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A 600-year annual ^{10}Be record from the NGRIP ice core, Greenland

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[1] Despite the extensive use of ^{10}Be as the most significant information source on past solar activity, there has been only one record (Dye-3, Greenland) providing annual resolution over several centuries. Here we report a new annual resolution ^{10}Be record spanning the period 1389–1994 AD, measured in an ice core from the NGRIP site in Greenland. NGRIP and Dye-3 ^{10}Be exhibits similar long-term variability, although occasional short term differences between the two sites indicate that at least two high resolution ^{10}Be records are needed to assess local variations and to confidently reconstruct past solar activity. A comparison with sunspot and neutron records confirms that ice core ^{10}Be reflects solar Schwabe cycle variations, and continued ^{10}Be variability suggests cyclic solar activity throughout the Maunder and Spörer grand solar activity minima. Recent ^{10}Be values are low; however, they do not indicate unusually high recent solar activity compared to the last 600 years. **Citation:** Berggren, A.-M., J. Beer, G. Possnert, A. Aldahan, P. Kubik, M. Christl, S. J. Johnsen, J. Abreu, and B. M. Vinther (2009), A 600-year annual ^{10}Be record from the NGRIP ice core, Greenland, *Geophys. Res. Lett.*, *36*, L11801, doi:10.1029/2009GL038004.

1. Introduction

[2] The cosmogenic isotope ^{10}Be plays a central role in retrieving information about past cosmic ray intensity and solar activity, factors whose effect on climate is under debate [i.e., *Carslaw et al.*, 2002; *Lockwood and Fröhlich*, 2007]. Deposition of atmospheric ^{10}Be into polar ice sheets, through wet (associated with precipitation) and dry deposition, creates a unique archive with the possibility of annually resolved information on past solar activity and consequently for understanding possible connections to past climate change [*Beer et al.*, 1990]. The isotope concentration in glacial ice is affected by changes in production rate and transport and deposition processes. Changes in production rate depend on solar activity and geomagnetic field strength. The transport and deposition is influenced by atmospheric mixing (e.g., stratosphere-troposphere exchange), scavenging and snow accumulation rate. Comparison with ^{14}C and modeling [*Heikkilä et al.*, 2008a] shows that production is the dominant global signal, while the transport or weather signal is weaker and of a local nature. Combined snow pit ^{10}Be measurements and local weather data covering almost a year at Law Dome, Antarctica, indicate that ~30% of short term ^{10}Be variability is related to meteorological factors [*Pedro et al.*, 2006]. The Law Dome site is, like Greenland, dominated by wet deposition.

[3] There are a few annual resolution ^{10}Be records which span short periods [e.g., *Aldahan et al.*, 1998; *Heikkilä et al.*, 2008b; *Moraal et al.*, 2005; *Smith et al.*, 2000; *Steig et al.*, 1996]. To our knowledge there is only one existing ^{10}Be record with annual resolution that covers several centuries, a record from the Greenlandic Dye-3 site (65.18°N, 43.83°W, 2480 m a.s.l.) covering the period 1428–1985 AD [*Beer et al.*, 1990, 1998]. A combination of two high resolution records will aid in isolating regional and local influences on ^{10}Be distribution in glacier ice, and indicate how well measured ^{10}Be in an ice core reflects the production signal. A new annual ^{10}Be record covering the past 600 years will also be optimal for reconstructing variations in the 11-year Schwabe cycle which plays a crucial role in obtaining a better understanding of the long-term behavior of the solar dynamo and its potential relationship to climate changes on decadal and centennial time scales. A recent annual record also enables calibration between ^{10}Be fluxes and high resolution neutron flux data, a cosmic ray parameter which has been monitored since 1953.

2. Method and Description

[4] To address some of the issues mentioned above, we have analyzed annual variability of ^{10}Be during the period 1389–1994 AD in the NG 97-S2 shallow core from the NGRIP site (75.10°N, 42.32°W, 2917 m a.s.l.), Greenland (see *Dahl-Jensen et al.* [2002] and *Hvidberg et al.* [2002] for details on NGRIP). The timescale is based on annual layer counting in deconvoluted δ^{18}O data, and has been synchronized to the GICC05 timescale [*Vinther et al.*, 2006]. Synchronization has been accomplished by matching volcanic reference horizons in the NG 97-S2 shallow core to those observed in the NGRIP deep core. Net accumulation rates are calculated from annual layer thicknesses with a coupled density/ice-flow model. Densities are based on [*Herron and Langway*, 1980] as modified by [*Johnsen et al.*, 2000] to better fit Greenland ice core density profiles. The ice-flow model is from [*Johnsen and Dansgaard*, 1992].

[5] The ^{10}Be in the most recent 318 annual layers was extracted at Eawag and measured at the Ion Beam Physics laboratory, ETH, Zurich, Switzerland. The ^{10}Be of the 288 older annual layers was extracted at the

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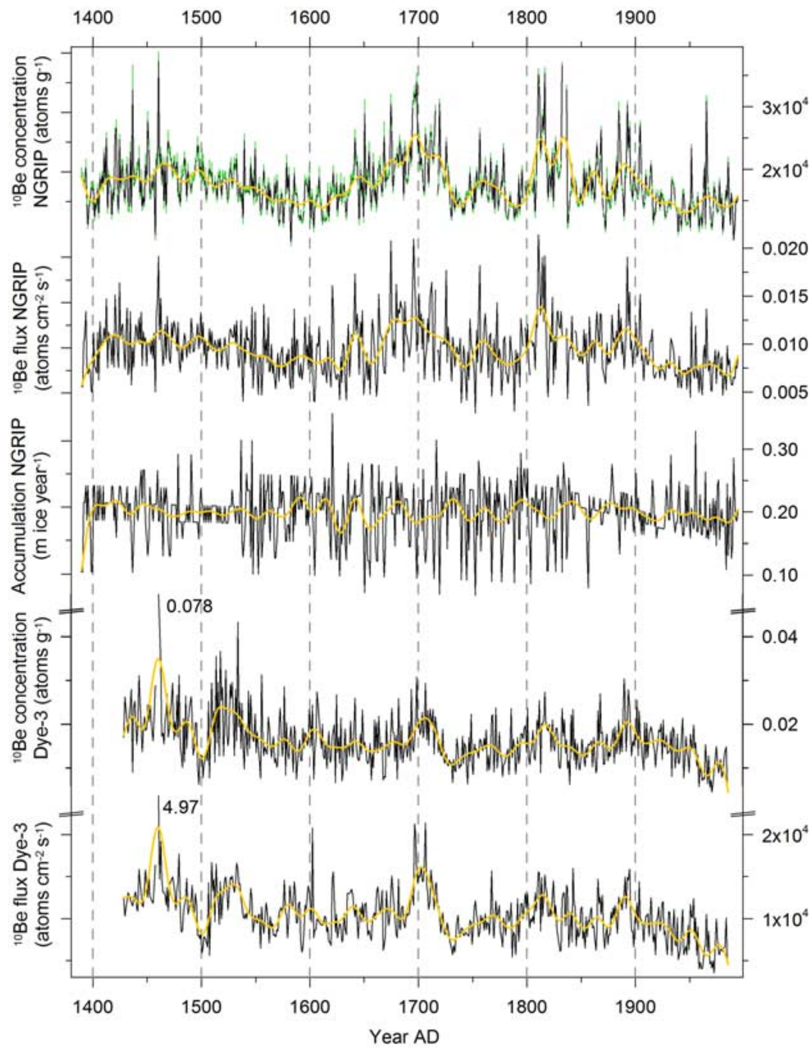

Figure 1. Data from the NGRIP ice core, along with Dye-3 data recalibrated to a new depth/age scale. To aid visual interpretation of larger scale variability and similarities between the different records, data filtered with a low pass Butterworth filter with a cut-off frequency of 1/22 years is shown with the raw data. Displayed is, from the top: NGRIP ^{10}Be concentration with AMS measurements standard errors, NGRIP ^{10}Be flux (calculated by multiplying the concentration of each sample with the accumulation of that year), NGRIP snow accumulation, and Dye-3 ^{10}Be concentration and flux. Note the axes breaks in the Dye-3 data, to allow for the large peaks at 1460 AD. NGRIP accumulation data is in meter ice per year; to translate into meter water equivalent simply multiply by 0.917.

Department of Earth Sciences and measured at the Tandem Laboratory, Uppsala University, Sweden. Both laboratories used the same chemical separation procedure and carrier solution and inter-calibrated standards to minimize inter-laboratory discrepancies.

[6] The Dye-3 ^{10}Be record has annual resolution after 1780 AD, while in the older part of the core the sampling was made equidistantly, leading to samples covering 0.4–2.3 years. The timescale is based on annual layer counting in H_2O_2 data for the period 1777–1986 AD. From 1424 to 1777 AD the timescale has been synchronized to the GICC05 timescale [*Vinther et al.*, 2006], by assuming identical accumulation rates in the Dye-3 core used for ^{10}Be measurements and the Dye-3 deep core. Dye-3 accumulation rates are calculated as for NGRIP. We have adjusted the existing Dye-3 ^{10}Be data to the new recalibrated timescale.

3. Results

[7] The ^{10}Be concentration and flux and snow accumulation rate are shown in Figure 1. NGRIP ^{10}Be concentration ranges between 0.8 and 3.9 $\times$ 10^4, with an average of 1.8 $\times$ 10^4 atoms g_{ice}^{-1}, and the flux is 0.003–0.023 with an average of 0.010 atoms cm^{-2} s^{-1}. The flux is the ^{10}Be deposition rate at the surface, and is calculated by multiplying each sample concentration with the snow accumulation of that specific year.

[8] NGRIP ^{10}Be data show high inter-annual variations which are superposed on wider fluctuations of an irregular nature. To some extent periods of high ^{10}Be values corre-

spond to grand solar activity minima, most prominently during the Maunder (~1645–1715 AD) and Dalton (~1790–1830 AD) solar minima, while less distinctly during the Spörer minimum (~1415–1535 AD). Since snow accumulation varies over time, the ^{10}Be flux and concentration curves differ somewhat. The long term variations are similar in both parameters, except during parts of the Dalton and Maunder minima.

[9] The Dye-3 ^{10}Be concentration ranges from 0.4 to 5.0×10^4 atoms g_{ice}^{-1}, while the flux range is 0.005–0.078 atoms cm^{-2} s^{-1} (Figure 1). ^{10}Be in NGRIP and Dye-3 data have similar long term variability, although annual variations differ. Occasionally peaks occur simultaneously in both cores, e.g., at 1460 AD. This specific peak, which is especially large in Dye-3, has also been observed in South Pole [*McCracken et al.*, 2004]. In the older part of the period, there is higher ^{10}Be variability in Dye-3 than in NGRIP.

[10] During the period when data is available from both sites the average measured concentration at Dye-3 (1.0×10^4 atoms g_{ice}^{-1}) is ~60% of NGRIP. This is at least in part a result of a dilution effect, since snow accumulation at Dye-3 is 2–3 times higher than at NGRIP, as is clearly shown by the Dye-3 flux which is 1.6 larger (0.016 atoms cm^{-2} s^{-1}) than the NGRIP average. The higher average ^{10}Be flux at Dye-3 suggests a geographic dependency of beryllium deposition, as has also been modeled [*Field et al.*, 2006; *Heikkilä et al.*, 2008a].

4. Discussion and Interpretation

[11] With the two geographically separated annual resolution ^{10}Be records we can examine to what extent flux and concentration represent regional deposition. A change in atmospheric circulation and transport patterns may bring air masses with varying ^{10}Be content over longer time scales. The difference in geographic location of NGRIP and Dye-3, regarding not only latitude and altitude but also distance from the coast, is likely to affect transport to and deposition at the two sites differently [*Heikkilä et al.*, 2008a]. Annual ^{10}Be signals at the two sites are not directly comparable, due to local weather effects. Temporally extensive local differences in ^{10}Be deposition are exposed by application of a low pass filter with a cut-off frequency of 1/22 years (Figure 1). Before the mid-16th century, ^{10}Be expressions are different in NGRIP and Dye-3, which could possibly be caused by a complex ice flow regime at Dye-3, where ice from the oldest strata has experienced significantly different summer melt and accumulation conditions than observed presently at the Dye-3 drill site [*Herron et al.*, 1981]. However, there are periods when long term ^{10}Be variations are similar in the two cores, especially when the flux is considered. Dye-3 flux decreases in the 20th century, a fact that has previously been used to support a theory that the sun has been unusually active since the 1940s [*Usoskin et al.*, 2003], although this conclusion has been disputed by [*Raisbeck and Yiou*, 2004], based on South Pole ^{10}Be data. Our new data from NGRIP does involve low ^{10}Be values during much of the 20th century, although by no means at an unusually low level. These different signals from the Greenland sites in the second half of the 20th century highlights the importance of using a combination of several high resolution datasets in conjunction to assess core uncertainties and local variability in ^{10}Be deposition in order to make confident reconstructions of past solar variability. It is also clear that it is preferable to have ^{10}Be records from sites with non-complex ice flow regimes, and no or infrequent summer melt, such as NGRIP and South Pole.

[12] With high resolution ^{10}Be datasets, the response in ^{10}Be to solar activity variability can be investigated in detail. Because the length of the Schwabe solar cycle during the investigated period varies between seven and 17 years, this is the first time where two datasets have sufficient resolution to capture this variability. Although ^{10}Be data from the southern hemisphere would be a great contribution in this context, existing data is of too low resolution to accurately reflect the Schwabe cycle variations. Since we here focus on decadal variations, we exclude lower resolution data and refer interested readers to previous studies where ^{10}Be from several cores has been compared [e.g., *Muscheler et al.*, 2007].

[13] We apply a band pass filter around the length of the Schwabe solar cycle, with an 8-year cut-off at the lower end to remove weather noise, and 16 years at the upper end (Figure 2). In concentrations, we note a very good agreement between cores in the last two centuries, while further back concentrations in the two cores are periodically out of phase. Between fluxes in the two cores, the agreement is stronger, and differences mainly occur in part of the 17th century. At times, one core indicates two cycles when the other only indicates one. For instance, around 1780 AD there are two cycles in NGRIP concentration where Dye-3 has only one. Around 1810 AD there is one peak indicated in the NGRIP flux data, while there are two in Dye-3. In the NGRIP data, there are similar occasional differences between the parameters; while concentration has two periods around 1580 AD, there is only one in the flux, and the opposite is true around 1650 AD. Around 1780 AD there is some phase shift between the two parameters. In Dye-3, differences between concentration and flux exist mainly around 1490–1530 AD and partly during 1680–1770 AD.

[14] In order to investigate how these periods and differences correspond to solar activity, we compare NGRIP and Dye-3 concentration and flux with frequencies found in the sunspot number record (Figure 2). We note that NGRIP ^{10}Be concentration and flux both have a negative relationship to solar activity, although there are occasional leads and lags before 1820 AD and during 1880–1910 AD in both ^{10}Be parameters relative to the solar data. In Dye-3, there are phase differences until around 1780 AD, after which ^{10}Be is well synchronized with the sunspots. This indicates that there is either some dating uncertainty in the older part of the cores, where Dye-3 dating was established by a different method than in the newer part, or there was a slower response in the ^{10}Be deposition to changes in solar activity. It should be stressed that the good agreement between NGRIP and Dye-3 fluxes suggest that remaining dating inaccuracies are small. In the period around 1800 AD when NGRIP ^{10}Be is slightly out of phase with the sunspot cycle, Dye-3 concentration is in phase, underlining the importance of having data from at least two high resolution cores for an accurate solar activity reconstruction. In addition, we reconfirm earlier findings [*Beer et al.*, 1998] of a

cyclically active sun during solar minima; a clear Schwabe cycle is present in both cores during the Maunder minimum, especially so in NGRIP.

[15] Finally, we consider the correlation between ^{10}Be from the ice cores with neutron data (Figure 3). While sunspots reflect the closed solar magnetic field, which is not directly related to the open magnetic field that modulates the cosmic ray intensity, neutron monitors record the cosmic ray intensity with high resolution and high precision. They therefore provide the best possible parameter to compare ^{10}Be with, except for the fact that ^{10}Be production is slightly more sensitive to cosmic rays with lower energy [*Beer*, 2000]. We observe a high degree of agreement of ^{10}Be concentration and flux in NGRIP and Dye-3 to the atmospheric neutron flux, which proves the usefulness of ^{10}Be in ice cores to reconstruct past solar activity.

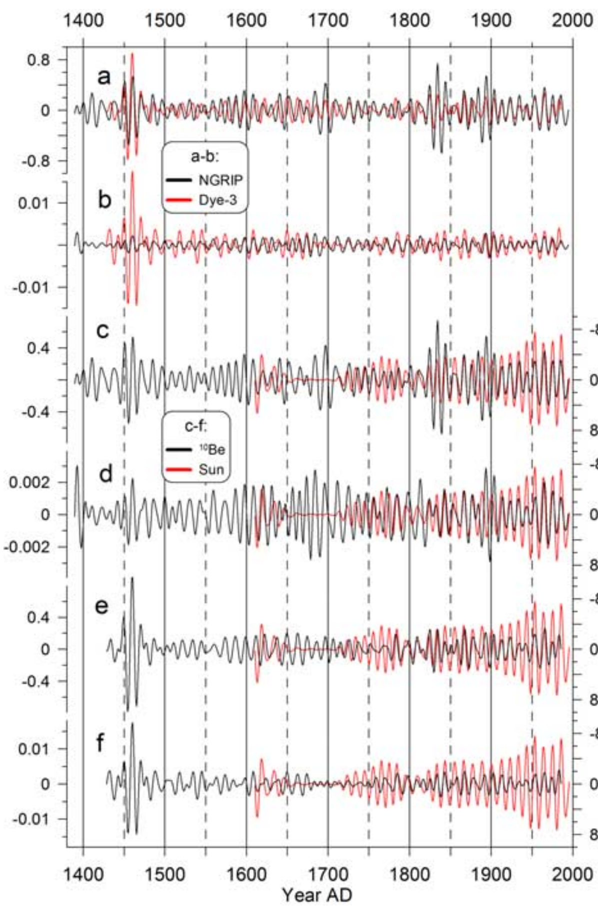

Figure 2. Band pass filtering of sunspot and ^{10}Be data around the length of the Schwabe cycle. Included is in (a) NGRIP and Dye-3 ^{10}Be concentration, (b) NGRIP and Dye-3 ^{10}Be flux, (c) NGRIP ^{10}Be concentration and sunspots, (d) NGRIP ^{10}Be flux and sunspots, (e) Dye-3 ^{10}Be concentration and sunspots, and (f) Dye-3 ^{10}Be flux and sunspots. In Figures 2d–2f, which illustrate how concentration and flux compare to solar activity as reflected in sunspot numbers, the sunspots axes are reversed. The data was normalized by removing the mean before band pass filtering of 8–16 years, using a Butterworth filter. The group sunspot number time series construction is described by *Hoyt and Schatten* [1998].

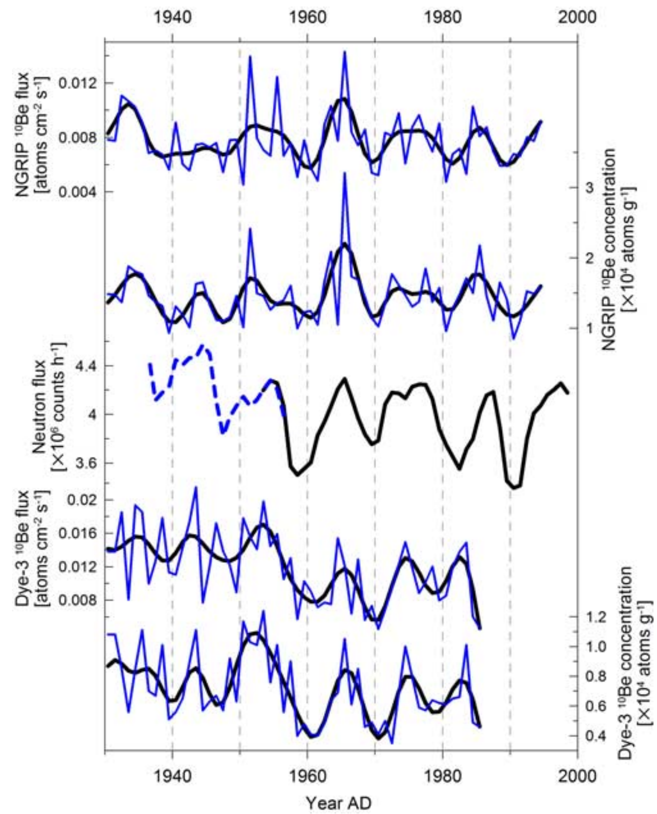

Figure 3. A comparison of NGRIP and Dye-3 ^{10}Be concentration and flux with neutron data since 1936 AD. ^{10}Be raw data is shown together with low pass, 1/6 year cut-off, filtered data. Neutron monitor data from 1953–1998 AD, ionization chamber data from 1936–1956 AD (dashed) [*McCracken and Beer*, 2007].

[16] In conclusion, our ^{10}Be data from NGRIP provides a new archive that is strongly needed for identifying temporal and spatial variability of ^{10}Be deposition over Greenland, thereby enabling more accurate solar activity reconstructions. Comparison over several centuries of our data with earlier data from Dye-3 indicates that despite the existence of local noise and some differences prior to the mid-16th century, the regional nature of the ^{10}Be signal in ice cores is confirmed. The good long-term agreement between ^{10}Be variations in both cores reflects a regional response to production and climate changes, but the disagreements in the earlier parts of the two records suggest that ^{10}Be should be measured in ice cores from locations with non-complex ice flow regimes. ^{10}Be deposition is anti-correlated to solar activity over the 11-year Schwabe solar cycle, and correlated to neutron monitor data. Periodicity in ^{10}Be during the Maunder minimum reconfirms that the solar dynamo retains cyclic behavior even during grand solar minima. We observe that although recent ^{10}Be flux in NGRIP is low, there is no indication of unusually high recent solar activity in relation to other parts of the investigated period.

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