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Climate of the Past Discussions

# *Interactive comment on* "Synchronizing $^{10}$Be in two varved lake sediment records to IntCal13 $^{14}$C" *by* Markus Czymzik et al.

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Response to the reviewers' comments We thank Quentin Simon for his constructive and very 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.

(1) Changes in sediment composition, their possible effects on 10Be deposition and how to correct for them

Apparently, we were not clear enough about the possible effects of changes in sediment composition on 10Be deposition in TSK and JC, and how we try to reduce them. Therefore, we modified the manuscript in two ways: (1) To improve the overview on



varying 10Be concentrations and sediment composition in TSK and JC, we now show in addition to Figs. 2 and 3 (10Be concentrations, Ti, SAR, TOC, Si and Ca proxy time-series vs. time) our 10Be records against sediment core depth in the new Figure S1, as suggested by Quentin Simon. (2) To be clearer about the possible modification of 10Be through changes in sediment composition as well as our correction procedure, we have extended and restructured Chapter 5.1, following the reviewer's comments. We now first present our statistical approach (multi-regression analyses) applied to detect suspicious similarities between changes in 10Be concentrations and proxy time-series in TSK and JC sediments. The resulting significant contributions to the multi-regressions with 10Be by TOC and Ca for both TSK and JC point to an influence of these proxies on our 10Be records. Therefore, we discuss in a second step the likely mechanisms behind the statistical linkages based on existing literature. This discussion supports the statistically inferred results, pointing to a preferential binding of 10Be to organic material and a reduced affinity for Ca (we provide additional references to support these findings). Third, based on the performed statistical analyses and inferred chemical behavior, we correct our 10Be concentration time-series from TSK and JC by subtracting the calculated bias in 10Be imprinted by TOC and Ca variations. The above analyses and corrections are exclusively based on the statistic similarities between the 10Be and TOC/Ca proxy records as well as the inferred chemical behavior of 10Be in lake sediments. They are not guided by similarities between our corrected 10Be time-series and 14C 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. Comparable linkages between 10Be and TOC, Ca, Ti, Fe and SAR were found in a previous study on 10Be in sediments from Lake Meerfelder Maar, supporting our findings (Czymzik et al., 2016, Quaternary Science Reviews).

The extended and restructured Chapter 5.1.: Environment and catchment conditions can add non-production variations to 10Becon records from lake sediments (Berggren et al., 2010; Czymzik et al., 2015). To detect and reduce these variations, we perform a three-step statistical procedure following Czymzik et al. (2016a), with a slight modification. First, multi-linear regressions were calculated between the 10Becon 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 (10Bebias) (Figs. 2, 3 and S1). Only the TOC and Ca time-series significantly contributed ($p<0.1$) to the final multi-regressions with 10Be for both TSK and JC sediments. These statistical connections between 10Be and TOC / Ca for TSK and JC point to depositional mechanisms of 10Be in lake sediment archives. 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 10Be to organic material (Figs. 2 and 3). This result is supported by significant positive correlations of 10Be 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 10Be for TSK ($r=-0.68$, $p<0.01$) and JC ($r=-0.62$, $p<0.01$) might point to a reduced affinity of 10Be for Ca (Figs. 2 and 3). A similar behavior was detected in studies about 10Be scavenging from the marine realm (Aldahan and Possnert, 1998; Chase et al., 2002, Simon et al., 2016). Based on the statistical connections and inferred chemical behavior of 10Be in sediments, the 10Bebias time-series from TSK and JC sediments were subtracted from the original 10Becon records in an attempt to construct an environment-corrected version of the 10Be record (10Beenvironment). However, this statistical approach also removes variability in the 10Becon records only coincident with variations in proxy time-series, but without a mechanistic linkage, potentially resulting in an overcorrection. Such coinciding variability can, for example, be introduced by solar activity variations causing 10Be production rate changes and climate variations imprinted in the proxy time-series. Therefore, final 10Be composite records (10Becomp) were calculated by averaging the 10Becon and 10Beenvironment records from each site. To enhance the robustness of



the corrections, the procedure was performed on the complete 10Becon records from TSK and JC covering all three grand solar minima. Uncertainty ranges of the calculated 10Becomp records are expressed as the differences between the 10Becon and 10Beenvironment time-series (Fig. 4). Calculated 10Becomp time-series from TSK and JC sediments yield modified trends, but similar multi-decadal variability as the original 10Becon 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 minima (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 10Becon records introduced by varying sedimentary TOC and Ca contents, but largely preserved multi-decadal variations connected with varying 10Be production rates (Figs. 2, 3 and 4). Comparable linkages between measured and corrected 10Be 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).

(2) Original TSK and JC 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 '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 in the new Chapter 3.3.

The new Chapter 3.3. '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:

(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. We wrote in the previous version of our manuscript (lines 2.25) that, to date, mainly ice core and tree archives benefit from the cosmogenic radionuclide synchronization method.

Following the reviewer, we now further specify in line 2.30 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) synchronizing a lake sediment record from Sweden to 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 (mainly on < 500-year time-scales) and paleomagnetic field intensity (mainly on > 500-year time-scales) on 10Be 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 10Be production rate changes induced by solar activity variations (decadal to centennial) and geomagnetic field strength (sub-millennial and longer) 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 10Be research. However, due to the same production mechanism and different geochemical behavior, the shared variance of 10Be and 14C records can be 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 10Be records from TSK and JC sediments to 14C production variations from the tree-ring based part of the IntCal13 calibration curve. We added that information in lines 2.25.

(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 10Be 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 3.5 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 10Be 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 ‘Chronology’. We added to Section 3.1. ‘Sediment subsampling and proxy records’ that a 20-year resolution equals on average about 20 mm sediment.

(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 10Be and the effects of radioactive decay on our time-series in the ‘Results’ section by adding the sentence: ‘Due to the 1.387 $\pm$ 0.012 Ma long half-life of 10Be (Korschinek et al., 2010) the effect of radioactive decay is negligible in our 10Be records’.

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

See our detailed answer 2 ‘Chronology’.

(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).

We added Figure S1 to the manuscript depicting a plot of our new 10Be data from TSK and JC against sediment core depth. We now highlight the investigated three grand solar minima in Fig. 6 using arrows.

(12) 4.30. What kind of non-production forcing parameters can explain part of the 10Be 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 10Be 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 10Been-vironment 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 10Be 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 10Be 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 10Be 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 10Be 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. We added ‘improved chronologies’ to the conclusions. The extended sentence from the conclusions: ‘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!

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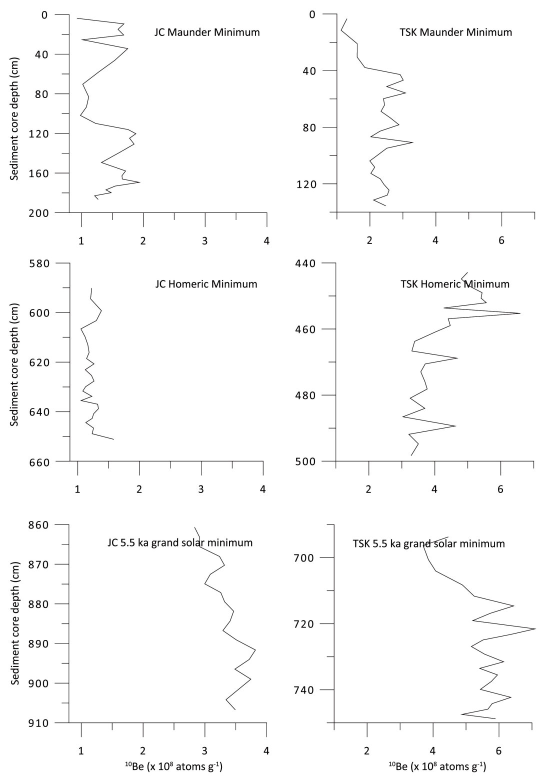


**Fig. 1.** Supp. Fig. 1