Synchronizing ^{10}Be in two varved lake sediment records to IntCal13 ^{14}C during three grand solar minima

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Abstract. Time-scale uncertainties between paleoclimate reconstructions often inhibit studying the exact timing, spatial expression and driving mechanisms of climate variations. Detecting and aligning the globally common cosmogenic radionuclide production signal via a curve fitting method provides a tool for the quasi-continuous synchronization of paleoclimate archives. In this study, we apply this approach to synchronize ^{10}Be records from varved sediments of Lakes Tiefer See and Czechowskie covering the Maunder-, Homeric- and 5500 a BP grand solar minima with ^{14}C production rates inferred from the IntCal13 calibration curve. Our analyses indicate best fits with ^{14}C production rates when the ^{10}Be records from Lake Tiefer See were shifted for 8 (-12/+4) (Maunder Minimum), 31 (-16/+12) (Homeric Minimum) and 86 (-22/+18) years (5500 a BP grand solar minimum) towards the past. The best fit between the Lake Czechowskie ^{10}Be record for the 5500 a BP grand solar minimum and ^{14}C production was obtained when the ^{10}Be time-series was shifted 29 (-8/+7) years towards present. No significant fits were detected between the Lake Czechowskie ^{10}Be records for the Maunder- and Homeric Minima and ^{14}C production, likely due intensified in-lake sediment resuspension since about 2800 a BP, transporting 'old' ^{10}Be to the coring location. Our results provide a proof of concept for facilitating ^{10}Be in varved lake sediments as novel synchronization tool required for investigating leads and lags of proxy responses to climate variability. However, they also point to some limitations of ^{10}Be in these archives mainly connected to in-lake sediment resuspension processes.

1. Introduction

Paleoclimate archives provide unique insights into the dynamics of the climate system under various forcing conditions (Adolphi et al., 2014; Brauer et al., 2008; Neugebauer et al., 2016). Particularly the timing and spatial expression of climate variations can provide valuable information about the underlying driving mechanisms (Czymzik et al., 2016b, 2016c; Lane et al., 2013; Rach et al., 2014). However, time-scale uncertainties between different paleoclimate records often inhibit the investigation of such climate variations. Climate independent synchronization tools offer the possibility for synchronizing individual paleoclimate archives and, thereby, robust studies of leads and lags in the climate system.

In addition to volcanic tephra layers (Lane et al., 2013), atmospheric trace gases (Pedro et al., 2011) and paleomagnetism (Stanton et al., 2010), cosmogenic radionuclides like ^{10}Be and ^{14}C provide such a synchronization tool (Adolphi et al., 2017; Adolphi and Muscheler, 2016). The isotopes are produced mainly in the stratosphere through cascades of nuclear reactions triggered by incident high energy galactic cosmic rays (Lal and Peters, 1967). The flux of these galactic cosmic rays into the atmosphere is, in turn, modulated on up to multi-centennial-scales mainly by solar activity changes (Stuiver and Braziunas, 1989). On >500-year intervals further cosmogenic radionuclide production changes induced by the varying geomagnetic field become increasingly important (Lal and Peters, 1967; Snowball and Muscheler, 2007; Simon et al., 2016). Detecting and aligning the externally forced cosmogenic radionuclide production signal via a curve fitting method enables the quasi-continuous synchronization of natural environmental archives (Adolphi and Muscheler, 2016; Muscheler et al., 2014).

One challenge with this approach is the unequivocal detection of the cosmogenic radionuclide production signal because of transport and deposition processes. Subsequent to production, ^{14}C oxidizes to $^{14}CO_2$ and enters the global carbon cycle. Varying exchange rates between Earth's carbon reservoirs add non-production variability to the atmospheric ^{14}C record (Muscheler et al., 2004). This uncertainty can theoretically be accounted for by calculating ^{14}C production rates using a carbon cycle model. However, changes in Earth's carbon reservoirs are difficult to assess (Köhler et al., 2006). ^{10}Be in mid-latitude regions is nearly exclusively scavenged from the atmosphere by precipitation (Heikkilä et al., 2013). Varying atmospheric circulation and scavenging during the about one month long tropospheric residence time (about 1 year stratospheric residence time) result in spatially non-uniform ^{10}Be deposition patterns (Aldahan et al., 2008; Raisbeck et al., 1981). Despite these non-production effects, common changes in ^{10}Be and ^{14}C records are considered to reflect the cosmogenic radionuclide production signal, due to their common production mechanism and different chemical behavior (Lal and Peters, 1967; Muscheler et al., 2016).

To date, synchronization studies based on cosmogenic radionuclides are mainly limited to ^{14}C records from trees and ^{10}Be time-series from Arctic and Antarctic ice cores (Raisbeck et al., 2017; Muscheler et al., 2014). For example, Adolphi and Muscheler (2016) synchronized the Greenland ice core and IntCal13 time-scales for the last 11000 years. Synchronizing ^{10}Be records in sedimentary archives opens the opportunity for the synchronization of paleoclimate records around the globe. Thereby, the temporal resolution of this approach is limited by the lowest resolution record involved. First studies underline the potential of varved lake sediments for recording the ^{10}Be production signal, down to annual resolution (Berggren et al., 2013, 2010, Czymzik et al., 2015, 2016a; Martin-Puertas et al., 2012).

In the following, we attempt to synchronize ^{10}Be records from varved sediments of Lakes Tiefer See (TSK) and Czechowskie (JC) covering the grand solar minima at 250 a BP (Maunder Minimum), 2700 a BP (Homeric Minimum) and 5500 a BP with ^{14}C production rates inferred from the IntCal13 calibration curve (Muscheler et al., 2014; Reimer et al., 2013). Annual ^{10}Be time-series from both lake sediment archives yield the broad preservation of the ^{10}Be production signal during solar cycles 22 and 23 (Czymzik et al., 2015). The targeted three grand solar minima comprise among the lowest solar activity levels throughout the last 6000 years (Steinhilber et al., 2012).

2. Study sites

TSK (53°35'N, 12°31'E, 62 m a.s.l.) and JC (53°52'N, 18°14'E, 108 m a.s.l.) are situated within the Pomeranian Terminal Moraine in the southern Baltic lowlands (Fig. 1) (Dräger et al., 2017; Ott et al., 2016; Słowiński et al., 2017). The lake basins are part of subglacial channel systems formed at the end of the last glaciation and had no major inflows during the Holocene (Dräger et al., 2017; Ott et al., 2016). Both lakes are of similar size (TSK: 0.75 km^2/JC: 0.73 km^2), but the catchment of JC (19.7 km^2) is about 4 times larger than that of TSK (5.5 km^2) (Fig. 1). TSK sediments during the investigated grand solar minima are composed of alternating intervals of organic-, calcite- and rhodochrosite varves as well as intercalated non-varved sections (Dräger et al., 2017). JC sediments for these time windows comprise endogenic calcite varves with couplets of calcite and organic/diatom sub-layers, and an additional layer of resuspended littoral material since about 2800 a BP (Ott et al., 2016; Wulf et al., 2013). TSK and JC are located at the interface of maritime westerly and continental airflow. Mean annual precipitation is similar at both sites, 640 mm a^{-1} at TSK and 680 mm a^{-1} at JC (Czymzik et al., 2015).

3. Methods

3.1. Sediment sub-sampling and proxy records

Continuous series of sediment samples at ~20-year resolution (about 20 mm sediment) were extracted for ^{10}Be measurements from sediment cores TSK11 and JC-M2015, based on varve chronologies (Dräger et al., 2017; Ott et al., 2016). Complementary sediment accumulation rate (SAR), geochemical X-ray fluorescence (µ-XRF) and total organic carbon (TOC) time-series were constructed using existing high-resolution datasets from the same sediment cores by calculating ^{10}Be sample averages (Dräger et al., 2017; Ott et al., 2016; Wulf et al., 2016). Measured µ-XRF data (cps) were normalized by dividing by the sum of all elements, to reduce the effects of varying sediment properties (Weltje and Tjallingii, 2008).

3.2. ^{10}Be extraction and AMS measurements

After spiking with 0.5 mg ^{9}Be carrier, authigenic Be was leached from 0.2 g ground sediment samples overnight with 8 M HCl at 60°C (Berggren et al., 2010). The resulting solutions were filtered to separate the undissolved fractions. Further addition of NH_3 and H_2SO_4 caused the precipitation of metal hydroxides and silicates, which were again removed by filtering. The remaining solutions were treated with EDTA to separate other metals and, then, passed through hydrogen form ion exchange columns in which Be was retained. Be was extracted from the columns using 4 M HCl and $Be(OH)_2$ precipitated through the addition of NH_3 at pH 10. The samples were washed and dehydrated three times by centrifuging and oxidized to BeO at 600°C in a muffle furnace. After mixing with Nb, AMS measurements of BeO were performed at the Tandem Laboratory of Uppsala University. Final ^{10}Be concentrations were calculated from measured $^{10}Be/^{9}Be$ ratios, normalized to the NIST SRM 4325 reference standard ($^{10}Be/^{9}Be = 2.68 \times 10^{-11}$) (Berggren et al., 2010).

3.3 Original chronologies

The age models for TSK and JC sediments were constructed using a multiple-dating approach. Microscopic varve counts were carried out for both lake sediments. Non-varved intervals in TSK sediments were bridged based on varved thickness measurements in neighboring well-varved sediment sections. Independent age control for the TSK and JC varve chronologies was provided by radiocarbon dating and tephrochronology (for details see: Dräger et al., 2016, Ott et al., 2016, 2017; Wulf et al., 2013). Resulting chronological uncertainties are ± 17 (TSK) and ± 4 years (JC) for the Maunder Minimum, ± 139 (TSK) and ± 29 years (JC) for the Homeric Minimum as well as ± 74 (TSK) and ± 56 years (JC) for the 5500 a BP grand solar minimum (see Fig. 6).

3.4. Time-scale synchronization

Lag-correlation analyses were applied to determine best fits between the ^{10}Be records from TSK and JC for the Maunder-, Homeric- and 5500 a BP grand solar minima and ^{14}C production rates inferred from the IntCal13 calibration curve (Muscheler et al., 2014; Reimer et al., 2013). Before the correlation, all time-series were 75 to 500-year band-pass filtered and normalized by dividing by the mean, to reduce noise and increase the comparability (Adolphi et al., 2014). Significance levels for all correlation coefficients were calculated using 10000 iterations of a non-parametric random phase test, taking into account autocorrelation and trend present in the time-series (Ebisuzaki, 1997). Chronological uncertainty ranges were reported as the time-spans in which significances of correlations are below the given significant level. Before the analyses, all time-series were resampled to a 20-year resolution.

4. Results

^{10}Be concentrations ($^{10}Be_{con}$) were measured in 78 sediment samples from TSK and 73 sediment samples from JC (Figs. 2, 3 and S1). $^{10}Be_{con}$ in TSK sediments range from 1.13 to 7.09 x 10^8 atoms g^{-1}, with a mean of 3.91 x 10^8 atoms g^{-1} (Figs. 2 and S1). $^{10}Be_{con}$ in JC sediments vary between 0.93 to 3.82 x 10^8 atoms g^{-1}, around a mean of 1.89 x 10^8 atoms g^{-1} (Figs. 3 and S1). Mean AMS measurement uncertainties are 0.12 x 10^8 atoms g^{-1} for TSK and 0.07 x 10^8 atoms g^{-1} for JC samples (Figs. 2, 3 and S1). Due to the 1.387 ± 0.012 Ma long half-life of ^{10}Be (Korschinek et al., 2010), the effect of radioactive decay is negligible in our ^{10}Be records.

5. Discussion

5.1. ^{10}Be production signal in TSK and JC sediments

Environment and catchment conditions can add non-production variations to $^{10}Be_{con}$ records from varved lake sediments (Berggren et al., 2010; Czymzik et al., 2015). In the following chapter we will, first, describe our approach used for detecting and correcting possible non-production features in our ^{10}Be time-series and, then, discuss possible mechanisms behind the statistically inferred connections.

To detect and reduce non-production effects in our ^{10}Be time-series, we perform a three-step statistical procedure following Czymzik et al. (2016a), with a slight modification. First, multi-linear regressions were calculated between the $^{10}Be_{con}$ records and TOC, SAR, Ca, Si, Ti proxy time-series from TSK and JC, reflecting changes in sediment accumulation and composition (Dräger et al., 2017; Ott et al., 2016; Wulf et al., 2016), to estimate the possible environmental influence ($^{10}Be_{bias}$). Only the TOC and Ca time-series with significant contributions ($p<0.1$) for TSK and JC were included to the final multi-regressions. Subsequently, the resulting $^{10}Be_{bias}$ time-series from TSK and JC sediments were subtracted from the original $^{10}Be_{con}$ records in an attempt to construct an environment-corrected version of the ^{10}Be record ($^{10}Be_{environment}$). However, this statistical approach also removes variability in the $^{10}Be_{con}$ records only coincident with variations in proxy time-series, but without a mechanistic linkage, potentially resulting in an overcorrection. Such coinciding variability can be introduced by solar activity variations causing ^{10}Be production changes and climate variations imprinted in the proxy time-series. Therefore, final ^{10}Be composite records ($^{10}Be_{comp}$) were calculated by averaging the $^{10}Be_{con}$ and $^{10}Be_{environment}$ records from each site. To enhance the robustness of the corrections, the procedure was performed on the complete $^{10}Be_{con}$ records from TSK and JC covering all three grand solar minima. Uncertainty ranges of the calculated $^{10}Be_{comp}$ records are expressed as the differences between the $^{10}Be_{con}$ and $^{10}Be_{environment}$ time-series (Fig. 4).

Calculated $^{10}Be_{comp}$ time-series from TSK and JC sediments yield modified trends, but similar multi-decadal variability as the original $^{10}Be_{con}$ records during the Maunder- (TSK: $r=0.84$, $p<0.01$; JC: $r=0.91$; $p<0.01$), Homeric- (TSK: $r=0.81$, $p<0.01$; JC: $r=0.74$; $p<0.01$) and 5500 a BP grand solar minimum (TSK: $r=0.89$, $p<0.01$; JC: $r=0.68$; $p<0.01$) (Fig. 4). These linkages suggest that our correction procedure predominantly reduced trends in the $^{10}Be_{con}$ records introduced by varying sedimentary TOC and Ca contents, but largely preserved multi-decadal variations connected with varying ^{10}Be production (Figs. 2, 3 and 4). Comparable linkages between measured and corrected ^{10}Be records (based on a similar approach) were found in Lake Meerfelder Maar sediments covering the Lateglacial-Holocene transition as well as in recent TSK and JC sediments (Czymzik et al., 2015, 2016a).

The statistical connections to TOC and Ca for TSK and JC might point to depositional mechanisms of ^{10}Be in lake sediment records. Significant contributions to the multi-regression as well as significant positive correlations for TSK ($r=0.62$, $p<0.01$) and JC ($r=0.77$, $p<0.01$) suggest a preferential binding of ^{10}Be to organic material (Figs. 2 and 3). This result is supported by significant positive correlations of ^{10}Be with TOC in two annually resolved time-series from varved sediments of TSK and JC spanning solar cycles 22 and 23 and in Meerfelder Maar sediments covering the Lateglacial-Holocene transition (Czymzik et al., 2015, 2016a).

Significant contributions of Ca to the multi-regressions as well as significant negative correlations with ^{10}Be for TSK ($r=-0.68$, $p<0.01$) and JC ($r=-0.62$, $p<0.01$) might point to a reduced affinity of ^{10}Be for Ca (Figs. 2 and 3). A similar behavior was detected in studies about ^{10}Be scavenging from the marine realm (Aldahan and Possnert, 1998; Chase et al., 2002, Simon et al., 2016).

5.2. $^{10}Be_{comp}$ and group sunspot numbers

To evaluate the preservation of the cosmogenic radionuclide production signal based on observational data, the $^{10}Be_{comp}$ time-series from TSK and JC were compared with a group sunspot number record reaching back to 340 a BP (AD 1610) (Svalgaard and Schatten, 2016) (Fig. 5). Since sunspot and cosmogenic radionuclide records reflect different components of the heliomagnetic field (closed and open magnetic flux) no perfect correlation is expected (Muscheler et al., 2016). Nevertheless, a comparison of a ^{14}C based solar activity reconstruction with group sunspot data points to a largely linear relationship between both types of data (Muscheler et al., 2016).

Variations in the $^{10}Be_{comp}$ records from TSK and JC resemble multi-decadal to centennial variability in the group sunspot number time-series with highest values around the Maunder Minimum (Fig. 5). Secondary $^{10}Be_{comp}$ maxima in TSK and JC sediments broadly coincide with the Dalton Minimum and solar activity minimum around 30 a BP (AD 1920) (Fig. 5). In JC sediments, the $^{10}Be_{comp}$ excursion from -50 to 0 a BP (AD 2000-1950) without an expression in the group sunspot number record as well as the about 20-year delayed Maunder Minimum response could be explained by transport of ‘old’ ^{10}Be from the littoral to the coring site (see details on the sub-layer of resuspended littoral sediments in JC varves back to 2800 a BP in Section 5.3) and/or spatially inhomogeneous ^{10}Be deposition patterns (Fig. 5).

5.3. Synchronizing TSK/JC ^{10}Be with IntCal13 ^{14}C

Shared variance of ^{10}Be and ^{14}C records can be interpreted in terms common changes in cosmogenic radionuclide production (Czymzik et al., 2016a; Muscheler et al., 2014). Moreover, it provides the opportunity to synchronize cosmogenic radionuclide records from different archives (Adolphi and Muscheler, 2016). Lag-correlation analyses were performed to synchronize the TSK and JC $^{10}Be_{comp}$ records covering the Maunder-, Homeric- and 5500 a BP grand solar minima with ^{14}C production rates from the IntCal13 calibration curve (Muscheler et al., 2014).

Best fits with IntCal13 ^{14}C production rates were obtained, when the $^{10}Be_{comp}$ records from TSK were shifted by 8 -12/+4 years (Maunder Minimum; r=0.47, p<0.1), 31 -16/+12 years (Homeric Minimum; r=0.68, p<0.01) and 86 -22/+18 years (5500 a BP grand solar minimum; r=0.37, p<0.05) towards the past (Fig. 6). All three best fits occur within the given chronological uncertainties of ± 17 years (Maunder Minimum), ± 139 years (Homeric Minimum) and ± 74 years (5500 a BP grand solar minimum) (Fig. 6). The on average <10-year resolution of the varve-based sedimentation rate chronology for TSK sediments around the Maunder Minimum due to non-varved intervals, does not affect our analyses conducted on records at 20-year resolution.

The best fit between the $^{10}Be_{comp}$ record from JC sediments during the 5500 a BP grand solar minimum and IntCal13 ^{14}C production rates (r=0.81, p<0.01) was determined, when the ^{10}Be record was shifted for 29 -8/+7 years towards present (within the given chronological uncertainty of ±56 years) (Fig. 6). No significant correlations between the $^{10}Be_{comp}$ records from JC and ^{14}C production rates were obtained for the Maunder- and Homeric Minima, within the respective varve counting uncertainties of ±4 and ±29 years (Fig. 6). This lack of significant correlation might be explained by a change in sedimentation at about 2800 a BP (Fig. 6). Since that time JC varves include an additional sub-layer of littoral calcite and diatoms transported to the profundal by wave driven water turbulences in fall. Presumably, the resuspended material also contains ‘old’ ^{10}Be inhibiting the clear detection of the expected ^{10}Be production signal (Fig. 6). Since the ^{10}Be signal present in the resuspended sediments is unknown, this uncertainty is difficult to correct for. Comparable influences of sediment resuspension were also found in a sample from an annually resolved ^{10}Be record from JC sediments covering the period AD 2009-1988 (Czymzik et al., 2015). A varve with an exceptionally thick (3.7 mm) layer of resuspended littoral diatoms and calcite deposited in fall 2003 reveals anomalous ^{10}Be concentrations (Czymzik et al., 2015).

6. Conclusions

Detecting and aligning the common cosmogenic radionuclide production variations allows the synchronization of ^{10}Be time-series from TSK sediments covering the Maunder-, Homeric- and 5500 a BP grand solar minima and JC sediments for the 5500 a BP grand solar minimum to IntCal13 ^{14}C production rates. These synchronizations provide a novel type of time-marker for varved lake sediment archives enabling improved chronologies and robust investigations of proxy responses to climate variations. Mismatches between ^{10}Be in JC sediments and ^{14}C production rates during the Maunder- and Homeric Minima are likely associated with in-lake resuspension of ‘old’ ^{10}Be, altering the expected ^{10}Be production signal.

Acknowledgements

MC was financed by a German Science Foundation 'Research Fellowship' (DFG grants CZ 227/1-1 and CZ 227/1-2). Further financial support was provided through an Endowment of the Royal Physiographic Society in Lund, a Linnaeus grant to Lund University (LUCCI) and the Swedish Research Council (Dnr: 2013-8421). FA is supported by the Swedish Research Council (VR grant: 4.1-2016-00218). AA thanks the UAEU for support through UPAR funding. This study is a contribution to the Virtual Institute of Integrated Climate and Landscape Evolution Analyses (ICLEA) grant number VH-VI-415, the Leibniz Association BaltRap network (The Baltic Sea and its southern lowlands: Proxy-environment interactions in times of rapid changes) and the climate initiative REKLIM Topic 8 'Abrupt climate change derived from proxy data' of the Helmholtz Association. We thank Inger Påhlsson for the extraction of ^{10}Be from sediment samples. ^{10}Be data from TSK and JC are available at the PANGAEA data library (www.pangaea.de). Quentin Simon and an anonymous reviewer are acknowledged for their constructive comments which helped to improve the manuscript.

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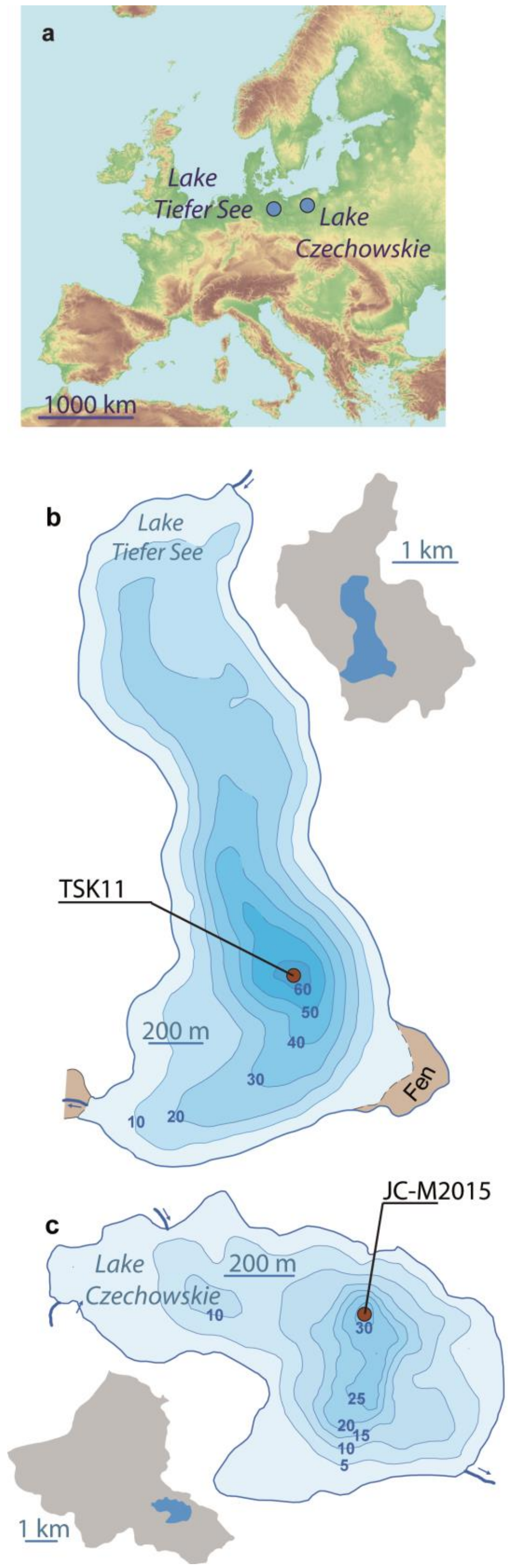


Figure 1. Settings of Lakes Tiefer See (TSK) and Czechowskie (JC). (a) Location of TSK and JC in the southern Baltic lowlands. (b) Bathymetric map of TSK with position of sediment core TSK11 and lake-catchment sketch. (c) Bathymetric map of JC with position of sediment core JC-M2015 and lake-catchment sketch.

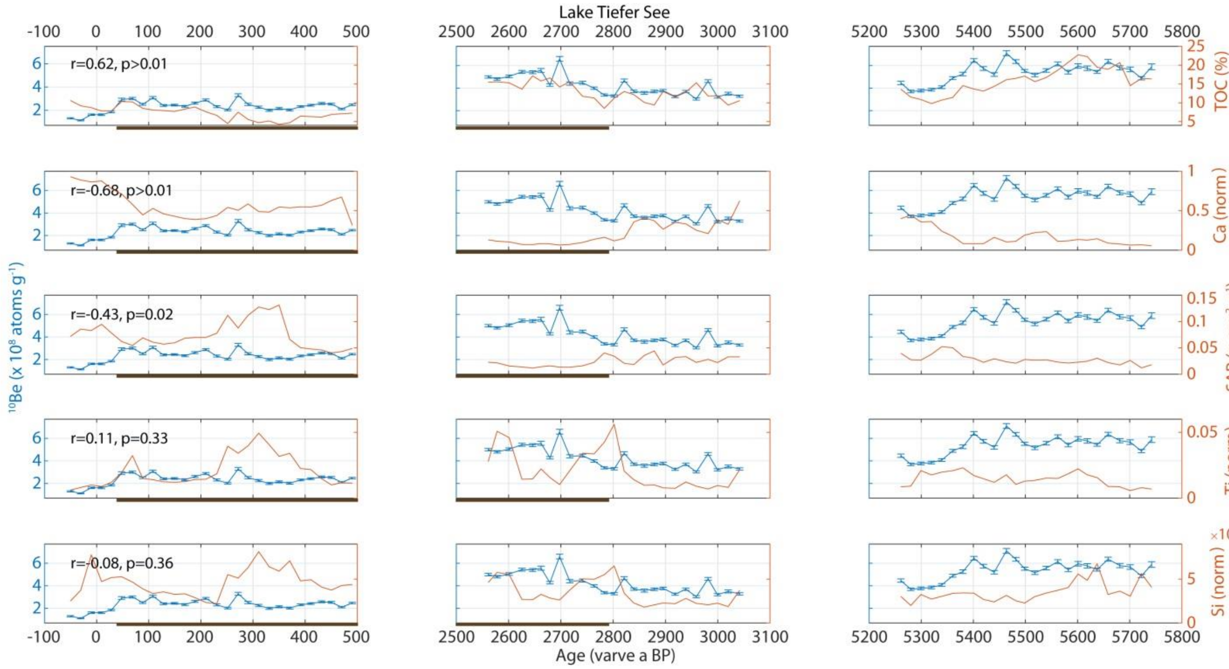


Figure 2. ^{10}Be concentrations ($^{10}Be_{con}$) in Lake Tiefer See (TSK) sediments around the Maunder-, Homeric- and 5500 a BP grand solar minima and corresponding proxy time-series from the same archive. $^{10}Be_{con}$ compared with sediment accumulation rates (SAR), total organic carbon (TOC), Ti, Ca and Si. Correlation coefficients were calculated for the complete time-series covering all three grand solar minima. Significance levels of correlations were calculated using 10000 iterations of a non-parametric random phase test taking into account trend and autocorrelation present in the time-series (Ebisuzaki, 1997). Error bars indicate AMS measurement uncertainties. Non-varved intervals in TSK sediments are indicated by bars.

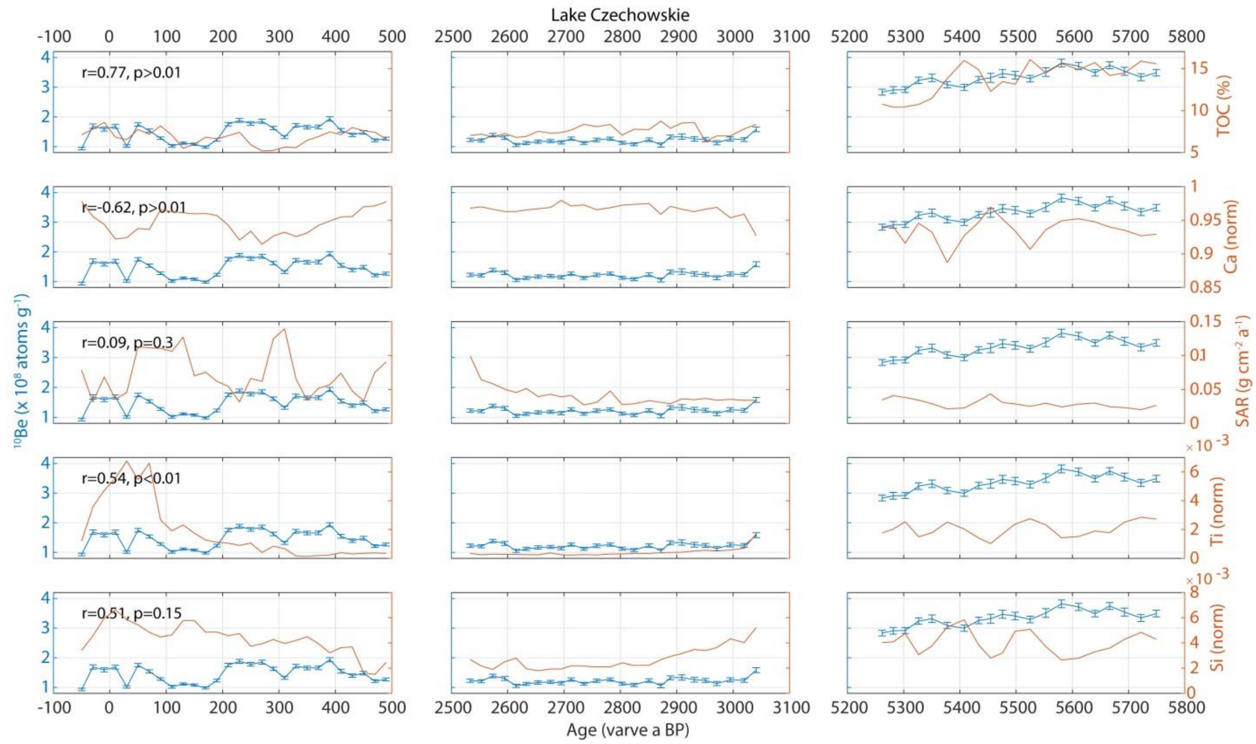


Figure 3. ^{10}Be concentrations ($^{10}Be_{con}$) in Lake Czechowskie (JC) sediments around the Maunder-, Homeric- and 5500 a BP grand solar minima and corresponding proxy time-series from the same archive. $^{10}Be_{con}$ compared with sediment accumulation rates (SAR), total organic carbon (TOC), Ti, Ca and Si. Correlation coefficients were calculated for the complete time-series covering all three grand solar minima. Significance levels of correlations were calculated using 10000 iterations of a non-parametric random phase test taking into account trend and autocorrelation present in the time-series (Ebisuzaki, 1997). Error bars indicate AMS measurement uncertainties.

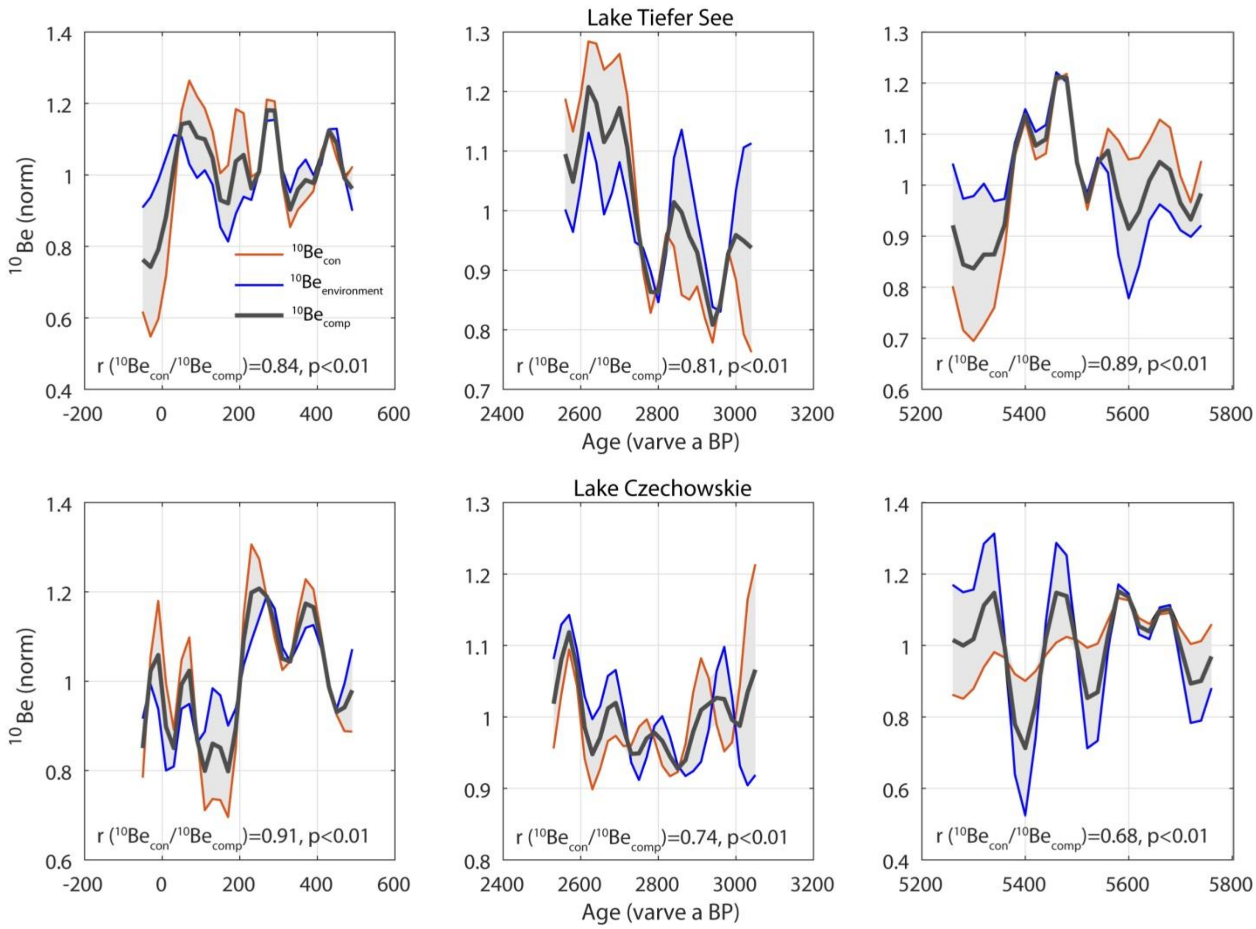


Figure 4. Lakes Tiefer See (TSK) and Czechowskie (JC) ^{10}Be concentration ($^{10}Be_{con}$), corrected ^{10}Be ($^{10}Be_{environment}$) and ^{10}Be composite ($^{10}Be_{comp}$) time-series around the Maunder-, Homeric- and 5500 a BP grand solar minima. All time-series are resampled to a 20-year resolution and normalized by dividing by the mean. A 75-year low pass filtered was applied to reduce noise. Uncertainty ranges of $^{10}Be_{comp}$ (gray shadings) are expressed as the differences between the $^{10}Be_{con}$ and $^{10}Be_{environment}$ time-series. Significance levels of correlations between $^{10}Be_{con}$ and $^{10}Be_{comp}$ were calculated using a random phase test (Ebisuzaki, 1997).

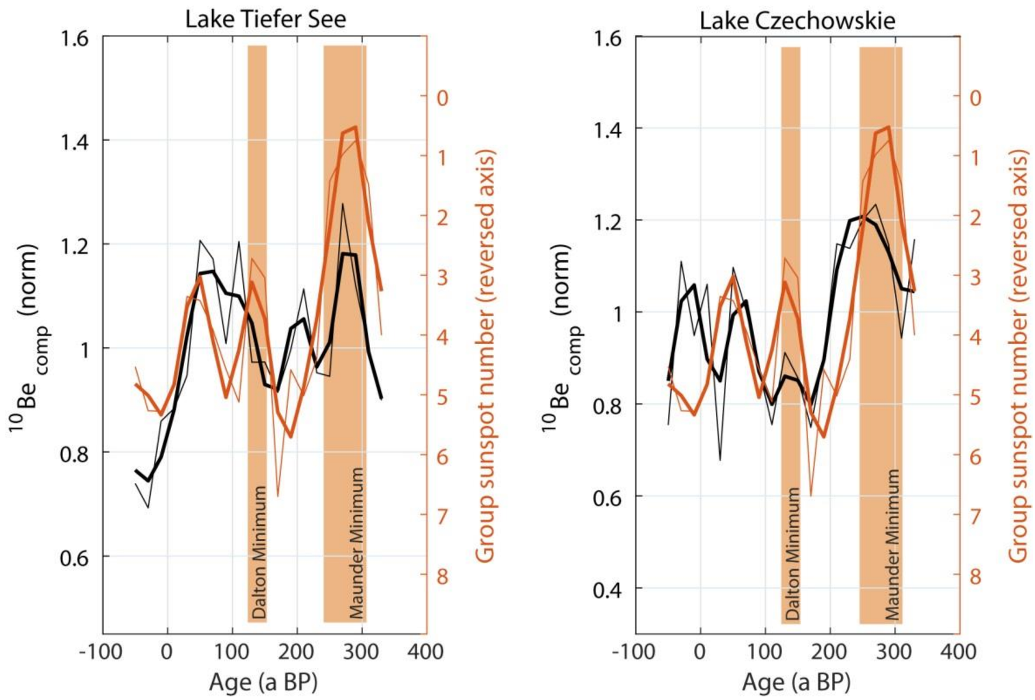


Figure 5. ^{10}Be composites ($^{10}Be_{comp}$) from Lakes Tiefer See (TSK) and Czechowskie (JC) compared with group sunspot numbers back to 340 a BP (Svalgaard and Schatten, 2016). Time-windows of the Maunder and Dalton solar minima are highlighted (Eddy, 1976; Frick et al., 1997). Time-series are shown at 20-year resolution (thin lines) and with a 75-year low-pass filter, to reduce noise (thick lines). $^{10}Be_{comp}$ records are normalized by dividing by the mean.

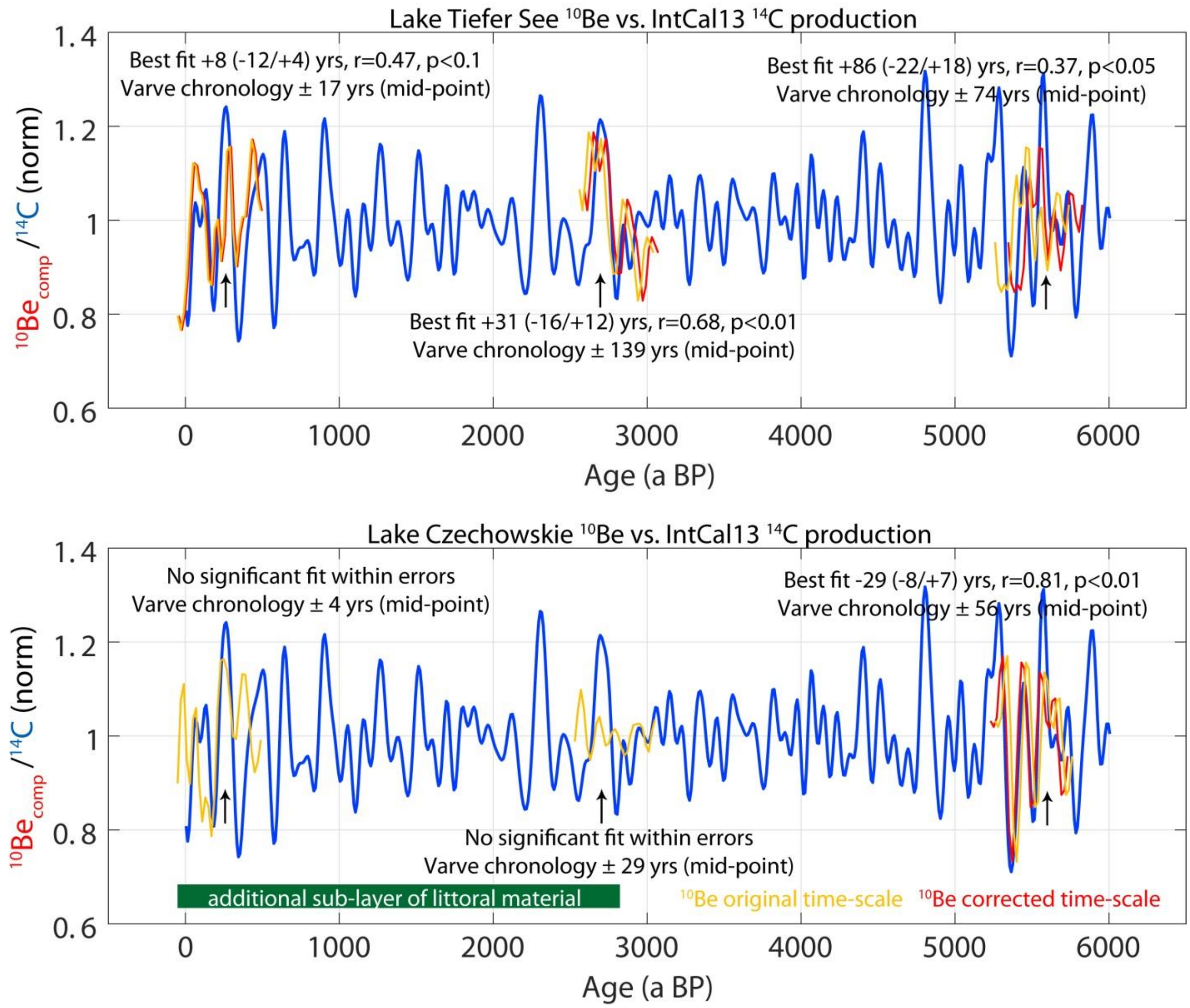
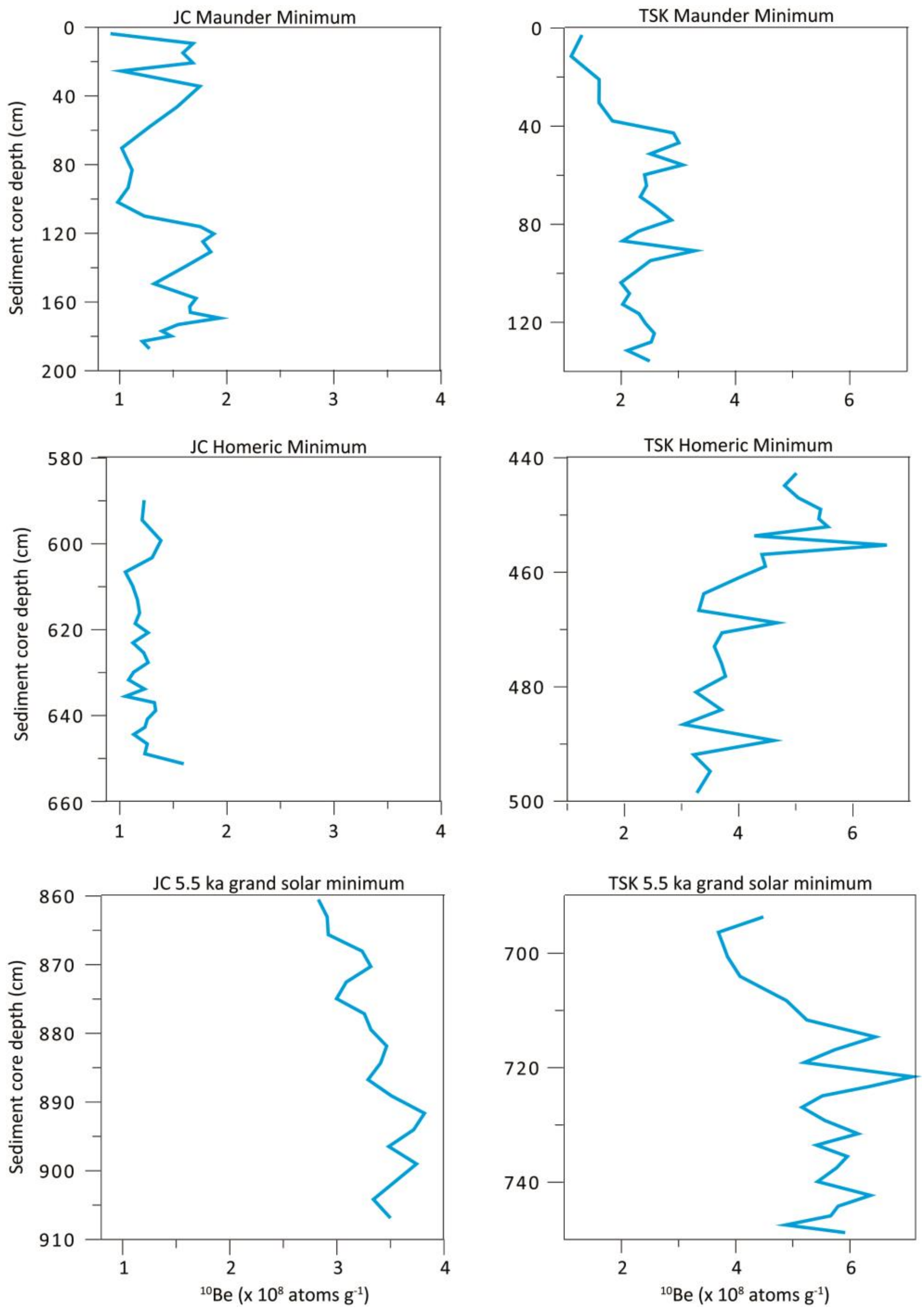


Figure 6. Synchronization of ^{10}Be composites ($^{10}Be_{comp}$) from Lakes Tiefer See (TSK) and Czechowskie (JC) for the Maunder-, Homeric- and 5500 a BP grand solar minima with ^{14}C production rates from the IntCal13 calibration curve (Muscheler et al., 2014). Best fits between the records were calculated using lag-correlation, based on given chronological uncertainties (Dräger et al., 2017; Ott et al., 2016). Significance levels of the correlations were calculated using 10000 iterations of a non-parametric random phase test taking into account autocorrelation and trend present in the time-series (Ebisuzaki, 1997). Uncertainies are given as the time-spans in which the significances of the correlations are below their respective significant levels. $^{10}Be_{comp}$ is shown on its original time-scale and, if applicable, synchronized with IntCal13 ^{14}C production rates. An interval with an additional sub-layer of resuspended littoral material in JC varves is indicated. Arrows mark the peaks of the targeted three grand solar minima.



Supplementary Fig S1. ^{10}Be concentrations in Lakes Tiefer See (TSK) and Czechowskie (JC) sediments around the Maunder-, Homeric- and 5.5 ka grand solar minima plotted against sediment core depth.

Response to the reviewers' comments

We thank Quentin Simon and an anonymous reviewer for their constructive and detailed comments which helped to significantly improve our manuscript. In the following, we will give a detailed response to all concerns that have been raised, first answering the main points of criticism, followed by a point-by-point reply.

Response to reviewer Quentin Simon:

Detailed Answer #1: Changes in sediment composition, their effects on ^{10}Be deposition and how to correct for them

Apparently, we were not clear enough about the possible effects of changes in sediment composition on ^{10}Be deposition in TSK and JC, and how we try to reduce them. Therefore, we modified our manuscript in two ways:

(1) To improve the overview on varying ^{10}Be concentrations and sediment composition in TSK and JC, we now show in addition to Figs. 2 and 3 (^{10}Be concentrations, Ti, SAR, TOC, Si and Ca proxy time-series from TSK/JC vs. time) our ^{10}Be records against sediment core depth in the new Figure S1, as suggested by Quentin Simon. Our ^{10}Be data on age and depth scale will be made available to the public in the PANGAEA data library.

(2) To be clearer about our research strategy, we have extended the introductory paragraph of Chapter 5.1. There, we now outline that we first present our statistical approach (multi-regression analyses) applied to detect suspicious similarities between changes in ^{10}Be concentrations and proxy time-series in TSK and JC sediments and, second, discuss possible mechanistic linkages behind the inferred connections.

The revised and extended introduction to Chapter 5.1. (lines 5.11-14):

Environment and catchment conditions can add non-production variations to $^{10}Be_{con}$ records from varved lake sediments (Berggren et al., 2010; Czymzik et al., 2015). In the following chapter we will, first, describe our approach used for detecting and correcting possible non-production features in our ^{10}Be time-series and, then, discuss possible mechanisms behind the statistically inferred connections.

Moreover, the above detection and correction procedures are exclusively based on statistic similarities between the ^{10}Be and other proxy records from the same archive as well as the inferred chemical behavior of ^{10}Be in lake sediments. They are not guided by similarities between our corrected ^{10}Be time-series and ^{14}C production rate variations and, hence, not subject to circle reasoning. Since we could not detect significant contributions of Ti, Fe and SAR to the multi-regressions, we did not include these proxies to the correction procedure. Supporting our findings, similar linkages between ^{10}Be and TOC, Ca, Ti, Fe and SAR were found in a previous study on ^{10}Be in sediments from Lake Meerfelder Maar (Czymzik et al., 2016, *Quaternary Science Reviews*).

Detailed answer #2: Original chronologies

We agree with the reviewer about the importance of the original TSK and JC chronologies for our synchronization study. Therefore, we added the new Chapter 3.3 ‘Original chronologies’ to the methods section of the manuscript providing an overview on that subject. For published details on the original TSK and JC chronologies we refer to the related papers by Dräger et al. (2016, *The Holocene*), Ott et al. (2016, *Journal of Quaternary Science*; 2017, *The Holocene*) and Wulf et al. (2013, *Quaternary Science Reviews*). In addition, we now report the uncertainties of the original TSK and JC chronologies during the investigated three grand solar minima.

The new Chapter 3.3. ‘Original chronologies’:

The age models for TSK and JC sediments were constructed using a multiple-dating approach. Microscopic varve counts were carried out for both lake sediments. Non-varved intervals in TSK sediments were bridged based on varved thickness measurements in neighbouring well-varved sediment sections. Independent age control for the TSK and JC varve chronologies was provided by radiocarbon dating and tephrochronology (for details see: Dräger et al., 2016, Ott et al., 2016, 2017; Wulf et al., 2013). Resulting chronological uncertainties are ± 17 (TSK) and ± 4 years (JC) for the Maunder Minimum, ± 139 (TSK) and ± 29 years (JC) for the Homeric Minimum as well as ± 74 (TSK) and ± 56 years (JC) for the 5500 a BP grand solar minimum (see Fig. 6).

Point-by-point reply to reviewer Quentin Simon:

In this paper, the authors address an essential issue in any paleo-studies, the chronology. They propose a method to help synchronizing varved lakes with other natural archives which is essential to improve our understanding of the mechanisms driving climatic variability. The group of authors already introduced this method for other sites or other time periods in several publications and pursued successfully their investigations in this paper that I recommend for

publication following some revisions. The aim of the paper is essentially methodological and I imagine that climatic discussion based on precise inter-correlation of TSK (less evident for JC) with other records, using the 10Be method, will be presented elsewhere (which is fair). The text would greatly benefit from several complementary notes on method, interpretation and discussion (see comment below). Given the rather short length of the present manuscript, it should be possible to provide these information without weighing too much on the final version of the paper. I listed below a series of comments and questions – voluntarily naïve or not – for which answers (integrated into the paper) should improved robustness an easy readability of the paper.
I would also suggest a slight change of the title to enclose all aspects of the paper: “Synchronizing 10Be in two varved lake sediment records to IntCal13 14C during grand solar minima” (see below).

(1) 2.5. The authors could explicitly mention all type of archives which (will) benefit from 10Be for global synchronization. What is the range of time-scale uncertainties associated with these different archives? This is particularly important since it implies different resolutions associated with inherent archive limitations. Despite the most robust archive-to-archive correlation possible (maybe provided by 10Be), these restrictions constitute a limiting factor for studying specific climatic mechanisms in some archives and/or from older ages, particularly about precise lead and lags in the climate system.

In the previous version of our manuscript we wrote that, to date, mainly ice core and tree archives benefit from the cosmogenic radionuclide synchronization method. Following the reviewer, we now further specify in lines 2.33-34 that in general sedimentary archives (marine and terrestrial) could profit from our new approach and added that the possible temporal resolution of a synchronization study is limited mainly by the lowest resolution of the involved records.

(2) 2.10. The authors can add paleomagnetism to the series of useful synchronization tools independent from climatic cycles

We added paleomagnetism to the list of synchronization tools and provided the reference Stanton et al. (2010, *Quaternary Geochronology*). This study synchronizes a varved lake sediment record from Sweden based on paleointensity variations.

(3) 2.15. Recent works of groups from, e.g., France (Ménabréaz, Valet, Simon) or Japan (Suganuma, Horiuchi) also documented geomagnetic field forcing on the 10Be production variation, is there an impact of these modulation on your records? More largely, what is the impact of solar activity and geomagnetic intensity variations on the magnitude of atmospheric 10Be production rates? Since authors are discussing a synchronization tool that can (will) be used for other time periods, presenting these elements is important because they explain why and how 10Be works, particularly at certain period of time.

We have to be more distinct about the role of both changes in solar activity (decadal to centennial) and paleomagnetic field intensity (sub-millennial and longer) on ^{10}Be production rate changes. Therefore, in addition to the reference to Snowball and Muscheler (2007, *The Holocene*), we now emphasize the different time-scales connected with ^{10}Be production rate changes induced by solar activity variations and geomagnetic field strength by providing the additional references Stuiver and Braziunas (1989, *Nature)* and Simon et al. (2016, *Journal of Geophysical Research*).

(4) 2.25. What is the result of this spatial heterogeneity? Does it complicate easy interregional correlations? If yes, to what extent? This is important for using 10Be as an accurate global synchronization tool of course.

Spatially inhomogeneous deposition is one of the major uncertainties in ^{10}Be research. However, due to the same production mechanism and different geochemical behavior, the shared variance of ^{10}Be and ^{14}C records are considered to reflect common atmospheric cosmogenic radionuclide production variations (e.g. Muscheler et al., 2014, *Quaternary Science Reviews*). That is one of the reasons why we compare our ^{10}Be records from TSK and JC sediments to ^{14}C production variations from the tree-ring based part of the IntCal13 calibration curve. We added that information in lines 2.27-29.

(5) 2.30. Add the recent Raisbeck et al. paper (Clim. Past, 13, 217–229, 2017) which discusses synchronization between Greenland and Antarctic ice cores using 10Be. Does "synchronization of terrestrial paleoclimate records around the globe" need to assume a global homogenization of 10Be production/deposition (see above)?

We now provide the reference Raisbeck et al. (2017, *Climate of the Past*). See our answer to Comment 4, dealing with spatial inhomogeneous ^{10}Be deposition.

(6) 2.35. Why only studying these three periods? Do you expect higher level of 10Be changes during these intervals? It might be interesting to give some precision here. Moreover, it could be a good idea to mention the three grand solar minima it in the title since your study is focused on these periods.

We added the 'three grand solar minima' to the title. In lines 3.7-8 we specify that the three grand solar minima were chosen, because they comprise among the lowest solar activity levels during the last 6000 years and provided the reference to the solar activity reconstruction by Steinhilber et al. (2012, *PNAS*).

(7) 3.15. What is the extent of sedimentary changes in both cores through the studied intervals? Are they related to any known (studied) climatic cycle? This is important since sedimentary changes can drastically disturb Be records in geological archives. For instance, the last two sentences dealing with current air masses and precipitations behavior are interesting for modern settings but do these parameters also prevailed during the periods scrutinized here?

See our Detailed Answer #1 'Changes in sediment composition and their effects on ^{10}Be deposition'.

(8) 3.20. To what range of depth intervals correspond a 20-year resolution? What is the sediment amount needed for method? How many years are integrated by the sampling (thickness of the sediment samples)? Also, I do understand that authors want to keep short, which is definitely not a bad idea, but since the chronology is central in the paper (e.g. Title) I find important to present how age models have been obtained (not simply referring to the original publications). What is their resolutions and uncertainties? There is no need to develop too far, but to provide with enough elements for the readers to judge the resolution and potential bias induced by inevitable age errors. This is particularly important since the paper discusses about age offsets with resolutions of only few years back to > 5 ka BP.

See our Detailed Answer #2 'Original chronologies'. We added to Section 3.1. 'Sediment sub-sampling and proxy records' that a 20-year resolution equals on average about 20 mm sediment (lines 3.25-27).

(9) 3.30/4.5. How do you homogenize sediment samples? What is the sediment weight used? Authors should write that they are interested only by the fraction adsorb or precipitated on sediments (sometimes called "authigenic"), and why are they interested by this fraction? They could precise that metal hydroxides and silicates are precipitated while Be remains in solution. Why precipitate at pH 10 and not 8.5? Are you not precipitating (or risk to precipitate) Boron at this pH level? These last two questions are probably not interesting for the paper, personal interest about the method. It could be useful to add a citation that provide with full description of the method followed here. Add at the end of the last sentence: "and corrected for radioactive decay (Chmeleff et al., 2010; Korschinek et al., 2010)". I totally understand that this correction does not change your results, but better be precise with radioactive elements. Retrieving the exact 10Be concentrations imply a correction for radioactive decay, even if changes occur at the margin given the sediment ages and the T1/2 of 10Be. Note also that authors could add somewhere in the text the half-life of both 14C and 10Be to give the time extent, and therefore theoretical limits, of these tracers (probably more useful for 10Be than for 14C which is already well known by the community).

We added the methodological information requested by Quentin Simon to the text. Moreover, we now provide information about the half-time of ^{10}Be and the effects of radioactive decay on our time-series in the 'Results' section by adding the sentence:

'Due to the 1.387 ± 0.012 Ma long half-life of ^{10}Be (Korschinek et al., 2010), the effect of radioactive decay is negligible in our ^{10}Be records'.

(10) 4.10/15. What is the time uncertainty associated with your data?

See our Detailed Answer #2 'Original chronologies'.

(11) 4.20. I would remove any mention to Figs. 2 and 3 in the results section as these figures are plotted versus age. Results versus ages are already part of a discussion because they imply a serious transformation through the application of age modeling. Presentation of the raw 10Be concentration data versus depth in new figures is maybe not mandatory since I guess these data will be available as supplementary material or easily available from the web. I know this comment is annoying but discussion will likely evolve while the data will remain, and are therefore important for the community. The authors should highlight directly on the figures the location and duration interval of the grand solar minima discussed (which do not represent the whole box intervals).

In addition to Figs. 2 and 3, we now also refer to the new Figure S1 depicting a plot of our new ^{10}Be data from TSK and JC against sediment core depth. We highlight the three investigated grand solar minima in Fig. 6 using arrows.

(12) 4.30. What kind of non-production forcing parameters can explain part of the ^{10}Be concentration variations in varved lake sediments? 2-3 sentences could help readers to rapidly understand such processes without having to refer to a third party (interested readers will of course go to these citations). I'm wondering why you selected these parameters specifically (i.e. TOC, SAR, Ca, Si, Ti)? Are their fluctuations representing correctly all lithological changes observed in the lakes (e.g. productivity, grain-size, mineralogy)?

See our Detailed Answer #1 'Changes in sediment composition and their effects on ^{10}Be deposition'.

(13) 5.5. I agree that significant contribution of TOC and Ca on the whole intervals justify their used to the multi-regressions treatment. Yet, it is possible that other elements presented in the paper also impact the 10Be signal within specific depth intervals (e.g. Ti since about 200 a BP in TSK). If they are associated with specific events linked to rapid climatic changes, how can you estimate their residual influence on the 10Beenvironment record calculated? Actually authors correctly discuss that matter later in the paragraph but it results into a blurry questioning about the reliability of the environmental correction procedure, essentially because the method does not rely on any mechanistic linkages between 10Beconc and TOC/Ca, as mentioned by the authors themselves. One could mention here that the method is mainly working because the outcome (10Becomp) is highly comparable with 14C production (Fig. 6) but, although valid, this argument is slightly circular. The main question remains: how to correctly remove, or say diminish, environmental variability imprints on 10Be records in lakes?

See our Detailed Answer #1 ‘Changes in sediment composition and their effects on ^{10}Be deposition’.

(14) 5.15. As the authors are interested by multi-decadal variations (see Figures 5 and 6), why not working on 10Beconc series directly as this variability is similar between both 10Becomp and 10Beconc series. This would avoid unnecessary and questionable data treatments while preserving the conclusion.

See our Detailed Answer #1 ‘Changes in sediment composition and their effects on ^{10}Be deposition’.

(15) 5.25/25. These two paragraphs are rather interesting but could be move above (5.5) to support the use of these two elements for the multi-regression method used to obtain the 10Bebias. Also, it would be interesting to discuss a little bit more (or cite references?) about the exact – or supposed – mechanisms explaining “preferential binding of 10Be to organic material”, while the affinity of 10Be to Ca has been indeed demonstrated in several studies already cited in the paper.

Please see our Detailed Answer #1 ‘Changes in sediment composition and their effects on ^{10}Be deposition’.

(16) 6.5. Does result differs when using 10Beconc instead of 10Becomp (see comment above)? In TSK, the unfiltered two 10Be peaks visually correlated with the two sunspot number lows, why not mentioning it? Do you have sedimentological elements to sustain a transport of “old” 10Be? By which processes such a transport can take place (physical remobilization or desorption form sediments previously deposited onto “shelves”)? It might be interesting to mention it here, or to refer to explanations provide later in the text.

See our Detailed Answer #1 ‘Changes in sediment composition and their effects on ^{10}Be deposition’.

(17) 6.20. Are you using this best fit result to propose a new chronology for TSK?

Yes, the successful synchronizations will be used as tie-points to improve the chronologies of TSK and JC sediments. We added the point ‘improving chronologies’ to the conclusions.

The extended sentence from the conclusions (lines 7.30-32):

‘These synchronizations provide a novel type of time-marker for varved lake sediment archives enabling improved chronologies and robust investigations of proxy responses to climate variations’.

(18) 7.5/10. Conclusion is fine and clearly wrap up the main objective of the paper, i.e. 10Be is a robust tool for synchronization (TSK) unless environmental imprint is too strong (JC).

Thank you!

Response to Anonymous Referee #2:

Detailed answer #3: Visualization of changes in ^{10}Be and sediment properties:

We visualize changes in sediment composition and accumulation by depicting the original ^{10}Be, TOC, Si, Ca, Ti and SAR records from Lakes Tiefer See and Czechowskie for the inspected three grand solar minima in Figs. 2 (for TSK) and 3 (for JC). In addition, we added the supplementary Fig. S1 to the revised manuscript showing our new ^{10}Be records from Lakes Tiefer See and Czechowskie against core depth.

Point-by-point reply to Anonymous Referee #2:

This manuscript by Czymzik and co-authors targets to a key issue in paleoclimate records i.e. time-scale uncertainties, which often inhibit the detailed investigation of multiple spatial high resolution climate proxy records. 10Be records from two varved lake sediment sequences from northern Germany and Poland are synchronized with IntCal13 calibration curve. This methodological approach is a novel attempt to synchronize lake sediment records using 10Be in order to investigate the leads and lags, unwanted but inherent features in all proxy records. Large (and growing) number of the high resolution paleoclimatic studies is published from lacustrine sediments but the detailed comparison of the proxy records suffer from the temporal uncertainties. From this perspective, the manuscript contains interesting ideas and is topical. The text is well written and structured and has illustrations of high quality to support results and interpretations very nicely.

The main point what I miss in this manuscript would be a visual illustration of the sediment composition and composition changes from the two sediment records with SAR, TOC and perhaps Ca, Ti and 10Be variability, at least for the time windows that were more closely inspected. Although the references to original publications are provided, the illustration would greatly help to follow the detailed discussion from two lake records with several proxies and time windows and changes in sedimentation. Overall, this manuscript is suited for the journal of Climate of the Past discussions and can be accepted with minor revision.

Specific comments:

Page 2 Line 26: Could it be shortly explained how the non-uniform 10Be depositional patterns are generally taken into account/expected to influence the records?

Non-uniform deposition patterns are presently one of the main uncertainties in ^{10}Be research (Adolphi and Muscheler, 2016, *Climate of the Past*). However, common changes of the cosmogenic radionuclides ^{10}Be and ^{14}C in different environmental archives are considered to reflect variations in the cosmogenic radionuclide production rate, due to their same production mechanism and different chemical behavior (Muscheler et al., 2016, *Solar Physics*). That is one of the reasons why we compare our ^{10}Be time-series from Lakes Tiefer See and Czechowskie to ^{14}C production rates inferred from the IntCal13 calibration curve. To account for the reviewer's comment, we added the following sentence to the manuscript and provide two references (lines 2.27-29):

'Despite these non-production effects, common changes in ^{10}Be and ^{14}C records are considered to reflect the cosmogenic radionuclide production signal, due to their common production mechanism and different chemical behavior (Lal and Peters, 1967, Muscheler et al., 2016).'

Another way to distinguish and reduce non-production effects in sedimentary ^{10}Be time-series is our here applied approach based on environmental proxy-series from the same archive. Thereby, it is assumed that coinciding changes the environment reflected by proxy time-series might leave an imprint in the ^{10}Be time-series (Czymzik et al., 2016, *Quaternary Science Reviews*).

Page 3 Line 9: No major inflows, today. Well, were there major inflows previously? What kind of changes in inflow system have occurred and when? Does this influence the sediment composition within the time interval of the study, e.g. the changes in sedimentation rate or sediment composition? If not, this should be mentioned as well.

Very low and rather stable contents of detrital grains in varved Lakes Tiefer See and Czechowskie sediments indicate that no major tributaries existed throughout the investigated three grand solar minima (and the complete Holocene). To include this information to the manuscript we revised the related sentence (lines 3.13-14) and provide two references:

'The lake basins are part of subglacial channel systems formed at the end of the last glaciation and had no major inflows during the Holocene (Dräger et al., 2017; Ott et al., 2016).'

Page 3 Line 20: at 20 year resolution. This is not clear to me; do you mean one sample every 20 years, or a sample comprising 20 years?

We need to be clearer about our sampling strategy. We use continuous series of sediment samples, each comprising about 20 years of sedimentation. Therefore, we changed the related sentence to:

‘Continuous series of sediment samples at ~20-year resolution (about 20 mm sediment) were extracted for ^{10}Be measurements from sediment cores TSK11 and JC-20 M2015, based on varve chronologies (Dräger et al., 2017; Ott et al., 2016).’

Page 3 Methods – Page 4 Results: Overall, this section leaves me a bit confused. For a reader I feel I am left with a tenuous grasp on the TSI and CJ records. Although the references are provided it would be helpful to shed light on these previously published varve records that are frequently referred in the text, e.g. where the non-varved sections are located and how the sediment composition changes (in time/depth scale)? An illustration of the records perhaps with some Ti, Ca TOC and even 10Be variation curves would be helpful to quickly get an overall picture of the two records.

See our Detailed Answer #3 ‘Visualization of ^{10}Be and sediment properties’. Moreover, we now add information about non-varved sediment sections in Lake Tiefer See to Fig. 2, by highlighting the respective time-intervals with bars and citing Dräger et al. (2016, *The Holocene*). We describe this new feature in the caption to Fig. 2.

Page 4 Line 27: Although references are provided it would be helpful to mention briefly how environmental and catchment conditions can influence the 10Becon variation in sediment record.

We discuss in detail possible mechanistic linkages between environmental effects and ^{10}Be deposition in Lakes Tiefer See and Czechowskie sediments at the end of Chapter 5.1, after describing and performing our procedure used for the attribution and correction of these effects. To be clearer about this sub-structure, we extended and reformulated the introductory paragraph of Chapter 5.1:

‘Environment and catchment conditions can add non-production variations to $^{10}Be_{con}$ records from varved lake sediments (Berggren et al., 2010; Czymzik et al., 2015). In the following chapter we will, first, describe and perform our approach used for detecting and correcting for possible non-production features in our ^{10}Be time-series and, then, discuss possible mechanisms behind the statistically inferred connections.’

Page 5 Line 12: The correlations could be added in the figure 4 similarly as is done in figures 2 and 3.

Done.

Page 5 Line 19: Could these depositional mechanisms be briefly described?

See our answer to comment 'Page 4, Line 27'.

Page 5 Line 20-21: At this point it does not become clear which correlations are referred. This becomes clear later in the paragraph but text would be easier to follow if the correlations were specified before showing the numbers.

We now mention the correlations between ^{10}Be and TOC before we provide the correlation coefficient and significance level (lines 6.5-7).

Page 6 Line 8-9: Why? Are there indications in the sediments that suggest resuspension of littoral sediments or changes in sediment focusing? The illustration of sediment composition (see general comments) could be helpful here.

See our Detailed Answer #3 'Visualization of ^{10}Be and sediment properties'. We added more detailed information on the sub-layer of resuspended littoral sediments in JC varves back to 2800 a BP in Section 5.3. To avoid repetition, we prefer not to go into detail at this point, but to hint more clearly to the later discussion (lines 6.25-29):

'In JC sediments, the $^{10}Be_{comp}$ excursion from -50 to 0 a BP (AD 2000-1950) without an expression in the group sunspot number record as well as the about 20-year delayed Maunder Minimum response could be explained by transport of 'old' ^{10}Be from the littoral to the coring site (see more details on the sub-layer of resuspended littoral sediments in JC varves back to 2800 a BP in Section 5.3) and/or spatially inhomogeneous ^{10}Be deposition patterns (Fig. 5).'

Page 6 Line 29-30: This (also) would be nicely clarified with the record-descripting illustration (see comment for Page 3-4 Methods-Results).

See our Detailed Answer #3 'Visualization of ^{10}Be and sediment properties'.

Page 7 Line 1-2: What is this layer? Does this occur at the time interval discussed in this paper at Page 6 Line 6 (from -50 to 0 BP)? If so, this could be mentioned already earlier. This would actually answer partly to the specific comment I made for Page 6 Line 8-9.

This sub-layer was deposited in fall AD 2003. It consists of the same littoral diatoms and patches of calcite deposited in Lake Czechowskie during this season since about 2800 a BP. However, during that year the fall layer was exceptionally thick (3.7 mm), containing comparably high amounts of 'old' ^{10}Be leading to anomalous ^{10}Be concentrations (Czymzik et al., 2015, *Earth and Planetary Science Letters*). Considering the reviewer's comment, we added more information about this exceptional sediment sub-layer to the manuscript (lines 7.22-25):

‘Comparable influences of sediment resuspension were also found in a sample from an annually resolved ^{10}Be time-series of JC sediments covering the period AD 2009-1988 (Czymzik et al., 2015). A varve with an exceptionally thick (3.7 mm) layer of resuspended littoral diatoms and patches of calcite deposited in fall 2003 reveals anomalous ^{10}Be concentrations (Czymzik et al., 2015).’

Figure 4: Why 10Becon and 10Beenvironment are out of phase in Lake Czechowskie from about 2700 to 3100 BP?

This is an effect of our 'environment correction' procedure. When the correction is large, the generated signal will look increasingly different from the original $^{10}Be_{con}$ record. That this looks partly like a phase shift is mere coincidence. We discuss in lines 7.17-25 that we do not obtain significant fits between Lake Czechowskie ^{10}Be and IntCal13 ^{14}C production during the Maunder- and Homeric Minima and point out that this is likely due to environmental influences on Lake Czechowskie ^{10}Be, which are challenging to correct for.

We thank Anonymous Referee #2!