Comment by Tim Heaton et al. (cp-2021-134-CC1-supplement.pdf)

The reviewer comments are in black text; our replies are in blue italicised text.

We congratulate the authors on a novel approach providing a first step to answering a key question regarding the past extent of sea ice in the polar regions (in this case Antarctica). As authors of the Marine20 curve, this is a topic which is of direct interest to us since, as noted by MyClymont et al. (under review), the extent and location of this ice makes a considerable difference to air-sea gas exchange and hence the concentration of ^{14}C in the surface ocean in polar regions. Currently very little is known about the extent of this ice, making calibration of ^{14}C from marine samples challenging.

We thank the comment authors for their positive comments.

In our comment, we restrict our attention to the calibration of polar ^{14}C samples. In brief our contribution consists of:

a) We would no longer recommend the use of Marine13 or any earlier marine product for any ^{14}C calibration – the statement in the Marine20 paper (Heaton et al., 2020) regarding Marine20 being unsuitable for polar calibration applies equally, if not more so, to the Marine13 curve (Reimer et al., 2013).

b) Calibration of ^{14}C marine samples from polar regions, from pre-Holocene time periods, is complicated since, at high-latitudes, the value of ΔR during glacials is unlikely to remain constant, or similar to the values seen during the recent past and Holocene. This is primarily due to localised sea-ice and regional winds during cold stadials.

c) Calibrating polar ^{14}C marine samples from cold stadials using any Marine calibration curve (Marine20 or any earlier product) and an estimate of ΔR based on samples from the recent past is likely to lead to bias and overconfidence. The true calendar age will likely be more recent than the calibrated age estimate generated using a constant ΔR based on samples from the recent past.

We agree with these three points, and respond to the detailed comments below.

We propose, for those wishing to calibrate polar ^{14}C marine samples, using two different values of ΔR – one representing a low ^{14}C -depletion scenario (corresponding to little sea-ice) similar to the Holocene; and the other a higher ^{14}C -depletion scenario (corresponding to higher levels of sea-ice). The true calendar ages of the samples should hopefully lie between the calibrated age estimates obtained in these two extreme scenarios.

We discuss the impact of this recommendation in the text below.

In this comment we discuss how one might adjust ΔR for the specific location of these snow petrels. We are currently in the process of providing a short note to describe to wider users how this adjustment might be done for any sample. In our comment, we introduce the term ΔR_{20} to refer to the value for use with the Marine20 calibration curve (and ΔR_{13} the value for the Marine13 curve).

Calibration of Marine ^{14}C Samples in Polar Regions

The aim of the marine calibration curves (such as Marine20 and earlier products) is to provide a "best estimate" of the global-scale surface water ^{14}C concentration that has factored out the effect of large-scale carbon cycle changes (e.g., changes in atmospheric

^{14}C, CO_2, ocean circulation, ...). The Marine20 curve should do this more accurately than Marine13.

However, if there are significant localised effects in the region from which the sample arose, such as polar sea ice, these will cause extra localised ^{14}C depletion. These effects mean ΔR_{20} will be significantly larger pre-Holocene, compared to post-Holocene, in polar regions.

Location specific estimates of the overall oceanic ^{14}C depletion (i.e. total MRA) are available under fixed carbon cycle and climate scenarios using the LSG ocean general circulation model (Butzin et al., 2020) at https://doi.pangaea.de/10.1594/PANGAEA.914500. These LSG estimates can be used for calibration – by adjusting the IntCal20 curve – however it is important to note these LSG scenarios are not transient, in terms of climate, and so calibrating against any individual scenario is still likely to lead to overconfidence.

We suggest that to calibrate marine ^{14}C samples from polar regions, one uses Marine20 but considers two extreme scenarios: one accounting for minimal further polar ^{14}C depletion for which the ΔR_{20} is small; the other for maximal further polar ^{14}C depletion for which ΔR_{20} is large. Calibrating against Marine20 under these two scenarios should provide bracketing calendar ages for the true age of the sample. We select these two ΔR^{20} values ($\Delta R^{\mathrm{Hol}}{}_{20}$ and $\Delta R^{\mathrm{Icy}}{}_{20} R$) based upon the latitudinal averages of the LSG model under the PD (present day) and GS (glacial) scenarios.

We thank the authors for this suggestion, and discuss the impact of their recommendation in the text below, and make changes to Table 1 to demonstrate the impact of these two calibration scenarios.

1) *Low-depletion ΔR – assuming no regional effect of sea ice cover*

Estimate a $\Delta R^{\mathrm{Hol}}{}_{20}$ (so-called since it is based on Holocene data) based on the Bjorck et al. (1991) pre-nuclear weapons testing samples. Then calibrate using this $\Delta R^{\mathrm{Hol}}{}_{20}$ estimate against Marine20. You will have to update your $\Delta R^{\mathrm{Hol}}{}_{20}$ to match the Marine20 curve. In your case, the correct $\Delta R^{\mathrm{Hol}}{}_{20}$ to use is 670 ± 50 ^{14}C yrs (updated to correspond to Marine20).

Calibrating under this scenario will provide a calendar age estimate assuming there is no regional sea ice and so there is no further localised depletion. Our calculations suggest that, using Marine20 and a $\Delta R^{\mathrm{Hol}}{}_{20}$ of 670 ± 50 ^{14}C yrs, then, e.g., 25980 ± 133 ^{14}C yrs BP will calibrate to 28,680 cal yr BP (median, with a 2σ interval of [28300, 29000] cal yr BP).

We provide an updated Table 1 where this calibration has been applied.

2) *High-depletion ΔR – including an effect for regional polar sea ice causing further localised depletion*

The calendar ages obtained above in the low depletion scenario (using a Holocene based $\Delta R^{\mathrm{Hol}}{}_{20}$) are probably too old (biased). There is likely further local ^{14}C depletion due to the sea ice, especially around the LGM.

To include the effect of the sea ice in your region, and get an idea of the likely bias, we can compare the regional LSG and global Marine20 estimates. This suggests that, during the last glacial period, there might be up to c.a. 1800 ^{14}C yrs additional ocean ^{14}C depletion at a latitude of 70ºS. This estimate is based upon a latitudinal average of the difference between Marine20 and the LSG GS scenario (having shifted the LSG so that its PD scenario aligns with Marine20 in the Holocene).

To approximately model the effect of this potential level of additional marine ^{14}C depletion then you boost your ΔR_{20} accordingly, i.e., use $\Delta R^{GS}{}_{20}$= 670 + 1800 = 2470 ^{14}C yrs. Our calculations indicate that, using this value of $\Delta R^{GS}{}_{20}$ and Marine20, 25980 +/- 133 ^{14}C yrs BP will calibrate to 26,920 cal yr BP (median, with a 2σ interval of [26500, 27200] cal yr BP).

We provide an updated Table 1 where this calibration has been applied.

Proposed new Table 1 for the manuscript:

Table 1 Radiocarbon dates and calibrated ages. All ^{14}C analyses were performed on bulk samples at CologneAMS, Germany. COL3022 was previously published (Berg et al., 2019). All calibrations to calendar ages used MARINE20 (Heaton et al., 2020). To explore the likely range of impacts of sea ice on our ^{14}C calibrations, we first apply the nearest Holocene *ΔR* of 670 ± 50 yr (Björck et al. 1991) which assumes no sea ice at WMM7 ($\Delta R^{no\ ice}$). Calibration assuming enhanced sea ice cover, as suggested for the last glacial stage, is undertaken by adding 1800 yr of additional ocean ^{14}C depletion as suggested by Heaton et al. (2020; 2021).

Depth (mm)	Unit	AMS Lab ID	Median Age (^{14}C yr BP)	+/- (^{14}C yr BP)	Calibrated age (cal. yr BP) MARINE20, $\Delta R^{no\ ice}$ 670 ±50 yr	Calibrated range (2σ)	Calibrated age (cal. yr BP) MARINE20, $\Delta R^{sea\ ice}$ 2470 ±50 yr	Calibrated range (2σ)
0	I	COL3022	21,550	110	23987	23668-24366	22061	21736-22358
0	I	COL4327	21,660	104	24124	23758-24495	22171	21859-22492
40	I	COL4326	23,170	114	25760	25488-26091	23810	23502-24167
79	I/II	COL4328	24,790	115	27350	27093-27614	25603	25263-25868
108	II/III	COL4329	25,980	133	28585	28215-28938	26825	26389-27126
135	III	COL4325	26,920	149	29531	29116-29867	27642	27266-28057
160	III	COL4324	27,730	148	30307	29949-30685	28522	28105-28912

What to plot in terms of calendar ages?

These two (high- and low-) depletion scenarios should provide a bracketing lower- and upper- set of calendar ages for each ^{14}C sample. These are however evidently very wide (the difference in the median calibrated ages under these two scenarios is 1760 cal yrs).

Around the LGM, we might expect the calendar ages obtained under the high-depletion scenario (i.e., option 2) to be more accurate, especially in such a polar location (around 70˚S). However, until we know more about sea ice extent and regional palaeoclimate it will be challenging to be definitive – the correct calendar ages could lie anywhere in between the two scenarios.

We agree that it is informative to see the range of ages generated using these two approaches. However, we also think it is important that we note clearly in the text that these are presented as end-member scenarios, with reality lying somewhere in between. As the snow petrels are foraging in open waters within the sea-ice pack or close to the sea-ice margin, where air-sea gas exchange is taking place, we consider that the high-depletion scenario is likely to be an over-estimate. If snow petrels are feeding in polynyas during our time interval, that situation in turn implies that there is better sea-ice exchange than the LSG scenario predicts.

We would suggest that when plotting the proxy on a timescale (as in Figures 3 – 6) that the high depletion scenario might be shown, but with a clear explanation that this is an extreme scenario (and likely providing the most recent estimates of the calendar ages). Further, we suggest that perhaps in the main text, Table 1 shows the calibrated ages under both extreme (high- and low-) depletion scenarios in separate columns.

As we note in our previous reply, we consider that the high-depletion scenario (which shows younger ages) is likely over-estimating the delta-R where our snow petrels are foraging. We prefer that when we show our data on a timescale (Figures 3-6), we show the data using the oldest likely ages (i.e. with $\Delta R^{\mathrm{Hol}}{}_{20}$) and acknowledge that these are maximum estimates with reference to Table 1. Adopting this approach also means that for those researchers using stomach-oil deposits to trace ice-sheet thinning histories (e.g. Hiller et al. (1988), and as reviewed by Hillenbrand et al., 2014) where the oldest data of snow petrel occupation is important, the palaeo-environmental and palaeo-glaciology data are using the same age model approaches, rather than two age models appearing in the literature for the same deposits.

We could show selected data under the two age estimates in Figure 6 (climate links) or instead as a separate Appendix (for example, as we do for comparing normalised and original XRF data). We think that a revised Figure 6 (shown overleaf) would be the best plot for showing the impact of our alternative age constraints in the context of other climate records, as it highlights the challenge of making millennial-scale links which we refer to in the main text.

We suggest it might be possible in the future for you to use the simultaneous sea-ice proxy information you have (i.e., stomach oil composition) to determine for each individual ^{14}C sample a suitable level of local depletion ΔR_{20} before calibration. This could use the sea-ice proxy as a sliding scale to transfer from the high- and low-depletion scenarios.

Perhaps as your project progresses further, it might also help us to determine sea ice extent in a way we can incorporate that information into future IntCal curves.

This is also our hope, that we can use our stomach-oil deposits to learn more about the sea-ice environment and its changes through time, so that we might contribute to improving chronological constraints.

Again, we would like to thank you for the opportunity to comment on your paper. It is an exciting project that we look forward to learning more about,

Timothy J. Heaton

Edouard Bard

Christopher Bronk Ramsey

Martin Butzin

Peter Kohler

Paula J. Reimer

Proposed revision to Figure 6 to show impact of different calibrations:

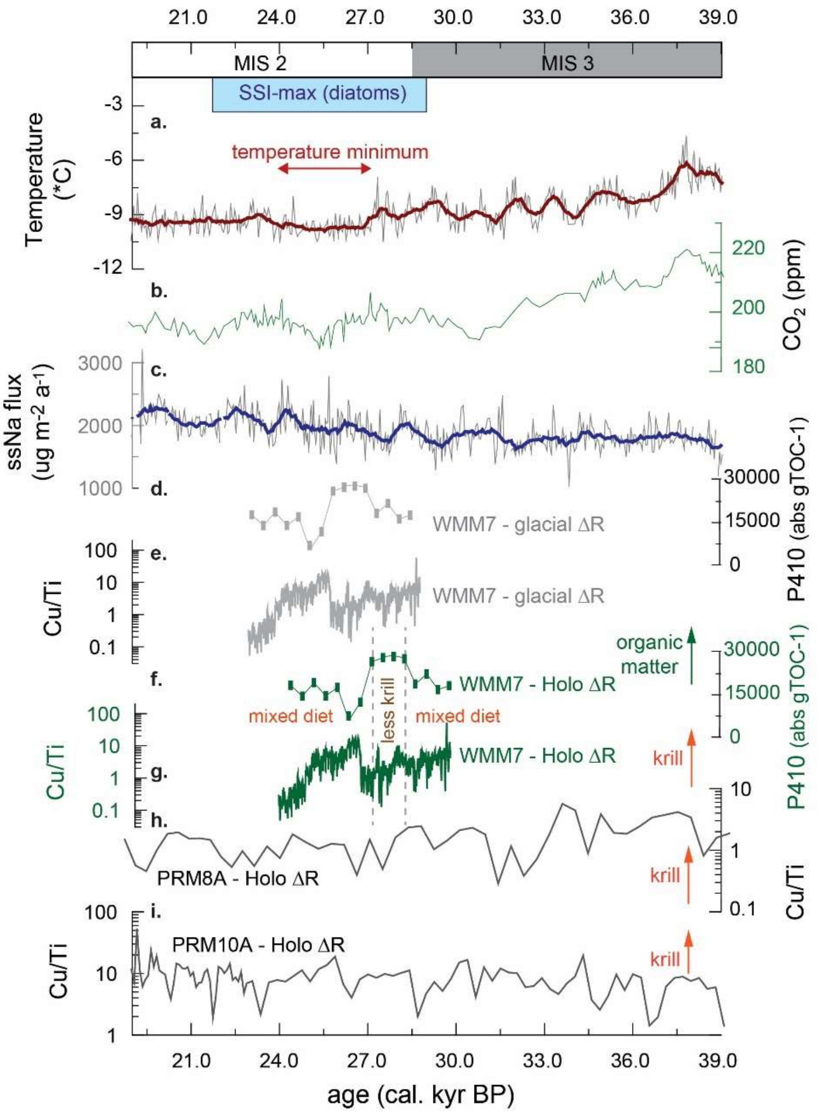

Figure 6: variations in snow petrel diet across the MIS 3-2 transition, including the interval of maximum summer sea-ice extent (SSI-max) in the Scotia Sea from Allen et al. (2011) and plotted in Fig.1. (a.) air temperature recorded by δD in EPICA-DML ice core (Jouzel et al., 2007); (b.) atmospheric CO_2 from West Antarctic Ice Sheet (WAIS) ice core (Bauska et al., 2021); (c) sea-salt Na flux from EPICA-DML ice core (Fischer et al., 2007); (d.) WMM7 chlorin pigment abundance, interpreted here as an enhanced phytoplankton/reduced krill signal, <u>plotted using the Holocene (low/absent sea ice) ΔR from Table 1 and Figs. 3-5</u>; (e.) WMM7 Cu/Ti ratio, interpreted here as evidence of enhanced krill inputs<u> plotted using the Holocene ΔR from Table 1 and Figs. 3-5</u>. As discussed in the text, we infer the loss of krill from the snow petrel diet ~25 ka to represent polynyas opening over the continental shelf; (f.) <u>WMM7 chlorin pigment abundance, interpreted here as an enhanced phytoplankton/reduced krill signal, plotted using the Glacial Stage (enhanced sea ice) ΔR from Table 1; (g.) WMM7 Cu/Ti ratio, interpreted here as evidence of enhanced krill inputs plotted using the Glacial Stage (enhanced sea ice) ΔR from Table 1</u>. (h.) and (i.) Cu/Ti signals in other DML stomach-oil deposits, from analysis in Berg et al. (2019) and re-calibrated using the <u>Holocene ΔR from Table 1</u>.

<u>Final Minor Addendum (Sterken et al., 2012):</u>

We wondered why you used a ΔR uncertainty of ± 100 ^{14}C yrs when Sterken et al. (2012) use the Bjorck et al. (1991) uncertainty of ±50. Normally, in the radiocarbon community, when one reports ± in this way, one is referring to the 1σ value. It is not necessary to double that for input into OxCal or CALIB although certainly justifiable given that the ΔR value was based on a 1903 penguin bone sample and when the Marine13 you were calibrating against assumed a constant reservoir offset from the atmosphere during the period of your samples.

Our rationale for this was to address the unknown uncertainties of the calculated delta-R value, but we welcome the recommendation to apply the published uncertainty, especially since Table 1 shows that there is larger calibrated age uncertainty associated with choice of delta-R.

In general, we think the ΔR value reported in Sterken et al. (2012) is slightly wrong for use against Marine13. This ΔR is based upon penguin bones which were collected in 1903 which have a ^{14}C age of 1280 ± 50 ^{14}C yrs BP (Bjorck et al., 1991). To work out ΔR_n, where n represents the Marine curve you are using, you have to look at the offset between that Marine curve and the observation in the specific year of interest:

Marine13 – the mean of Marine13 in 1903 (47 cal yr BP) is 450 ^{14}C yrs BP (not the 400 ^{14}C yrs BP as stated by Sterken et al., 2012). Using the correct Marine13 values this would equate to a ΔR_{13} of 830 ± 50 ^{14}C yrs (not 880). We think Sterken (2012) may have erroneously subtracted the difference between the present-day (i.e., at 0 cal BP) Marine and IntCal curves. This is not the correct way to calculate the depletion since IntCal does not go through 0 ^{14}C yrs BP at 0 cal yrs BP.

Marine20 − the mean of Marine20 in 1903 is 610 ^{14}C yrs BP. This equates to a ΔR_{20} of 670 ± 50 ^{14}C yrs as stated in your suppl. information.

We thank the authors for this clarification, and as noted above we will use the recommended ΔR_{20} of 670 ± 50 ^{14}C yrs.

References

Bjorck, S., Hjort, C., Ingolfsson, O., & Skog, G. (1991). Radiocarbon dates from the Antarctic Peninsula region -problems and potential. *Quaternary Proceedings*, *1*, 55–65. http://inis.iaea.org/search/search.aspx?orig_q=RN:24035146

Butzin, M., Heaton, T. J., Kohler, P., & Lohmann, G. (2020). A Short Note on Marine Reservoir Age Simulations Used in IntCal20. *Radiocarbon*, *62*(4), 865–871. https://doi.org/DOI: 10.1017/RDC.2020.9

Heaton, T. J., Kohler, P., Butzin, M., Bard, E., Reimer, R. W., Austin, W. E. N., Bronk Ramsey, C., Grootes, P. M., Hughen, K. A., Kromer, B., Reimer, P. J., Adkins, J., Burke, A., Cook, M. S., Olsen, J., & Skinner, L. C. (2020). Marine20—The Marine Radiocarbon Age Calibration Curve (0–55,000 cal BP). *Radiocarbon*, *62*(4), 779–820. https://doi.org/DOI: 10.1017/RDC.2020.68

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatte, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., ⋯ van der Plicht, J. (2013). IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP. *Radiocarbon*, *55*(4), 1869–1887. https://doi.org/10.2458/azu_js_rc.55.16947

Sterken, M., Roberts, S. J., Hodgson, D. A., Vyverman, W., Balbo, A. L., Sabbe, K., Moreton, S. G., & Verleyen, E. (2012). Holocene glacial and climate history of Prince Gustav Channel, northeastern Antarctic Peninsula. *Quaternary Science Reviews*, *31*, 93–111. https://doi.org/https://doi.org/10.1016/j.quascirev.2011.10.017

Heaton, T. J., Köhler, P., Butzin, M., Bard, E., Reimer, R. W., Austin, W. E. N., Bronk Ramsey, C., Grootes, P. M., Hughen, K. A., Kromer, B., Reimer, P. J., Adkins, J., Burke, A., Cook, M. S., Olsen, J., and Skinner, L. C.: Marine20—The Marine Radiocarbon Age Calibration Curve (0–55,000 cal BP), Radiocarbon, 62, 779-820, 10.1017/RDC.2020.68, 2020.