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Solar and climate influences on ice core ^{10}Be records from Antarctica and Greenland during the neutron monitor era

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ABSTRACT

Cosmogenic ^{10}Be in polar ice cores is a primary proxy for past solar activity. However, interpretation of the ^{10}Be record is hindered by limited understanding of the physical processes governing its atmospheric transport and deposition to the ice sheets. This issue is addressed by evaluating two accurately dated, annually resolved ice core ^{10}Be records against modern solar activity observations and instrumental and reanalysis climate data. The cores are sampled from the DSS site on Law Dome, East Antarctica (spanning 1936–2009) and the Das2 site, southeast Greenland (1936–2002), permitting inter-hemispheric comparisons. Concentrations at both DSS and Das2 are significantly correlated to the 11-yr solar cycle modulation of cosmic ray intensity, $r_{xy} = 0.54$ with 95% CI [0.31; 0.70], and $r_{xy} = 0.45$ with 95% CI [0.22; 0.62], respectively. For both sites, if fluxes are used instead of concentrations then correlations with solar activity decrease. The strength and spectral coherence of the solar activity signal in ^{10}Be is enhanced when ice core records are combined from both Antarctica and Greenland. The amplitudes of the 11-yr solar cycles in the ^{10}Be data appear inconsistent with the view that the ice sheets receive only ^{10}Be produced at polar latitudes. Significant climate signals detected in the ^{10}Be series include the zonal wave three pattern of atmospheric circulation at DSS, $r_{xy} = -0.36$ with 95% CI [-0.57; -0.10], and the North Atlantic Oscillation at Das2, $r_{xy} = -0.42$ with 95% CI [-0.64; -0.15]. The sensitivity of ^{10}Be concentrations to modes of atmospheric circulation advises caution in the use of ^{10}Be records from single sites in solar forcing reconstructions.

1. Introduction

The atmospheric production rate of cosmogenic ^{10}Be is proportional to cosmic ray intensity, which in turn is modulated by variations in solar activity and the Earth's geomagnetic field strength (Lal and Peters, 1967). This relationship is exploited in the use of ^{10}Be records from polar ice cores to reconstruct solar activity prior to the era of instrumental records (e.g. Bard et al., 2000; Vonmoos et al., 2006; Muscheler et al., 2007b; Usoskin et al., 2009; Delaygue and Bard, 2011; Shapiro et al., 2011; Steinhilber et al., 2012). Such reconstructions provide crucial information for assessing the role of solar forcing in past climate change (e.g. Bard et al., 2000; Steinhilber et al., 2012) and for attributing present climate change (e.g. Ammann et al., 2007). However, different solar reconstructions are not all in agreement and the reliability of ^{10}Be as a solar proxy has sometimes been questioned (Lal, 1987; Webber and Higbie, 2010).

^{10}Be is produced by interactions between N and O atoms and secondary particles of the cosmic-ray induced atmospheric cascade (Lal and Peters, 1967). Globally, $\sim 60-70\%$ of the columnar production occurs in the stratosphere, with the remainder in the upper troposphere (e.g. Masarik and Beer, 2009; Kovaltsov and Usoskin, 2010). Following production, it is assumed (due to its valence charge, small ionic radius and strong chemical adsorption affinity) that ^{10}Be is rapidly scavenged by ambient aerosol then transported with air-masses (Igarashi et al., 1998; Aldahan et al., 2008). Observational and modeling studies report atmospheric residence times for the aerosol-bound ^{10}Be of ~ 1 yr in the stratosphere and several weeks in the troposphere before deposition to the Earth's surface (e.g. Raisbeck et al., 1981; Jordan et al., 2003; Heikkilä et al., 2009; Pedro et al., 2011a).

Key factors limiting the reliability of ^{10}Be-based solar reconstructions include (1) the confounding effect of non-production related signals introduced during the atmospheric transport and deposition

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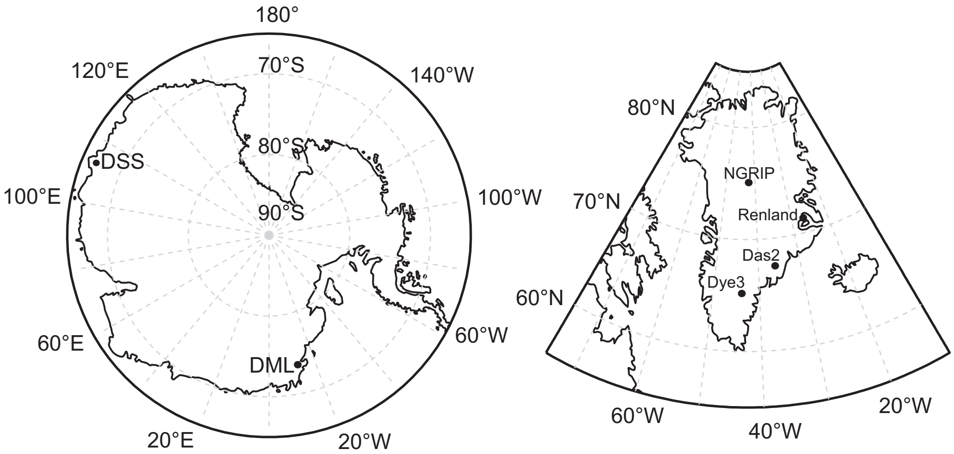

Fig. 1. Map showing the location of the DSS (Law Dome Summit South) and Das2, southeast Greenland ice core sites from which the new ^{10}Be records presented in the text were obtained. The locations of additional ice core ^{10}Be records used in the bipolar ^{10}Be composite are also shown: DML (Dronning Maud Land), Renland, NGRIP and Dye 3.

of the isotope to the ice sheets (e.g. Lal, 1987; Pedro et al., 2006; Field et al., 2006; Field and Schmidt, 2009; Pedro et al., 2011b; Baroni et al., 2011) and (2) debate about where in the atmosphere the ^{10}Be deposited to the ice core sites is produced (e.g. Mazaud et al., 1994; Steig et al., 1996; Bard et al., 1997; Field et al., 2006; Heikkilä et al., 2009; Muscheler and Heikkilä, 2011). The first factor is critical since incorrectly attributing climate-induced signals in ^{10}Be to changes in solar activity risks drawing false conclusions about solar forcing of climate. The second factor is important since different assumptions regarding atmospheric source regions directly affect the amplitudes of reconstructed solar variations. Here we address this issue through direct intercomparison of annually resolved and accurately dated ice core ^{10}Be data with modern instrumental records.

Two new ^{10}Be records are presented, one from the DSS site, Law Dome, East Antarctica and one from the Das2 site, southeast Greenland (see Fig. 1 for locations). The exceptionally high snow accumulation rates at both sites, 0.68 m ice yr^{-1} at DSS (Morgan et al., 1997) and 0.90 m ice yr^{-1} at Das2 (Hanna et al., 2006), preserve thick and clear annual snow layers permitting unambiguous dating of the records. To assess the strength of production signals the measured concentrations and calculated ^{10}Be fluxes are evaluated against cosmic ray intensities as recorded by ground-based neutron monitors since the 1950s and also against modeled atmospheric ^{10}Be production rates (Kovaltsov and Usoskin, 2010). Potential climate signals are examined through intercomparison of the ^{10}Be data with climate variables for which there is an a priori reason to suspect an influence on ^{10}Be deposition or transport: (i) observed accumulation rates; (ii) dominant modes of atmospheric circulation affecting vertical and meridional atmospheric mixing; (iii) moisture transport pathways in the southern and northern high latitudes; and (iv) ice core stable water isotope composition (δ^{18}O). Having identified significant climate signals at both sites, we test whether constructing a composite series, using ^{10}Be records from both Antarctica and Greenland, is effective in reducing the climate signals and enhancing the solar/production signal.

Finally, following Steig et al. (1996) and Moraal et al. (2005) we use the amplitudes of the 11-yr solar cycles in the ^{10}Be records to constrain the atmospheric source regions of ^{10}Be deposited to the ice sheets.

2. Materials and methods

The DSS ^{10}Be record was sampled from the top 66.62 m of the DSS0506 core, drilled at 66°46.33′S 112°48.43′E, elevation 1370 m asl. The Das2 record was sampled from the 84 m Das2 core, drilled at 67°31.64′N, 36°03.69′W, elevation 2936 m. Dating of the cores and derivation of annual accumulation rates followed previous methods (Palmer et al., 2001; Hanna et al., 2006; van Ommen and Morgan, 2010, for additional details see Supplementary methods). The DSS record spans 1936–2009 and the Das2 record spans 1936–2002. Each ^{10}Be sample integrates deposition over a complete year. The sampling was conducted in a way that reduces the potential for aliasing by seasonal cycles in ^{10}Be concentrations (see Supplementary methods).

^{10}Be measurements were conducted following previous methods at the ANTARES AMS facility, ANSTO, Australia (Fink and Smith, 2007; Pedro et al., 2011a; Simon et al., in press). Measurements were normalised to the National Institute of Standards and Technology USA ^{10}Be standard reference material SRM-4325, utilising the Nishiizumi et al. (2007) ^{10}Be:^{9}Be ratio of $(2.79 \pm 0.02) \times 10^{-11}$. Standard errors in ^{10}Be concentrations (comprising random and systematic measurement errors) ranged from 2.0% to 5.8% with a median of 2.9% for DSS and 1.4–3.5% with a median of 2.6% for Das2. Chemistry procedural blanks gave ^{10}Be:^{9}Be ratios of $< 5 \times 10^{-15}$ and corresponding corrections (typically $< 1-2\%$) were applied to the ^{10}Be measurements.

Atmospheric production rates were calculated using the CRAC:10Be model (Kovaltsov and Usoskin, 2010) and annual average values of the solar modulation constant (Φ). The Φ record is based on neutron monitor counting rates from 1951 to 2010 (adopted from Usoskin et al., 2011) and on the group sunspot number before 1951 (adopted from Usoskin et al., 2002; Vieira et al., 2011). Unless specified the pre-1951 production data is not used here in quantitative analysis as it is less reliable than that from the neutron monitor era. The influence of changes in the strength and configuration of the geomagnetic field on production rates are small on annual to decadal timescales (see e.g. Muscheler et al., 2007b) and are not considered here. We report annual average production rates that are vertically integrated over the entire atmospheric column and averaged over all latitudes (hereafter ‘global production rates’), and also columnar production rates averaged over only the geographical latitude range 60–90°S/N, (hereafter ‘polar production rates’). Note that other recent models of ^{10}Be production (e.g. Masarik and Beer, 2009) yield production rates that are 30–40% lower than CRAC:10Be. However, for the purpose of this study the absolute production rate is not consequential. Rather, the important detail is the relative production variation during the neutron monitor era, and on this the models are in reasonable agreement (demonstrated in Section 3.3).