Reply to Bard et al.

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We appreciate the comments by Bard et al. which gives us the possibility to clarify our results (Muscheler et al., 2007). To put the very specific comments by Bard et al. into perspective we start our reply by summarizing our main findings and arguments. Our main result is a high-quality reconstruction of solar activity for the past millennium, including a thorough assessment of uncertainties. The following conclusions were *inter alia* presented in the abstract: “In general, the ^{10}Be and ^{14}C records exhibit good agreement... “, “Differences between ^{10}Be records from Antarctica and Greenland indicate that climatic changes have influenced deposition of ^{10}Be during some periods...”, and “The tree-ring ^{14}C record and ^{10}Be from Antarctica indicate that recent solar activity is high but not exceptional with respect to the last 1000 yr”. The main line of evidence presented in our reconstruction of solar activity from radioisotopes is as follows: (i) The production rates of ^{10}Be and ^{14}C depend non-linearly on the intensity of the geomagnetic and solar magnetic fields. These non-linear relationships, as quantified by Masarik and Beer (1999), are used to convert ^{14}C and ^{10}Be records into solar activity records. (ii) ^{14}C (recorded in tree rings) and ^{10}Be (recorded in polar ice) become involved in completely different physical- and biogeochemical processes after their production, and thus provide independent information. (iii) Different reconstructions of geomagnetic activity and their uncertainties are discussed (e.g. Yang et al., 2000; Korte and Constable, 2005). (iv) A hierarchy of carbon cycle models is used to convert the decadally to annually (after 1500 AD) resolved tree-ring ^{14}C record into solar activity, taking into account long-term trends in the geomagnetic field. The ^{14}C-based solar activity record is combined with instrumental neutron flux data. Uncertainties in reconstructed solar activity arising from uncertainties in the ^{14}C tree-ring data, the carbon cycle models, and the instrumental data are quantitatively assessed through sensitivity and Monte Carlo analyses. (v) Six different ^{10}Be ice core records were presented and their agreement and disagreement and problems discussed. The ^{10}Be records are potentially affected by site-specific effects (changes in atmospheric circulation pattern, accumulation rate changes, etc.) and records from Greenland and Antarctica show different trends over part of the last century. A stacked ^{10}Be record was produced; at each point in time the ^{10}Be data value with the largest deviation from the average was removed to reduce site-specific biases. The stacked ^{10}Be record is converted to solar activity using the production model of Masarik and Beer (1999). (vi) The resulting ^{14}C and ^{10}Be-based solar activity records are compared to sunspot records and the solar irradiance reconstruction of Bard et al. (2000). These results are summarized in figure 1.

In contrast to Bard et al. (1997) it was not our intention to pick out the seemingly best ^{10}Be record to create a "superior" ^{10}Be-based solar modulation record but to produce a truly *independent* ^{10}Be-based solar modulation record. We wanted to show the potential of the ^{10}Be data and the problems associated with them. Despite the uncertainties of individual records we obtain good agreement between ^{10}Be and ^{14}C records if we include all available ^{10}Be data. The ^{10}Be signal in an ice core is a composite of several factors (solar and geomagnetic modulation, transport and deposition processes). Not all of these processes are quantitatively understood to date and, therefore, we think that the best independent approach is to combine different records from different sites. For this purpose all available records should be considered. In this respect we consider the South Pole record measured by Raisbeck et al. (1990) as very useful but it is not a priori clear that this is a superior record. If agreement with the ^{14}C data is the one and only criterion used to judge the quality of the ^{10}Be data it is better to simply use the ^{14}C-based solar modulation record.

Bard et al. (2000) and Bard et al. (1997) prefer the ^{10}Be record from Antarctica because they argue that it agrees better with ^{14}C data than the ^{10}Be records from Greenland. They stress that their calculated $\Delta^{14}C$ record based on the South Pole ^{10}Be data correlates better with the $\Delta^{14}C$ tree-ring record (R=0.81; Bard et al., 1997) than earlier work by Beer et al. (R=0.58; Beer et al., 1988). However, the significance of a correlation depends on the degrees of freedom and Beer et al. (1998) studied a 5000-year long period whereas Bard et al. (1997) concentrated only on the last 1150 years. Figure 4 in Bard et al. (1997) and Figure 13b in Muscheler et al. (2007) show that the agreement between South Pole ^{10}Be data and ^{14}C is not perfect. Furthermore, Usoskin et al. (2004) see other reasons (better apparent agreement with the group sunspot number) to choose the ^{10}Be record from Southern Greenland as the preferred proxy for solar activity changes. We wanted to avoid a prejudiced approach, i.e. one that already includes requirements for the outcome of the calculations, because this precludes any possibility for obtaining an independent result. It is obvious from Figure 7 in Muscheler et al. (2007) that individual ^{10}Be records do not always agree and at least some exhibit deviations from the global ^{10}Be production rate. However, a bias can only be avoided if all available ^{10}Be records are given equal weight in the analysis.

Bard et al. (2007) raise important questions about the interpretation of radionuclide records, which we will try to clarify in the following:

Greenland bias: It is true that the data from Southern Greenland (Dye3) show a stronger trend in ^{10}Be concentration during the last 150 years than the Antarctic records (Raisbeck and Yiou, 2004). This trend mainly arises from differences after 1950 AD and neither the Dye3 nor the South Pole records fully agree with the neutron monitor data. It is not true that the Greenland records are responsible for a long-term decrease in ^{10}Be concentration in the average ^{10}Be record. The important calibration period of the last 100 years is covered by two records from Antarctica and one record from Greenland, which would lead to an Antarctic bias, if there is one.

Spurious Peaks and quality of the ^{10}Be record: It is obvious that there are peaks in the averaged ^{10}Be record that have no counterpart in the ^{14}C record. We mentioned the reasons for this difference and we do not interpret any of these peaks as the result of real changes in solar activity. We retained all ^{10}Be records since a selection of data would bias the result. In a latter step we introduced a method to remove some of the outliers, which is based exclusively on agreement and disagreement between the individual ^{10}Be records (Muscheler et al., 2007).

Time scales of the averaged ^{10}Be data: There are uncertainties and errors in the ice cores time scales. We clearly state that: ”*Comparison between ^{10}Be and ^{14}C production records indicate that the ice core time scales can have errors of up to 20 years, but in most cases the dating errors are smaller*”. These errors can cause additional uncertainties in the shorter-term variations (T<20 yr) but not in the longer-term changes. The new dating of the Greenland ice cores is certainly an advancement for the interpretation of the ice core records (Vinther et al., 2006). However, it is irrelevant in this context since it suggests only minor revisions (<10 yr, in most cases they are close to 0) to the time scale we used for our analysis. The changes are well within the stated uncertainties.

Changing accumulation rate and influence on the ^{10}Be data: There is no doubt that the strong snow accumulation rate variations during the last ice age had a strong impact on the concentration of ^{10}Be in the ice (e.g. Raisbeck et al., 1990; Wagner et al., 2001). In Central Greenland Yiou et al. (1997) observed roughly doubled ^{10}Be concentrations during periods of halved snow accumulation. However, it is less clear how relatively smaller changes in accumulation rate influence the ^{10}Be concentration in snow and ice. Andersen et al. (2006) show that accumulation rate changes are smaller than 15% for single years and less than 5% for 100 year averages during the last 1000 years. We did not try to correct for such influences since it would require a more detailed understanding of how climate changes influence the deposition of ^{10}Be. However, Bard et al. (2007) repeat a valid point and it is true that part of the disagreement could be due to such effects which we call "*residual climate signal*" or "*climate artifact*" in our paper. With regard to the dust contribution Baumgartner et al. (1997) showed that the dust-associated ^{10}Be contribution to the GRIP ice core is < 5% for the Holocene and can be neglected.

Polar enhancement factor: Mazaud et al. (1994) introduced the concept of estimating the latitudinal ^{10}Be contributions for the total ^{10}Be deposition at high latitudes. Such an approach considers the fact that the geomagnetic shielding of cosmic rays is maximal at the equator and absent at the poles. By contrast, solar-induced ^{10}Be production variations are stronger at high latitudes. Consequently, incomplete ^{10}Be mixing in the atmosphere leads to an enhanced solar signal in the ^{10}Be deposition at high latitudes. To account for this fact, Bard et al. (1997)

introduced a so-called “polar enhancement coefficient” (PEC). It is certainly true that ^{10}Be is not well-mixed in the atmosphere due to the relatively short atmospheric residence time of ^{10}Be in the atmosphere (particularly the troposphere). However, Bard et al. (1997) make the extreme assumption that ^{10}Be deposition in polar ice reflects only the production of ^{10}Be at latitudes higher than 60 degrees. Based on this assumption they estimate that the amplitudes of solar induced ^{10}Be production changes in Antarctica have to be multiplied by the factor 0.65 to make the ^{10}Be signal comparable with the atmospheric ^{14}C which is globally relatively well mixed. In our opinion this factor is wrong for 4 reasons:

1. In reality, the separation of Antarctica from the rest of the world is not as rigorous as Bard et al. (1997) assumed. Long-range transport of dust, volcanic debris and nuclear bomb fallout as well as model calculations (Field et al., 2006) prove that there is a coupling with the rest of the atmosphere and, therefore, the polar enhancement factor must be closer to 1. Reconstructions of air mass trajectories (Kahl et al., 1997) and the interpretation of stable isotopes in Greenland (Johnsen et al., 1989) also point to a significant transport from lower latitudes.

2. ^{10}Be records from Greenland and from Antarctica show a doubling of the ^{10}Be flux during periods of very low geomagnetic field intensity (Wagner et al., 2000; Raisbeck et al., 2006). This doubling is very close to the global average ^{10}Be production rate increase. According to the assumption by Bard et al. (1997) that polar ice cores reflect only ^{10}Be produced above 60 degrees the geomagnetic field changes should not be visible at all.

3. Bard et al. (1997) failed to include the fact that changes in solar activity affect ^{14}C and ^{10}Be production rates in a different way. Solar-induced ^{14}C production variations are 20-30% enhanced compared to solar-induced ^{10}Be production variations (Lal, 1988; Masarik and Beer, 1999). It is crucial to include this fact if ^{10}Be and ^{14}C records are compared on a quantitative basis.

4. The correlation analysis of Bard et al. (1997) includes the last 1150 years. This means that long-term changes (partly due to the uncorrected geomagnetic field influence on the ^{10}Be data) have a significant influence on the result. Concentrating on solar peaks in Figure 4 in Bard et al. (1997) indicates that the ^{10}Be-based $\Delta^{14}C$ underestimates the measured $\Delta^{14}C$ changes on shorter time scales. This is especially evident for the Wolf and Maunder minima.

We included the results of Field et al. (2006) because they calculated the ^{10}Be transport and deposition with a general circulation model. Their result is independent from the comparison of ^{10}Be and ^{14}C and it suggests a smaller latitudinal bias (PEC = 0.8 versus PEC = 0.5 in Bard et al. (1997) when ^{10}Be and ^{14}C production rate differences are included). Such a relatively small correction factor does not influence our conclusions (Figure 9b in Muscheler et al., 2007). As mentioned, comparisons of ^{10}Be data from Greenland with ^{14}C and independent geomagnetic field data do not point to such a bias (Wagner et al., 2000, Muscheler et al., 2000; Muscheler et al., 2005) which is the reason why we did not include it in earlier calculations.

Geomagnetic influence: Bard et al. (2007) seem to acknowledge that it was conceptually wrong not to include the effects of the geomagnetic dipole field in a paper addressing the long-term solar variability. The long-term decrease during the past millennium has been well known for more than 25 years (McElhinny and Senanayake, 1982). With regard to the use of different geomagnetic field corrections, we emphasize that the large errors connected to palaeomagnetic data lead to significant uncertainties in all reconstructions of solar activity that are based on radionuclide records. As Bard et al. (2007) show in Figure 1 these uncertainties increase back in time. The output of the CALS7K.2 model (Korte and Constable, 2005) relies heavily upon the intensity data contained in the Yang et al. (2000) data compilation. A more up-to-date geomagnetic intensity database (GEOMAGIA50) is now available (Donadoni et al., 2007) and if we restrict the data points to those with the highest rankings in terms of materials, number of specimens per data point (>3) and preferred method (Thellier or Coe or microwave with partial thermo-remanent magnetization checks) we find clear evidence for a steadily declining trend in field intensity between 1000 AD and 1910 AD. Since raw data and model output (Korte and Constable, 2005) point to a different long-term change we decided to include both records in our calculations (e.g. Figure 6, dark and light grey band in Figure 9a). However, as we stated in our paper: *"due to the large error bars of Yang et al. (2000) the results usually agree within the errors"*.

Comparison with the irradiance record of Bard et al. (2000): The solar irradiance reconstruction of Bard et al. (2000), which is simply the linearly-scaled and smoothed ^{10}Be record from the South Pole, is widely used in climate modeling. Our Figure 13 illustrates the fact that geomagnetic field changes and the solar modulation influence the radionuclide production rates in a non-linear way and that the geomagnetic influence must not be neglected. In addition, the comparison of the different radionuclide records strongly suggests that there are also climatic effects in the ^{10}Be record from the South Pole, which, therefore, are included in the irradiance reconstruction by Bard et al. (2000). For the long-term trend in solar modulation the main uncertainty arises from the uncertain geomagnetic dipole field estimates and not from the uncertain potential polar bias. The connection between the ^{14}C and ^{10}Be records and solar irradiance is not obvious. The solar modulation function is certainly a better surrogate of processes occurring on and within the Sun than the ^{10}Be concentration measured in ice or the ^{14}C record. However, it is still an open question by how much the solar irradiance changed from the Maunder minimum to today and how this change is related to the solar modulation function.

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Figure:

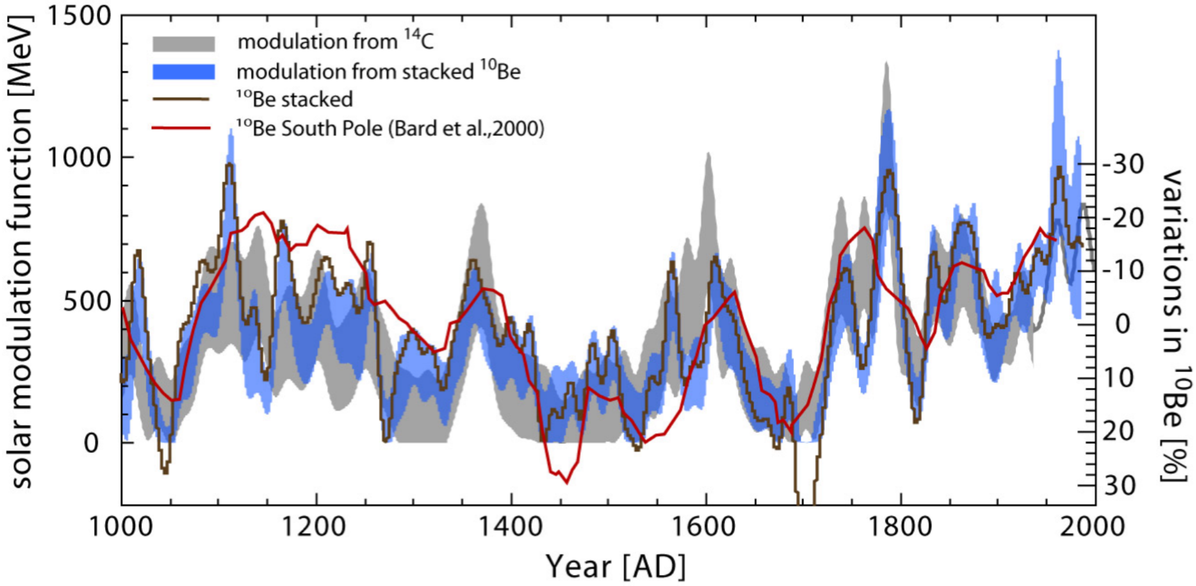

Figure 1: Summary of our results and differences to the South Pole record that underlies Bard et al.'s analysis. The grey band shows the most likely ^{14}C-based solar modulation record (Figure 6b in Muscheler et al., 2007). The blue band shows the solar modulation from the stacked ^{10}Be record (without "outlier" and corrected for a slight polar bias according to Field et al., 2006). The uncertainty bands indicate ±1 standard deviations arising from uncertainties in the radioisotope records and in the geomagnetic field. Reconstructed modulations are higher, but still within the uncertainty band, when applying the model-based geomagnetic reconstruction of Korte and Constable (2005) instead the Yang et al. data. Usually, the reconstructions agree within uncertainties although not all ^{10}Be peaks can be trusted as real changes in solar activity. However, the composite ^{10}Be and ^{14}C solar modulation records confirm variations (e.g. around 1800 AD) that are not present in the South Pole record. Variations in the ^{10}Be concentration in ice (right scale) are shown for the stacked and low-pass filtered ^{10}Be record where "outliers" where removed (brown) and the smoothed South Pole ^{10}Be record from Bard et al., 2000 (red).