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^{10}Be and δ^2H in polar ice cores as a probe of the solar variability's influence on climate

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By using the technique of accelerator mass spectrometry, it is now possible to measure detailed profiles of cosmogenic (cosmic ray produced) ^{10}Be in polar ice cores. Recent work has demonstrated that these profiles contain information on solar activity, via its influence on the intensity of galactic cosmic rays arriving in the Earth's atmosphere. It has been known for some time that, as a result of temperature-dependent fractionation effects, the stable isotope profiles δ^2O and δ^2H in polar ice cores contain palaeoclimate information. Thus by comparing the ^{10}Be and stable isotope profiles in the same ice core, one can test the influence of solar variability on climate, and this independent of possible uncertainties in the absolute chronology of the records. We present here the results of such a comparison for two Antarctic ice cores; one from the South Pole, covering the past *ca.* 1000 years, and one from Dome C, covering the past *ca.* 3000 years.

INTRODUCTION

One of the most fundamental, and controversial, aspects of solar–terrestrial relations is the extent to which solar activity – as reflected by sunspot number (or their more modern analogues such as the geomagnetic 'aa' index or 10.7 cm and He spectral lines) – is related to climate. Therefore, any system that can potentially address this question, especially in an objective and quantitative fashion, deserves careful attention. It is one such system, ^{10}Be and stable isotope ratios in polar ice cores, that we consider here.

It has been established for some time now that the flux of galactic cosmic rays arriving at the Earth is inversely correlated with the 11-year solar activity cycle. Although the mechanism for this relation is still not understood in detail, it basically appears to arise mainly because the interplanetary magnetic fields embedded in the outflowing solar wind are disturbed by shock waves associated with energetic solar flare events. Because the production rate of cosmogenic (i.e. cosmic ray produced) isotopes in the atmosphere is proportional to the galactic cosmic ray flux, their abundance is also inversely correlated with solar activity. (Although energetic solar flare particles can also produce cosmogenic isotopes, averaged over time their contribution compared with the galactic cosmic ray production is estimated to be quite small.)

The best-known cosmogenic isotope is ^{14}C. However, because it forms a gaseous molecule (CO_2) and is in dynamic equilibrium with large reservoirs of carbon in the biosphere and oceans, short-term changes in the ^{14}C production rate lead to strongly damped changes in the atmospheric ^{14}C:^{12}C ratio. Thus for example, the *ca.* 30% production rate changes in the 11-

year solar cycle are barely discernable in $^{14}C:^{12}C$ ratios from dendrochronologically dated tree-ring sequences. However, for longer time periods, high-precision ^{14}C measurements in these tree-ring sequences do show significant variations, at least some of which are believed to be caused by changes in solar activity. Indeed, the Maunder Minimum type 'wiggles' in the tree-ring ^{14}C record constitute probably one of our strongest evidences that solar activity has varied on timescales longer than the 11-year cycle (see H. E. Suess & T. W. Linick and C. P. Sonett & S. A. Finney, this Symposium).

The only other long-lived isotope that is formed by cosmic-ray-induced nuclear reactions with nitrogen and oxygen, the principal components of the atmosphere, is ^{10}Be (half-life 1.5 Ma). Because beryllium does not form a gaseous species in the atmosphere it quickly attaches itself to aerosols, and is transported to the Earth's surface by precipitation and dry deposition in *ca.* 1 year. Changes in the production rate of this isotope are thus rapidly and strongly reflected in its deposition rate. Unfortunately, the short atmospheric residence time and meteorological influence on ^{10}Be deposition result in changes in the ^{10}Be concentration in geological reservoirs that are not as directly related to the global production rate as is $^{14}C:^{12}C$. However, recent work – including results presented here – demonstrate that ^{10}Be profiles in polar ice cores do appear to give a record of solar activity comparable with that of $^{14}C:^{12}C$ in tree rings.

It has been known for some time that the stable isotope ratios (generally presented as $\delta^{18}O$ or $\delta^{2}H$, the deviation from standard ocean water) in polar ice cores are related to the climate at the time the precipitation occurred. The best illustration of this (see, for example, figure 1) are the observed changes in these isotopic ratios during the last glacial to interglacial transition *ca.* 10000 years ago.

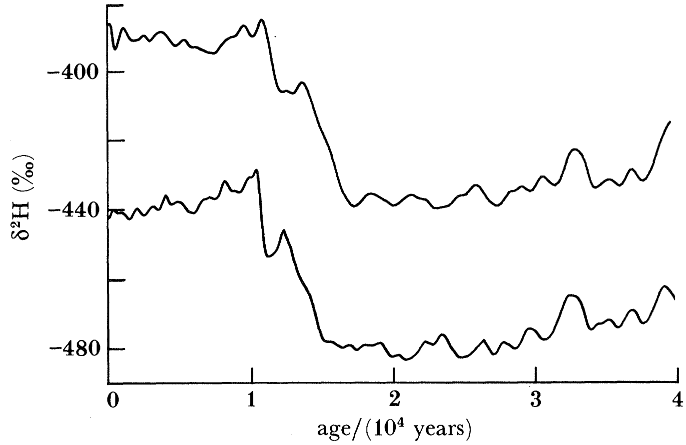

FIGURE 1. Smoothed profiles of $\delta^{2}H$ as a function of time in ice from Dome C (upper curve) and Vostok (lower curve), Antarctica (see Jouzel *et al.* 1989).

We thus see that we have a system that fulfils the conditions mentioned earlier, namely, a geological reservoir containing an objective, quantitative record of both solar activity and climate. By comparing these two records, one can thus estimate the degree of influence of solar activity on the climate. It is important to point out that, because both records can be obtained from the same core, such a comparison can be made *independently* of the absolute timescale for the samples.

RESULTS

South Pole

We begin by considering a 127 m ice core drilled at the South Pole in 1984. The ^{10}Be profile from this core, which has been obtained recently (Raisbeck & Yiou 1990), is shown in figure 2. The core has been dated by identifying previously dated volcanic signals in the ice (Kirchner 1988). To average out some of the meteorological 'noise' in the ^{10}Be signal, and make the time resolution more comparable with that observed in the ^{14}C record, this raw ^{10}Be signal can be subjected to various degrees of smoothing. An example of this, using a spline function, is shown in figure 2 as the dark solid curve.

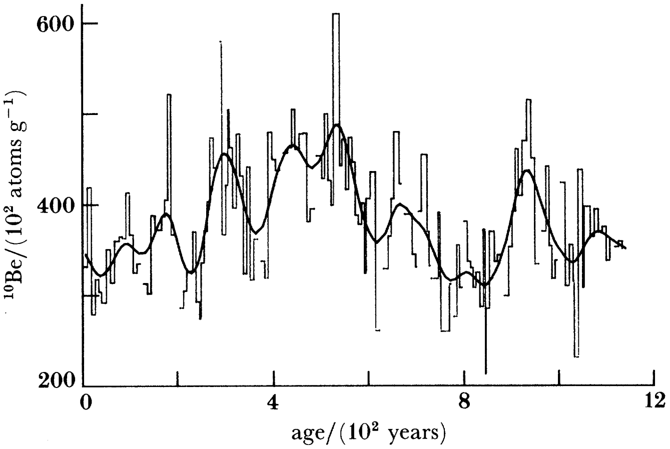

FIGURE 2. Concentration of ^{10}Be as a function of time in a 127 m ice core from the South Pole station, Antarctica. The histogram represents the raw data and the smoothed curve has been obtained by using a spline function.

In figure 3 we show a comparison of the smoothed ^{10}Be record with that of the bidecadal tree ring δ^{14}C record of Stuiver & Pearson (1986) and Pearson & Stuiver (1986). Taking into account an expected lag in the ^{14}C response (because of longer atmosphere residence time and exchange with the biological and oceanic reservoirs) compared with that of ^{10}Be, there is a strong resemblance of these two completely independent curves. This resemblance is, in our

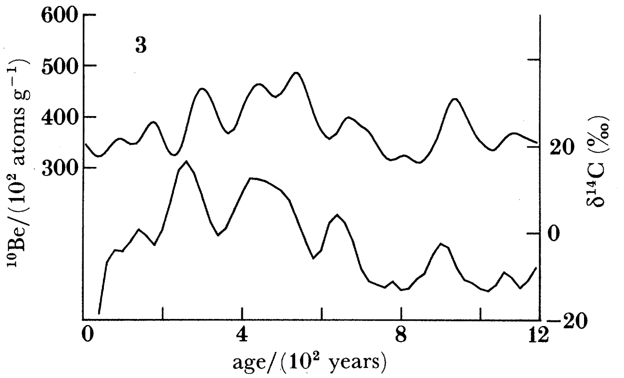

FIGURE 3. Comparison of smoothed ^{10}Be concentration in ice at South Pole (from figure 2) with δ^{14}C in dendrochronologically dated tree rings (see text).

opinion, one of the strongest pieces of evidence to date that the ^{10}Be ice core data are indeed recording solar modulation induced production rate changes.

Because there has been considerable discussion at this meeting on possible cyclicity of solar activity, we show in figure 4 the results of a preliminary spectral analysis of the ^{10}Be profile from the South Pole core, using a multitaper method (Yiou *et al.* 1990), based on a technique pioneered by D. J. Thompson (this Symposium). The results suggest statistically significant cyclicity at frequencies of 92 and 202 years.

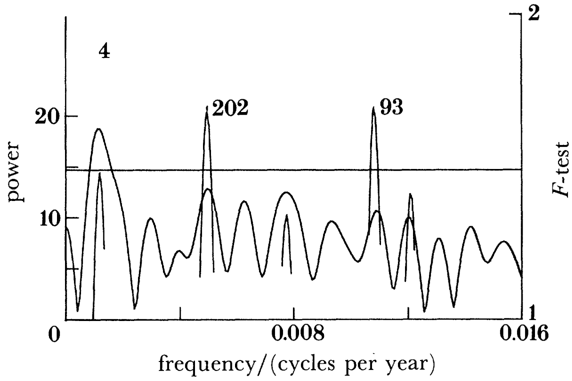

FIGURE 4. Multitaper spectral analysis of ^{10}Be concentration in South Pole ice over the past *ca.* 1100 years, showing power (left scale) and significance according to F-test (right scale). The horizontal line represents an F-test confidence level of 90 %.

In figure 5 we show the recently obtained δ^2H profile for the South Pole core (Petit *et al.* 1990). The same depth-to-age conversion as for the ^{10}Be curve has been used here. It can be observed that the raw δ^2H data contains even more high-frequency 'noise' than the ^{10}Be signal. Once again the spline smoothed data is shown as a heavy solid curve.

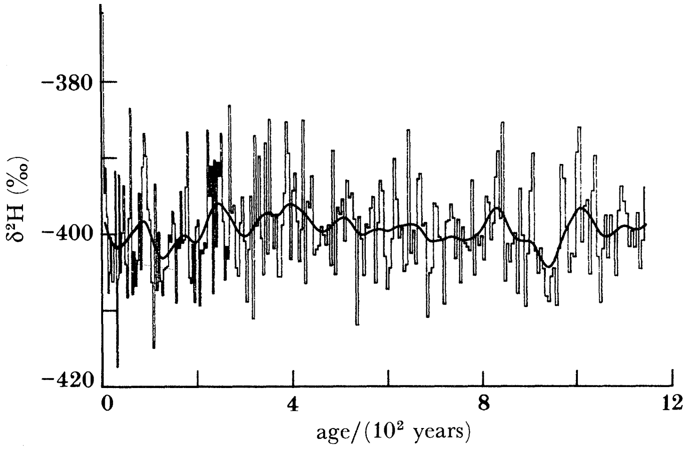

FIGURE 5. δ^2H as a function of time in the same South Pole ice core used for ^{10}Be measurements shown in figure 2. Histogram represents raw data and the smoothed curve has been obtained by using a spline function.

We can now look for a possible correlation in the ^{10}Be and δ^2H data. To make a visual comparison, it is obviously preferable to show the smoothed curves (figure 6). However, the data are then no longer independent, making it impossible to obtain a quantitative estimate of the degree of significance from a cross-correlation analysis. We have therefore carried out the correlation analysis on the raw ^{10}Be and δ^2H data, after resampling to have the same sampling intervals. Depending on the averaging interval used, the correlation coefficient varies from 0.007 (127 intervals of *ca.* 8 years) to 0.205 (32 intervals of *ca.* 35 years). None of these is statistically significant at the 10% level.

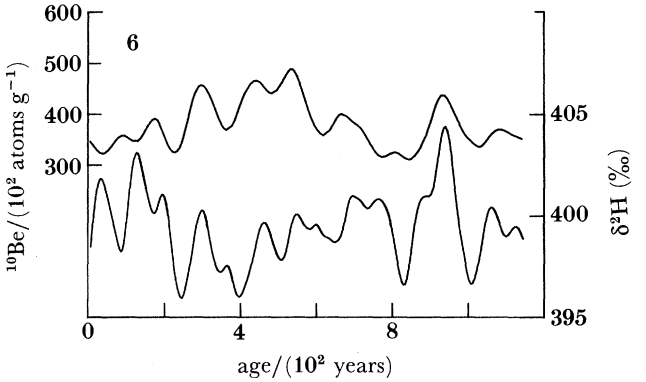

FIGURE 6. Comparison of smoothed ^{10}Be concentration and δ^2H in South Pole ice core.

Dome C

To extend the above type of analysis to a longer timescale, and another site, we now consider results from another Antarctic ice core at Dome C. Both the ^{10}Be (Raisbeck & Yiou 1988) and δ^2H (Benoit *et al.* 1982) data from this core have been previously published. We thus show directly in figure 7 the smoothed profiles derived from these measurements, adopting the timescale of Raisbeck & Yiou (1988). We stress that, although the absolute timescale in this case is considerably more uncertain than for the South Pole core, the use of the same depth-to-age conversion for both profiles means that our correlation analysis is independent of the timescale adopted. Once again the correlation has been carried out on the raw data after resampling. The result is a correlation coefficient of 0.136 (160 intervals of *ca.* 20 years) or 0.150 (80 intervals of *ca.* 40 years) that again is not significant.

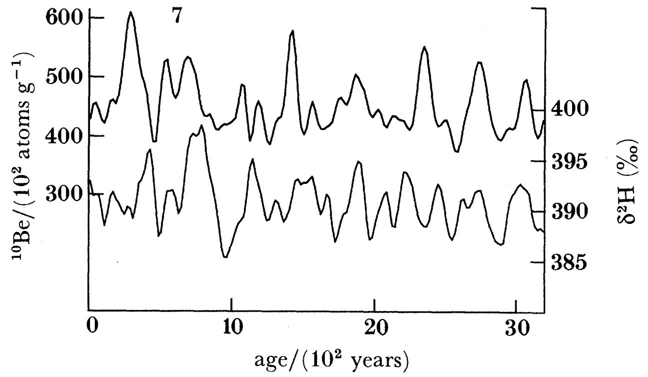

FIGURE 7. Comparison of smoothed ^{10}Be concentration and δ^2H in Dome C ice core.

Discussion and conclusions

We have shown above that there is no obvious correlation between solar activity (as indicated by ^{10}Be) and climate (as indicated by δ^2H) in two ice cores from Antarctica representing approximately the past 1000 and 3000 years. There are at least three possible explanations for this.

1. ^{10}Be is not a reliable indicator of solar activity. Although the ^{10}Be concentration in polar ice obviously contains a certain amount of meteorologically induced 'noise', we believe the remarkable correlation with ^{14}C seen in figure 3, as well as a recent comparison of ^{10}Be from Arctic and Antarctic ice cores (Beer *et al.* 1990) argue strongly in favour of a production rate origin for the main 100–200-year structure in the ^{10}Be record. Moreover, the magnitude of these variations is quite consistent with that predicted between periods of solar maximum and minimum. We thus consider it highly likely that the ^{10}Be record in polar ice is a good proxy indicator of solar activity for the time periods considered here.

2. δ^2H is not a reliable indicator of climate. As was mentioned earlier, and illustrated in figure 1, there seems to be no doubt that large changes in global climate, such as the glacial to interglacial transition occurring *ca.* 10–15 thousand years ago, are clearly recorded in the δ^2H (or δ^{18}O) signal of Antarctic ice. The change in surface temperature corresponding to this transition has been estimated as *ca.* 9 °C (Jouzel *et al.* 1989). The similarity in fine structure of the two curves in figure 1, from ice cores separated by *ca.* 500 km, suggests that, provided they last *ca.* 10^3 years, regional temperature changes as small as 1–2 °C can also be inferred from such records, although the global significance of these has not yet been demonstrated. For temperature changes on shorter timescales (*ca.* 10^2 years) characteristic of the solar variability being studied here, the situation is less clear. For example, even δ^2H records from two adjacent cores drilled at Dome C showed insignificant correlation, except possibly when smoothed over fairly long (*ca.* 500 year) time intervals (Benoit *et al.* 1982). This can probably be attributed to the low (*ca.* 3 g cm^{-2} a^{-1}) and irregular precipitation rate at this site, which can introduce significant noise into the stable isotope records over shorter time periods. On the other hand, a comparison of the δ^2H signal and annual mean temperature over a 20-year period at the South Pole, where the precipitation rate is significantly larger (*ca.* 8 g cm^{-2} a^{-1}), showed a high degree of correlation (Jouzel *et al.* 1983). Thus it seems reasonable to assume that this site should be recording temperature variability on the timescale being examined here, although once again the global significance of such changes remains uncertain. In summary then, although stable isotope ratios in polar ice cores have demonstrated their validity as indicators of large global climate change, their sensitivity for discerning modest global temperature changes on timescales (*ca.* 10^2 years) relevant to the solar activity variations under consideration here requires further studies.

3. There is no significant correlation between solar activity and climate. Such a conclusion would undoubtedly be unpalatable to many of the participants at this meeting, especially in the light of recent results showing an apparent correlation of solar irradiance with the activity level (P. Foukal, this Symposium). Because of the uncertainties in the climate signal mentioned above, we do not believe the data presented here exclude some level of solar activity–climate correlation. However, at the very least we have shown that there have been century-long periods of substantial change in solar activity during the past few thousand years, without

correspondingly large changes in Antarctic temperatures. Thus if a solar activity–climate relation does exist, it apparently is rather subtle, and will not be readily resolvable by the approach considered here.

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Discussion

N. O. WEISS (*University of Cambridge, U.K.*). I know that the 11-year activity cycle can be followed in the Milcent ice core from Greenland. Is it possible to detect this cycle in the ice core from the South Pole as well? At present the ^{10}Be record offers the only means of following the solar cycle back through the Maunder Minimum and over the past 1000 years. From the theoretical point of view it is extremely important to establish whether phase was maintained through the Maunder and Spörer Minima or not. This would allow us to distinguish between nonlinear dynamos and oscillators with stochastic perturbations. I hope therefore that the groups involved in analysing ice cores will succeed in providing an annual record of ^{10}Be abundance that covers the last millennium.

G. M. RAISBECK. The low accumulation rate on the Antarctic plateau, compared with the Arctic, makes it more difficult to record short-term variations such as the 11-year solar cycle. In the South Pole core, however, annual cycles of stable isotopes are apparently retained, so there is some hope that an 11-year cycle of ^{10}Be could be extracted. Although the time interval of the samples used in the present work were too long for such a study, we plan to examine this problem in the future.

JENNY ALLSOP (*Deep Geology Research Group*, *British Geological Survey*, *Nottingham*, *U.K.*). The slide, comparing the profile for ^{14}C with those for ^{10}Be and ^{2}H from polar ice cores, provided a good comparative index between ^{14}C and ^{10}Be indicating a relation between solar activity and variations in the Earth's climate. However, the use of a single comparative index for the whole of the ^{2}H profile may be misleading. The ^{2}H profile showed a good optical match on either side of a large, central area of divergence between ^{2}H and ^{10}Be that appeared to be almost a mirror image. A 'running' statistical comparative index may have illustrated that one large inconsistency between these profiles had caused the low index value.

If the reason for the low index is purely because of the large, single divergence, then ^{2}H may, in fact, reflect the same variations seen in the ^{10}Be and ^{14}C profiles under 'normal' conditions. Therefore, if a reasonable explanation for this divergence can be found, this may provide additional data on a particular climatic situation that has not as yet been considered.

G. M. Raisbeck. It is true that there are some portions of the ^{10}Be and δ^2H curves that seem to be correlated, and may indicate a causal relation. However, even two random curves will show similar behaviour over limited intervals and, in the absence of an *a priori* reason for choosing some intervals and not others, it is statistically dangerous to draw any conclusions from such *a posteriori* observations.

G. de Q. Robin (*Scott Polar Research Institute, Cambridge, U.K.*). Are the ^{10}Be data expressed in terms of ^{10}Be per unit mass corrected for changes in the rate of accumulation on ice sheets? The data shows that this was approximately halved during the last ice age.

I also comment that the noise level in δ-records in ice cores is highly dependent on the accumulation rate. Data from Dome C indicate that we need a core length between 100 and 150 years to estimate the mean temperature change of precipitation to within 1 °C from the δD record. We are not likely to see an 11- or 22-year periodicity in the δD record from Dome C, although we may just see this periodicity at the South Pole, where precipitation is at least double that at Dome C.

G. M. Raisbeck. Our data are expressed as ^{10}Be concentration per unit mass of ice. As Dr Grove points out, we do find an approximately factor of two increase in this concentration during ice age periods, and we have interpreted this as being as a result of a corresponding reduction in accumulation rate of ice during those periods. It is in fact this complication that prevents us from estimating possible differences in the average solar activity between these ice ages and interglacials. However, using the same temperature-accumulation relations, one would predict a maximum effect on the ^{10}Be concentration during the Holocene of only *ca.* 10%, i.e. considerably smaller than the effects attributed to solar modulation.

With regard to your remarks on extracting short-term temperature estimates from the δ^2H data in low accumulation rate areas, we are in complete agreement, as I hope the written text makes clear.