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^{10}Be measured in a GRIP snow pit and modeled using the ECHAM5-HAM general circulation model

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[1] ^{10}Be measured in a Greenland Ice Core Project (GRIP) snow pit (1986–1990) with a seasonal resolution is compared with the ECHAM5–HAM GCM run. The mean modeled ^{10}Be concentration in ice ($1.0 \cdot 10^4$ atoms/g) agrees well with the measured value ($1.2 \cdot 10^4$ atoms/g). The measured ^{10}Be deposition flux (88 atoms/m^2/s) also agrees well with the modeled flux (69 atoms/m^2/s) and the measured precipitation rate (0.67 mm/day) agrees with the modeled rate (0.61 mm/day). The mean surface temperature of −31°C estimated from δ^{18}O is lower than the temperature measured at a near-by weather station (−29°C) and the modeled temperature (−26°C). During the 5-year period the concentrations and deposition fluxes, both measured and modeled, show a decreasing trend consistent with the increase in the solar activity. The variability of the measured and modeled concentrations and deposition fluxes is very similar suggesting that the variability is linked to a variability in production rather than the local meteorology. **Citation:** Heikkilä, U., J. Beer, J. Jouzel, J. Feichter, and P. Kubik (2008), ^{10}Be measured in a GRIP snow pit and modeled using the ECHAM5-HAM general circulation model, *Geophys. Res. Lett.*, *35*, L05817, doi:10.1029/2007GL033067.

1. Introduction

[2] Cosmogenic radionuclides, whose production is modulated by solar activity, provide an excellent tool to study past solar changes. ^{10}Be, archived in ice cores, is widely used to reconstruct solar activity during the Holocene [*McCracken et al.*, 2004; *Muscheler et al.*, 2007; *Vonmoos et al.*, 2006]. Such reconstructions depend strongly on the assumption that ^{10}Be measured at one specific drilling site reflects the global ^{10}Be production rate. However, it has been argued that changes in weather conditions at the drilling site can affect the measured ^{10}Be, substantially lowering the signal to noise ratio of ^{10}Be [e.g., *Lal*, 1987].

[3] While low-pass filtering of ^{10}Be records helps to reduce weather-induced fluctuations, long–term changes in transport to or precipitation rates in the polar regions can have an impact on the measured ^{10}Be. To study transport effects on ^{10}Be fluxes in the past atmospheric general circulation models (GCMs) have been used [*Field et al.*, 2006; Heikkilä, U., J. Beer, and J. Feichter, Modeling cosmogenic radionuclides ^{10}Be and ^{7}Be during the Maunder Minimum with the general circulation model ECHAM5-HAM, submitted to *Atmospheric Chemistry and Physics Discussions*, 2007]. However, it is difficult to validate these model results because observational data are scarce. Also, because the temporal resolution of most ^{10}Be records is on the order of years, the model results cannot be fully tested.

[4] During the drilling of the Greenland Ice Core Project (GRIP) ice core at Summit, central Greenland (71.1°N, 39.5°W, 3210 m a.s.l.), a 5-m deep snow pit was dug. This pit is ideally suited for comparing modeled and measured ^{10}Be. The resolution obtained (∼2 months) even allows comparison of modeled temperature and precipitation with the measured proxy δ^{18}O.

[5] This study had two main goals. The first of these was to investigate how well a GCM can reproduce the seasonal and annual variability of ^{10}Be measured in Greenland. If a GCM is able to simulate properly the ^{10}Be concentrations in precipitation under present-day conditions, it can be applied to earlier periods with greater confidence. The second goal was to test whether the solar signal can be detected in the modeled and measured ^{10}Be concentrations over a short period of time. To answer this question, we compared variations in the measured and modeled ^{10}Be concentrations in precipitation and deposition fluxes with variations in the ^{10}Be production signal.

2. Methods

2.1. Digging and Measurement

[6] The GRIP pit was dug in direct proximity to the main GRIP drill site at Summit. It was approximately 5 meters deep. The firn of the pit was divided into 50 samples of 10 cm, corresponding to a resolution of ∼2 months. ^{10}Be was measured in Zurich at Accelerator Mass Sprectrometry facility of ETH/PSI.

[7] δ^{18}O was measured by mass spectrometry at LSCE Saclay with the accuracy of 0.5% and 0.05%. In polar regions concentrations in precipitation of this isotope, influenced by fractionation processes occurring between the oceanic source of water vapor and the precipitation at the measurement site, are closely linked with the temperature prevailing during snow formation and thus to the temperature at the measurement site. It shows well marked seasonal cycles with high values in summer and can be used to date the successive snow layers as long as seasonal variations are not smoothed out by diffusion of water vapor in firn. Therefore, δ^{18}O profiles can be used to estimate past temperature changes even at seasonal level.

2.2. Model Description and Setup

[8] The model employed for this study was the ECHAM5-HAM general circulation model. ECHAM5 is a fifth–generation model [*Roeckner et al.*, 2003] developed at

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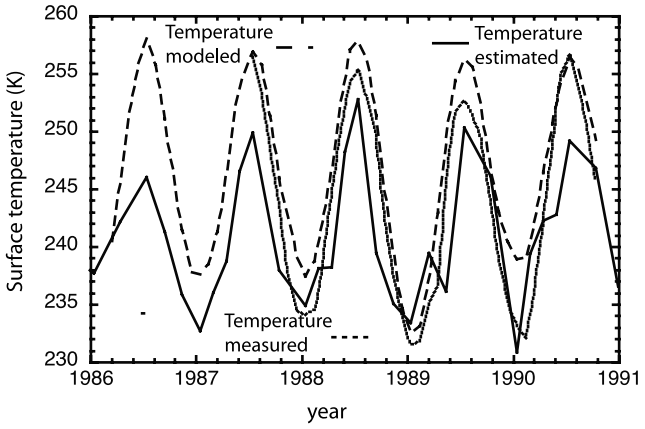

Figure 1. Comparison of the modeled surface temperature at Summit, Greenland, with the temperature measured at the near−by weather station in Greenland, and with the surface temperature estimated from the δ^{18}O data.

the Max Planck Institute for Meteorology from the weather prediction model of the European Centre for Medium-Range Weather Forecasts (ECMWF), which incorporates the additional aerosol module HAM [*Stier et al.*, 2005]. This model has already been used to simulate the production, atmospheric transport and deposition, both wet and dry (contributes less than 10% in Greenland), of ^{10}Be on a global scale [*Land and Feichter*, 2003; Heikkilä et al., submitted manuscript, 2007].

[9] For this run a model version with 31 vertical levels extending up to 10 hPa (∼30 km), was used. The horizontal resolution employed was roughly 2.8° × 2.8°. This run was forced with prescribed observational sea surface temperatures and sea ice cover obtained from the international model intercomparison AMIP2 project. The production of ^{10}Be is a function of latitude and altitude and also varies temporally with varying solar activity and geomagnetic field intensity. The latter can be considered as constant during the 5-year period considered within this study. For the model input the ^{10}Be production was interpolated to the correct latitude, altitude and solar activity parameter Φ using the ^{10}Be production function calculated by *Masarik and Beer* [1999]. The Φ values, with monthly resolution, were taken from http://jag.cami.jccbi.gov/cariprofile.asp. Validation of the model with worldwide observations of ^{7}Be indicated that this production rate leads to somewhat low deposition fluxes (Heikkilä et al., submitted manuscript, 2007). Since the deposition flux is determined by the global production rate, this indicates that the source strength might be underestimated. The production rate was therefore increased by 50% consistently from earlier model experiments. The model run was allowed to spin up for 5 yr, and the following 5 yr, from 1986 to 1990, were used for the analysis.

3. Results

3.1. Proxy δ^{18}O

[10] The ice from the pit was dated by interpreting the maxima and minima of δ^{18}O as winter and summer, respectively, and linearly interpolating the months in between. The errors are on the order of ±1 month.

[11] δ^{18}O measured in ice cores is used as an indirect proxy for reconstructing the past temperature and precipitation rate during periods for which there are no direct observations. It is therefore of great interest to use the high resolution data from the snow pit to compare the temperatures and precipitation rates estimated from the δ^{18}O proxy with direct instrumental and modeled data. The temperature estimated from the measured δ^{18}O [*Johnsen et al.*, 1989] along with the modeled surface temperature for Summit, is shown in Figure 1 together with the temperature measured at the near−by weather station Cathy (72.3°N, 38.0°W, 3210 m asl) in Greenland (available from http://amrc.ssec.wisc.edu/greenlandstations.html). The weather station data is available from May, 1987. Comparison of the modeled and estimated temperature with the temperature measured at the Cathy weather station shows that during winter the temperature estimated from δ^{18}O agrees well with the measured temperature but is slightly low during summer. The modeled temperature generally agrees well with the measured temperature but is ∼2°C higher during the winter of 1987/1988 and the summers of 1988 and 1989. During the winter of 1989/1990 the modeled temperature is significantly (∼5°C) too high. The main reason for higher modeled temperatures is that the grid size of the model is too large to resolve the altitude of Summit, the highest point of Greenland. The average temperatures are −32°C (estimated from δ^{18}O) and −27°C (modeled) for this 5-year period. The average (May 1987 till December 1990) temperature measured at the weather station is −29°C and lies between the modeled temperature (−26°C) and the temperature estimated from the δ^{18}O (−31°C) for the same period. The generally good agreement between the estimated temperature from the δ^{18}O and the measured temperature gives confidence for using this proxy for long-term reconstructions of the temperature.

[12] The precipitation rate was calculated directly from the thickness of the sample layer using the measured density of the samples, but because of dating uncertainties we will consider only annual means here. Figure 2 illustrates the comparison of mean annual measured precipitation rate with modeled precipitation rate and the estimated precipitation rate derived from the δ^{18}O data [*Johnsen et al.*, 1989]. Interestingly, the modeled precipitation rate reproduces the year-to-year variability in the measured data very well, but the overall mean value of the modeled precipitation rate is up to 10% too low. However, these differences are negligible when considering the uncertainties of the measured precipitation rate. The precipitation rate estimated from the δ^{18}O data does not show the same annual variability but the order of magnitude is comparable with both the modeled and measured precipitation rates. The indirect proxy δ^{18}O is not well suited for short-term changes because of the complicated character of the fractionation processes which determine its magnitude. The average rates are 0.67 mm/day water equivalent (W. E.), 0.61 mm/day W. E. and 0.52 mm/day W. E. for the measured, modeled and estimated rates, respectively.

3.2. Measured and Modeled ^{10}Be Concentrations in Precipitation

[13] The ^{10}Be concentrations measured in the firn, together with the simulated ^{10}Be concentrations in precipita-

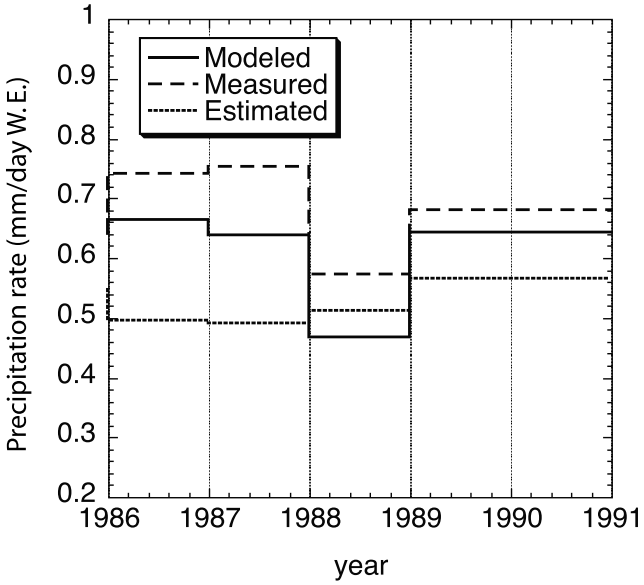

Figure 2. The annual mean precipitation rate at Summit, Greenland: modeled, measured, and estimated from the measured δ^{18}O.

tion are shown in Figure 3. As the temporal resolution of the ^{10}Be measurements is coarser than that of the model, a 5-month running mean filter was applied to the monthly mean modeled concentrations. The overall agreement between the measured and modeled ^{10}Be concentrations is good, with even the seasonal structure being reproduced during most years. In 1986, the modeled concentrations are lower than the measured concentrations. In 1989, the measured ^{10}Be concentration peaks during the second half of the year, whereas the modeled ^{10}Be concentration peaks in the summer months, as it does during the other years. This shift is probably not caused by a shift in the dating, because the surface temperature shows no shift (Figure 1). The differences are likely to be caused by local sub-scale processes which the model cannot resolve.

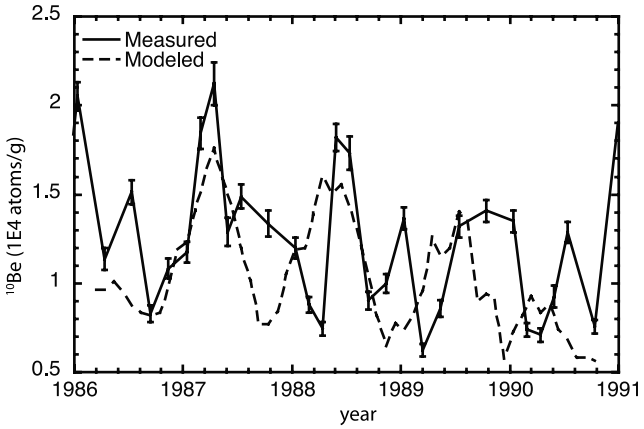

Figure 3. Comparison of measured ^{10}Be concentrations in precipitation from the GRIP snow pit (solid line) with the measurement errors, with the monthly mean modeled ^{10}Be concentrations in precipitation filtered with a 5-month running mean filter (dashed line).

Table 1. Mean ^{10}Be Concentrations in Precipitation and Deposition Fluxes and Accumulation Rates Measured and Modeled From 1986 to 1990

	Measured	Modeled	Units
^{10}Be concentration	1.2	1.0	10^4 atoms/g
Accumulation rate	0.67 (0.52[a])	0.61	mm/day W.E.
^{10}Be deposition flux	88 (74[a])	69	atoms/m^2/s

[a]Estimated from δ^{18}O as in the work by *Johnsen et al.* [1995].

[14] The mean measured and modeled concentrations in precipitation, deposition fluxes and precipitation rates are shown in Table 1. The modeled concentration in precipitation ($1.0 \cdot 10^4$ atoms/g) agrees well with the measured concentration ($1.2 \cdot 10^4$ atoms/g). Using the accumulation rate of the firn we calculate an average ^{10}Be flux of 88 atoms/m^2/s. If we use the precipitation rate estimated from the δ^{18}O data, a slightly lower flux (74 atoms/m^2/s) is obtained. The modeled flux is 25% lower than the observed flux, 69 atoms/m^2/s.

[15] To investigate how well the ^{10}Be concentrations in the ice reflect solar activity we compared the ^{10}Be trends. Figure 4 shows the ^{10}Be concentrations in precipitation and deposition fluxes in relative units together with Φ and the global ^{10}Be production rate. Annual means are used to describe the typical temporal resolution within an ice core (>1 year), thus filtering out any seasonal variability. The correlation coefficients between the annual mean ^{10}Be concentration, measured and modeled, and the global production rate are 0.91 and 0.58, respectively, for the 5 data points. Between the ^{10}Be deposition flux and global production rate the correlation coefficients are 0.88 and 0.79 suggesting that a strong correlation exists.

[16] The fact that the variability of the ^{10}Be concentration in firn mirrors that of the ^{10}Be deposition flux suggests that this variability is not related to variability in the local precipitation rate. This is consistent with an earlier finding that during the past 800 years at Milcent, Greenland, the ice accumulation rate remained relatively constant [*Beer et al.*, 1988]. The ''long-term'' decreasing trend in both the concentration and flux of ^{10}Be follows a simultaneous

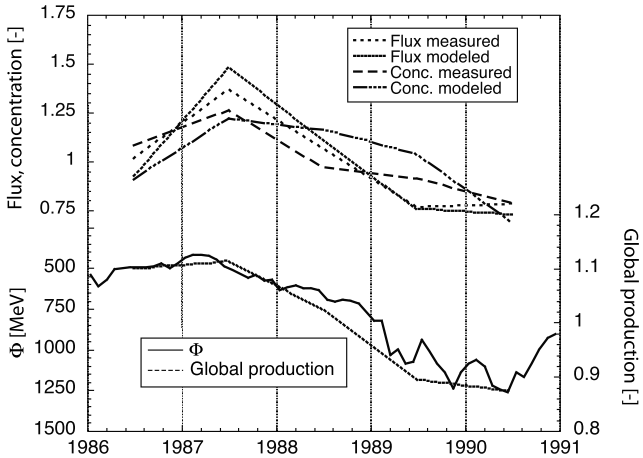

Figure 4. (top) Comparison of normalized ^{10}Be annual mean measured and modeled concentrations in precipitation and deposition fluxes and (bottom) the solar activity parameter Φ (MeV) with the global ^{10}Be production (normalized).

increasing (decreasing) trend in Φ (global production rate). Thus, although local effects may raise the noise level, they do not raise it enough to mask the production signal. This finding also emphasizes the importance of taking into account the solar modulation of the ^{10}Be production in modeling studies. Neglecting the decreasing trend in the monthly ^{10}Be production would have resulted in substantial worsening of the agreement between the modeled and measured ^{10}Be.

4. Summary and Conclusions

[17] ^{10}Be in a shallow GRIP ice snow pit from Summit, Greenland, covering the period of 1986 to 1990 was measured with a resolution of 2 months and the resulting data were analyzed with respect to solar modulation of the ^{10}Be production rate. A simulation with the ECHAM5-HAM general circulation model (GCM) reveals a very good agreement between the measured ^{10}Be concentrations in precipitation ($1.2 \cdot 10^4$ atoms/g) and the modeled ^{10}Be concentrations in precipitation ($1.0 \cdot 10^4$ atoms/g). The modeled precipitation rate at Summit (0.61 mm/day W. E.) also agrees well with the measured accumulation rate (0.67 mm/day W. E.). The modeled ^{10}Be deposition flux (69 atoms/m^2/s) is slightly lower than the measured value (88 atoms/m^2/s).

[18] The measured and modeled ^{10}Be both exhibit a higher variability than the solar activity parameter Φ and the global ^{10}Be production rate. This indicates that local weather effects do have an impact on the measured ^{10}Be concentrations in precipitation. However, variability in the modeled ^{10}Be concentration is very similar to that of the modeled ^{10}Be deposition flux indicating that the ^{10}Be variability observed was not a result of variability in the precipitation rate. This is in accordance with earlier studies. Moreover, a clear decreasing trend, following the increase in the solar activity during the 5-year period analyzed is visible. In the case of much longer ^{10}Be records in ice cores, a low-pass filter can be applied to improve the signal-to-noise ratio.

[19] The successful simulation of contemporary ^{10}Be concentrations in Greenlandic ice using the ECHAM5-HAM GCM provides confidence that this model is also capable of simulating ^{10}Be for past climatic conditions. GCMs therefore prove to be useful tools in interpreting ^{10}Be in ice cores not only in terms of changes in the ^{10}Be production rate but also in terms of atmospheric transport and deposition processes.

[20] **Acknowledgments.** We thank Gerhard Wagner for his help with sample preparation. We are grateful to the German Computer Center (DKRZ) for providing us with the computing time. This work is supported by the Swiss National Science Foundation.

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