ICE CORE DATA ON CLIMATE AND COSMIC RAY CHANGES

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Abstract
Ice cores represent archives which contain unique information about a large variety of environmental parameters. Climatic information is stored in the form of stable isotopes, greenhouse gases and various chemical substances. The content of cosmogenic nuclides such as $^{10}\text{Be}$ and $^{36}\text{Cl}$ provide long-term records of the intensity of the cosmic ray flux and its modulation by solar activity and the geomagnetic dipole field. Cosmogenic nuclides are produced by the interaction of cosmic ray particles with the atmosphere. After production, these nuclides are transported and distributed within the environment, depending on their geochemical properties. Some of them are removed from the atmosphere by snow and incorporated into ice sheets and glaciers. The analysis of the Greenland ice cores GRIP and GISP2 are discussed in terms of climate and cosmic ray changes during the past 50'000 years.

1. ARCHIVE ICE
Polar ice sheets are formed from snow. The snowflakes grow together to grains which slowly increase in size. Due to the pressure of the overlying new snow layers, the grains become more and more compacted and finally turn into ice. The consequence of this formation process is that the ice not only preserves all the atmospheric constituents such as aerosols and dust, it also contains air bubbles that enable to determine the atmospheric composition and in particular the reconstruction of greenhouse gases in the past. This unique property makes ice the only archive that virtually stores all the climate forcing factors (greenhouse gases, aerosols and volcanic dust, solar irradiance) except internal variability. Ice cores also contain information on the corresponding climate response (temperature, precipitation rate, wind speed, atmospheric circulation). Another important property of ice is that it flows. This can be seen in Fig. 1, which schematically depicts an ice-sheet. The ice slowly flows towards the margin of the ice sheet, where it partly melts and partly breaks up as icebergs. Under steady-state conditions, the ice lost in the ablation area is replaced by snow falling on the accumulation area where new layers are formed continuously. As a consequence of the horizontal movement of the ice, the annual layers become thinner with increasing depth, as indicated in Fig. 1.

This leads to another special property of the archive ice. The depth–age relationship is non-linear, which has the advantage that the uppermost part of the core is well resolved and the total time period covered is long (of the order of $10^5$ years for polar ice cores). The disadvantage of this non-linear time-scale is, however, that dating ice is difficult and relies strongly on correct modeling of the ice-flow. The main ice sheets are situated in polar regions (Greenland, with a maximum thickness of approx. 3 km and Antarctica, with a thickness of up to 4 km). Smaller ice sheets at lower latitudes can only be found at high altitudes (Andes, Himalayas, Alps) [1].

There is a steadily growing number of parameters which can be measured in ice cores. It is beyond the scope of this paper to discuss all these parameters. In Table 1, a small selection of those related to climate forcing and climate response is given.
Figure 1: Formation of an ice sheet. The snow falling in the accumulation region turns into ice that slowly flows towards the ablation area where it breaks up into ice-bergs or melts. As a consequence of the flow characteristics the thickness of annual layers decreases with increasing depth.

Table 1. Climate parameters measured in ice cores.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proxy for</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>Greenhouse gases</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>Greenhouse gases</td>
</tr>
<tr>
<td>SO$_4$</td>
<td>Volcanic eruptions</td>
</tr>
<tr>
<td>Ash</td>
<td>Volcanic eruptions</td>
</tr>
<tr>
<td>$^{10}$Be, $^{36}$Cl</td>
<td>Solar activity</td>
</tr>
<tr>
<td>$\delta^{18}$O</td>
<td>Temperature</td>
</tr>
<tr>
<td>Borehole temperature</td>
<td>Temperature</td>
</tr>
<tr>
<td>Annual layer thickness</td>
<td>Precipitation rate</td>
</tr>
<tr>
<td>Dust</td>
<td>Wind speed</td>
</tr>
<tr>
<td>Anions / cations</td>
<td>Atmospheric circulation</td>
</tr>
</tbody>
</table>

As an example, $\delta^{18}$O of the GRIP ice core is shown in Fig. 2. $\delta^{18}$O (relative deviation of the $^{18}$O/$^{16}$O ratio in ice from a standard in %) reflects mainly the temperature at which snow is formed.

Figure 2: $\delta^{18}$O measured in the GRIP ice core from Greenland. Low values indicate cold climate. During the last 10'000 years the temperature was relatively stable compared to the preceding glacial period.
Figure 2 shows that during glacial times the temperature in Greenland was characterized by abrupt changes (so-called Dansgaard-Oeschger events) of up to 20°C within a few decades. The last 10,000 years, the so-called Holocene, however, looks comparatively stable. The Dansgaard-Oeschger events were probably caused by abrupt changes in the ocean circulation, transporting heat to high latitudes. In the following, we will concentrate on what cosmogenic radionuclides in ice cores can tell us.

2. COSMOGENIC RADIONUCLIDES IN ICE

The cosmic ray particles (87% protons, 12% helium nuclides, 1% heavier particles) that enter the Earth’s atmosphere react with Nitrogen, Oxygen and Argon, producing a cascade of secondary particles. These nuclear processes produce a variety of cosmogenic nuclides such as $^{10}$Be, $^{14}$C and $^{36}$Cl. These nuclides are listed in Table 2 together with their main properties.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half-life (years)</th>
<th>Target</th>
<th>Production rate (atoms cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}$Be</td>
<td>1.5 $10^5$</td>
<td>N, O</td>
<td>0.018</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>5730</td>
<td>N, O</td>
<td>2.0</td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>3.01 $10^5$</td>
<td>Ar</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

The physics of the production processes is well understood and therefore the production rate can be calculated for each point in the atmosphere, depending on the heliospheric modulation and the geomagnetic field intensity, provided the involved nuclear cross-sections are known [2]. As an example, Fig. 3 shows the dependence of the mean global production rate of $^{10}$Be as a function of solar modulation parameter $\Phi$ ($\Phi = 0$: quiet sun, $\Phi = 1'000$: very active sun) and the geomagnetic field intensity $B$ in relative units ($B = 1$ corresponds to the present field intensity). As can be seen, the dynamic range between no magnetic field ($B = 0$), no solar modulation ($\Phi = 0$) and doubled magnetic field ($B = 2$), very active sun ($\Phi = 1'000$) is about one order of magnitude. Note that the dependencies are non-linear and that production changes by only a factor 3-4 were observed so far.

Figure 3: Dependence of the relative mean global $^{10}$Be production rate on the geomagnetic field intensity and the solar activity parameter $\Phi$. The production rate 1 corresponds to a geomagnetic field 1 and a $\Phi$ of 550 corresponding to the average solar activity.
The transport of the cosmogenic nuclides produced in the atmosphere is not as well understood as the production processes. \(^{14}\text{C}\) forms CO\(_2\) and exchanges between the main reservoirs of the carbon cycle (atmosphere, ocean, biosphere). \(^{10}\text{Be}\) and \(^{36}\text{Cl}\) become attached to aerosols or exist in gaseous form (H\(^{36}\text{Cl}\)). After a mean residence time of 1 to 2 years they are removed from the atmosphere mainly by wet precipitation.

In Polar Regions, the aerosols are removed by the snow that forms the ice sheet. Assuming a production rate of 0.018 \(^{10}\text{Be}\) atoms cm\(^{-2}\) s\(^{-1}\) (Table 2) and a precipitation rate of 100 cm y\(^{-1}\), a simple calculation reveals an average \(^{10}\text{Be}\) concentration of approximately 10\(^7\) atoms per kg of ice. Extremely sensitive detection techniques are necessary to measure 10\(^7\) atoms. Due to the long half-life, decay counting is not feasible. However, accelerator mass spectrometry (AMS), using single atom detection is suitable to do the job [3]. A known amount of stable \(^{9}\text{Be}\) (typically 0.5 mg) is added to each sample. This leads to a \(^{10}\text{Be}/^{9}\text{Be}\) ratio in the range of 10\(^{-13}\) to 10\(^{-12}\). After extraction of the Be from the water by ion exchange technique, a BeO sample is produced. This sample is put into the ion source of the AMS system and an ion beam is produced and accelerated to high energy (20 MeV) by means of a tandem accelerator. This high energy destroys the molecular background and enables suppression of the isobaric background (\(^{10}\text{B}\) in the case of \(^{10}\text{Be}\)). In the following, some of the results obtained so far are discussed:

### 3. GEOMAGNETIC MODULATION

To reconstruct the geomagnetic field from the \(^{10}\text{Be}\) and \(^{36}\text{Cl}\) fluxes we assume that the \(^{10}\text{Be}\) and \(^{36}\text{Cl}\) fluxes at Summit are proportional to their average global production rate.

![Graph](image)

Figure 4: Comparison between the geomagnetic field reconstructed from a combined \(^{10}\text{Be} - ^{36}\text{Cl}\) record from the GRIP ice core [4] with the paleomagntic data derived from a mediterranean sediment core [5].

Figure 4 shows the geomagnetic field intensity for the period 20-60 kyr BP, reconstructed from the combined \(^{10}\text{Be}\) and \(^{36}\text{Cl}\) flux in the GRIP ice core [4]. The shaded area indicates the uncertainty in the calculated field intensity. Also shown is the field measured on a Mediterranean sediment core [5]. The correlation between the geomagnetic field intensities obtained from these two independent reconstructions is very high (\(r^2=70\%\)). In our calculation of the geomagnetic field intensity, the combined \(^{10}\text{Be}\) and \(^{36}\text{Cl}\) flux was normalized in such a way that a value of 10\% of its current value is assumed for the minimum of the calculated geomagnetic field intensity at about 40 kyr BP (Laschamp event). The normalization is also supported by new data from sediment cores of the Atlantic ocean [6].

The Laschamp event corresponds to a period of increased cosmic ray flux and therefore provides a test case for the proposed relationship between cosmic ray flux, cloud cover, and climate change [20]. The maximum of the combined flux of \(^{10}\text{Be}\) and \(^{36}\text{Cl}\) should be correlated
with the $\delta^{18}$O data (note the inverse scale) and CH$_4$ data (Fig. 5). However, this is clearly not the case. During the Laschamp event (36-41.5 kyr B.P.) the combined flux of $^{10}$Be and $^{36}$Cl is not significantly ($p < 0.1$) correlated with either $\delta^{18}$O ($r^2 = 0.07\%$) or CH$_4$ ($r^2 = 0.09\%$). The same applies over the entire time interval shown in Figure 5 ($r^2 = 0.3\%$ and $0.4\%$, respectively) [7].

![Figure 5: Comparison of the combined $^{10}$Be-$^{36}$Cl flux with the climate parameters $\delta^{18}$O and CH$_4$. According to the proposed relationship between cosmic ray flux and climate (Svensmark, this volume) a correlation between the three parameters is expected for the Laschamp geomagnetic minimum (shaded area) which is not present [7].](image)

4. SOLAR MODULATION

Direct observations clearly reveal that part of the solar variability is cyclic. In the following, we will concentrate only on cycles with time scales of years and longer. Cycles with periodicities from centuries to millennia are based on indirect or proxy data. Since these data (e.g. $^{10}$Be, $^{14}$C) represent a complex combination of different signals it is not always possible to unambiguously attribute a cycle to solar variability.

One way of distinguishing between solar variability induced signals and others is to compare $^{10}$Be and $^{14}$C. Both radionuclides are produced by similar nuclear reactions in the atmosphere. Their respective production rate and their dependence on solar activity can be calculated [2]. However, after production their geochemical behaviour differs completely.

A comparison of the two radionuclide records therefore allows us to distinguish between the production signal caused by solar and geomagnetic modulation and the system signal caused by the climate affecting the transport and the exchange processes between the different reservoirs.
The results from such comparisons indicate that, for the past several millennia, the short-term (decades to centuries) fluctuations in the Δ¹⁴C record are mainly due to production variations, most probably caused by solar modulation.

It is important to note that cycles associated with solar activity do not have a fixed periodicity. For example in the case of the sunspot cycle, the periodicity varies between 9 and 17 years. This raises the important question whether the periodicity averaged over longer times remains constant or not [8, 9]. To answer this question, longer and very precisely dated records of solar activity are needed than are presently available.

The most prominent solar cycle is the 11-y Schwabe cycle discovered by Schwabe in 1843 when analysing his 17 year-long sunspot data. In Fig. 6, the sunspot cycle based on sunspot groups [10] is shown for the period 1600-1999 together with the inversely plotted ¹⁰Be concentration measured in the Dye 3 ice core from South Greenland [9].

![Figure 6: Comparison of sunspot numbers with ¹⁰Be concentration. Periods of local reduced solar activity are dashed.](image)

In view of the fact that sunspot numbers and heliospheric modulation of the ¹⁰Be production rate are different representations of a common cause, i.e. solar activity, the agreement is good. A detailed analysis shows that the ¹⁰Be signal lags behind the sunspot signal by about 1 year, corresponding to the mean residence of ¹⁰Be in the atmosphere. It is interesting to note that the Schwabe cycle is still present in the ¹⁰Be record during the Maunder minimum [11].

A 90-year cycle was discussed by Gleissberg when analysing the auroral record [12]. The Dye 3 annual ¹⁰Be record going back to 1423 also shows the 90-year Gleissberg cycle [13].

The 205-year DeVries cycle is the most prominent periodicity in the Δ¹⁴C record during the Holocene. However, as with other periodicities, its amplitude and periodicity are variable with time. Since the sunspot record is too short to detect the 205-year DeVries cycle, its attribution to solar variability is based on indirect evidence.

Cycles with longer periodicities (e.g. 1000-2000 years) could not yet be attributed to solar modulation.

An especially interesting feature of the sunspot record is the period from 1645 to 1715 A.D. which is characterized by an almost complete absence of sunspots (Fig. 6), the so-called Maunder minimum. Since then, solar activity has steadily grown with the exceptions of a few less pronounced minima: the Dalton minimum (1790-1830) and some weaker minima around 1890 and 1960.

5. SOLAR FORCING OF CLIMATE CHANGE

The two main problems related to solar forcing and climate change are:

1. The lack of a quantitative solar forcing function. The physical processes responsible for changes in solar irradiance are not yet well understood, especially as far as long-term changes are concerned. All attempts so far are therefore based mainly on various assumptions leading to differences of about a factor of 2. Longer forcing records are based on simple linear regression models [16].

There may be other effects on the atmosphere caused by the interaction of the heliosphere with the magnetosphere and by cosmic rays with the atmosphere which could also contribute to climate change [17].

2. The response function of the climate system to solar forcing is probably variable in time and not well known. There is an increasing number of experiments with global circulation models (GCM) including solar forcing. However, these model runs do not take into account the change in the spectral energy distribution and its potential effects on the atmosphere (e.g. ozone).

In view of all these uncertainties, which would be the best strategy to detect solar induced climate changes? One approach is to use the Milankovic forcing that is caused by planetary gravitational effects on the orbital parameters of the earth [18]. Although only changes of the eccentricity causes changes in the total solar irradiance, the fact that the latitudinal forcing function can be calculated precisely for any time offers the unique opportunity to study the response function on longer time-scales (≥ 10 ky). Another straightforward approach is to search for fingerprints of solar forcing. All we know for sure is that solar irradiance changed in phase with solar activity over the past two Schwabe cycles. It is reasonable to assume that longer solar activity changes are associated with larger changes in solar irradiance [15]. Therefore, good...
candidates for solar forcing effects are solar minima, in particular grand minima. In fact, instrumental temperature records reveal cold events during the local minima around 1810, 1890 and 1960 (Fig. 5).

The Maunder and Spoerer minima occurred during the so-called “little ice-age”, a period characterized by a general advance of glaciers. The more high-resolution climate records become available, the more evidence is found that abrupt climate changes indeed often coincide with solar minima (Van Geel, this volume)[19].

With regard to the question of the underlying physical mechanisms of solar forcing, a crucial test is the phase relationship. While the proposed mechanism of cosmic ray induced cloud formation tolerates no phase shift between cosmic ray flux and climate response [20], this is less the case for changes in solar irradiance that may be coupled by slow processes with the modulation of cosmic rays.

6. CONCLUSIONS

Ice cores contain a large number of proxies for different climate parameters such as for temperature ($\delta^{18}$O), greenhouse gases (CO$_2$, CH$_4$) and aerosols (chemical constituents). In the form of cosmogenic nuclides ($^{10}$Be, $^{36}$Cl) they also provide unique information about the cosmic ray flux which is modulated by the geomagnetic dipole field and the solar activity that can be traced back in time over the past ca. 60'000 years.

The suggested relationship between geomagnetic field, galactic cosmic rays, and climate could not be confirmed for the period of the Laschamp event (36-41.5 kyr B.P.).

$^{10}$Be measurements show that solar variability has a cyclic component with periodicities of 11, 90, 205 and possibly more years. However, the relationship between solar activity and solar irradiance is not yet understood in detail.

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REFERENCES


