30TH INTERNATIONAL COSMIC RAY CONFERENCE

Long-term changes in cosmic rays derived from cosmogenic radionuclides

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Abstract: Direct continuous records of cosmic rays are restricted to the past 50 years, the era of neutron monitors. Ionization chambers provide an additional 20 years of data. In order to investigate cosmic rays on centennial to millennial time scales one has to rely on cosmogenic radionuclides which can be considered as natural neutron monitors. Combining ^{10}Be from ice cores with ^{14}C from tree rings we construct a cosmic ray record going back almost 10'000 years.

Introduction

Following the discovery of the cosmic radiation in 1912, instrumental difficulties precluded continuous monitoring of its intensity for several decades. Starting in 1951 a global network of sophisticated, inter-calibrated neutron monitors has kept track of the changes in the cosmic ray flux with a temporal resolution of minutes and high precision. Between 1936 and 1971 cosmic rays were also measured with ground-level ionization chambers, however, they exhibited several forms of long-term instability. Carefully intercalibrated ionization chambers were flown on balloons between 1933 and 1969 and the long-term changes in sensitivity were estimated to be <1% [1].

While the mean cosmic ray flux since 1951 does not show much of a long-term trend, the balloon borne ionization chambers revealed a clear decreasing trend from 1937 to 1957 which was originally ignored due to the lack of corroborating evidence, but which has been recently validated using the cosmogenic record. [2]. To extend the cosmic ray record further back in time one has to rely on cosmogenic radionuclide neutron monitors provided by nature.

Cosmogenic radionuclides as natural neutron monitors

As pointed out earlier by Beer [3] cosmogenic radionuclides such as ^{10}Be and ^{14}C can be considered as a natural neutron monitor. Instead of counting instantaneously every neutron entering the detector the natural neutron monitor stores the primarily neutron induced cosmogenic radionuclides in natural archives such as ice sheets and tree rings where they can be found and counted later. This provides the unique opportunity to go back in time and to reconstruct the cosmic ray flux over at least the past 10,000 years. The disadvantages compared to a modern neutron monitor are (1) the time resolution is limited to about 1 year and (2) the relatively small signal to noise ratio.

^{14}C is produced by thermal neutrons interacting with nitrogen (^{14}N(n,p)^{14}C). The mean global production rate is about 2 ^{14}C atoms cm^{-2} s^{-1}. The ideal archive for ^{14}C atoms are tree rings that are formed annually and store the atmospheric ^{14}C/^{12}C ratio with a slight isotopic fractionation which can be corrected for by measuring δ^{13}C.

^{10}Be on the other hand is produced by high-energy spallation reactions of neutrons (82 %) and protons (8 %) with nitrogen (87 %) and oxygen (13 %). After a mean residence time of about

1 year ^{10}Be is removed from the atmosphere and stored in ice sheets and sediments. Ice sheets are formed by annual snow layers which under the pressure of the overlying layers slowly turn into ice and preserve the annual fallout of ^{10}Be for up to one million years.

^{10}Be and ^{14}C

In order to demonstrate the performance of ^{10}Be and ^{14}C as natural neutron monitors we compare the calculated relative annual production changes of ^{10}Be and ^{14}C with the measured relative annual count rate of the Climax neutron monitor for the period 1953 to 2004. The relative changes are calculated by dividing the annual values by the corresponding mean value of the time interval (1953-2004).

For this demonstration we calculate the ^{10}Be and ^{14}C production changes using the solar modulation potential, ϕ, given by Usoskin [4]; the local interstellar spectrum according to Castagnoli and Lal [5]; and the production calculations by Masarik & Beer [6]. The results are shown in Fig. 1.

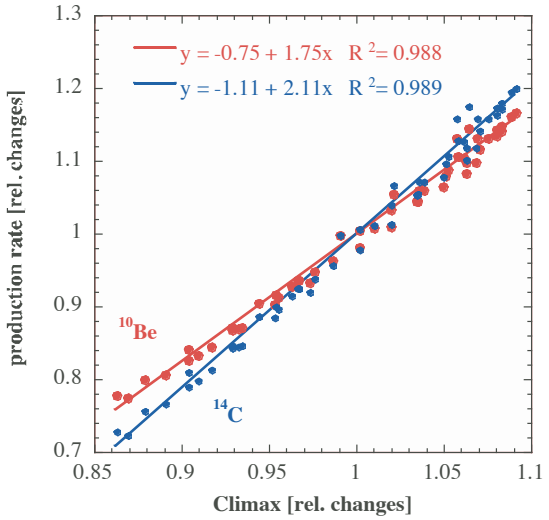

Figure 1: Comparison of the relative production changes of ^{10}Be (red) and ^{14}C (blue) with the corresponding relative changes of the count rate of the Climax neutron monitor. The steeper slope of ^{14}C indicates a larger sensitivity due to the fact that ^{14}C is produced by thermal neutrons.

The scatter plots show an almost linear relationship between the cosmogenic radionuclides and the Climax neutron monitor for ϕ values ranging from 300 to 1140 MV, while being consistent with the curvature in the relationship derived elsewhere for $0<\phi<1400$ MV [2]. The slopes are larger than 1 indicating that both cosmogenic radionuclides, and in particular ^{14}C, are more sensitive to solar modulation than is the Climax neutron monitor. However, as we now discuss, the production rates of cosmogenic radionuclides depend not only on the involved nuclear reactions but also on the so-called system effects, and the characteristics of the transport from the point of production to the point of deposition or archiving.

System effects

A modern neutron monitor is operated at a fixed geographical position. As a consequence the cut-off rigidity for the present geomagnetic field is constant and therefore also the yield function. In the case of a cosmogenic radionuclide monitor the situation is completely different. Due to atmospheric mixing there is no fixed cut-off rigidity and assumptions have to be made about the degree to which ^{10}Be and ^{14}C are mixed. The ^{10}Be and the ^{14}C system are very different (Fig. 2).

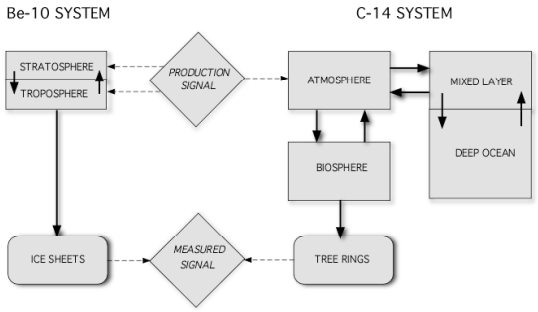

Figure 2: Comparison of the ^{10}Be system with the ^{14}C system. While ^{10}Be gets attached to aerosols and is removed from the atmosphere within about 1 year, ^{14}C forms $^{14}CO_2$ and starts exchanging between atmosphere, biosphere and ocean. As a consequence of the two different systems the common atmospheric production signal is altered in different ways. Therefore the measured signals cannot be compared directly and a carbon cycle model has to be used to calculate the ^{14}C production signal.

After production ^{10}Be becomes quickly attached to aerosols particles. While the residence time of the aerosols in the stratosphere (where more than 50% of the nuclides are produced) is larger than 1 year it takes on the average less than 1 month for the ^{10}Be to be removed from the troposphere mainly by wet precipitation. To illustrate the sensitivity of the observations to the degree of mixing we repeat the calculation for the period 1953 to 2004 assuming that a) the low latitude tropospheric production below 30° does not reach the polar regions; b) the polar ice sheets only reflect production changes above 60°, c) the atmosphere is completely mixed as assumed in Fig. 1, and d), using the empirical mixing model M3 used in some earlier publications [2,7].

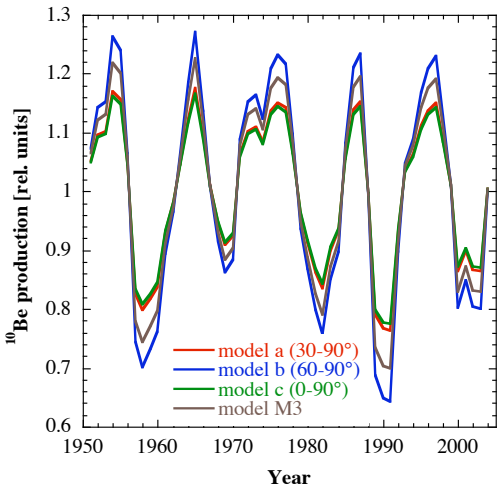

Figure 3: Effects of different atmospheric mixing models on the relative ^{10}Be production rate for the period 1953-2004.While model b is unrealistic we favor model a which only slightly differs from a complete atmospheric mixing (model c), or model M3.

While the complete separation of the polar region from the rest of the globe is probably unrealistic (model b), the evidence suggests that the global mixing is close to either model a or model M3 [7]. To fully account for the transport of ^{10}Be, a global circulation model (GCM) is required that includes the physical processes responsible for the stratosphere-troposphere exchange, the formation and transport of aerosols, and the scavenging processes.

The ^{14}C system is completely different from the ^{10}Be system. The main difference is that ^{14}C forms $^{14}CO_2$ and exchanges between the large reservoirs in the atmosphere, biosphere and the ocean (Fig. 2). As a result of the much longer residence times (atmosphere: 10 y, biosphere: 60 y, ocean: 1000 y) the atmosphere can be considered as globally well mixed. On the other hand, short-term variations are strongly dampened and delayed depending on the rate of change.

As a consequence of the filtering effect of the carbon system the measured ^{14}C content in tree rings does not provide directly the cosmic ray induced production changes. In order to determine the atmospheric production variations a carbon cycle model has to be applied [8]. This model is characterized by the sizes of the reservoirs and the exchange rates between them. If, in a first step, these parameters are considered as constant then all measured ^{14}C changes are attributed to atmospheric production changes. The same holds true in the case of ^{10}Be. Assuming that the ^{10}Be changes in the ice reflect directly the atmospheric production changes attributes all transport and scavenging effects to production effects. In summary, ^{10}Be and ^{14}C records contain both a common cosmic ray production component, but also different system effects which *a priori* cannot be distinguished from the production component.

Separation of production and system effects

To separate the production and system effects, and to extract the cosmic ray intensity signal, we make use of the fact that changes in the cosmic ray intensity affect ^{14}C and ^{10}Be in a very similar way. By way of contrast, climate changes are expected to cause completely different system effects. Therefore we can extract the common signal by applying the statistical procedure of principal component analysis (pca). For this purpose we took the Holocene part of the ^{10}Be GRIP record [9] covering the period 305-9300 cal y BP and the ^{14}C production rate calculated using the box diffusion model of Siegenthaler [8]. Both records were interpolated to 1 year and low-pass filtered (1/100y). Principal component analysis was then performed after a rough adjustment of the GRIP time scale to the tree ring time scale. The first principal component in Fig. 4, the pro-

duction component, explains about 90% of the total variance while the second component, the system effects, accounts for about 10%. Fig. 4 shows the first principal component together with the ^{10}Be record (panel a) and the ^{14}C record (panel b).

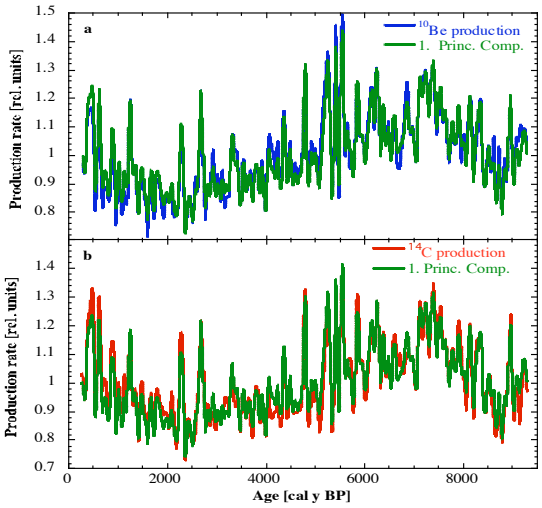

Figure 4: Comparison of the first component of the principal component analysis (in green) with the measured relative ^{10}Be (panel a) and ^{14}C (panel b) production changes. The first or production component explains about 90% of the total variance of the low-pass (1/100y) filtered data.

The main features of the first principal component, which we propose provides the best estimate for the cosmic ray intensity, are (1) the long-term trend which mainly reflects the secular changes in the geomagnetic field, and (2) the short-term fluctuations which are due to solar modulation.
Note that the lower envelope of the curve represents periods of strong modulation, similar to the present epoch, while the upper envelope corresponds to episodes of "Grand Minima". The Spoerer, Wolf and Oort Grand Minima are the left most peaks in Figure 4.

Conclusions

Cosmogenic radionuclides such as ^{10}Be and ^{14}C, together with their natural archives (ice sheets, tree rings) can be considered as natural neutron monitors with a low temporal resolution (>1 y) and a relatively small signal to noise ratio. However, they offer the unique opportunity to reconstruct the cosmic ray intensity over at least the past 10,000 years. Combining ^{10}Be and ^{14}C records using the statistical process of principal component analysis shows that on centennial time scales the production signal accounts for about 90% of the total variance in the data and seems to be a promising tool to reduce the contributions made by system effects. Adding ^{10}Be records from different sites will help to even further reduce the non-production component of the signal.

Acknowledgments

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