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Large amplitude solar modulation cycles of ^{10}Be in Antarctica: implications for atmospheric mixing processes and interpretation of the ice core record.

E. J. Steig,[1,2] P. J. Polissar,[1,3] M. Stuiver,[1] P M. Grootes,[1,4] and R. C. Finkel[5]

Abstract. ^{10}Be concentrations in an ice core at Taylor Dome, Antarctica show greater variation over the last 75 years than similar ^{10}Be time-series from Greenland. Like the Greenland records, the new Antarctic data exhibit a strong periodicity which follows expected changes in the production rate of ^{10}Be over the 11-year solar cycle. Noting that the amplitude of production-rate variation is both latitude and altitude dependent, we estimate the relative contribution of ^{10}Be from different atmospheric reservoirs. The calculations yield a relatively small (<35 %) contribution from the low-to-mid latitude stratosphere, suggesting a weak coupling between Antarctic ^{10}Be and geomagnetic field intensity.

Introduction

Modulation of the cosmic ray flux by the geomagnetic field and the solar wind causes variation in the production rate of cosmogenic isotopes in the atmosphere. Records of cosmogenic ^{10}Be in Greenland ice cores exhibit variations which coincide with known periodicities in solar activity [*Beer et al.*, 1988; 1990]. The identification of geomagnetic field changes in ^{10}Be records has proven more difficult, in part because the expected low-frequency variations are masked by climatic effects [*Yiou et al.*, 1985; *Lal*, 1987]. Interpretation of low-frequency ^{10}Be variations is further complicated by the difficulty of isolating the separate effects of geomagnetic and solar variability [*Beer et al.*, 1987; *Raisbeck and Yiou*, 1985].

Over the 11-year solar cycle, ^{10}Be production variations of about ±20% are predicted for the high-latitude stratosphere [*Lingenfelter*, 1963; *Lal and Peters*, 1967; *O'Brien*, 1979; *Lal*, 1988], compared with variation of <5% at the geomagnetic equator. The modulation of cosmic rays by the geomagnetic field, on the other hand, is greatest at the equator. Atmospheric mixing thus plays a critical role in determining local atmospheric ^{10}Be concentrations and the ^{10}Be flux from atmosphere to surface.

A question of particular importance is whether or not there is significant deposition, at polar latitudes, of ^{10}Be produced in the low-latitude stratosphere. If so, then a strong geomagnetic signal is expected in the ice-core ^{10}Be record. *Mazaud et al.* [1994] approached this question by optimizing the fit between geomagnetic field variations estimated from ocean sediment cores [*Tric et al.*, 1992], and ^{10}Be concentrations in the Vostok ice core [*Raisbeck et al.*, 1987] over the last 150 ka. In this paper, we take a similar approach, but compare the Antarctic ^{10}Be flux with estimates of solar rather than geomagnetic variability.

Relationship among solar variability, ^{10}Be concentrations and atmospheric circulation

Our goal was to obtain an estimate of the amplitude of the ~11-year solar modulation cycle of ^{10}Be in Antarctica. Samples were collected from a firn core at 2 to 3-year resolution and in a 4-meter deep snowpit at ~0.5 year resolution at Taylor Dome, Antarctica (77° 50' S, 158°40' E, 2400 m). ^{10}Be analyses were made at the Lawrence Livermore Center for Accelerator Mass Spectrometry [*Davis et al.*, 1990; *Southon et al.*, 1990]; analytical precision is better than 5%. Dating was achieved by locating bomb-radioactivity horizons in the firn [*Dibb et al.*, 1990] and assuming a constant accumulation rate (7.5 g cm^{-2}a^{-1}). Independent dating control by oxygen isotope (δ^{18}O) stratigraphy indicates that the assumption of constant accumulation rate is reasonable (Figure 1).

In Figure 2, Taylor Dome ^{10}Be concentrations are shown as a function of time. Also shown is the neutron counting rate at Deep River, Canada [*NRC*, 1994]. The neutron counting rate is directly related to the cosmic ray flux, and therefore to the ^{10}Be production rate at any point in the earth's atmosphere [*O'Brien and Burke*, 1973].

Comparison of the ^{10}Be and neutron counter data show that there is an ~11-year periodicity common to both records. Following *Beer et al.* [1990], we attribute this periodicity to solar modulation of production. An alternate causal mechanism for the observed 11-year periodicity of ^{10}Be is solar forcing of climate [*Lal*, 1987]. There is indeed evidence for an approximately ~11-year periodicity in δ^{18}O data [*Stuiver et al.*, 1995] from an ice core in central Greenland. However, this periodicity is absent in both δ^{18}O and electrical conductivity data at Taylor Dome. Therefore, although long-term climate changes and high-frequency 'noise' may be superimposed on production-rate variations, there is at present little evidence for a meteorological contribution to the 11-year periodicity observed for ^{10}Be at Taylor Dome.

Amplitude of the 11-year cycle at Taylor Dome

To quantify the relationship between cosmic ray flux and ^{10}Be deposition rates, we applied a 9-13 year bandpass filter to the data. Taking autocorrelation into account, comparison

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[1] Also at Quaternary Isotope Laboratory, University of Washington, Seattle, WA 98195

[2] Now at Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO 80309 (email: steig@stripe.colorado.edu)

[3] Hampshire College

[4] Now at Leibniz C-14 Laboratory of the Christian Albrechts Universitat Kiel, Leibnizstraße 19, Kiel, Germany

[5] Lawrence Livermore National Laboratory

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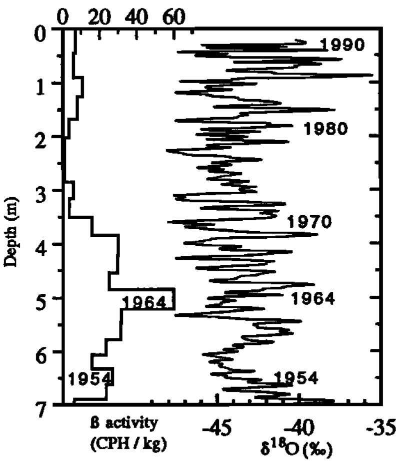

Figure 1. $\delta^{18}O$ and ß radiation profiles at Taylor Dome Antarctica. Numbers show dates of counted year (assuming that $\delta^{18}O$ peaks are annual) and of known bomb-radiation peaks.

of the 11-year-periodic components of the snow-pit ^{10}Be and the neutron data yields a correlation coefficient of r = 0.89 at lag 1 year (n_{eff} = 49). The 1-year lag is expected from the ~1-year residence time of ^{10}Be in the atmosphere [*Raisbeck and Yiou,* 1981; *Beer et al.,* 1990]. Before filtering, all data were numerically re-sampled, using low-degree cubic splines [*Rasmussen,* 1991], to obtain average values over identical one-year intervals. This procedure should ***underestimate*** the 11-year amplitude for the firn-core at Taylor Dome, which was sampled at relatively low resolution.

Figure 3 shows a comparison of the filtered ^{10}Be data from Taylor Dome (A.D. 1920 - 1994) and from Dye 3, Greenland (1860 - 1985), plotted relative to the average ^{10}Be concentration at each site. Also shown are sunspot numbers and the filtered Deep River neutron counter data. The amplitude of the ^{10}Be variations at Taylor Dome is on average larger than at Dye 3. There are no variations in the entire Dye 3 data set (1875-1985) as large as the largest observed at Taylor Dome over the last 75 years. This suggests a fundamental difference between the northern and southern hemisphere sites. A possible explanation is that ^{10}Be deposition at Taylor Dome (77°50'S) reflects ^{10}Be production from a higher-latitude atmospheric reservoir than does ^{10}Be deposition at Dye 3 (latitude 65°N).

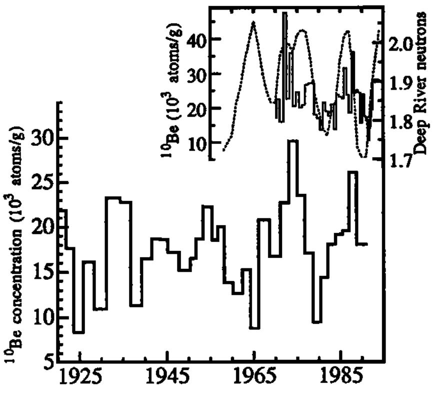

Figure 2. ^{10}Be concentrations at Taylor Dome from a firn core (lower) and a snow pit (upper). Dashed line shows mean annual neutron count (10^6/hr) at Deep River, Canada for comparison.

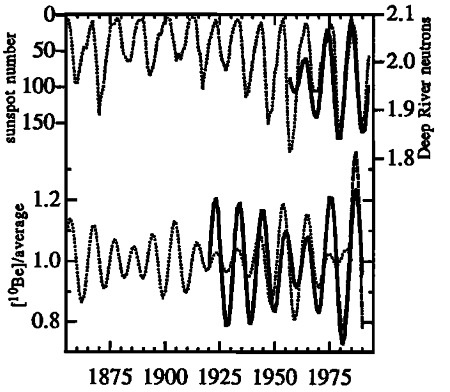

Figure 3. Lower: bandpass-filtered (9-13 year) ^{10}Be data from Taylor Dome, Antarctica (—) and Dye 3, Greenland (········ [*Beer et al.* ,1990]). Dashed line shows filtered snow pit ^{10}Be from Taylor Dome. Data are plotted relative to the average. For clarity, the Dye 3 data have been shifted forward by ~0.5 years. Upper: filtered Deep River neutron counting rate (—) and Wolf mean annual sunspot numbers (·········).

We used the calculations of *O'Brien et al.* [1991] to integrate total production over various latitude and altitude ranges as a function of the Deep River neutron counting rate. *O'Brien et al.'s* calculations agree closely with empirical observations of the neutron-flux/altitude relationship [*Simpson et al.,* 1953], and with the earlier calculations of *Lingenfelter* [1963] and *Lal and Peters* [1967]. Because we use ratios, the absolute production rate of ^{10}Be is not important here, although implicit in our model is that the scavenging ratio (the proportion of atmospheric ^{10}Be that is deposited per unit time) is constant, or at least non-periodic.

Figure 4 compares the neutron counting rate with the variation in ^{10}Be at Taylor Dome for the years 1958-1994. Also shown are predicted variations integrated over 1) the whole atmosphere, 2) stratosphere only, and 3) the polar stratosphere. We estimate the uncertainty in the average slopes of the theoretical curves to be ±10%, based on comparison among different calculations of cosmogenic nuclide production rates [*Lal,* 1988; *Lingenfelter,* 1963; *O'Brien et al.,* 1991]. A best-fit straight or parabolic line to the Taylor Dome data is statistically distinct (>95% confidence) from both the whole atmosphere and whole stratosphere predicted values.

Discussion

The data suggest that there is some contribution, possibly significant, of polar stratospheric ^{10}Be to the Antarctic ^{10}Be flux. This conflicts with the traditional view that at high latitudes there is little input of cosmogenic isotopes produced in the stratosphere [*Lal and Peters,* 1967], but is consistent with observations of ozone and aerosol concentrations in the Antarctic [*Fox et al.,* 1995; *Maenhaut et al.,* 1979; *Manney et al.,* 1994; *Santee et al.,* 1995; *Toon et al.,* 1986; *Crutzen and Arnold,* 1986; *Deshler et al.,* 1995; *Gobbi et al.,* 1991].

To quantify the relative contribution of non-polar ^{10}Be to polar ^{10}Be, we calculate a sensitivity factor,

$$\partial(^{10}Be/^{10}Be_{mean}) \Big/ \partial\phi$$

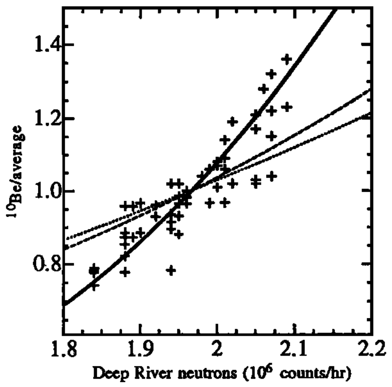

Figure 4. Comparison of predicted and measured ^{10}Be production as a function of counting rates at the Deep River neutron monitor, 1958 - 1994. Crosses show 1-year mean data from bandpass-filtered Taylor Dome data shown in Figure 3. Lines show predicted values for entire atmosphere (····), stratosphere only (---), and polar stratosphere only (—).

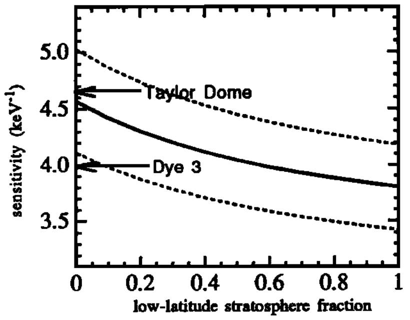

Figure 5. Sensitivity of the polar ^{10}Be flux to changes in the cosmic ray flux, as characterized by the Ehmert potential, ϕ, as a function of the fraction of ^{10}Be derived from the low-latitude stratosphere. Curved lines show theoretical sensitivities near a mean value of ϕ = 450 MeV; bold line is from calculation of *O'Brien et al.* [1991]. Dotted lines denote estimated 2σ uncertainty. Arrows show empirically determined values for Taylor Dome and Dye 3. Least squares 2$^{\text{nd}}$ order polynomial fit gives 95% confidence limits of ± 0.4 keV for the Taylor Dome value.

where ϕ is the Ehmert potential, a measure of solar modulation of the cosmic ray flux [*Ehmert*, 1960]. For a typical solar cycle, ϕ varies from 300 to 600 MeV, with an average value of 450 MeV [*Lal*, 1988]; ϕ = 450 MeV corresponds to a counting rate at Deep River of 1.97 × 10^6 neutrons/hour [*O'Brien and Burke*, 1973].

We divide the atmospheric ^{10}Be production into geomagnetically 'modulated' and 'unmodulated' components, corresponding to the low latitude (0° to 60°) and high-latitude (60° to 90°) atmosphere. The boundary at 60° corresponds to a break in slope in theoretical cosmogenic isotope production curves and is meaningful also from the perspective of atmospheric dynamics, since 60° approximates the location of the polar vortex [e.g. *Kakegawa et al.*, 1986]. Although geomagnetic and geographic latitudes are different, this difference is negligible because production rates are nearly independent of latitude poleward of 60° [e.g. *Lingenfelter*, 1963].

Figure 5 depicts the sensitivity of ^{10}Be production to changes in Ehmert potential for different mixing ratios between ^{10}Be derived from high latitudes and from the low-latitude stratosphere. Comparison between the calculated and observed sensitivities shows that at most 35% of the Antarctic ^{10}Be flux can be derived from low-latitude sources. In contrast, the amplitude of variation of ^{10}Be observed in the Dye 3 core [*Beer et al.*, 1990] is consistent with a well-mixed stratosphere [*Monaghan*, 1987]. This conclusion is at odds with recent work of *Mazaud et. al.*, [1994], who were able to produce a reasonable match between the Vostok, Antarctica, ^{10}Be record and ocean-sediment proxy records of geomagnetic field strength. As has been done here, *Mazaud et al.* [1994] divided the atmospheric ^{10}Be sources into 'unmodulated' and 'modulated' components; they determined a value of 75% for the modulated component. The discrepancy with our value of <35% suggests that 1) ocean-sediment geomagnetic records approximate geomagnetic field variations rather poorly [*Raisbeck et al.*, 1994] 2) the slight adjustment made by *Mazaud et al.* [1994] to the accepted Vostok timescale [*Jouzel et al.*, 1993] to achieve their best-fit match introduces errors, 3) the fraction of 'modulated' ^{10}Be in the ice core record is variable, or 4) the theoretical production rate variations are in error. The first three possibilities draw into question the validity of using ^{10}Be ice core records as proxies for the geomagnetic modulation of cosmogenic isotope production.

Conclusions

Evidently, a relatively small proportion of the Antarctic ^{10}Be flux is derived from latitudes at which variations in geomagnetic field strength are important. If our 75-year record is applicable to the distant past, then the ^{10}Be record from Antarctic ice cores should contain only a small geomagnetic signal. The global average variation over the last 10 ka is on the order of ±25%; assuming a maximum 35% contribution from the low-latitude stratosphere, geomagnetic modulation accounts for variation of at most ±10% at Taylor Dome.

This conclusion is satisfying from the point of view of glaciology, because it suggests that ^{10}Be concentrations can be used to determine accumulation rates in ice cores [*Lorius et al.*, 1989; *Raisbeck et al.*, 1987; 1992; *Steig et al.*, 1995; *Yiou et al.*, 1985]. The rather minimal effect of geomagnetic modulation on the Antarctic ^{10}Be flux makes reasonable the assumption of a "constant" ^{10}Be flux over millennial timescales. The effect of solar variability, of course, must still be considered, but our results suggest that comparison of ^{10}Be records among Antarctic and Greenland ice cores may allow us to separate the geomagnetic and solar contributions to changes in cosmogenic isotope production rates.

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E.J. Steig, M. Stuiver and P.M. Grootes, Dept. of Geological Sciences, 351310, Univ. of Washington, Seattle, WA 98195

P.J. Polissar, School of Natural Sciences, Hampshire College, Amherst, MA 01002

R. C. Finkel, Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, L-231, Livermore, CA 94550

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