1998). It has also been applied to an early Holocene interval of the GRIP ice core (Muscheler et al., 2004). In the present work, a clear and detailed correlation of the ^{10}Be flux in the Dome Fuji core with the ^{14}C production signal was observed, which greatly facilitated the construction of a ^{10}Be–^{14}C age model.

2. Dome Fuji station and ^{10}Be fallout in Antarctica

Dome Fuji station is located in inland Antarctica (Fig. 1: 77°19′S, 39°42′E, 3810 m a.s.l), where several ice cores, including two "deep" ones, have been drilled by Japanese Antarctic Research Expedition (JARE) teams (e.g., Watanabe et al., 1997, 2003). In this study, we analyzed a "shallow" ice core obtained in 2001 (core DF2001 described in Horiuchi et al. (2007b) with the DF01 core).