^{10}Be concentration in the ice shelf of Queen Maud Land, Antarctica

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The radionuclide ^{10}Be is produced in the atmosphere by cosmic rays. When it filters out and settles in polar ice, it becomes a powerful tool to study the variations of the cosmic ray intensity in the distant past and, from that, solar activity before the era of systematic solar observations.[6] The relationship between the cosmic ray intensity and the ^{10}Be concentration is, however, an inferred one, because cosmic rays have been observed only during the past 50 years or so, while there are only a few ^{10}Be records for this period. We report here on a pilot experiment to cut ice from the exposed ice shelf near the South African base, SANAE, in Queen Maud Land, Antarctica, from which this ^{10}Be/cosmic ray relationship may eventually be established experimentally.

Introduction

Cosmic rays come from the galaxy and beyond. Their intensity has been measured continuously during the past 50 to 60 years, both on Earth and in space. At energies <10 GeV per nucleon (magnetic rigidity $P \approx 10$ GV), the cosmic ray intensity varies in response to solar activity. As an example, Fig. 1 shows the counting rate of the SANAE neutron monitor (71°40′S, 2°51′W, lower cutoff rigidity 0.8 GV) from its inception in 1965. The variation, with a dominant 11-year periodicity, is called solar modulation of the galactic cosmic ray intensity. To first order, this variation is in anti-phase with solar activity as measured by the sunspot number,[8] also shown in Fig. 1. Physically, the modulation is due to the heliospheric magnetic field (HMF) and its irregularities that are embedded in the solar wind. The charged cosmic ray particles scatter off these field irregularities, which causes an inward diffusive flux into the heliosphere. The irregularities are carried outward by the solar wind (speed ~ 400 km/s), which also leads to an effective outward cosmic ray convection. When the sun is active, the HMF is more disturbed and stronger, the scattering and outward convection are more effective, and fewer cosmic rays can penetrate into the inner heliosphere, leading to a lower intensity.[12] Cosmic ray modulation therefore provides an indirect means to study aspects of solar activity such as the solar wind, and solar and heliospheric magnetic fields.

Solar activity has been studied systematically much further back into the past than the cosmic ray era, by observations of the number of sunspots,[8] as shown in Fig. 2. This firmly establishes the 11-year cycle as a semi-permanent feature, as well as the so-called Grand Minima of solar activity, such as the Maunder (AD 1645–1715), Dalton (AD 1800–1830), and Gleissberg (AD 1880–1910) minima. Sunspots are, however, not directly related to the heliomagnetic processes that cause this modulation,[11] and are therefore not the best indicator to infer past levels of the cosmic ray intensity and the parameters that influence it.

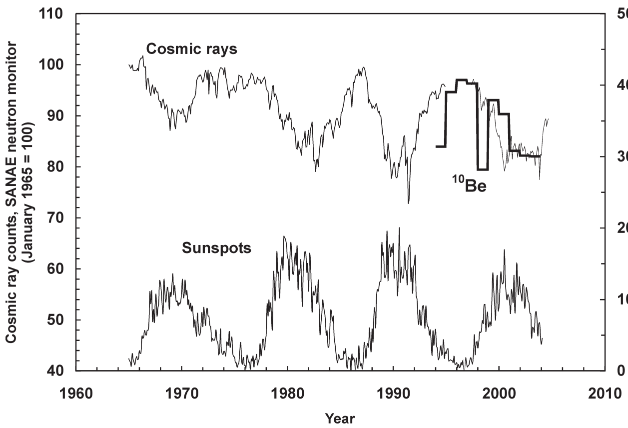

Fig. 1. Cosmic ray intensity as recorded by the SANAE neutron monitor since 1965, together with sunspot measurements.[8] The histogram in thick lines is the ^{10}Be concentration measured in the pilot experiment, with the concentration scale shown in Fig. 4.

When cosmic rays strike the atmosphere, they fragment the nuclei of air molecules, one of the fragmentation products being the isotope ^{10}Be. This ^{10}Be settles in polar ice, and its concentration in cores drilled in Antarctica and Greenland during the past 20 years[5,14] has produced an indirect cosmic ray record that extends over the past 100 000 years.[17] Several aspects of experimental and theoretical ^{10}Be/cosmic ray studies can be found in Caballero-Lopez *et al.*[6] and McCracken *et al.*[11]

The relationship between the ^{10}Be concentration in polar ice and the cosmic ray intensity is an inferred one, based on calculations of the ^{10}Be yield by the nuclear processes in the atmosphere,[9,16] and its transport to polar regions. This relationship is difficult to measure because in vertically drilled boreholes, the uppermost layers of firn (partially consolidated snow) from the last 50 years or so are not sufficiently compacted to come out as a solid core. This upper part of the borehole must often be supported by metal casing. Percolation of melt-water in the firn causes additional uncertainties. A further problem in the ^{10}Be/cosmic ray relationship is the uncertainty about how quickly the ^{10}Be settles. Owing to the spectrometric effects of the geomagnetic field on the charged cosmic ray particles, the ^{10}Be

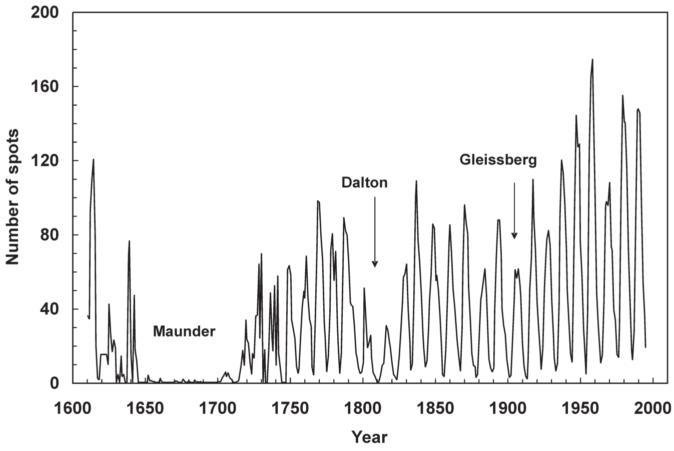

Fig. 2. Sunspot numbers back to 1600.[8]

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concentration in polar ice will be different if it settles fast and locally, as opposed to the situation where there is global mixing before it settles after a much longer time.[10,11,15] The ratio between the amplitudes of the 11-year cycles in the ^{10}Be and the data from a high latitude neutron monitor, each expressed as a percentage of the relevant sunspot minimum value, is a sensitive measure of this mixing effect. Thus, it varies between ~2.3 for local production and ~1.7 for global mixing, and an accurate measurement of this ratio is an important goal of the planned experiment. In addition, the distinction between wet and dry deposition[7] might be necessary to explain the transfer of ^{10}Be from the atmosphere into the firn and ice. These processes and their relative importance depend on the accumulation rate of snow at the site.[2] Pits of several metres depth have been dug[4,15] in the polar ice to measure the ^{10}Be concentration deposited in recent times more accurately, while there are also other studies on shallow cores.[1] These experiments have not yet yielded conclusive results on how to infer the galactic cosmic ray flux reliably, because every location seems to be unique and no one is perfect in terms of recording past changes in galactic cosmic ray intensity. To improve our knowledge about ^{10}Be as a tool to reconstruct cosmic ray intensity, it is crucial to enlarge our database of the past few decades regarding ^{10}Be production and its atmospheric transport. It is in this situation that the ice shelf in Queen Maud Land, Antarctica, offers a promising and cost-effective opportunity, because it is frequently visited and little investment has to be made in infrastructure and equipment to sample this ice.

Pilot experiment

Figure 3 shows the ice shelf at ~ 70°15′S, 2°50′W, where the supply vessel *SA Agulhas* offloads on its annual relief voyage. It is between 30 and 50 m high, and annual accumulation layers of ~1 m thick are clearly visible. The accumulation is mostly due to drift snow from other regions because the local precipitation is very low; from 1960 to 1994 there were, on average, only 14 snow days per year. This drift is expected to be fairly local in extent, within a few hundred kilometres, and the clearly visible annual melt layer that forms in summer is an indication that different years probably do not get mixed. Owing to the height of the shelf, an offloading ramp of between 10 and 15 m depth has to be cut every season. The aim of the main experiment is eventually to cut ice from the face of the shelf, but for the pilot experiment the offloading ramp offers an easy and safe opportunity to test equipment and techniques, and to acquire experience.

This pilot experiment was conducted during the December 2003/January 2004 voyage of the *SA Agulhas.* Samples were cut from the exposed annual layers within the ramp. Two techniques were tested, namely a 10-cm-diameter core driller applied horizontally, and a mechanical chain saw to cut vertical wedges of ~1 m height (the full thickness of the layer), ~30 cm wide at the front face, and ~50 cm deep on the two sloping faces of the wedge. This second technique proved to be the fastest and easiest by far. It also yielded an integrated record for the whole year, not just for parts of it. Between 1 and 2 kg of the back portion of this wedge, farthest away from the face, was used as sample. After adding a spike of 0.3 mg ^{9}Be, the samples were melted. Subsequently, the Be was filtered (pore size 45 μm) and separated from the water and retained, using ion-exchange columns. This allowed us to transport the samples after the expedition in a convenient way to Dübendorf (EAWAG), Switzerland, where they were processed and prepared for measurement with the Zurich AMS facility, jointly operated by the Paul Scherrer Institute and ETH Zurich.

Fig. 3. The ice shelf in Queen Maud Land, showing the annual layers of ice and the 2003/4 offloading ramp that was used for the pilot experiment.

Two ramps were actually used: the one cut for the 2003/4 season, as well as the one used for the previous 2002/3 season. Both these ramps were sampled on the same expedition, in the 2003/4 season. This gave an opportunity to test repeatability.

Results and discussion

The measurements are summarized in Table 1, showing the year level, a label, mass and thickness of ice in the sample, and the ^{10}Be concentration. These data are plotted in Fig. 4. The error bars in the figure are the average values of those shown in the table, namely $\pm 0.05 \times 10^4$ atoms/g for the 2003/4 ramp and $\pm 0.02 \times 10^4$ atoms/g for the 2002/3 ramp. There are two results for the 2002/3 ramp, with and without the annual melt layer. The difference between them is marginally significant, but will not be explored here.

There is a large difference in ^{10}Be concentration between the two ramps. In the 2003/4 ramp it is about 4 times higher than in the 2002/3 one, except for the last two years. This difference is puzzling. It would be surprising if this were due to local variations in ^{10}Be deposition because the ramps are only ~300 m apart. Another explanation is that the ^{10}Be leaks or filters out of the ice as it stands exposed. This may be due to sea spray and mist penetrating the ice and dissolving the ^{10}Be. This does not, however, explain why the varying concentrations observed in the 2003/4 ramp leak out in such a manner as to produce a fairly constant concentration after a year of exposure in the 2002/3 ramp. It is also unclear why the concentration in the two uppermost layers are so different, and where the ^{10}Be goes to if it dissolves. It probably cannot penetrate through the annual ice layers. There may also be processes involved which are connected to strong winds leading to air (and ^{10}Be) movement in the firn. These questions must be addressed in follow-up experiments, in part, by taking surface samples from many different locations in the general vicinity of the SANAE base.

The time variation of the ^{10}Be concentration in the 2003/4 ramp is approximately as expected, as is demonstrated by plotting it as a histogram onto the cosmic ray intensity of Fig. 1. It is arbitrarily normalized so that its variation has the same amplitude as that of the cosmic ray variation. In 1998 there is a big discrepancy with the cosmic ray intensity, with a much lower concentration than expected. This discrepancy cannot be attributed to any known effect. The 1994 concentration is also low. The other points are in general agreement with the cosmic ray intensity, but the ^{10}Be concentration lags up to one year behind the cosmic ray inten-

Table 1. ^{10}Be concentration measured in the two ramps as described in the text.

Year	2003/4 ramp			2002/3 ramp with layer			2002/3 ramp without layer		
	Label	Mass (g)/ thickness (cm)/ layer (cm)	^{10}Be (atoms/g × 10^4)	Label	Mass (g)/ thickness (cm)/ layer (cm)	^{10}Be (atoms/g × 10^4)	Label	Mass (g)	^{10}Be (atoms/g × 10^4)
1991(2)				OR12	1358/73/11	0.314 ± 0.019			
1992(3)				OR11	1974/80/10	0.289 ± 0.016	ORN11	890	0.256 ± 0.020
1993(4)				OR10	1018/69/3	0.264 ± 0.017	ORN10	1030	0.282 ± 0.020
1994(5)	NR9	890/69/1	0.982 ± 0.039	OR9	2174/82/7	0.244 ± 0.014	ORN9	1160	0.585 ± 0.035
1995(6)	NR8	922/94/1	1.431 ± 0.086	OR8	1070/77/5	0.234 ± 0.015	ORN8	1040	0.235 ± 0.017
1996(7)	NR7	950/108/6	1.531 ± 0.061	OR7	1344/94/6	0.288 ± 0.017	ORN7	1214	0.352 ± 0.024
1997(8)	NR6	1044/45/1	1.502 ± 0.046	OR6	856/47/7	0.284 ± 0.018	ORN6	1180	0.362 ± 0.027
1998(9)	NR5	890/101/a	0.793 ± 0.036	OR5	1320/63/3	0.116 ± 0.008	ORN5	1160	0.349 ± 0.016
1999(0)	NR4	1102/110/5	1.365 ± 0.048	OR4	2064/101/11	0.322 ± 0.017	ORN4	1152	0.275 ± 0.020
2000(1)	NR3	828/112/1	1.250 ± 0.066	OR3	2106/121/8	0.320 ± 0.014	ORN3	1150	0.260 ± 0.014
2001(2)	NR2	1295/85/b	0.948 ± 0.035	OR2	1824/94/9	0.460 ± 0.019	ORN2	1140	0.252 ± 0.018
2002(3)	NR1B	1352/137/3	0.908 ± 0.031	OR1B	906/27/1	1.220 ± 0.043	ORN1BA2	1130	1.317 ± 0.053
2003	NR1A	972/30/0	0.902 ± 0.040	OR1A	2164/150/0	1.465 ± 0.044			

a, Several thin layers; b, unidentified.
Columns 3 and 6 give the mass of the sample, the thickness of the annual layer including the melt layer, and the thickness of the melt layer. The thickness numbers for the "ORN" samples in columns 8–10 are the same as those in column 6. The uppermost layer (1A) was for 2003, but it was very thin (~30 cm) in the 2003/4 ramp. The next layer (1B) probably was 2002, but it could also be 2003. The opposite situation holds for layers 1A and 1B in the 2002/3 ramp. This causes an uncertainty of one year, denoted by (), in deeper layers.

sity, which agrees with earlier estimates of the mean atmospheric residence time.[3,13] Determining this phase lag is one of the prime objectives of this experiment.

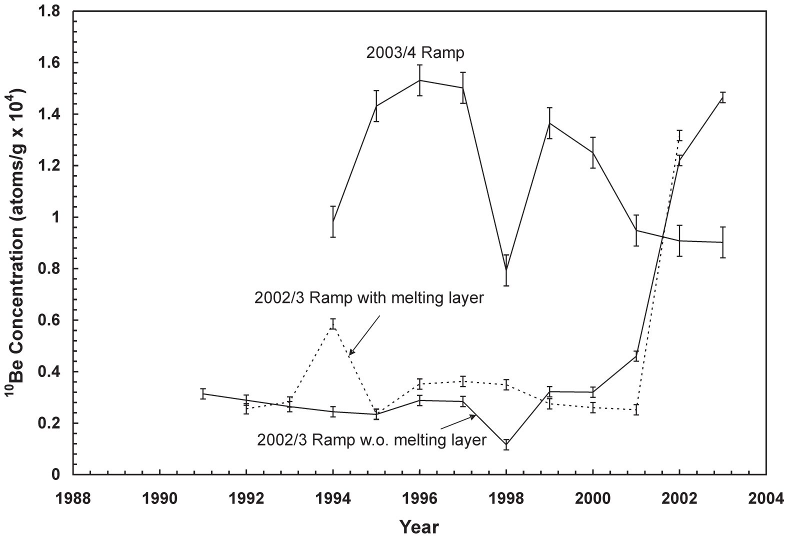

Fig. 4. This figure is a plot of the ^{10}Be concentrations shown in Table 1.

Conclusions

This pilot experiment has established a workable technique to sample ice from the ice shelf, but it has delivered unexpected first results which may be due to a variety of reasons. The experiment was repeated on 23–25 January 2005, using the same two ramps, but the results cannot be processed before July 2005. The first aim of this second attempt is to test repeatability and/or whether ageing effects can be seen after an additional year of exposure to the atmosphere. If these new results show that the concentration in the 2003/4 ramp is reduced to that of the 2002/3 ramp, it confirms the leakage hypothesis, and further cutting from the exposed ice shelf, as planned for the main experiment, will not be meaningful. If, however, these discrepancies are resolved and the reasons for them are properly understood, sampling from the shelf itself will begin. This will not be done in summer, but in September/October when there is still bay ice from the winter season below the shelf, so that the work, to be done in abseiling mode, can be guided from the top and bottom of the shelf.

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