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The Influence of Orbital Forcing on ^{10}Be Deposition in Greenland Over the Glacial Period

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Understanding the transport and deposition of the cosmogenic isotope ^{10}Be is vital for the application of the isotope data to infer past changes of solar activity, to reconstruct past Earth's magnetic field intensity and climate change. Here, we use data of the cosmogenic isotope ^{10}Be from the Greenland ice cores, namely the NEEM and GRIP ice cores, to identify factors controlling its distribution. After removing the effects of the geomagnetic field on the cosmogenic radionuclide production rate, the results expose imprints of the 20–22 ka precession cycle on the Greenland ^{10}Be records of the last glacial period. This finding can further improve the understanding of ^{10}Be variability in ice sheets and has the prospect of providing better reconstructions of geomagnetic and solar activity based on cosmogenic radionuclide records.

Keywords: orbital forcing, ^{10}Be, atmospheric transport, aerosol, ice core, Greenland, glacial period

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INTRODUCTION

The cosmogenic radionuclides (e.g., ^{10}Be) from different natural archives can provide important information of past changes in the solar and geomagnetic field (e.g., Muscheler et al. (2005a), Muscheler et al. (2007), Muscheler et al. (2005b), Zheng et al. (2021a)) and climate changes (e.g., Beck et al., 2018). Consequently, understanding factors controlling the cosmogenic radionuclide deposition on long-time scales is important for its applications. Effects of Earth's orbital forcing, including precession (change in the direction of the Earth's axis with a cycle of about 19–23 ka), obliquity (the axial tilt which changes between 22.1° and 24.5°with a cycle of about 41 ka) and eccentricity (how round or elliptic the Earth's orbit is and consists of cycles of 413, 125 and 95 ka that loosely combine into a 100°ka cycle) on the Earth's climate have been known for a long time (**Supplementary Figure S1** and details therein). These changes, which are termed as Milankovitch cycles, result in variability of the insolation (W/m^2) of solar irradiance at the top of the atmosphere dependent on positions on Earth with time (Berger, 1988; Berger and Loutre, 1991). The summer insolation at 65°N is considered critical to the growth and decay of the northern hemisphere ice sheets. Reproduction of the Milankovitch orbital forcing cycles in the Earth's natural climate archives has been crucial for the understanding of the driving forces of climate change over the last million years. In addition to these long term climatic changes, the climate records of the last glacial period are punctuated by shorter-term events, such as the Heinrich and the Dansgaard-Oeschger events, at variable amplitudes (Alley, 2000; Barker et al., 2011).

As galactic cosmic rays (GCR) interact with nitrogen and oxygen in the atmosphere ^{10}Be is produced through spallation (Lal and Peters, 1967). It is well known that the ^{10}Be production rate depends on the solar- and geomagnetic modulation of GCR reaching the Earth's atmosphere. The effects of these modulations are found in the ^{10}Be records as solar cycles (Muscheler et al., 2007; Berggren et al., 2009) and geomagnetic events (such as the Laschamps geomagnetic excursion; e.g. Aldahan and Possnert, 1998; Bonhommet and Zahringer, 1969; Raisbeck et al., 1987). Nevertheless, the transport processes from the stratosphere where about 65% of the production of ^{10}Be occurs and the transport within the troposphere are still major uncertainties for the interpretation of ^{10}Be records. Furthermore, the removal of ^{10}Be from the troposphere via wet and dry deposition is expected to change significantly with large changes in climate. Milankovitch orbital forcing could play a major role in this system as it affects atmospheric circulation driven by different heating rates in the atmosphere through local insolation differences.

Here we assess the effects of orbital forcing cycles on ^{10}Be records of the last glacial period from the NEEM and GRIP ice cores in Greenland. The results are discussed in terms of causes of changes in the ^{10}Be signals, the reliability of the obtained correlations with orbital forcing cycles and implications for a better understanding of aerosol transport and deposition.

MATERIALS AND METHODS

The ^{10}Be data used here are from the two longest Greenland ^{10}Be records, namely from the NEEM (The North Greenland Eemian Ice Drilling; Zheng et al. (2021b)) and GRIP (The Greenland Ice Core Project; Adolphi et al. (2014), Muscheler et al. (2004), Vonmoos et al. (2006), Wagner et al. (2001), Yiou et al. (1997)) ice core projects (**Supplementary Figure S2**). The section of the GRIP record used here covers the period from 11.7 to 104 ka BP (before the present 1950 A.D.), and the NEEM data covers the period 11.7 to 108 ka BP. Yiou et al., 1997 found that some GRIP samples, which were filtered through a 0.45-micron mesh size filter before preparation, show a loss of meteoric ^{10}Be on the filter. This loss of ^{10}Be to total ^{10}Be in the GRIP ice core is estimated at around 20% for the last glacial period (Baumgartner et al., 1997). To compensate for the average ^{10}Be loss, we multiply the results for the samples filtered by 0.45-micron mesh size filter with 1.25. In addition to the ^{10}Be concentration, the ^{10}Be flux is calculated here by adapting calculated snow accumulation rates for the NEEM ice core from Rasmussen et al. (2013) and for the GRIP ice core from Johnsen et al. (1997) and Seierstad et al. (2014). All data are resampled at a 1000-years resolution to smooth out short-term variations.

We analyze the ^{10}Be data in concert with the δ^{18}O data from NEEM (NEEM community members, 2013; Schüpbach et al., 2018) and GRIP ice core (Johnsen et al., 1997; Rasmussen et al., 2014). To assess the common transport and deposition effects on aerosols and ^{10}Be, we include the SO_4^{2-} and NO_3^- data from the NEEM ice core (Schüpbach et al., 2018) and the Greenland Ice Sheet Project (GISP2) ice core (Mayewski et al., 1990; Yang et al., 1995; Taylor et al., 1996; Mayewski et al., 1997). There are no NO_3^- and SO_4^{2-} data for the GRIP ice core, and thus we used the NO_3^- and SO_4^{2-} data from the GISP2 ice core, which was drilled only 30 km away from the GRIP site. The available Ca^{2+} data from the GRIP and GISP2 projects indicate a strong correlation ($R = 0.9$) and thus support our use of the GISP2 chemical data. The atmospheric sulfate and nitrogen complexes are the aerosol particles commonly considered as important constituents for the adsorption of atmospheric ^{10}Be (Igarashi et al., 1998).

To investigate the climate effects on ^{10}Be deposition, we need to correct the ^{10}Be data for the geomagnetic field influence on the cosmogenic radionuclide production rates. We use the independent geomagnetic record PISO-1500 (Channell et al., 2009) and a marine ^{10}Be/^{9}Be stack (Simon et al., 2016). PISO-1500 is reconstructed through synchronizing and stacking 13 globally distributed and high-quality paleointensity records. PISO-1500 data is converted to the ^{10}Be production signal (denoted as PISO1500 $^{10}Be_{prod}$) using the production model from Poluianov et al. (2016) with the local interstellar spectra by Herbst et al. (2017). For the calculations, we used a constant solar modulation parameter of 500 MeV. Finally, we averaged the normalized PISO1500 $^{10}Be_{prod}$ and normalized marine ^{10}Be/^{9}Be stack to get the final production signal of ^{10}Be (**Supplementary Figure S3**; denoted as $^{10}Be_{prod}$). Also, it is important to mention that there are still large uncertainties in the geomagnetic field reconstructions as described by Panovska et al. (2019). The uncertainties in the geomagnetic data and the ^{10}Be record likely affect the match between the two records. The $^{10}Be_{prod}$ shows high values over the 32, 40, 60–65 and near 95–100 ka BP which is related to the documented paleomagnetic excursions (**Supplementary Figure S3**). The $^{10}Be_{prod}$ is more comparable to the ^{10}Be fluxes in terms of amplitude than the ^{10}Be concentrations, which are influenced by the accumulation rates due to dilution effects.

The geomagnetic correction was performed by dividing the normalized $^{10}Be_{prod}$ from the normalized ^{10}Be data (Savranskaia et al., 2021). The resulting records are denoted as ^{10}Be $conc_{climate}$ and ^{10}Be $flux_{climate}$ (**Figure 1**). We have used here linear regression Pearson correlation and factor analysis to decipher potential links between ^{10}Be and the above-mentioned parameters. Some of the records have also been analyzed using the Fast Fourier transform (FFT) and wavelet transform methods to study periodic variations.

RESULTS AND DISCUSSIONS

The ^{10}Be records of the NEEM and GRIP ice cores indicate similar concentrations and fluxes (**Figure 1**). The minimum and maximum values are 0.92 and 5.82 (x10^4 at/g ice) for the NEEM and 1.06 and 7.63 (x10^4 at/g ice) for the GRIP data with average values of 2.29×10^4 and 3×10^4 at/g ice, respectively (**Table 1**). The general profiles of the ^{10}Be concentration and flux data are also comparable with the clear occurrence of the highest concentrations and fluxes zone around 40–42 ka representing the well-known Laschamps geomagnetic excursion. Another zone of

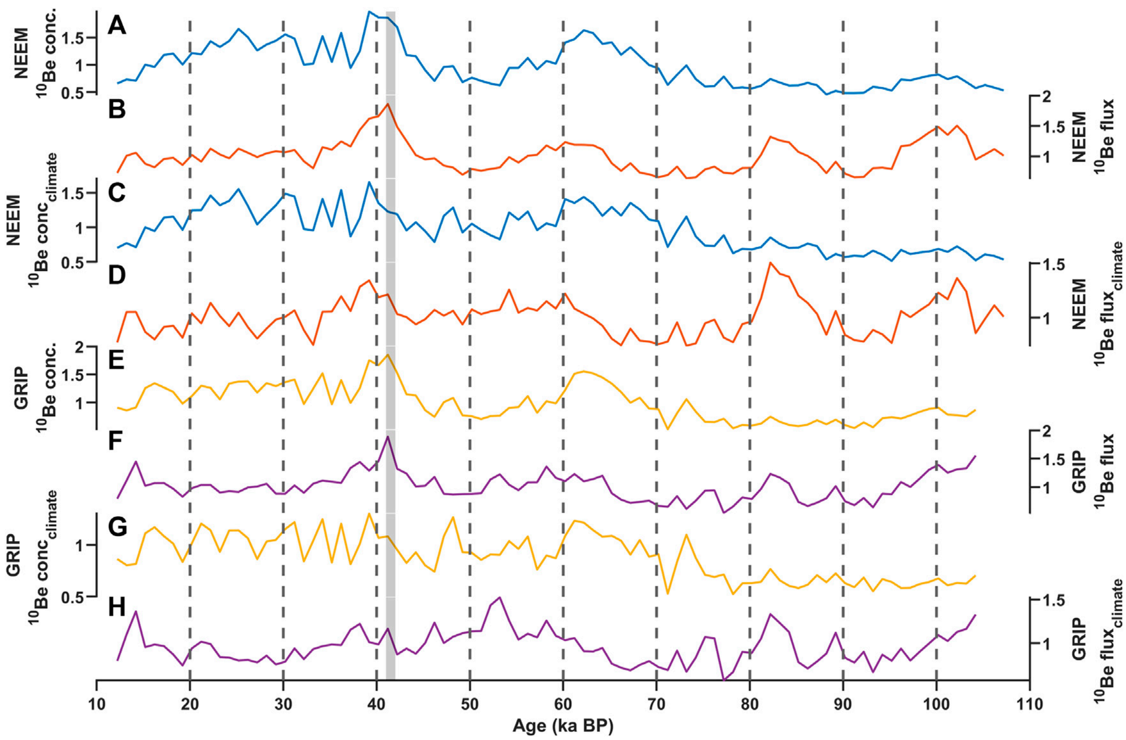

FIGURE 1 | ^{10}Be records of NEEM ice core showing concentrations **(A)**, fluxes **(B)** and the corrected records for geomagnetic modulation referred to as ^{10}Be conc$_{climate}$ **(C)** and ^{10}Be flux$_{climate}$ **(D)** **(E–H)** the same for the record from the GRIP ice core. The grey bar shows the peak due to the Laschamps geomagnetic excursion during 41–42 ka BP. All data are resampled at a 1000-years resolution for the analysis (see text) and normalized for the overlap period.

TABLE 1 | Summary data for the raw data ranges of ^{10}Be concentration and flux and snow accumulation rate in the NEEM and GRIP ice cores.

	NEEM ^{10}Be conc. (x10^4 at/g ice)	NEEM ^{10}Be flux (x10^6 at/cm^2/y)	GRIP ^{10}Be conc. (x10^4 at/g ice)	GRIP ^{10}Be flux (x10^6 at/cm^2/y)	NEEM accu. Rate (m/y)	GRIP accu. Rate (m/y)
Min	0.917	0.062	1.063	0.119	0.037	0.060
Max	5.815	0.288	7.625	0.825	0.128	0.244
Average	2.287	0.128	2.999	0.312	0.067	0.122

high concentration occurs around 60–65 ka in both ice core records. The variability in δ^{18}O of the two ice cores is similar to accumulation rates without unusual changes along with the Laschamps geomagnetic excursion (**Supplementary Figure S4**). The relatively strong and significant correlation ($R = 0.91$, $p < 0.01$, **Supplementary Figure S5**) between the ^{10}Be conc$_{climate}$ of the NEEM and GRIP records and the well-defined occurrence of the Laschamps geomagnetic excursion (40–42 ka; **Figure 1**) in both records suggest regional patterns for ^{10}Be deposition suitable for production and climate interpretations. However, there are some minor differences in the profiles of the production corrected records (^{10}Be conc$_{climate}$ and ^{10}Be flux$_{climate}$) of the NEEM and GRIP ice cores (**Figure 1**). Those differences can be attributed to the uncertainties in ^{10}Be measurements, different temporal resolution and ice core timescales, and most likely to different local climate influences at the two sites.

Despite the differences in the two ice core records, a clear wave-like pattern is apparent in the ^{10}Be flux$_{climate}$ profiles, which is comparable to the variations in the solar insolation (**Figure 2**). The correlation between the ^{10}Be flux$_{climate}$ and insolation for the NEEM and GRIP records are $R = 0.57$ and 0.58, respectively (**Supplementary Figure S5**). In addition, there is a marked periodicity of 21 ka ± 3 ka in the ^{10}Be flux$_{climate}$ of both ice cores (**Supplementary Figure S6**). Indication of the 21 ka periodicity also occurs in the δ^{18}O data of both ice cores, but the 41–44 ka periodicity is more significant **Supplementary Figure S6**). Although one may argue that the ^{10}Be climatic signal is an inherited snow accumulation signal, this effect is not extractable by the raw ^{10}Be data without correction for the geomagnetic effect. In addition, there is a large difference in the accumulation rate between the NEEM and GRIP ice cores (**Supplementary**

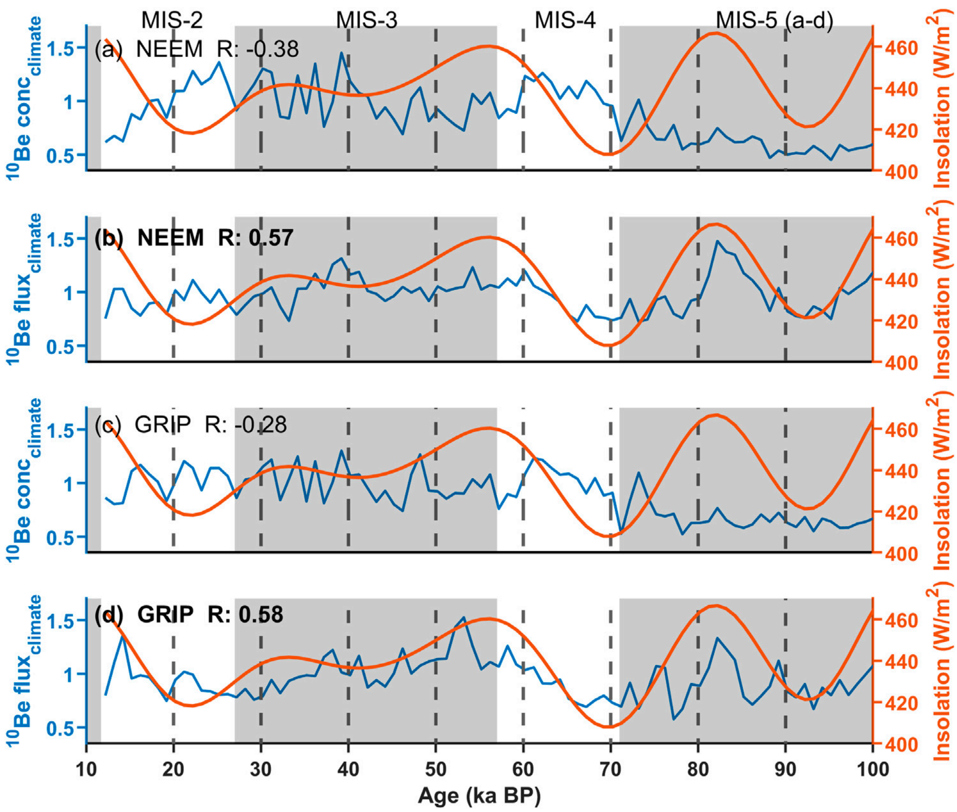

FIGURE 2 | Comparison of the geomagnetic corrected ^{10}Be records (^{10}Be $conc_{climate}$ and ^{10}Be $flux_{climate}$) of NEEM and GRIP ice cores and summer insolation at 65°N over the last glacial period. The R-value is the Pearson correlation between ^{10}Be and insolation. The R in bold indicates the significant value ($p < 0.01$, student t-test adjusted by the autocorrelation following (Hu et al., 2017)).

Figure S4), which is not manifested by the ^{10}Be concentration records (**Supplementary Figure S3**).

The cyclic pattern in the ^{10}Be $flux_{climate}$ of both ice cores is paralleled with relatively good correlation values (R = −0.37 to −0.45) with the precession cycle (**Supplementary Figure S5**). The results from the Fast Fourier Transform (FFT) (**Supplementary Figure S6**) and wavelet transform (**Supplementary Figure S7**) further confirm a cyclicity around 20–22 ka (will be referred to as the 21 ka cycle) in both the NEEM and GRIP ^{10}Be $flux_{climate}$ records that support the reflection of the orbital precession cycle.

It is well known that most atmospheric ^{10}Be attaches to aerosols and would likely follow their transport pathways. To shed some light on this issue, we analyze SO_4^{2-} and NO_3^- concentration data in the ice cores that are directly linked to aerosol loading (Schüpbach et al., 2018). The concentration of SO_4^{2-} and NO_3^- from the NEEM and GISP2 ice cores were resampled at 1000-years intervals and compared with resampled data of ^{10}Be and summer insolation (**Supplementary Figure S8**). The correlation between ^{10}Be $conc_{climate}$ and the concentration of SO_4^{2-} and NO_3^- is strong and significant, with R values from 0.57 to 0.88 ($p < 0.01$) (**Supplementary Figure S5**). In addition, a significant negative correlation is observed between SO_4^{2-} and NO_3^- and precession cycles, which is comparable to that found between the $^{10}Be\_flux_{climate}$ and precession cycles. Factor analysis (**Supplementary Figure S9**) also indicates a strong connection between the cluster load of ^{10}Be $conc_{climate}$, SO_4^{2-} and NO_3^- (related to aerosols loading and sources) at score values above 0.7 along with the first factor. The presented different correlation methods point to a strong link between aerosols and ^{10}Be and indicate that aerosols' transport pathways and deposition have similar influencing factors as the transport/deposition of the cosmogenic radionuclides in glacial times.

To further discuss the climate signal in the ^{10}Be data, we create a composite record by averaging the NEEM and GRIP ^{10}Be $flux_{climate}$ (**Figure 3**). This stack record indicates a change around the midpart of MIS-4 (around 65 ka), which is also associated with an amplitude swing in the insolation record. Results of running correlation analysis between ^{10}Be and $\delta^{18}O$ and between ^{10}Be and SO_4^{2-} and NO_3^- also manifest a change in trends around 65–70 ka (**Supplementary Figure S10**). These observations suggest a possible indirect impact of solar insolation on the ice core records close to the transition from MIS-5 to MIS-4. This pattern suggests direct reflection of the solar insolation signal by the ^{10}Be (concentration and flux) irrespective of the changes in snow accumulation rate. The finding here of the 21 ka precession cyclicity in the ^{10}Be flux supports a link of the cosmogenic radionuclide transport and deposition as a response to the effects of orbital forcing.

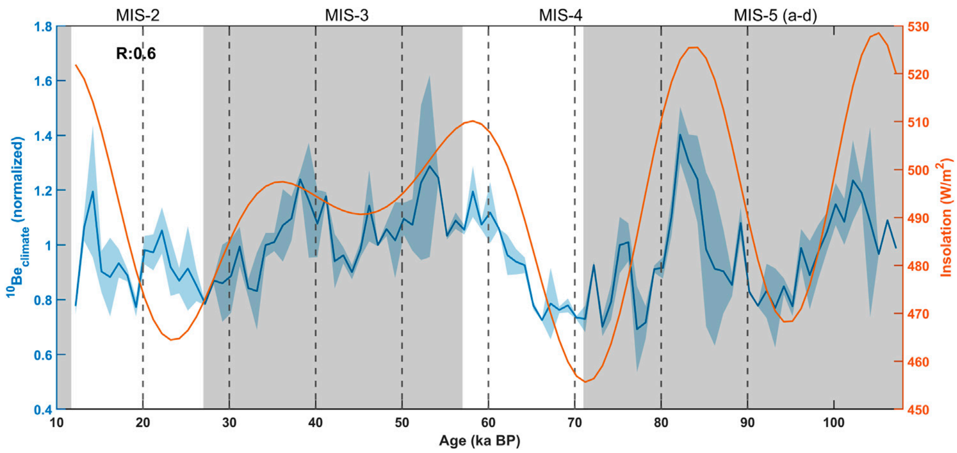

FIGURE 3 | Stack ^{10}Be record based on NEEM and GRIP ^{10}Be flux$_{climate}$ records showing variability comparable to the summer insolation (TOA) at 65°N at a periodicity of 21°ka. The shaded area represents a 2-standard deviation error. The R in bold indicates the significant value (p < 0.01, student t-test adjusted by the autocorrelation following (Hu et al., 2017)).

CONCLUSION

^{10}Be variabilities in the NEEM and GRIP ice cores from the last glacial period were analyzed to explore the link between ^{10}Be transport and deposition to orbital forcing. After removing the effects of the geomagnetic field and solar modulation from the ^{10}Be record, the results indicate imprints of the 21 ka precession cycles in the ^{10}Be records. This finding might help to improve our understanding of the aerosol transport to the Greenland ice sheet during the last glacial.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

AS wrote the first manuscript in correspondence with RM, MZ and AA. AS and MZ performed the analysis. RM and AA initiated the study. All authors discussed and edited the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.743640/full#supplementary-material.

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