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Solar forced Dansgaard/Oeschger events?

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[1] It has been suggested that the strong climatic changes during the last ice age, the so-called Dansgaard/Oeschger (D/O) events, could have been prompted by solar activity changes. This hypothesis is based on the apparent cyclic occurrence of the D/O events and the solar influence on climate during the Holocene on similar time scales. We test this hypothesis by comparing the ^{10}Be and δ^{18}O records from the GRIP ice core. A superimposed epoch analysis allows us to reduce the noise in the data and to extract estimates of solar activity changes in connection to the D/O events. This comparison does not provide convincing evidence for a persistent solar influence on these strong climatic oscillations during the last ice age. **Citation:** Muscheler, R., and J. Beer (2006), Solar forced Dansgaard/Oeschger events?, *Geophys. Res. Lett.*, *33*, L20706, doi:10.1029/2006GL026779.

1. Introduction

[2] By comparing radionuclide-based estimates of changes in solar activity with records of ice rafted debris (IRD) in the North Atlantic, *Bond et al.* [2001] concluded that there is a persistent solar influence on the surface hydrology in the North Atlantic during the Holocene. The IRD changes occur with a "quasi periodicity" of approximately 1500 years which is similar to the pacing of the D/O events during the last ice age. This raises the question if the variable Sun was also responsible for these strong climatic changes. The apparent cyclicity of the D/O events might indicate that external forces were influencing these climatic changes [*Rahmstorf*, 2003; *Braun et al.*, 2005]. However, other studies conclude that the 1470 yr periodicity is solely caused by 3 D/O events [*Schulz*, 2002] or that the climate shifts are noise driven and have no underlying periodicity [*Ditlevsen et al.*, 2005]. These conclusions critically depend on the time scales and the new dating of the NGRIP ice cores suggests revisions to the previously applied time scales [*Svensson et al.*, 2006]. In addition, the states of the climate system during the Holocene and the last ice age were very different and it is not apparent that the supposedly small solar forcing could play a dominant role during both periods. Nevertheless, the Sun exhibits cyclic changes that could have a deciding influence on climate if the climate system is at a tipping point. The release of fresh water into the North Atlantic and its influence on the ocean thermohaline circulation has been suggested to be an important factor influencing the fast changes in the North Atlantic region during the last ice age [*Rooth*, 1982; *Broecker et al.*, 1990]. Reduced solar activity could lead to a globally cooler climate. However, if reduced solar activity leads to increased stability of the ice sheets and less fresh water flux into the North Atlantic it could favor a stronger meridional overturning circulation and thus lead to a local warming in this region.

[3] Here we will not address the questions whether a small solar forcing can influence the thermohaline circulation during the last ice age and to what extent feedback mechanisms could amplify solar forcing. The goal of this paper is to investigate what a comparison of the ^{10}Be data as a proxy of solar variability with the climate proxy δ^{18}O tells us regarding the forcing of the D/O events.

2. Reconstructing Solar Activity Changes

[4] Cosmogenic radionuclides (such as e.g. ^{14}C, ^{10}Be and ^{36}Cl) are produced in the Earth's atmosphere by galactic cosmic rays. Their production rates depend on the geomagnetic and heliomagnetic shielding [*Lal and Peters*, 1967; *Masarik and Beer*, 1999]. Therefore, radionuclide records provide estimates about the strength of the magnetic field carried by the solar wind. These records are in qualitative agreement with independent solar indices as for example the sunspot record during the last 400 years. For periods preceding direct solar observations radionuclide records are the most reliable tools to estimate past changes in solar activity. Polar ice cores are the best natural archives to store the ^{10}Be and ^{36}Cl history for the last 100,000 years. Since climatic changes can also be inferred from such ice cores this makes them perfect archives to study the solar influence on climate without uncertainties in the relative timing. However, uncertainties in interpreting ^{10}Be and ^{36}Cl records arise due to the potential climatic influence on the radionuclide deposition. It is crucial not to erroneously assign a climate-induced change in the radionuclide records to variations in solar activity. This could lead to the wrong conclusion that solar variations caused this climate change.

[5] The reconstruction of past changes in solar activity can be especially treacherous for the period preceding the relatively stable Holocene climate. The strong climate changes during the last ice age and during the last deglaciation had a significant impact on the ^{10}Be deposition. The problem can be illustrated by the following example. *Sharma* [2002] estimated the solar activity variations in the past by assuming that a compilation of ^{10}Be records measured in sea sediments represents changes in solar activity and geomagnetic field intensity. After correction for the geomagnetic influence this record shows low solar activity which is synchronous with the phases of cold climate. He concluded that solar activity may control the

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100,000 years glacial-interglacial cycles. If we apply the same approach to the ^{10}Be records from Central Greenland we would come to completely opposite conclusions. Since the ^{10}Be deposition during the last ice age is slightly lower than we would expect based on independent geomagnetic field reconstructions [*Muscheler et al.*, 2005] we would infer relatively high solar activity during the last ice age with this approach. Therefore, it can be misleading to interpret ^{10}Be records exclusively in terms of production rate changes. In the following we will show how we can estimate the variable solar activity from the GRIP ^{10}Be record. It will allow us to investigate if there is evidence that the climate changes during the last ice age are related to solar activity changes.

[6] The GRIP ^{10}Be record was measured with an average temporal resolution of approximately 40 years for the period from 18,000 to 60,000 years BP. Besides the differences mentioned above there is generally a good agreement between geomagnetic field records and the ^{10}Be flux to Summit for this period [*Wagner et al.*, 2000; *Muscheler et al.*, 2005]. This indicates that the millennial-scale changes in the ^{10}Be flux primarily reflect changes in the ^{10}Be production rate. Since a climate influence on the shorter-term changes of the ^{10}Be flux cannot be excluded we need additional information to extract the solar influence on this record. Such additional information is available from sunspot observations and from radionuclide records during the Holocene when the climate was more stable. These records exhibit cycles that can be connected to changes in solar activity. Besides the well-known 11-yr ("Schwabe") sunspot cycle there are also longer-term cycles such as the 88-yr ("Gleissberg") and 207-yr ("de Vries" or "Suess") cycle [e.g., *Damon and Sonett*, 1991; *Stuiver et al.*, 1991]. The Maunder minimum can be regarded as one expression of the solar 207-yr cycle [*Muscheler et al.*, 2004a] and the lack of sunspots during this period connects this cycle to solar activity changes [*Eddy*, 1976]. If changes in the ^{10}Be flux during the last ice age resemble in amplitude and duration the ^{10}Be and ^{14}C changes during the Maunder minimum this can be considered as an indication that the changes in the ^{10}Be flux are indeed caused by the variable solar activity.

[7] There are also patterns of variability in the radionuclide records that do not necessarily exhibit clear peaks in the frequency spectrum. For example, the 207-yr cycle appears to be modulated throughout the Holocene. Phases with strong 207-yr variability repeat with a periodicity of 2200 years [*Damon and Sonett*, 1991]. We observe a similar situation in the 1500-yr band. Although not constant in frequency and amplitude, strong variability in the radionuclide records repeats with a periodicity of about 1500 years [*Bond et al.*, 2001]. While in the early Holocene this pattern is characterized by single strong peaks during mid and late Holocene several shorter-term changes are part of this long-term pattern [*Bond et al.*, 2001]. The production origin of such changes is confirmed by the good agreement between ^{10}Be and ^{14}C records during the Holocene [*Beer et al.*, 1988; *Muscheler et al.*, 2004b]. It was suggested that shorter-term production rate changes in radionuclide records could be produced by the variable geomagnetic field intensity [*Snowball and Sandgren*, 2002; *St-Onge et al.*, 2003]. However, on time scales shorter than 500 years the changes

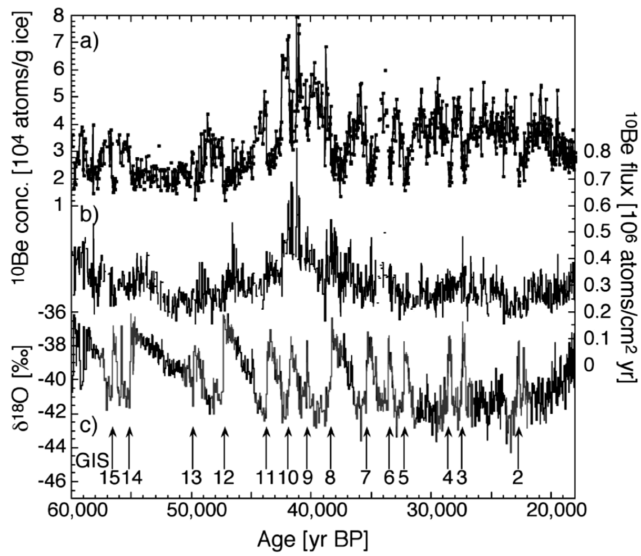

Figure 1. (a) ^{10}Be concentration, (b) ^{10}Be flux and (c) the δ^{18}O record from the GRIP ice core for the period from 60,000 to 18,000 years BP. The starts of the warm phases in Greenland (Greenland Interstadials, GIS), the so-called D/O events, are labeled in the lowest panel.

in the geomagnetic field are too small to explain the changes in radionuclide records.

3. Data and Method

[8] Figure 1 shows the ^{10}Be concentration and flux together with the δ^{18}O record from the GRIP ice core. We will investigate if there is an indication that solar activity changes had an influence on the rapid warmings at the beginning of the Greenland Interstadials 2 to 15 [*Dansgaard et al.*, 1993]. For this period we have a high-resolution ^{10}Be record and a good understanding of the influence of the variable accumulation rate on the ^{10}Be deposition [*Wagner et al.*, 2001b; *Muscheler et al.*, 2004b]. It is obvious that the ^{10}Be concentration (Figure 1a) is strongly influenced by the variable accumulation rate. However, after calculating the ^{10}Be flux (Figure 1b) most of this obvious climate influence on the ^{10}Be deposition vanishes. For this analysis we used the ss09sea time scale and accumulation rate suggested by *Johnsen et al.* [2001]. This accumulation rate reconstruction is largely supported by the newest counting of the annual layers in the NGRIP ice core [*Svensson et al.*, 2006]. Our analysis depends on where the start of the climate change is placed in the δ^{18}O record. Figure 2a illustrates this problem. It shows Greenland interstadial 8 that seems to start with a rather flat slope in δ^{18}O that is followed by a second phase with a rapid warming. Since it is difficult to define the starting point of the flat slope and since other D/O events exhibit different characteristics we will concentrate in the following on the fast δ^{18}O changes with a slope steeper than 2‰ within 50 years. This is a common feature of all of the D/O events.

[9] ^{10}Be ice core records usually exhibit short-term "weather" noise that makes it very difficult to unambiguously attribute single high values to phases of low solar activity or the opposite for single low values. This is

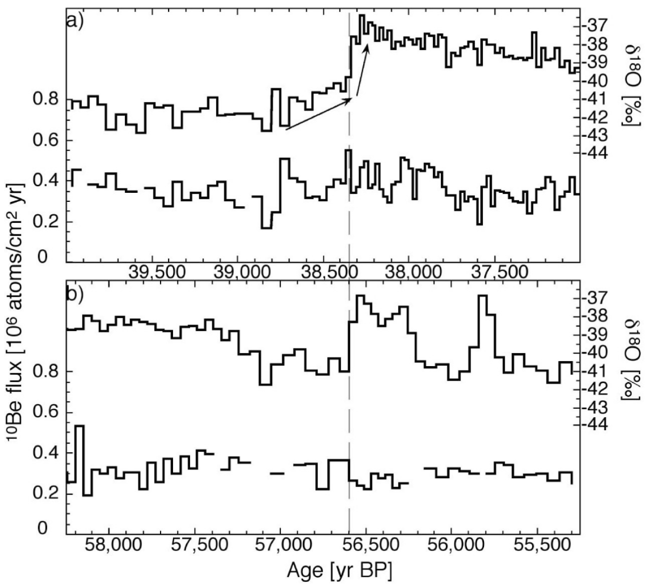

Figure 2. GRIP δ^{18}O and ^{10}Be flux for Greenland Interstadial number (a) 8 and (b) 15. GIS8 is an example for the difficulty of identifying the start of the climate change. Figure 1b shows one of the clearest hints for a solar connection to the D/O events.

particularly true when studying D/O events. To reduce this uncertainty we average the solar signal and climate proxy record over the different D/O events to get a mean solar signal and a mean climate reaction. Figure 3a shows the superposition of the δ^{18}O records for the 14 Greenland interstadials together with the corresponding ^{10}Be flux data in panel c. To remove the influence of long-term changes in the geomagnetic field intensity on the averaged ^{10}Be flux we normalized the individual ^{10}Be records by dividing them with a second order polynomial fit to the data. Since this polynomial is fitted to the 2000-yr long extracts of the ^{10}Be record (Figure 3) it has no influence on the short-term changes that we want to study in connection with a potential solar trigger for the D/O events. The black lines show the average δ^{18}O and ^{10}Be curves together with the standard deviation (light gray) and the error of the mean (dark gray).

4. Discussion

[10] The lack of a significant change in the ^{10}Be flux at the start of the D/O events supports our assumption that the calculation of the ^{10}Be flux removes the main climate dependency visible in the ^{10}Be concentration. If high solar activity has been responsible for the start of the rapid warmings we would expect low values in the ^{10}Be flux at the start of these events. However, the averaged ^{10}Be flux is not particularly low around t = 0 (Figure 3). It seems rather unlikely to us that climate and solar induced changes in the ^{10}Be flux cancel out each other at the beginning of the D/O events, and that thereby the solar influence on climate is masked. The strongest feature in the averaged ^{10}Be flux is a 100-year long period of increased ^{10}Be flux (approx. 10%) before start of the D/O event. During the first part of this period the average climate and accumulation rate were relatively stable and a climate influence on the ^{10}Be flux should be of minor importance. This is confirmed by the increase in the ^{10}Be concentration (Figure 3b). However, the second part of this peak originates from the increasing accumulation rate which is partly caused by the 5-pt smoothing that was applied to the accumulation record to remove unrealistically large short-term variations (Sigfus Johnsen, personal communication). This implies that the average ^{10}Be flux cannot be considered significantly different in connection to the D/O events.

[11] To further investigate the significance of the elevated ^{10}Be levels we compare it with a period that is well known for its change in solar activity, the Maunder minimum. Figure 3d shows the normalized ^{14}C production rate for the period 750–1950 AD [*Muscheler et al.*, 2006]. The

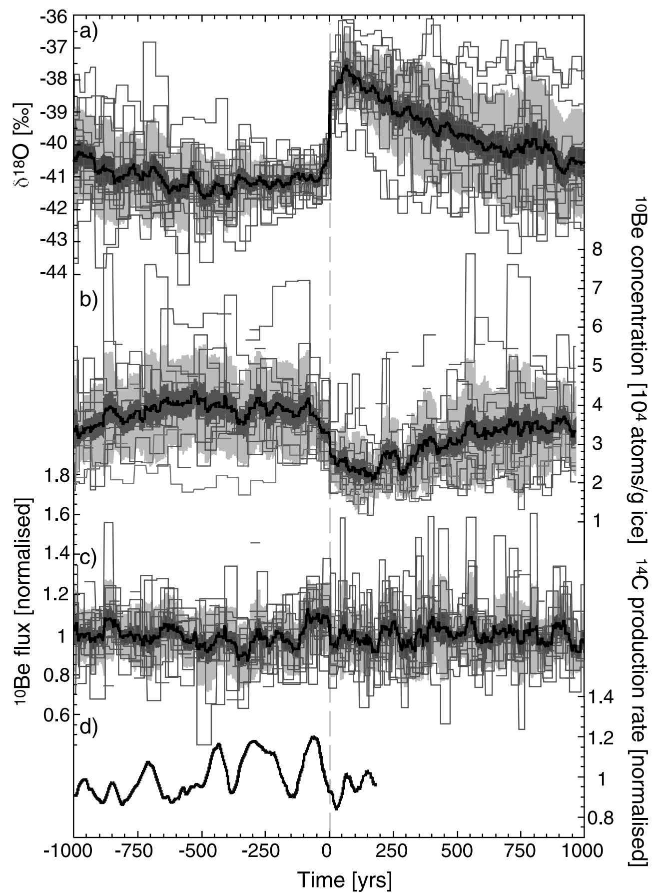

Figure 3. Superposition of the (a) δ^{18}O, (b) ^{10}Be concentration and (c) ^{10}Be flux for 14 Greenland Interstadials and (d) the comparison with ^{14}C production rate changes during the last 1250 years. The thin gray curves show the individual records aligned by the common increase in δ^{18}O. The black lines show the average data together with the standard deviation (light gray band) and the error of the mean (dark gray band). Figure 3d shows the normalized ^{14}C production rate for the past 1250 years [*Muscheler et al.*, 2006]. The amplitudes of the ^{14}C variations are adjusted (−30%) to correct for the differences between the ^{10}Be and ^{14}C production rates [*Masarik and Beer*, 1999]. The ^{14}C production record shows 40-yr averages which corresponds to the average time resolution of the ^{10}Be record. The Maunder minimum is centered around −50 years.

Maunder minimum represents a typical solar induced change. Many more of these grand minima can be found in the ^{10}Be and ^{14}C records throughout the Holocene [*Vonmoos et al.*, 2006]. We would expect that the average ^{10}Be flux exhibits a change with a similar amplitude if the D/O events would align typical solar induced changes in the ^{10}Be flux. New model results indicate that solar-induced ^{10}Be changes at high latitudes could be amplified by approximately 20% compared to the global average ^{10}Be change which would amplify the ^{10}Be signal even more [*Field et al.*, 2006]. Compared to such a grand minimum the average ^{10}Be increase before the D/O event is much smaller which implies that we don't see a persistent solar influence on the D/O events. This, however, doesn't exclude the possibility that some of the D/O events are triggered by solar activity changes.

[12] Figure 2b shows a case where the ^{10}Be levels could point to a connection between solar activity and a D/O event. If there is indeed this connection for some of the D/O events, low solar activity could have delayed the start of the rapid warming or the change towards higher solar activity could have triggered the start of the warming events. One could also speculate that low solar activity contributed to the stabilization of the ice sheets that, thereby, favored a subsequent local warming due to reduced meltwater fluxes to the oceans.

[13] It is also possible to obtain robust estimates of solar activity changes by isolating the known solar cycles in the radionuclide records. *Wagner et al.* [2001a] showed that the 207-yr cycle is present in the ^{10}Be data from the GRIP ice core. If we compare this cycle with the δ^{18}O changes we do not observe a constant phase relationship between this cycle and the starts of the D/O events. Therefore, also this comparison does not indicate that there is a persistent solar influence on the strong climate changes during the last ice age.

5. Conclusions

[14] It is possible to extract limited but reliable information about changes in solar activity from ice core ^{10}Be records for the period of the last ice age. Our superimposed epoch analysis does not indicate a fixed phase relationship between solar (^{10}Be flux) and climate (δ^{18}O) induced changes. Therefore, we do not find convincing evidence for a persistent solar influence on the D/O events.

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