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Interactive comment on “Modeling cosmogenic radionuclides ^{10}Be and ^7Be during the Maunder Minimum using the ECHAM5-HAM General Circulation Model” by U. Heikkilä et al.

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Anonymous Referee 1

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1.GENERAL COMMENTS The Maunder Minimum (MM), 1645-1715, is the most pronounced of several cold spells between about 1450 and 1890 that are collectively known as the Little Ice Age (LIA). During the MM there was almost a complete absence of sunspots, suggesting solar variability as the climate forcing agent. Solar variability is independently suggested by an increase of about 30 reports the results of a modeling study that addresses to what extent the observed increases of ^{10}Be concentrations in the ice cores could be due to cli-

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mate (transport) changes rather than production rate (solar) variations. This is a very interesting and important question to address. The paper is well written and I recommend it for publication in ACP after the following comments are addressed.

2. SPECIFIC COMMENTS

a. ABILITY OF THE MODEL TO REPRODUCE PRESENT-DAY (PD) REGIONAL CLIMATE.

- Since this paper concerns regional climate change, it is important to establish the capability of the model to reproduce regional climate realistically. For the PD, the comparison of the model with observation is shown in Figs.2-6. These comparisons show reasonable agreement in overall magnitudes and seasonal variations. However, since the size of the 10Be variation between the PD and MM is only 30% discrepancy is not particularly important when considering *relative* changes of the MM with respect to PD (which could, for example, be simply accommodated by a 10Be production cross section error). However further comments/clarifications are required on the following aspects: - In Figs.3 and 4, the impressive seasonal agreement between observation and model probably simply primarily reflects the seasonal variation of precipitation. If so, this should be pointed out.

Local surface air concentrations are controlled by a multitude of processes including small-scale and large-scale transport processes, precipitation along the transport path, boundary layer turbulence etc. The impact of precipitation at the measurement site on air concentrations is quite small.

- In Fig.5, the observed PD 10Be deposition flux in Greenland varies by up to a factor 1.5 with respect to latitudinal band. Why is this variation not reproduced by the model? If we are to trust the model to interpret a factor 1.3 variation (MM/PD) in 10Be deposition flux at a given Greenland ice core location, then

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we need to be convinced this could not in part be generated simply by a small latitudinal shift of the present-day pattern.

There are several reasons for this: the measurements cover several years, which do not overlap with the modeled years. Also, several measurements which vary by a factor of 1.5, fall within one grid box of the model meaning that the observed differences are related to subgrid scale processes which the model cannot resolve. Due to these reasons we assume that an agreement within a factor of 2 between the modeled and measured fluxes is satisfying. Also it has to be kept in mind that considering the MM/PD variability, we are interested in large-scale pattern changes in Greenland, not in individual grid points of the model.

- Fig.6 shows the model underestimates ^{10}Be stratospheric concentrations by up to a factor 5. Why, and what are the consequences?

Figure 6. shows a huge discrepancy (factor of 5) between instantaneous observations taken at different longitudes and times. Because the aircraft measurements reflect momentary weather conditions and tropopause height these observations only provide a range within which the modeled concentrations should lie. Therefore we show the modeled zonal mean values. While the model underestimates some of the observed concentrations by a factor of 5, at the same time it overestimates other observations.

The fact that the modeled zonal mean values tend to be on the lower side of the spectrum of the observations shows that the stratosphere-troposphere exchange in the model is somewhat too effective. This is discussed in the text. This influences the stratospheric concentrations, but according to the mass balance, the average Be-10 content in the downward fluxes remains unchanged. In the troposphere the effect is small, especially in the polar areas.

b. ABILITY OF THE MODEL TO REPRODUCE MAUNDER MINIMUM (MM) REGIONAL CLIMATE

- Borehole temperature measurements suggest that the global average temperature during the MM may have been about 0.7°C cooler than the mid twentieth century, before appreciable anthropogenic CO₂ emissions. The simulation appears to insert a manual reduction of sea surface temperatures to simulate the MM, along with a reduction of the solar constant by 1.5 W/m². The latter corresponds to about 0.26 W/m² at the top of the atmosphere. Assuming a climate sensitivity of 0.7 K/Wm⁻², this would produce a temperature change of about 0.2°C, which is insufficient to generate the cool MM climate. Does the GCM used in the present study show a 0.7°C cooler mean global climate during the MM? This number should be quoted in the paper. If the model produces only a modest cooling then how does this qualify the conclusions of the paper?

The model does give a global average temperature lower by 0.7 K in MM than in PD. This is quoted now in the manuscript as well.

- In fact, current estimates of the reduction of solar irradiance during the MM are substantially (about a factor 3) smaller than those used in the present simulation. So this model - and moreover, no model, since the detailed climate forcing mechanism of the MM is unknown - does not include a realistic physical mechanism to generate the MM climate. This point should be made clear in the paper. If the forcing mechanism is not known then this fundamentally underpins the level of confidence attached to the conclusions.

The uncertainty of the solar forcing during the Maunder Minimum is large, as well as the climate response to these forcings. We are not able to validate the simulated temperature or precipitation rates during the Maunder Minimum, we can only compare them with other estimates. However, the main result of this study namely that the Be-10 deposition is mostly determined by its production rate even in a significantly cooler climate is still valid, although the generation of the cooler climate might include some uncertainty.

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The fact that the model is able to simulate the present day climate and Beryllium deposition and air concentrations reasonably well, as well as those concentrations which we can compare with measured concentrations during the MM corroborates our conclusions.

- There is good evidence to suggest that the Inter Tropical Convergence Zone (ITCZ) shifted southwards during the LIA, on a global scale. This implies a significant movement of the atmospheric circulation cells in the tropics, which could easily have caused a corresponding rearrangement at higher latitudes, possibly affecting circulation patterns over Greenland. The flux of ^{10}Be can vary by a factor 10 at a given latitude depending on the relative amount of wet and dry deposition. Since there is a large contrast of precipitation across PD Greenland (a factor 10 or so), it follows that a small change of circulation patterns could have a large effect (large compared with 30) on the ^{10}Be deposition flux. Even layer-counting may not avoid the uncertainty in the wet/dry transport ratio, when converting ^{10}Be concentration into ^{10}Be flux, since there may be climatic variations in the rate of sublimation of snow after deposition. Does the GCM used in this study show such a shift of the ITCZ? What uncertainty does this introduce on the overall conclusion of the paper?

In this model run no significant shift of the ITCZ was observed. Whether this is realistic or not, cannot be answered based on the present knowledge. However, a shift in the tropics would not necessarily have a large impact on Greenlandic precipitation rates.

The precipitation rates in Greenland vary between 1.5 mm/day (Dye3, Milcent) in the south and 0.5 mm/day in the north (GRIP, NGRIP) and are generally high compared with the Antarctic precipitation rates (<0.1 mm/day in Vostok or South Pole). The model reproduces these precipitation changes quite well. It estimates a rather constant ratio of dry to total deposition (wet+dry) of Be-10 in Greenland of approximately 0.9-0.95, which does not vary significantly with latitude. Therefore, changes in precipitation pattern in Greenland should not influence the wet/dry deposition ratio.

c. COMPARISON WITH FIELD ET AL. (JGR 111, D15107, 2006) AND THE 14C RECORD Despite the above reservations - which could apply to **any** GCM study of the MM climate - I would like to stress the importance of modeling studies such as the one reported here. These models provide important insights on the climate processes involved in transporting ¹⁰Be and similar radionuclides to their archives. I expect the models will ultimately provide reliable results with a high level of confidence. However, for the reasons indicated above, I feel that this study (and that of Field et al.) should not be considered as definitive. Indeed, Field et al., using the ECHAM5-HAM GCM, reach the opposite conclusion of the present paper, which perhaps illustrates the uncertainties that exist in the conclusions of both papers. The limitations of the present study should be made more explicit in the paper in order to avoid a busy reader from drawing unreasonably firm conclusions.

This is a misunderstanding. Field et al, [2006] used a different GCM, the ModelE GCM of Goddard Institute for Space Studies. In spite of using different models, both studies come to very similar conclusions. Both model studies are able to simulate the present-day climate and the distribution of Be-10 deposition fluxes and air concentrations reasonably well, which gives confidence to varied climate simulations.

So who is right: this paper, which finds a relatively small climatic influence on the ¹⁰Be deposition fluxes during the MM, or else Field et al., which finds large climate effects - comparable to the production changes? The most convincing argument is the experimental comparison of ¹⁰Be and ¹⁴C production between the MM and PD, which supports the conclusions of the present paper. Carbon-14 has a completely different transport mechanism (it rapidly oxidises to ¹⁴CO₂ and then enters the well-mixed carbon cycle). The good agreement between the ¹⁰Be-derived and ¹⁴C-derived measurements of the production changes indicates that the ¹⁰Be ice cores reliably measure GCR changes since the MM. The present authors have in previous papers stressed the good agreement between

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10Be and 14C measurements during the Holocene, and this should be pointed out again in the present paper. This, finally, is the most convincing argument that there was a true production increase of around 30% during the MM.

Unfortunately it is not possible to compare our results in detail with previous results by Field et al. [2006] because their experiments were different in character from our Maunder Minimum experiment. They separated the different factors which affect the polar Be-10 fluxes (modulation of the production of Be-10 and different climatic effects) to assess their relative contributions to the deposition changes. Our goal was to change both the Be-10 production and the climate to identify the dominant component. Unfortunately these results do not allow a direct comparison in magnitude with experiments where only the Be-10 production or climate is changed.

Nevertheless, we now included a more detailed comparison in the manuscript. Field et al, [2006] conclude that "Be-10 response to climate should not be neglected when inferring production changes" and "Interpreting the Be-10 record without accounting for possible climate-related changes carries the risk of inferring the existence of solar changes that are larger than those which actually occurred". We would like to stress that they do not state that the climatic effects would distort the production signal. Unfortunately this misinterpretation has been used as an argument against the use of Be-10 for solar activity reconstructions [i.e. Foukal et al, Nature 443, 2006] The conclusion of Field et al. [2006] that climatic effects do have an influence on the Be-10 fluxes is in agreement with our results. Our intent was to go a step further and to quantify these climatic effects.

Both the model experiment as well as the good agreement between Be-10 in ice cores and C-14 in tree rings point to a dominant production signal which means that Be-10 is suitable to reconstruct the solar activity. The GCM experiments help us to further reduce the effect of the climate on the Be-10 concentration and to improve the solar activity reconstructions.

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