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Solar and climatic effects on ^{10}Be

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Abstract. To understand contemporary climate change and anthropogenic climate forcings, it is necessary to quantify solar forcing, the most significant natural forcing on centennial timescales. The close correlation between the production of the cosmogenic isotope ^{10}Be and changes in heliomagnetic activity makes ^{10}Be an attractive proxy for studying changes in solar output.

1. Introduction

Beryllium-10 is produced primarily in the lower stratosphere and upper troposphere. The average residence time in the lower stratosphere is one to two years (Davidson et al. 1981). Eventually the ^{10}Be is transported to the lower troposphere and deposited at the surface. This quick transition from production to deposition differentiates ^{10}Be from ^{14}C, whose response to short-term production changes is significantly damped by the carbon cycle, decreasing ^{14}C's usefulness as an indicator of multi-decadal and centennial changes in solar activity (Bard et al. 1997). In particular, ^{10}Be's short atmospheric residence time leads to high-resolution signals in well-dated polar ice core records (McHargue and Damon 1991), which accounts for ^{10}Be's persistent popularity as a proxy for changes in solar output despite uncertainties regarding the relationship between solar irradiance and heliomagnetic activity, (McCracken et al. 2004; Lean et al. 2002).

A complicating factor is the possibility that climatic effects may confound solar signals in the ^{10}Be record. Processes that affect the distribution of ^{10}Be in the troposphere – such as changes in stratosphere-troposphere exchange (STE) or aerosol scavenging efficiency, both of which may change with climate – could distort the degree to which ice core records reflect production changes. Similarly, because a more or less active hydrologic cycle may dilute or exaggerate ^{10}Be snow concentrations, any process that affects precipitation could also obscure a production-rate signal. By using the GISS ModelE GCM to selectively vary climate and production functions, we model ^{10}Be flux values and then calculate concentration changes at key coring sites. We present results for solar and geomagnetic changes and compare them to variations in ^{10}Be concentration as functions of (a) ocean changes related to the "Younger Dryas" and the 8.2 kyr event and (b) atmospheric changes due to varying volcanic and greenhouse gas forcings.
The different experiments are summarized in Table 1. To simulate the production of ^{10}Be,

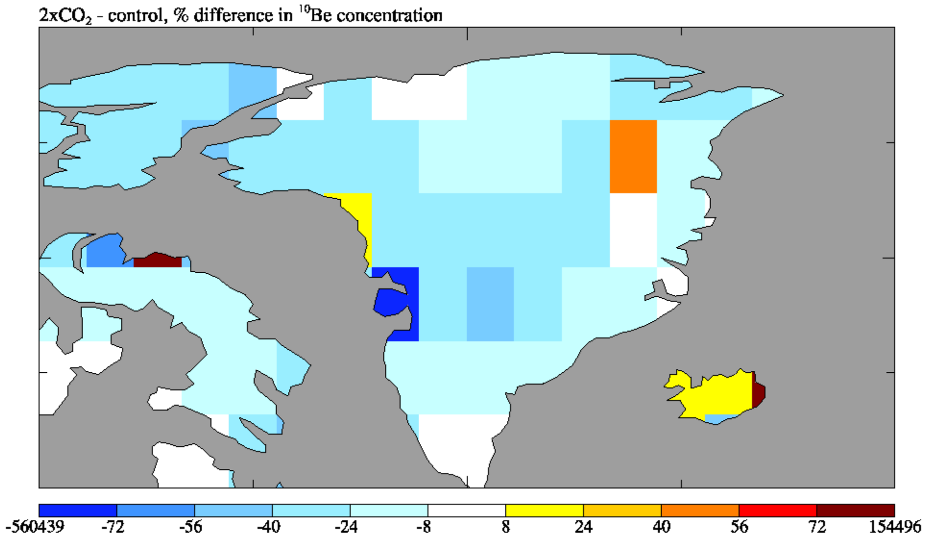

Fig. 1. Percent change in ^{10}Be snow concentration for 2xCO$_2$ simulation relative to the control run.

we used the calculated source functions from Masarik and Beer (1999) and assumed a control solar activity modulation parameter of ϕ = 700 MeV. This value is meant to represent long-term mean solar activity and is roughly the midpoint between recent solar minimum (400-500 MeV) and maximum (900-1000 MeV) values. The source function also assumes present-day geomagnetic field strength (M=1). These parameters result in a mean production rate of about 0.0184 atoms/cm^2 s^1.

2. Production-change experiments

Various studies (Bard et al. 1997; Steig et al. 1996; Mazaud et al. 1994; McCracken et al. 2004) have used statistical and mathematical techniques to estimate the degree to which solar and geomagnetic changes are enhanced or suppressed in high-latitude ^{10}Be records. We performed one simulation with reduced geomagnetic field strength (75% of its present-day value) and one simulation with the solar modulation constant reduced to its approximate value during a solar minimum (ϕ = 500 MeV). For each simulation, the global average increase in ^{10}Be production is roughly 10%, however in the solar minimum run, polar deposition is enhanced by a factor of 1.22 relative to the change in global average deposition. For the geomagnetic minimum run, polar deposition is reduced by a factor of 0.8. Our solar value is smaller than the enhancement estimated in Bard et al. (1997) (approximately 1.54-1.67, when the ratio is taken as described above). Our geomagnetic value agrees well with the enhancement of 0.75 in Mazaud et al. (1994). These results confirm that the expression of geomagnetic impacts on ^{10}Be is muted (relative to the global mean) over polar ice-sheet regions, while the effects of solar changes are augmented.

3. 2xCO$_2$ experiments

Analysis of a 2xCO$_2$ simulation illustrates by means of exaggeration the possible climate and transport effects that have influenced ^{10}Be flux during warm periods in the past. The global radiative forcing is around 4 W/m^2 and global mean temperature increases by 2.7deg C. There is greater warming over land masses and precipitation increases over the intertrop-

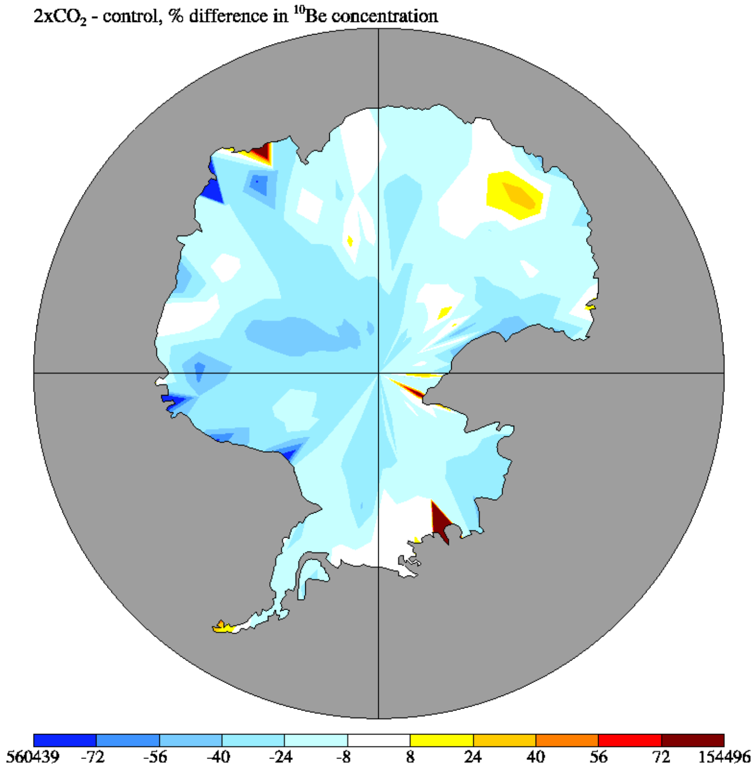

Fig. 2. Percent change in ^{10}Be snow concentration for $2xCO_2$ simulation relative to the control run.

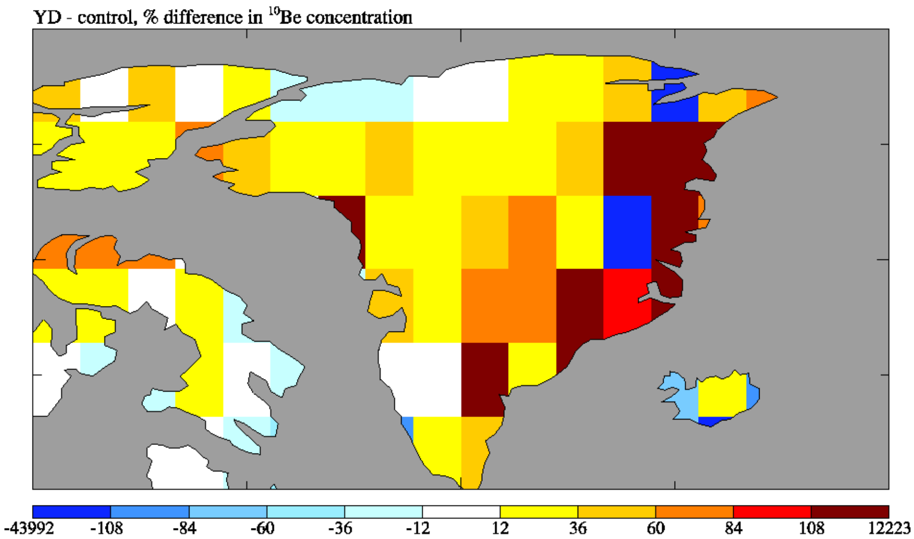

Fig. 3. Percent change in ^{10}Be snow concentration for YD simulation relative to the control run.

Table 1. Model experiments (M = present-day geomagnetic field strength)

Run	Ocean Temp.	Atmosphere	Comments
control 1	fixed SST	preindustrial GHG	ϕ=700 MeV M = 1
solar min.	fixed SST	-	ϕ=500 MeV M = 1
geo. min.	fixed SST	-	ϕ=700 MeV M = 0.75
"Younger Dryas"	fixed SST (no NADW)	-	
control 2	mixed layer	-	
2xCO_2	mixed layer	560 ppm CO_2	
volcanic	mixed layer	1991 volcanic aerosols (Pinatubo) repeating eruptions	

ical convergence zone as well as over mid- to high northern latitudes and Antarctica. Similar to the findings reported in Land and Feichter (2003), our results show increased transport of ^{10}Be from the stratosphere to the troposphere. However changes in precipitation dominate over changes in atmospheric ^{10}Be concentrations: for both Greenland and Antarctica, accumulation increases by 10-50%, and ^{10}Be snow concentration drops accordingly by 8-40% (see figures 1 and 2). Beryllium-10 records during warm climates therefore seem likely to be characterized by a "dilution" effect, with only slight modifications due to changes in deposition.

4. North Atlantic Ocean Circulation Changes

As a counterpoint to the 2xCO_2 simulation, we look at how the ^{10}Be record might change in response to a cooler climate forced by North Atlantic Deep Water (NADW) changes. The Younger Dryas (YD) cold event is thought to have been accompanied by an abrupt reduction in NADW production (Broecker and Denton 1990; Rind et al. 2001a,b) and is apparent in the GISP2 ice core from approximately 13 to 11.7 kya. We simulate the YD using SST and sea-ice parameters fully derived from a coupled ocean-atmosphere model simulation involving complete NADW shutdown (Rind et al. 2001a). In the YD run, cold sea surface temperatures off Greenland's southeastern coast cool air over the northern North Atlantic, increasing surface pressure and reducing precipitation. As a result, atmospheric ^{10}Be concentrations between 50deg N and 90deg N increase by 3-21%. The ^{10}Be-enriched air leads to increased concentrations in wet deposition and increased dry deposition over Greenland. This increased deposition is combined with reduced accumulation over central Greenland, which further enhances the snow concentration increases (figure **??**). The overall result is that ^{10}Be snow concentrations increases by more than 36% over most of eastern Greenland in the YD scenario, with 68% increase at Summit – roughly two-thirds of the observed change of approximately 100% described in Finkel and Nishiizumi (1997).

5. Volcanic experiments

To analyze the effect that eruption-related cooling might have on ^{10}Be deposition, we run the model for 100 years and simulate a Pinatubo-like eruption once per decade. We compare data from the two coldest years following each eruption (20 years total) with data averaged over the entire 100-year simulation. Changes in ^{10}Be over Greenland are negligible, however cooling over Antarctica leads to decreases in accumulation over the central and eastern parts of the ice sheet. The reduced accumulation results in 5-15% increases in ^{10}Be snow concentration. Collectively, these changes suggest that climate impacts associated with volcanism are unlikely to affect Greenland ^{10}Be records significantly, but may have a more variable influence on Antarctic records.

6. Conclusions

Model simulations using ^{10}Be were performed to see how changes in production function and climate may impact ^{10}Be flux over polar ice-coring areas. In the production change experiments, changes in ^{10}Be deposition at the poles relative to the global average change are consistent with those from earlier studies (Bard et al. 1997; Mazaud et al. 1994). In the reduced NADW experiment, the model simulates ^{10}Be snow concentration increases at Summit that are roughly two-thirds as large as those seen in the ice core record; this is accomplished without the benefit of any change in ^{10}Be production. In the runs with radiative forcings, changes in snow concentrations are dominated by changes in precipitation: warming in the 2xCO_2 run leads to diluted ^{10}Be over ice sheets, and cooling in the volcanic run leads to lower precipitation and higher snow concentrations over Antarctica. Taken together, these experiments illustrate the difficulty of ascribing specific causes to changes in the ^{10}Be ice core record, and in particular of distinguishing between climate-related and solar-related changes.

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