Persistent link between solar activity and Greenland climate during the Last Glacial Maximum

Florian Adolphi*1, Raimund Muscheler1, Anders Svensson2, Ala Aldahan3,4, Göran Possnert6, Jürg Beer6, Jesper Sjølde, Svante Björck1, Katja Matthes1 and Rémi Thiéblemont7

1Department of Geology—Quaternary Sciences, Lund University, 22362 Lund, Sweden, 2Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark, 3Department of Earth Sciences, Uppsala University, 75236 Uppsala, Sweden, 4Department of Geology, United Arab Emirates University, 17551 Al Ain, UAE, 5Tandem Laboratory, Uppsala University, 75120 Uppsala, Sweden, 6Swiss Federal Institute of Aquatic Science and Technology, Eawag, 8600 Dübendorf, Switzerland, 7Division of Ocean Circulation and Climate, GEOMAR Helmholtz Centre for Ocean Research Kiel, 24105 Kiel, Germany. *e-mail: Florian.Aadolphi@geol.lu.se

Changes in solar activity have previously been proposed to cause decadal- to millennial-scale fluctuations in both the modern and Holocene climates1. Direct observational records of solar activity, such as sunspot numbers, exist for only the past few hundred years, so solar variability for earlier periods is typically reconstructed from measurements of cosmogenic radionuclides such as 10Be and 14C from ice cores and tree rings5,7. Here we present a high-resolution 10Be record from the ice core collected from central Greenland by the Greenland Ice Core Project (GRIP). The record spans from 22,500 to 10,000 years ago, and is based on new and compiled data6,8. Using 14C records5,7,8 to control for climate-related influences on 10Be deposition, we reconstruct centennial changes in solar activity. We find that during the Last Glacial Maximum, solar minima correlate with more negative δ18O values of ice and are accompanied by increased snow accumulation and sea-salt input over central Greenland. We suggest that solar minima could have induced changes in the stratosphere that favour the development of high-pressure blocking systems located to the south of Greenland, as has been found in observations and model simulations for recent climate9,10. We conclude that the mechanism behind solar forcing of regional climate change may have been similar under both modern and Last Glacial Maximum climate conditions.

The Sun is the main energy source for the Earth's climate system. Satellite observations indicate variations in total solar irradiance (TSI) of about 1 W/m2 associated with the solar 11 yr cycle1. Despite these small changes in forcing there is compelling evidence for a solar influence on climate arising from palaeoclimate studies (see ref. 1 and references therein). One proposed mechanism to amplify the Sun's influence on climate involves the relatively large modulation of the solar ultraviolet output, which alters the radiative balance in the stratosphere through ozone feedback processes and eventually propagates downwards causing changes in the tropospheric circulation7. Palaeoclimate studies allow an assessment of solar forcing of climate under various past orbital configurations and mean climate states, and thus may provide valuable insight into climate sensitivity to and mechanisms of solar forcing.

Before the satellite era and observations of sunspots, cosmogenic radionuclides, such as 10Be and 14C, provide the most reliable information about solar variability. Their atmospheric production rates depend on the flux of galactic cosmic rays impinging on the Earth's atmosphere, which is in turn modulated by the variable shielding through the Earth's and solar magnetic fields2, the latter being correlated to TSI variations during the satellite era3. In addition to this production component, palaeo-records of 10Be (from, for example, ice cores) and 14C (from, for example, tree rings and speleothems) are affected by ‘system effects’ such as changes in transport and deposition (ref. 11 and references therein), and the carbon cycle4, respectively. As the expected system effects are fundamentally different for the two radionuclides, a combined analysis of 10Be and 14C records can help to isolate production rate variations more reliably. In summary, a reconstruction of past solar variability from cosmogenic radionuclides requires an assessment of system effects in 14C and/or 10Be records, and the elimination of production rate variations due to geomagnetic modulation. Further support for a solar origin of production rate variations can be drawn from identification of well-known long-term solar cycles, and comparison of the inferred amplitudes to expectations deduced from physically based models12. In the absence of suitable data this approach has so far been limited to the Holocene (for example, ref. 3). Nevertheless, the presence of the solar de Vries cycle (~207 yr) during parts of the last glacial has been demonstrated from 10Be alone13. Here we present the first reconstruction of solar activity variations for the end of the last glaciation from 22.5 to 10 kyr BP.
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rate changes on ice-core $^{10}$Be concentrations, especially visible at transitions between stadials and interstadials (Fig. 1). However, both records show similar high-frequency variations after normalization (Methods and Fig. 2). This shows that accumulation rate changes do not dominate the records on sub-millennial timescales when accumulation rate changes are small. Moreover, the normalized $^{10}$Be variations are largely independent of other atmospheric aerosol species measured in the GISP2 ice core indicating minor climate-related depositional influences on $^{10}$Be (Supplementary Fig. 1). The normalization also removes unresolved differences in the millennial variations of the GISP2 and GRIP $^{10}$Be series (Supplementary Fig. 2). Most importantly, the resulting $^{10}$Be record is consistent with the tree-ring and speleothem $^{14}$C production rates even over stadial–interstadial transitions where system effects are expected to be largest (Fig. 2 and Supplementary Figs 3 and 4). The $^{14}$C production rates were derived from the $^{14}$C records (Fig. 1) using a carbon-cycle box-diffusion model that corrects for known carbon cycle effects on the atmospheric $^{14}$C content (Supplementary Methods and Supplementary Fig. 6).

The difference of $^{10}$Be concentrations and fluxes reflects the known effects of snow accumulation (thousand years before present, AD 1950) based on new and published $^{10}$Be data from the GRIP and GISP2 ice cores supported by independent estimates of atmospheric $^{14}$C concentrations. In addition, we provide the first evidence for a solar forcing of Greenland climate during Greenland Stadial 2 (GS-2, 22.9 – 14.7 kyr BP; ref. 14) that seems coherent with increased frequencies of high-pressure blocking patterns south of Greenland during low-solar-activity winters – a relationship that has been reported previously from modern observations and climate model experiments.

The new high-resolution GRIP $^{10}$Be record (10.8 – 18.6 kyr BP, see Supplementary Methods) is shown in Fig. 1. In combination with previously published GRIP/GISP2 $^{10}$Be data the resulting record covers the investigated period with an average resolution of about 20 years. In the following we will address the above-mentioned points to evaluate the GRIP/GISP $^{10}$Be record as a proxy record for solar variability.

The difference of $^{10}$Be concentrations and fluxes reflects the known effects of snow accumulation rate changes on ice-core $^{10}$Be concentrations, especially visible at transitions between stadials and interstadials (Fig. 1). However, both records show similar high-frequency variations after normalization (Methods and Fig. 2). This shows that accumulation rate changes do not dominate the records on sub-millennial timescales when accumulation rate changes are small. Moreover, the normalized $^{10}$Be variations are largely independent of other atmospheric aerosol species measured in the GISP2 ice core indicating minor climate-related depositional influences on $^{10}$Be (Supplementary Fig. 1). The normalization also removes unresolved differences in the millennial variations of the GISP2 and GRIP $^{10}$Be series (Supplementary Fig. 2). Most importantly, the resulting $^{10}$Be record is consistent with the tree-ring and speleothem $^{14}$C production rates even over stadial–interstadial transitions where system effects are expected to be largest (Fig. 2 and Supplementary Figs 3 and 4). The $^{14}$C production rates were derived from the $^{14}$C records (Fig. 1) using a carbon-cycle box-diffusion model that corrects for known carbon cycle effects on the atmospheric $^{14}$C content (Supplementary Methods and Supplementary Fig. 6).

![Figure 1. Key data used in this study.](image-url)

**Figure 1. Key data used in this study.** a, δ$^{18}$O variations as recorded in the GRIP ice core. b, $^{10}$Be concentrations from the GRIP (red: this study, black: refs 4,5) and GISP2 (ref. 6; blue) ice cores. c, $^{10}$Be fluxes using accumulation rates inferred from the GICC05 age scale (ref. 28 and references therein) and ice-flow modelling (line colouring as in b). d, $^{14}$C (that is, $^{14}$C concentration after correction for fractionation and decay, relative to a standard) from the tree rings (pink) and Hulu Cave speleothem H82 (ref. 8; black). Black dots indicate single measurements and grey shading shows the ±1 σ envelope (Supplementary Methods). Top bar, INTIMATE event stratigraphy. GS, Greenland Stadial; GI, Greenland Interstadal.
The agreement of $^{10}$Be and $^{14}$C records strongly supports our interpretation of the $^{10}$Be record being production dominated. The coherence of $^{10}$Be and H82 $^{14}$C slightly decreases back in time, which is probably due to the variable sampling resolution of the H82 speleothem and timescale differences. Nevertheless, for most of the time the normalized $^{10}$Be and $^{14}$C records are consistent within errors and indicate similar spectral properties (Supplementary Fig. 4) and amplitudes (Fig. 2 c,d). It should be noted that the timescales have not been adjusted, which would increase consistency between the records but prevent an independent comparison.

The quantification of geomagnetic modulation is an additional uncertainty of solar activity reconstructions from cosmogenic radionuclides. However, it has been shown that detectable geomagnetic influences on Holocene cosmogenic radionuclide production rates are limited to timescales of several centuries to millennia. In addition, the relative variations of solar-induced production rate changes are independent of the geomagnetic field intensity except for very low field strengths. Hence, the applied normalization of the $^{10}$Be and $^{14}$C production rates minimizes the influence of the geomagnetic field on our solar activity reconstruction focused on centennial variations. We note that applying this normalization to a stack of Holocene cosmogenic radionuclide records leads to a linear scaling to the correspondingly band-pass-filtered TSI reconstruction, where geomagnetic field reconstructions have been considered explicitly (Supplementary Fig. 7). This does not preclude a remaining geomagnetic field influence in the $^{10}$Be data, but the absence of high-quality, high-resolution global geomagnetic intensity data inhibits a more detailed assessment.

In further support for the reliability of our solar activity reconstruction we see a coherent amplitude modulation of the well-known solar de Vries cycle (~207 yr) in both $^{10}$Be and $^{14}$C production rates (Fig. 2d), closely resembling the Holocene modulation pattern (Supplementary Fig. 8). Moreover, the relative amplitude of the $^{10}$Be variations is within the expected ranges induced by solar activity variations as inferred from physics based production rate...
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\[ \delta^{18}O \] from the GRIP (ref. 21) and GISP2 (ref. 22) ice cores reveals a significant positive correlation \( r^2 = 0.3 \) and \( 0.2, p < 0.01 \), for \(^{10}\text{Be}\) concentrations and flux, respectively) during GS-2 (Fig. 3 and Supplementary Fig. 9). Significant (95%) spectral coherence of \( \delta^{18}O \) and the solar activity proxy \(^{10}\text{Be}\) at known solar cycle wavelengths (Supplementary Fig. 5) strengthens the hypothesis of a solar influence on climate. This sun–climate relationship is accompanied by increased inputs of sea salt, higher snow accumulation, and a decrease in terrestrial aerosols (Supplementary Fig. 10). This pattern is interpreted as episodes of a more meridional atmospheric circulation during solar minima advecting relatively moist North Atlantic air masses to Greenland. Modern observations indicate that this type of flow pattern is enhanced during winters with high-pressure blocking situations south of Greenland, which in turn have been found to occur more often during solar minimum periods\(^9\). Recently, this mechanism was also shown to be present on centennial timescales\(^10\). Supporting this, we find increased meridional wind speeds south of Greenland accompanied by increased precipitation over the ice sheet during solar minima winters in the twentieth-century reanalysis\(^23\) and high-top chemistry–climate model experiments (Fig. 4 and Supplementary Methods). On synoptic scales these high-pressure blocking situations can be described as cyclonic Rossby wave breaking events over the North Atlantic, often accompanied by a southward...
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Displacement of the eddy-driven jet and negative North Atlantic Oscillation anomalies\(^{24,25}\). Both are connected to solar variability in reanalysis and model experiments (Fig. 4). At present, there are no high-top chemistry-climate model experiments under glacial boundary conditions to test whether this mechanism applies during the glacial. However, a multi-model study indicates that the presence of the Laurentide ice sheet leads to favourable conditions for cyclonic wave breaking during the Last Glacial Maximum (LGM) compared with today\(^{24}\), and hence may be indicative of more frequent high-pressure blocking. In addition, despite an altered atmospheric circulation during the LGM the weather patterns that led to precipitation over the ice sheet were probably comparable to present-day conditions\(^{25}\). Hence, increased winter precipitation over the Greenland ice sheet through enhanced meridional moisture transport would result in a net depletion of the ice-core \(\delta^{18}O\) signal, which is otherwise dominated by summer precipitation during the LGM (ref. 27). An increased winter-summer temperature difference during the LGM (ref. 27) would amplify this effect. Hence, we reason that the increased winter precipitation during periods of low solar activity could explain the positive correlation between our solar activity reconstruction and GRIP/GISP2 \(\delta^{18}O\) signal, which is otherwise dominated by summer precipitation during the LGM (ref. 27). An increased winter-summer temperature difference during the LGM (ref. 27) would amplify this effect. Hence, we reason that the increased winter precipitation during periods of low solar activity could explain the positive correlation between our solar activity reconstruction and GRIP/GISP2 \(\delta^{18}O\) signal, which is otherwise dominated by summer precipitation during the LGM (ref. 27).

Methods

Normalization of production rates. Following ref. 20 we normalize the \(^{14}\)C production rates and \(^{10}\)Be concentrations and fluxes by dividing each record by its low-pass-filtered copy (\(P_{LP150}\), cutoff 1/500 yr\(^{-1}\)). Before this, each record is low-pass-filtered (\(P_{LP500}\), cutoff 1/150 yr\(^{-1}\)) to reduce noise and increase comparability between the \(^{14}\)C and \(^{10}\)Be records arising from their different and irregular sampling resolution. This normalization is summarized in equation (1):

\[
P_{\text{normalized}} = \frac{P_{LP150}}{P_{LP500}}
\]

where \(P\) is the production rate (that is, \(^{10}\)Be concentrations or fluxes, or \(^{14}\)C production rates).

References

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