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.

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 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.

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 (ΔR_{20}^{Hol} and ΔR_{20}^{Icy}) based upon the latitudinal averages of the LSG model under the PD (present day) and GS (glacial) scenarios.

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

Estimate a ΔR_{20}^{Hol} (so-called since it is based on Holocene data) based on the Björck et al. (1991) pre-nuclear weapons testing samples. Then calibrate using this ΔR_{20}^{Hol} estimate against Marine20. You will have to update your ΔR_{20}^{Hol} to match the Marine20 curve. In your case, the correct ΔR_{20}^{Hol} 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 ΔR_{20}^{Hol} 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).

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 ΔR_{20}^{Hol}) 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 ΔR_{20}^{GS}= 670 + 1800 = 2470 ^{14}C yrs. Our calculations indicate that, using this value of ΔR_{20}^{GS} 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).

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 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.

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.

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 Köhler
Paula J. Reimer

Final Minor Addendum (Sterken et al., 2012):

We wondered why you used a ΔR uncertainty of ± 100 ^{14}C yrs when Sterken et al. (2012) use the Björck 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.

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 (Björck 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}Cyrs (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}Cyrs 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}Cyrs as stated in your suppl. information.

<u>References</u>

Björck, 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., Köhler, 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., 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., & 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., Hatté, 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