AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL090896

Solar Activity of the Past 100 Years Inferred From ^{10}Be in Ice Cores—Implications for Long-Term Solar Activity Reconstructions

Minjie Zheng[1], Florian Adolphi[1,2,3], Jesper Sjolte[1], Ala Aldahan[4], Göran Possnert[5], Mousong Wu[6], Peng Chen[7,8], and Raimund Muscheler[1]

[1]Department of Geology, Lund University, Lund, Sweden, [2]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany, [3]Department of Geosciences, University of Bremen, Germany, [4]Department of Geology, United Arab Emirates University, Al Ain, United Arab Emirates, [5]Tandem Laboratory, Uppsala University, Uppsala, Sweden, [6]International Institute for Earth System Science, Nanjing University, Nanjing, China, [7]School of Earth Sciences and Engineering, Hohai University, Nanjing, China, [8]State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China

Key Points:

- Summer NEEM ^{10}Be concentrations are generally higher than winter ^{10}Be concentrations due to the stratospheric intrusion
- Erroneous Dye 3 ^{10}Be data can bias solar activity estimates for the past toward too low
- ^{10}Be and sunspot data suggest higher solar activity than extensions of the neutron monitor data before 1951

Supporting Information:

- Supporting Information S1
- Data Set S1

Correspondence to:

M. Zheng,
minjie.zheng@geol.lu.se

Citation:

Zheng, M., Adolphi, F., Sjolte, J., Aldahan, A., Possnert, G., Wu, M., et al. (2021). Solar activity of the past 100 years inferred from ^{10}Be in ice cores—Implications for long-term solar activity reconstructions. *Geophysical Research Letters*, *48*, e2020GL090896. https://doi.org/10.1029/2020GL090896

Received 23 SEP 2020
Accepted 23 DEC 2020

Author Contributions

Minjie Zheng, Raimund Muscheler, and Florian Adolphi initiated the study. Minjie Zheng performed the analysis and wrote the first manuscript in correspondence with Raimund Muscheler, Florian Adolphi, Jesper Sjolte, Ala Aldahan and Mousong Wu. Minjie Zheng prepared the ice samples with the help of Peng Chen. Göran Possnert conducted the ^{10}Be measurements at the Uppsala University. All authors discussed the results and edited the manuscript.

Abstract Differences between ^{10}Be records from Greenland and Antarctica over the last 100 years have led to different conclusions about past changes in solar activity. The reasons for this disagreement remain unresolved. We analyze a seasonally resolved ^{10}Be record from a firn core (North Greenland Eemian Ice Drilling [NEEM] ice core project) in Northwestern Greenland for 1887–2002. By comparing the NEEM data to ^{10}Be data from the NGRIP and Dye3 ice cores, we find that the Dye3 data after 1958 are significantly lower. These low values lead to a normalization problem in solar reconstructions when connecting ^{10}Be variations to modern observations. Excluding these data strongly reduces the differences between solar reconstructions over the last 2,000 years based on Greenland and Antarctic ^{10}Be data. Furthermore, ^{10}Be records from polar regions and group sunspot numbers do not support a substantial increase in solar activity for the 1937–1950 period as proposed by previous extensions of the neutron monitor data.

1. Introduction

Cosmogenic radionuclide records (e.g., ^{10}Be in ice cores) have commonly been used as proxies for past solar and geomagnetic variations prior to the direct observational period. Due to its cosmic ray origin, the production rate of ^{10}Be is modulated by the solar and geomagnetic shielding, hence providing a physical link to past changes in solar activity. After production, ^{10}Be attaches to aerosols then resides about 1–2 years in the stratosphere and a few days to weeks in the troposphere (e.g., Heikkilä, 2007; McHargue & Damon, 1991). Subsequently, it gets scavenged from the air by wet and dry depositions. Therefore, the interpretation of ^{10}Be data from natural archives, such as ice cores, is complicated by the transport and scavenging processes of ^{10}Be. These climate effects on ^{10}Be add significant uncertainties to solar activity reconstructions, leading to different results (e.g., Bard et al., 2000; Muscheler et al., 2007; Usoskin et al., 2003). Muscheler et al. (2016) illustrated the disagreements between solar activity reconstructions depending on the use of Antarctic or Greenland ^{10}Be data for the last 2,000 years. They suggested that this most likely reflects different climate/weather influences on these records for the past 100 years. As the most recent decades are important for normalizing the radionuclide records to modern observations, such differences affect the estimates of solar activity levels further back in time.

To assess the atmospheric circulation and depositional influences on ^{10}Be, one approach is to study high-resolution (subannual) ^{10}Be data, which permits the understanding of the seasonal influence of different climatic conditions on ^{10}Be. For example, Zheng et al. (2020) found different meteorological influences on summer and winter ^{10}Be records from a North Greenland Eemian Ice Drilling (NEEM) firn core in Northwestern Greenland for the period 1951–2002. They also suggested that the tropopause over the mid-latitudes in Northern Hemisphere plays an essential role in ^{10}Be deposition in Greenland. Besides, multiple ^{10}Be records are helpful to detect discrepancies between records and reduce uncertainties arising from climate influences or data quality issues. There are two existing annually resolved ^{10}Be records from Greenland covering the last several hundred years: the North Greenland Ice Core Project (NGRIP) record

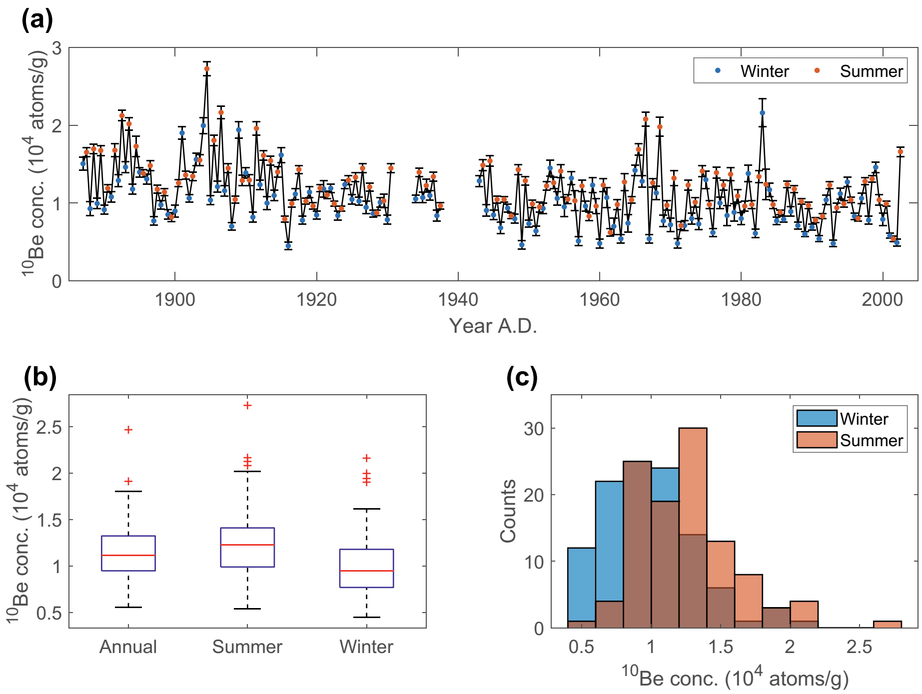

Figure 1. (a) ^{10}Be concentrations for 1887–2002 together with their measurement uncertainties. ^{10}Be concentrations for 1951–2002 are from Zheng et al. (2020). Summer values are indicated in red, while winter concentrations are shown in blue. (b) Box-whisker-plots of ^{10}Be data. The box encompasses quartiles from 25% to 75%, and the central horizontal line indicates the median. Whiskers indicate the upper and lower limits excluding outliers shown by crosses (greater than 1.5 times the interquartile range). (c) Histograms of winter and summer ^{10}Be data.

from Berggren et al. (2009) and the Dye3 record from Beer et al. (1990). These records, however, do not agree well. The Dye3 ^{10}Be concentrations show a decrease of 53% from the year 1885 to 1985, while the NGRIP data exhibit only a decrease of 29%. This difference can lead to different conclusions regarding the present solar activity level compared to the past. The reason for this difference has not been resolved yet. Additional ^{10}Be records covering this period could contribute to identifying the underlying reasons for the difference and help improve reconstructions of past solar activity.

In this study, we analyze a seasonally resolved ^{10}Be record from a NEEM firn core covering the period 1887–2002 (77.45°N, 51.06°W, 2450 m.a.s.l., Figure S1), extending the previously published record (1951–2002) from the same core (Zheng et al., 2020). We discuss the production influences on the ^{10}Be record. Subsequently, we compare the NEEM ^{10}Be record with (bi-)annually resolved data from other Greenland ice cores and investigate the reasons for different trends of NGRIP and Dye3 ^{10}Be records over the last 100 years, as well as the possible implications for solar reconstructions over the last 100 years and the last 2,000 years. Finally, together with available ^{10}Be records from Greenland and Antarctica and group sunspot numbers, we further discuss solar activity changes for the period 1937–1950, where the extension of the neutron monitor data suggest a substantial increase in solar modulation (McCracken & Beer, 2007).

2. Data and Analytical Methods

The ^{10}Be data used here arise from a firn core (NEEM07S1) drilled at the NEEM site in Northwestern Greenland covering the period 1887–2002 (Figure 1a). ^{10}Be measurements of the top part core (1951–2002) were published (Zheng et al., 2020), and the rest (1887–1950) are new measurements. Seasonal layers in the firn core are identified using the analysis of NEEM δ^{18}O measurements in the same core (Zheng et al., 2018). The winter season is defined from November to April and summer from May to October. The annual ^{10}Be concentration is calculated using the accumulation weighted average of the seasonal ^{10}Be data. The year is defined starting from November to October of the subsequent year (e.g., November 1887–October 1888, for the year 1888). The ^{10}Be preparation at the Lund University and the accelerator mass spectrometry measurement at the Uppsala University were conducted following procedures given in Sturevik-Storm et al. (2014). Standard errors of ^{10}Be concentrations (1887–1950) range from 3.2% to 11.8% with a median of 4.8%. Unfortunately, samples of the year 1931–1933 and 1938–1942 were missing and could not be found at the ice storage facility at the Copenhagen University. The ^{10}Be flux is calculated using ^{10}Be concentration times the corresponding ice equivalent accumulation rate and ice density (Figure S2b). The ice equivalent accumulation rates in the firn core are calculated as defined by Steen-Larsen et al. (2011).

Spearman rank correlation is used to quantify the strength of the relationship between datasets since it is less sensitive to outliers and the distribution of the investigated datasets compared to Pearson correlation coefficients.

3. Results

The results indicate significant correlations between seasonal ^{10}Be concentrations and fluxes ($R > 0.7$, $p < 0.05$, Figure S3) and between fluxes and respective accumulation rates on seasonal and annual scales ($R > 0.5$, $p < 0.05$, Figure S4b), but insignificant correlations between seasonal and annual ^{10}Be concentrations and snow accumulation rates ($p > 0.05$, Figure S4a). Furthermore, we calculate the residual record by linearly detrending the accumulation dependency from the ^{10}Be flux record, and the resulting residual record is highly correlated with the NEEM ^{10}Be concentration ($R = 0.9$, Figure S2c). Therefore, the calculation of ^{10}Be fluxes likely introduces a spurious signal via the multiplication of ^{10}Be concentrations with local snow accumulation rates. This result supports a previous study suggesting NEEM ^{10}Be concentrations on such time scales and during a relatively stable climate are independent of the local accumulation rates while the flux is not (Zheng et al., 2020). In addition, ^{10}Be concentration is the parameter directly measured in the ice. Consequently, we mainly focus on ^{10}Be concentrations rather than fluxes in the subsequent data analysis and discussion.

Winter NEEM ^{10}Be concentrations range between 0.45×10^4 and 2.16×10^4 atoms/g with a mean of 0.99×10^4 atoms/g, summer concentrations range between 0.54×10^4 and 2.72×10^4 atoms/g with a mean of 1.25×10^4 atoms/g, and the annual range is between 0.55×10^4 and 2.47×10^4 atoms/g with a mean of 1.16×10^4 atoms/g (Table S1 and Figures 1b and 1c). The winter ^{10}Be concentration is significantly correlated with the summer ^{10}Be concentration ($R = 0.35$, $p < 0.05$). The summer ^{10}Be concentrations are, on average, about 26% ($p < 0.05$, *t*-test, Figure 1a and Table S1) higher than the winter values. Note that the accumulation rates are about twice as high in summer than in winter, which again supports that ^{10}Be concentrations are little influenced by varying dilution effects due to changing accumulation rates during the investigated period. The higher ^{10}Be values during summer could be attributed to the intrusions of stratospheric air enriched with ^{10}Be, therefore elevating ^{10}Be concentrations. Beer et al. (1991) found two peaks in subseasonally resolved Dye3 ^{10}Be data for late spring and mid-autumn. The first peak is attributed to the local stratospheric intrusion, while the second peak is proposed to arise from the delayed transport of ^{10}Be from mid-latitude stratospheric intrusions. Here, the summer for NEEM ^{10}Be is defined from May to October. Therefore, the high NEEM ^{10}Be values during summer could be the combined influence of local stratospheric intrusions and the delayed transport of ^{10}Be from mid-latitude stratospheric intrusions. Higher ^{10}Be values in austral summer were also noticed in Antarctic records and linked to enhanced stratospheric input (Heikkilä & Smith, 2013; Pedro et al., 2011). Both winter and summer ^{10}Be records show a significant decreasing trend for 1887–2002 (Figure S5; $p < 0.05$, tested by Mann-Kendall method, Gilbert, 1987). The winter ^{10}Be data (−2.8%/decade) shows a similar decreasing trend as the summer ^{10}Be (−2.9 %/decade).

4. Discussion

4.1. Periodicity Analysis

To evaluate the solar signal in the ^{10}Be data, we compare the ^{10}Be data with the periodicities found in the group sunspot number (GSN; Svalgaard & Schatten, 2016). The GSN record is reconstructed by a reassessment of historical and modern sunspot observation data and does not depend on other proxies (e.g., cosmogenic radionuclides). Bandpass filtering shows that summer and winter ^{10}Be records exhibit the solar 11-year cycle as known from the group sunspot number record (Figure 2), although the phases are shifted

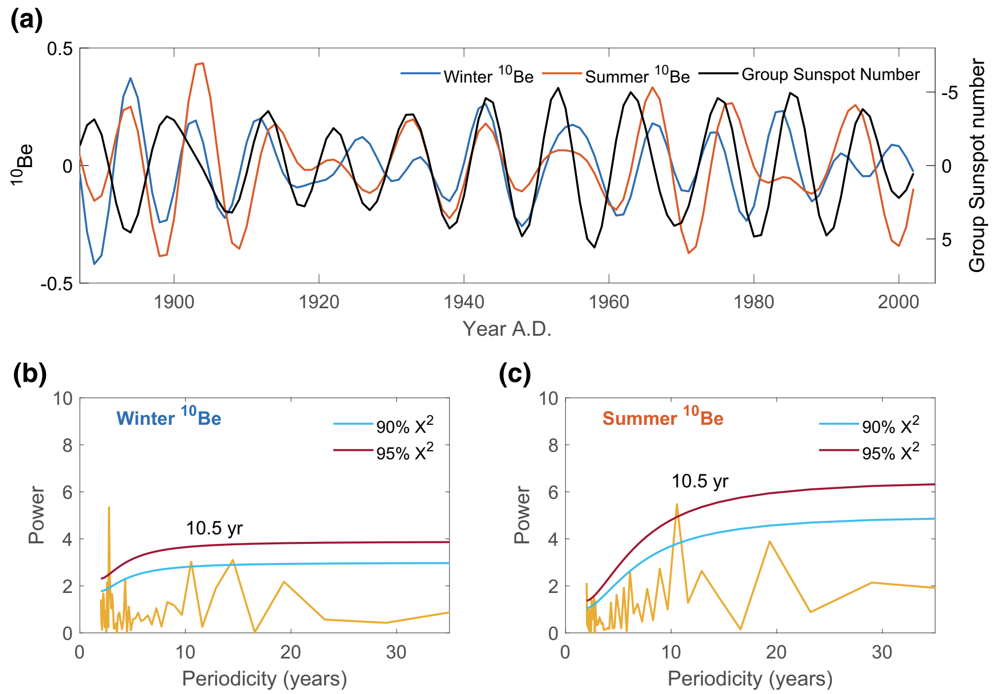

Figure 2. (a) Bandpass filtered (1/8–1/15 year^{-1}) winter and summer NEEM ^{10}Be concentrations compared to the group sunspot numbers focusing on the Schwabe 11-year cycle. (b and c) Fourier spectrums of the detrended winter and summer NEEM ^{10}Be with the 90% and 95% red-noise false-alarm levels.

in the early 1900s. This is supported by the FFT-spectra showing significant (summer = 95%, winter = 90%, chi-square test) peaks at around 10.5 years. The NEEM ^{10}Be records are significantly correlated with group sunspot numbers with and without a 1-year lag that could be expected from atmospheric transport and mixing (Table S2). The significant correlations agree well with the correlations to ^{10}Be production rates based on neutron monitor data for 1951–2002 in our previous study (Zheng et al., 2020).

4.2. Greenland ^{10}Be Records for the Period 1887–2002

Now, we compare the annually resolved NEEM data with two annually resolved ^{10}Be records from the NGRIP (Berggren et al., 2009) and Dye3 ice-cores (denoted as Dye3$_{long}$; Beer et al., 1990) and a bi-annually resolved Dye3 ^{10}Be record from the Dye3 site (denoted as Dye3$_{short}$ record; Beer et al., 1985) (Figure 3). It should be noted that Dye3$_{long}$ and Dye3$_{short}$ are from two separate cores from the same site in southern Greenland. The data are normalized to their common period (1900–1977) before comparison. We found the ^{10}Be records agree well with each other for the period 1887–1957, while after 1958, the Dye3$_{long}$ ^{10}Be record shows unusually lower ^{10}Be concentrations compared to the other three records (Figure 3a). It should be noted that the Dye3 accumulation rates do not change significantly after 1958 and, therefore, the too low ^{10}Be values after 1958 cannot be explained by a dilution effect due to increased accumulation rates (Figure S6a). Most importantly, the Dye3$_{long}$ ^{10}Be concentrations after 1958 are also lower than the Dye3$_{short}$ record (Figure S7). The average ratio of Dye3$_{long}$/Dye3$_{short}$ is 0.99 for the period 1900–1957, but 0.66 for the period 1958–1977. The Dye3$_{long}$ ^{10}Be record also shows higher correlations to Dye3$_{short}$ ^{10}Be for the period 1900–1957 ($R = 0.48$, $p < 0.05$) and their root mean square error is lower ($RMSE = 0.18$) than between 1958 and 1977 ($R = 0.38$, $p > 0.05$; $RMSE = 0.47$). Since those two ^{10}Be records are from the same location, it is unlikely that the unusually low values of Dye3$_{long}$ ^{10}Be after 1958 can be attributed to meteorological influences. Indeed, we have compared Dye3$_{long}$ ^{10}Be concentrations with snow accumulation rates and the North Atlantic Oscillation (NAO) circulation pattern, a major mode of atmospheric variability that can influence the ^{10}Be transport and deposition processes in Southern Greenland (e.g., Hurrell & Deser, 2009; Pedro et al., 2012). The NAO index is derived as the leading principal component of the pressure anomalies (500 hPa) over the Atlantic sector (20–80°N, 90°W–40°E) from the 20th-century reanalysis V3 data set

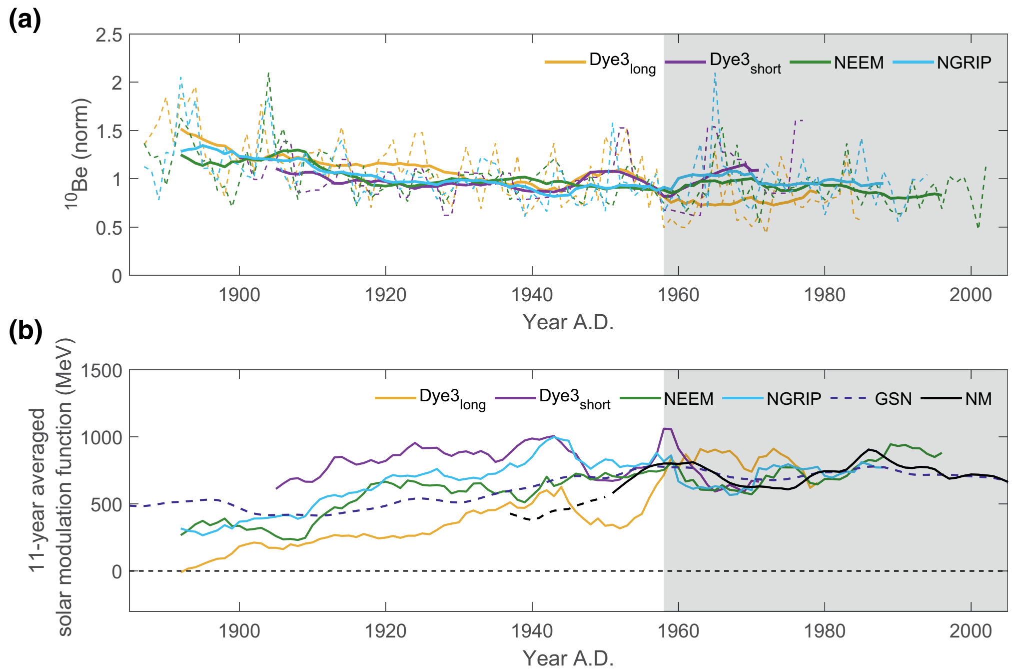

Figure 3. (a) Normalized ^{10}Be concentrations from Greenland ice cores (normalized to the overlap period of 1900–1977). The dashed line indicates the annual data, while the solid line indicates the 11-year running average data. (b) 11-year running averaged solar modulation function based on neutron monitor data and its extension (NM; Herbst et al., 2017), group sunspot numbers (GSN) and solar modulation based on 11-year running averaged ^{10}Be records (normalized to 1951 to 1977). Details of the group sunspot number-based solar modulation calculation are described in supplementary. The black dashed line indicates the modulation reconstructed by the extension of the neutron monitor data. The shaded area indicates the period after 1958.

(Slivinski et al., 2019). We do not find any significant correlations or changes for meteorological data after 1958 (Figure S6). Therefore, we suggest that the unusually low $\text{Dye3}_{\text{long}}$ ^{10}Be values after 1958 are likely connected to a data quality issue instead of being related to production or meteorological changes. This data issue could be due to the fact that ^{10}Be measurements were in its infancy when the Dye3 samples were prepared and measured in the 1980s. For example, the isobar background (^{10}B) could be less well separated with the AMS machines at that time and its correction was challenging. However, it is hard to pin down the actual reason for this potential data problem (Jürg Beer, personal communication).

4.3. Implication for Past Solar Reconstructions

It should be stressed that an accurate estimation of the ^{10}Be-production rate after 1951 is crucial for solar reconstruction. This period forms the direct overlap to modern neutron monitor measurements and is crucial for connecting (normalizing) paleo-cosmogenic radionuclide records to direct measurements of the galactic cosmic ray flux into the atmosphere (Muscheler et al., 2016). Here we calculate the solar modulation function from ^{10}Be following Muscheler et al. (2016). All ^{10}Be data are normalized to the overlap period with the neutron monitor period (1951–1977). In this calculation, we assume that the ^{10}Be concentrations reflect the globally averaged relative changes in ^{10}Be production rates. Records are calculated with the production rate model from Poluianov et al. (2016) using the local interstellar spectra by Herbst et al. (2017). The geomagnetic field changes are small on annual to decadal timescales and are ignored for the solar reconstruction over the last 100 years (e.g., Muscheler et al., 2007). Since we focus on decadal variations, ^{10}Be records are smoothed by an 11-year running average first. We compared the ^{10}Be-based solar modulation to solar modulation based on neutron monitors (adopted from Herbst et al., 2017) and group sunspot numbers (Figure 3b). We convert the group sunspot numbers (Svalgaard & Schatten, 2016) to solar modulation based on the method by Solanki et al. (2000) and Usoskin et al. (2002). The details of solar modulation calculation based on group sunspot number data are described in the supplementary (Text S1).

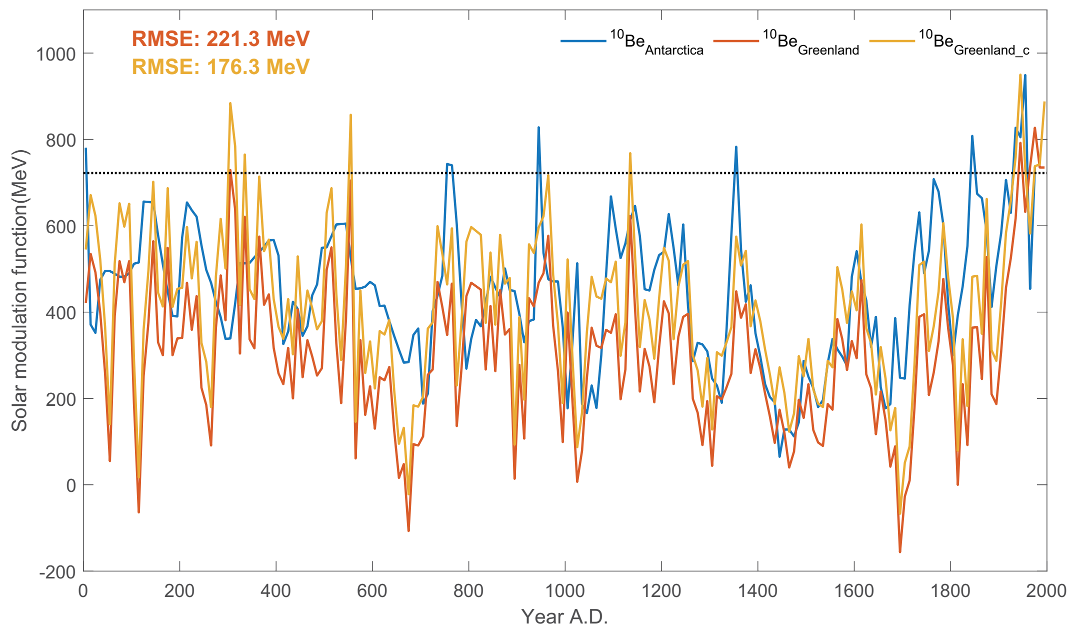

Figure 4. Solar modulation reconstructions over the last 2,000 years based on polar ^{10}Be data. Records are calculated with the geomagnetic-field model result from Nilsson et al. (2014) and the production-rate calculation from Poluianov et al. (2016). For details, see Muscheler et al. (2016) and supporting information. The horizontal-thick dotted line shows the average solar modulation inferred from the instrumental data from 1951 to 2000 AD.

NEEM ^{10}Be-based and NGRIP ^{10}Be-based solar modulations show good agreement with the GSN-based solar modulation (*RMSE* = 145 MeV for NGRIP for 1887–1994 and 110 MeV for NEEM for 1887–2002). While $Dye3_{long}$-based and $Dye3_{short}$-based solar reconstructions show less agreement with GSN-based solar modulation (*RMSE* = 240 MeV for $Dye3_{long}$ for 1887–1985 and *RMSE* = 268 MeV for $Dye3_{short}$ for 1900–1977). The unusually large decrease in $Dye3_{long}$ ^{10}Be data after 1958 leads to a strong increase in solar modulation toward today. In consequence, the solar modulation potential derived from $Dye3_{long}$ is much lower before 1958 compared to NEEM, NGRIP, and group sunspot numbers (even negative values in the early 1890s). The reconstruction based on $Dye3_{short}$ ^{10}Be, however, shows much higher values for 1900–1940 compared to the solar modulation based on group sunspot numbers.

The $Dye3_{long}$ and NGRIP records are commonly used for long-term solar reconstructions. They are usually the only two records used to connect Greenland ^{10}Be records to absolute solar modulation estimated from the neutron monitor data (e.g., Muscheler et al., 2016). To investigate how the above-discussed $Dye3_{long}$ data quality issue can affect solar reconstructions, we reconstruct the solar modulation based on Greenland and Antarctic ^{10}Be (denoted as $^{10}Be_{Greenland}$ and $^{10}Be_{Antarctica}$) over the last 2,000 years following the same procedure as Muscheler et al. (2016). We use the production-rate calculation from Poluianov et al. (2016) and the geomagnetic data from Muscheler et al. (2016), which combines the geomagnetic model result (Nilsson et al., 2014) with the modern values (Jackson et al., 2000; Thébault et al., 2015). Details of reconstructions are described in the supplementary (Text S2) and Muscheler et al. (2016). We further create a "corrected solar modulation" based on Greenland ^{10}Be records by excluding the $Dye3_{long}$ data after 1958 (denoted $^{10}Be_{Greenland\_c}$).

The $^{10}Be_{Greenland\_c}$-based reconstruction shows a better agreement (smaller RMSE value) with the $^{10}Be_{Antarctica}$ reconstruction compared to $^{10}Be_{Greenland}$ (Figure 4). The averaged value of $^{10}Be_{Greenland\_c}$ (414 MeV on average) for the whole period is much closer to $^{10}Be_{Antarctica}$ (447 MeV on average) than $^{10}Be_{Greenland}$ (305 MeV on average). The $^{10}Be_{Greenland\_c}$-based reconstruction shows fewer negative values compared to $^{10}Be_{Greenland}$. The low $Dye3_{long}$ data after 1958 lead to a relatively higher normalization value of Greenland ^{10}Be data and, thus, a too low inferred solar modulation in the past. Therefore, differences in solar modulation reconstructions from Greenland and Antarctica can be, at least partly, attributed to the low $Dye3_{long}$ ^{10}Be values after 1958. Furthermore, after removing the suspected problematic $Dye3_{long}$ data, the reconstruction from

Greenland ^{10}Be does not support earlier claims of unusually high recent solar activity over the last 100 years (e.g., Solanki et al., 2004; Usoskin et al., 2003), but it supports the conclusions based on Antarctic ^{10}Be data (e.g., Raisbeck & Yiou, 2004) and ^{14}C (e.g., Muscheler et al., 2005). This also suggests that previous studies that mainly rely on the Dye3 data for the past 100 years (e.g., Solanki et al., 2004; Usoskin et al., 2003) are influenced by this data problem. However, it should be noted that sporadic differences between reconstructions (e.g., the 1800s) still exist that could be attributed to regional climate influences on ^{10}Be transport and deposition or data quality issues.

4.4. Comparison With Neutron Monitor Extension for the Period 1937–1950

Another interesting point is that the reconstructed solar modulations based on the group sunspot number and ^{10}Be records do not show a strong increase for the period 1937–1950, as suggested by the neutron monitor extension data by McCracken and Beer (2007) (Figure 3b). This pre-1951 extension of the neutron monitor data is crucial because it is commonly used to connect ^{14}C records for solar reconstructions, since ^{14}C after 1951 cannot be linked to neutron monitor data due to the influence of anthropogenic activities on atmospheric ^{14}C. To further investigate the solar trend from 1937 to 1950, we include all available annually resolved ^{10}Be records from Greenland covering this period: NGRIP (Berggren et al., 2009), NEEM (this project), Das2 (Pedro et al., 2012), Renland (Aldahan et al., 1998) and $Dye3_{long}$ (Beer et al., 1990). The $Dye3_{long}$ data after 1958 are excluded due to the above-discussed data quality issue. To reduce site-specific noise, we averaged all Greenland ^{10}Be records (referred to Greenland $^{10}Be_{stack}$) after normalizing the data over the overlap period (Figure S8a). To further reduce the weather noise, the Greenland $^{10}Be_{stack}$ record is smoothed by a 3-year running average before calculating the solar modulation. The Greenland $^{10}Be_{stack}$ based solar modulation shows higher values (926 MeV on average) than the one based on the extension of the neutron monitor (476 MeV on average) for the period 1937–1950 and does not suggest the same strong increase (Figure S8b). We further look at the only available annually resolved ^{10}Be record from the Antarctic ice core for this period, the DSS ^{10}Be record (Figure S8a) (Pedro et al., 2012). Influences of atmospheric circulation and precipitation on ^{10}Be differ between Greenland and Antarctica due to their geographical location, hence, we separately discuss ^{10}Be records from these two regions. The DSS ^{10}Be based solar modulation also shows no strong increase for the period 1937–1950, although lower (606 MeV on average) values than Greenland $^{10}Be_{stack}$ based reconstruction (Figure S8b). Overall, polar ^{10}Be and group sunspot number records do not support the strong increase of solar activity, as indicated by the extension of the neutron monitor data. Investigating the reasons for the strong trend in the neutron-monitor data extension is beyond the scope of the paper. However, this analysis and the sunspot-based solar modulation reconstruction imply that the previous extension of the neutron monitor data probably underestimates solar modulation before 1951 AD.

5. Conclusion

We present and analyze a long time series of seasonally resolved ^{10}Be for the period 1887–2002 from the NEEM07S1 firn core. We observe a seasonal cycle in the NEEM ^{10}Be record with high concentrations during summer and low concentrations during winter. The high ^{10}Be values during summer could be due to the local stratospheric intrusions and delayed transport of ^{10}Be from mid-latitude stratospheric intrusions. Both summer and winter NEEM ^{10}Be records are significantly correlated with group sunspot numbers, reflecting the solar modulation of cosmic rays. Summer and winter ^{10}Be show a similar significant decreasing trend for the period 1887–2002. By comparing the NEEM ^{10}Be record to two ^{10}Be records from Dye3 ($Dye3_{long}$ and $Dye3_{short}$ records) and one from NGRIP, we find that the $Dye3_{long}$ ^{10}Be data after 1958 are unusually low. By comparing to another ^{10}Be record from the same location, we suggest that this low $Dye3_{long}$ data can likely be attributed to a data quality issue, not local meteorological influences. By excluding the $Dye3_{long}$ ^{10}Be data after 1958, differences in solar reconstructions based on Greenland and Antarctic ^{10}Be data are significantly reduced. Furthermore, together with all available annually resolved ^{10}Be records for the 1937–1950 period, we observe that ^{10}Be records from polar ice cores and group sunspot numbers do not suggest a strong increase in solar activity, as seen in the previous extension of the neutron monitor data. We propose that future solar activity reconstructions should carefully assess the systematic differences between different ^{10}Be records, especially when connecting radionuclide variations to modern neutron monitor data.

Data Availability Statement

The new NEEM ^{10}Be data are available at the supplementary file and an online data repository at figshare.com (https://doi.org/10.6084/m9.figshare.13488792.v1). The NEEM ^{10}Be data for 1951–2002 are available in Zheng et al. (2020).

Acknowledgment

Minjie Zheng is supported by the China Scholarship Council (CSC) under grant CSC no. 201606710087 (grant to Minjie Zheng) and the Royal Physiographic Society of Lund (2016, 2017, and 2018, grants to Minjie Zheng). This work was partially supported by the Swedish Research Council (Dnr: 2013–8421, grant to Raimund Muscheler). Florian Adolphi is supported by a grant of the Swedish Research Council (Dnr: 2016–00218). Jesper Sjolte is supported by the strategic research program of ModEling the Regional and Global Earth system (MERGE) hosted by the Faculty of Science at Lund University. Ala Aldahan acknowledges the UAEU through the UPAR funding. Mousong Wu is supported by the National Key Research and Development Program of China (2016YFA0600204), the National Natural Science Foundation of China (41901266), and the Natural Science Foundation of Jiangsu Province (BK20190317). The authors thank the many persons involved in logistics, drilling, and ice-core processing and analysis. NEEM is directed and organized by the Center of Ice and Climate at the Niels Bohr Institute and US NSF, Office of Polar Programs. It is supported by funding agencies and institutions in Belgium (FNRS-CFB and FWO), Canada (NRCan/GSC), China (CAS), Denmark (FIST), France (IPEV, CNRS/INSU, CEA and ANR), Germany (AWI), Iceland (RannIs), Japan (NIPR), South Korea (KOPRI), The Netherlands (NWO/ALW), Sweden (VR), Switzerland (SNF), the United Kingdom (NERC), and the USA (US NSF, Office of Polar Programs) and the EU Seventh Framework programs Past4Future and Water under the Ice.

References

Aldahan, A., Possnert, G., Johnsen, S. J., Clausen, H. B., Isaksson, E., Karlen, W., & Hansson, M. (1998). Sixty year ^{10}Be record from Greenland and Antarctica. *Proceedings of the Indian Academy of Sciences*, *107*(2), 139–147. https://doi.org/10.1007/BF02840464

Bard, E., Raisbeck, G., Yiou, F., & Jouzel, J. (2000). Solar irradiance during the last 1200 years based on cosmogenic nuclides. *Tellus B: Chemical and Physical Meteorology*, *52*(3), 985–992. https://doi.org/10.1034/j.1600-0889.2000.d01-7.x

Beer, J., Andree, M., Oeschger, H., Stauffer, B., Balzer, R., Bonani, G., et al. (1985). ^{10}Be variations in polar ice cores. In: Greenland ice core: Geophysics, geochemistry, and the environment (Vol. 33, pp. 66–70). Washington, DC: American Geophysical Union.

Beer, J., Blinov, A., Bonani, G., Finkel, R. C., Hofmann, H. J., Lehmann, B., et al. (1990). Use of ^{10}Be in polar ice to trace the 11-year cycle of solar activity. *Nature*, *347*(6289), 164–166. https://doi.org/10.1038/347164a0

Beer, J., Finkel, R. C., Bonani, G., Gäggeler, H., Görlach, U., Jacob, P., et al. (1991). Seasonal variations in the concentration of ^{10}Be, Cl−, NO_3−, SO_4^{2-}, H_2O_2, ^{210}Pb, ^3H, mineral dust, and $\sigma^{18}O$ in greenland snow. *Atmospheric Environment.*, *25*(5–6), 899–904. https://doi.org/10.1016/0960-1686(91)90131-p

Berggren, A. M., Beer, J., Possnert, G., Aldahan, A., Kubik, P., Christl, M., et al. (2009). A 600-year annual ^{10}Be record from the NGRIP ice core, Greenland. *Geophysical Research Letters*, *36*(11), L11801. https://doi.org/10.1029/2009gl038004

Gilbert, R. O. (1987). *Statistical methods for environmental pollution monitoring*. New York, NY: Van Nostrand Reinhold Co. Inc..

Heikkilä, U. (2007). *Modeling of the atmospheric transport of the cosmogenic radionuclides ^{10}Be and ^7Be using the ECHAM5-HAM general circulation model* (Doctoral dissertation), Zurich, SW: ETH. https://doi.org/10.3929/ethz-a-005560259

Heikkilä, U., & Smith, A. M. (2013). Production rate and climate influences on the variability of ^{10}Be deposition simulated by ECHAM5-HAM: Globally, in Greenland, and in Antarctica. *Journal of Geophysical Research: Atmosphere*, *118*(6), 2506–2520. https://doi.org/10.1002/jgrd.50217

Herbst, K., Muscheler, R., & Heber, B. (2017). The new local interstellar spectra and their influence on the production rates of the cosmogenic radionuclides ^{10}Be and ^{14}C. *Journal of Geophysical Research: Space Physics*, *122*(1), 23–34. https://doi.org/10.1002/2016ja023207

Hurrell, J. W., & Deser, C. (2009). North Atlantic climate variability: The role of the North Atlantic Oscillation. *Journal of Marine Systems*, *78*(1), 28–41. https://doi.org/10.1016/j.jmarsys.2008.11.026

Jackson, A., Jonkers, R. T., & Walker Matthew, R. (2000). Jonkers ArtFour centuries of geomagnetic secular variation from historical records. *Philosophical Transactions of the Royal Society of London*, *358*(1768), 957–990. https://doi.org/10.1098/rsta.2000.0569

McCracken, K. G., & Beer, J. (2007). Long-term changes in the cosmic ray intensity at Earth, 1428-2005. *Journal of Geophysical Research*, *112*, A10101. https://doi.org/10.1029/2006ja012117

McHargue, L. R., & Damon, P. E. (1991). The global beryllium 10 cycle. *Reviews of Geophysics*, *29*(2), 141–158. https://doi.org/10.1029/91RG00072

Muscheler, R., Adolphi, F., Herbst, K., & Nilsson, A. (2016). The revised sunspot record in comparison to cosmogenic radionuclide-based solar activity reconstructions. *Solar Physics*, *291*(9–10), 3025–3043. https://doi.org/10.1007/s11207-016-0969-z

Muscheler, R., Joos, F., Beer, J., Müller, S. A., Vonmoos, M., & Snowball, I. (2007). Solar activity during the last 1000yr inferred from radionuclide records. *Quaternary Science Reviews*, *26*(1–2), 82–97. https://doi.org/10.1016/j.quascirev.2006.07.012

Muscheler, R., Joos, F., Muller, S. A., & Snowball, I. (2005). Climate: How unusual is today's solar activity? *Nature*, *436*(7050), E3–E4.

Nilsson, A., Holme, R., Korte, M., Suttie, N., & Hill, M. (2014). Reconstructing Holocene geomagnetic field variation: New methods, models and implications. *Geophysical Journal International*, *198*(1), 229–248. https://doi.org/10.1093/gji/ggu120

Pedro, J. B., Heikkilä, U. E., Klekociuk, A., Smith, A. M., van Ommen, T. D., & Curran, M. A. J. (2011). Beryllium-10 transport to Antarctica: Results from seasonally resolved observations and modeling. *Journal of Geophysical Research*, *116*(D23), D23120. https://doi.org/10.1029/2011jd016530

Pedro, J. B., McConnell, J. R., van Ommen, T. D., Fink, D., Curran, M. A. J., Smith, A. M., et al. (2012). Solar and climate influences on ice core ^{10}Be records from Antarctica and Greenland during the neutron monitor era. *Earth and Planetary Science Letters*, *355–356*, 174–186. https://doi.org/10.1016/j.epsl.2012.08.038

Poluianov, S. V., Kovaltsov, G. A., Mishev, A. L., & Usoskin, I. G. (2016). Production of cosmogenic isotopes ^7Be, ^{10}Be,^{14}C, ^{22}Na, and ^{36}Cl in the atmosphere: Altitudinal profiles of yield functions. *Journal of Geophysical Research: Atmosphere*, *121*(13), 8125–8136. https://doi.org/10.1002/2016jd025034

Raisbeck, G. M., & Yiou, F. (2004). Comment on Millennium scale sunspot number reconstruction: evidence for an unusually active sun since the 1940s. *Physical Review Letters*, *92*(19), 199001. https://doi.org/10.1103/PhysRevLett.92.199001

Slivinski, L. C., Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Giese, B. S., McColl, C., et al. (2019). Toward a more reliable historical reanalysis: Improvements for version 3 of the twentieth century reanalysis system. *Quarterly Journal of the Royal Meteorological Society*, *145*(724), 2876–2908. https://doi.org/10.1002/qj.3598

Solanki, S. K., Schüssler, M., & Fligge, M. (2000). Evolution of the sun's large-scale magnetic field since the maunder minimum. *Nature*, *408*(6811), 445–447 https://doi.org/10.1038/35044027

Solanki, S. K., Usoskin, I. G., Kromer, B., Schüssler, M., & Beer, J. (2004). Unusual activity of the Sun during recent decades compared to the previous 11,000 years. *Nature*, *431*(7012), 1084–1087. https://doi.org/10.1038/nature02995

Steen-Larsen, H. C., Masson-Delmotte, V., Sjolte, J., Johnsen, S. J., Vinther, B. M., Bréon, F. M., et al. (2011). Understanding the climatic signal in the water stable isotope records from the NEEM shallow firn/ice cores in northwest Greenland. *Journal of Geophysical Research*, *116*. D06108. https://doi.org/10.1029/2010jd014311

Sturevik-Storm, A., Aldahan, A., Possnert, G., Berggren, A. M., Muscheler, R., Dahl-Jensen, D., et al. (2014). ^{10}Be climate fingerprints during the Eemian in the NEEM ice core, Greenland. *Scientific Reports*, *4*, 6408. https://doi.org/10.1038/srep06408

Svalgaard, L., & Schatten, K. H. (2016). Reconstruction of the sunspot group number: The backbone method. *Solar Physics*, *291*(9–10), 2653–2684. https://doi.org/10.1007/s11207-015-0815-8

Thébault, E., Finlay, C. C., Alken, P., Beggan, C. D., Canet, E., Chulliat, A., et al. (2015). Evaluation of candidate geomagnetic field models for IGRF-12. *Earth, Planets and Space*, *67*(1), 79. https://doi.org/10.1186/s40623-015-0273-4

Usoskin, I. G., Mursula, K., Solanki, S. K., Schüssler, M., & Kovaltsov, G. A. (2002). A physical reconstruction of cosmic ray intensity since 1610. *Journal of Geophysical Research: Space Physics*, *107*(A11), 745–751. https://doi.org/10.1029/2002JA009343

Usoskin, I. G., Solanki, S. K., Schussler, M., Mursula, K., & Alanko, K. (2003). Millennium-scale sunspot number reconstruction: evidence for an unusually active sun since the 1940s. *Physical Review Letters*, *91*(21), 211101. https://doi.org/10.1103/PhysRevLett.91.211101

Zheng, M., Adolphi, F., Sjolte, J., Aldahan, A., Possnert, G., Wu, M., , & Muscheler, R. (2020). Solar and climate signals revealed by seasonal ^{10}Be data from the NEEM ice core project for the neutron monitor period. *Earth and Planetary Science Letters*, *541*, 116273. https://doi.org/10.1016/j.epsl.2020.116273

Zheng, M., Sjolte, J., Adolphi, F., Vinther, B. M., Steen-Larsen, H. C., Popp, T. J., & Muscheler, R. (2018). Climate information preserved in seasonal water isotope at NEEM: relationships with temperature, circulation and sea ice. *Climate of the Past*, *14*(7), 1067–1078. https://doi.org/10.5194/cp-14-1067-2018

References From the Supporting Information

Horiuchi, K., Uchida, T., Sakamoto, Y., Ohta, A., Matsuzaki, H., Shibata, Y., & Motoyama, H. (2008). Ice core record of ^{10}Be over the past millennium from Dome Fuji, Antarctica: A new proxy record of past solar activity and a powerful tool for stratigraphic dating. *Quaternary Geochronology*, *3*(3), 253–261. https://doi.org/10.1016/j.quageo.2008.01.003

Muscheler, R., Beer, J., Wagner, G., Laj, C., Kissel, C., Raisbeck, G. M., et al. (2004). Changes in the carbon cycle during the last deglaciation as indicated by the comparison of ^{10}Be and ^{14}C records. *Earth and Planetary Science Letters*, *219*(3–4), 325–340. https://doi.org/10.1016/s0012-821x(03)00722-2

Nishiizumi, K. (2007). *Cosmogenic radionuclides in the Siple Dome A ice core*. Retrieved from http://nsidc.org/data/nsidc-0307

Raisbeck, G. M., Yiou, F., Jouzel, J., Petit, J. R., Weiss, N. O., Allsop, J., et al. (1990). ^{10}Be and δ^2H in polar ice cores as a probe of the solar variability's influence on climate. *Philosophical Transactions of the Royal Society of London*, *330*(1615), 463–470. https://doi.org/10.1098/rsta.1990.0027

Yiou, F., Raisbeck, G. M., Baumgartner, S., Beer, J., Hammer, C., Johnsen, S., et al. (1997). Beryllium-10 in the Greenland ice core project ice core at summit, Greenland. *Journal of Geophysical Research*, *102*(C12), 26783–26794. https://doi.org/10.1029/97jc01265