

Response to Anonymous Referee 2

Referee comments are in regular font

Our responses are in italics

Review of: “Characterization of in situ cosmogenic ^{14}C production, retention and loss in firn and shallow ice at Summit, Greenland”

by Benjamin Hmiel et al., submitted to The Cryosphere.

This manuscript targets understanding and constraint of the production, movement and retention of in-situ cosmogenic ^{14}C in ice. This is done based on the analysis of ^{14}C at different depths in the firn, both, in gas from the porous, open firn space (firn air) and the gas trapped in extracted firn/ice samples (firn matrix and bubbly ice below the firn zone, respectively). The authors achieved to perform the highly challenging analysis of ^{14}C in firn and ice with convincingly high accuracy, which is a fantastic achievement. While the contribution to in-situ ^{14}C (and total ^{14}C) from production by neutrons is relatively well studied and seems reasonably well understood, more recent findings indicated that the signal from production by deep-penetrating muons via the negative muon and fast muon capturing mechanisms is lower than one would expect based on the literature by around a factor of 5 (Dyonisius et al., 2023). This is a relevant difference and can have important implications on the interpretation of results in a variety of research areas where cosmogenic isotope production affecting the background is an issue. The manuscript therefore strongly focuses to further investigate this discrepancy. A modelling framework, essentially combining a previously established ^{14}C production model (Balco et al., 2008; adapted for a firn/ice matrix) with the firn gas transport model by Buizert et al. (2012) and a new box model to consider retention (or leakage, respectively) of the evolving ^{14}C partition/fraction to the firn gas was accordingly developed. For the processes and conditions assumed in this model approach and compiled up-to-date atmospheric histories used for input, a close match between model results and the paleo-observational data was achieved but noteworthy, includes a variety of free (tunable) parameters (factors) associated with the various, archive specific (at least partly inter-related) physical and chemical processes and mechanisms involved. The authors show these parameters to be well constrained and thus reasonably close predictions of the expected cosmogenic ^{14}C in-situ contribution to ^{14}C (and likely also $^{14}\text{CO}_2$) should be achievable, which is certainly valuable and beneficial for future studies in firn and ice.

The paper is very well written, the analytical methods are of highest standard (pushing the boundaries) as are the technical aspect of the modeling. However, while the study confirms the previous findings of lower-than-expected contribution from the negative muon and fast muon capturing mechanisms, it needs to be seen if a revision of the respective production rate estimates is required or if a lack of understanding in many of the complex (and directly related) processes in ice and firn currently remains the more likely explanation. My main concern is linked to this last point (see details below), and I suggest the manuscript to be published after minor reviews.

We thank the referee for their very in-depth review, and address the points below.

Main issues

General:

The topics covered by the manuscript, from the analytics to the postprocessing of measured data as well as interpretation, are manifold and rather complex. Therefore, and although the authors already did a great job in writing, the manuscript is challenging to read and comprehend. What I struggled most with, was to keep the overview what model parameters/input and mechanisms are well (or reasonably well) determined based on previous studies and which are introduced factors, required to allow matching of model results with the data (model tuning factors; to just name some examples e.g. R , f_{μ^-} , $f_{\mu f}$ or factors introduced to account for (additional?) uncertainty like F_n). I thus suggest providing an overview table, where the relevant parameters and reconstructed input (e.g. $P_n(0)$, “baseline” atmospheric ^{14}CO) is summarized including the relevant description and some associated information (e.g. uncertainty).

We can include such an overview table of model parameters in the revised manuscript to assist readers with keeping track of the model parameters.

Such an overview would not only facilitate reading, but also be beneficial for the reader to understand if a tight match between model result and data or a well constrained factor is largely the result of an in-depth understanding of processes and mechanisms at play or at least partly the result of a sufficient high number of free parameters allowing for tight model tuning.

To clarify, our main goal in the model-data comparison is not to arrive at a single set of tunable parameters that yields the best match to the data, but rather to determine the possible range of values for each of the tunable parameters.

There are indeed several adjustable parameters in the model (R_1 , L_1 , F_n , f_{μ^-} , $f_{\mu f}$, atmospheric ^{14}CO history). However, we are only trying to determine the possible ranges of R_1 , L_1 , f_{μ^-} , $f_{\mu f}$, and not all at once. F_n (0.9 – 1.1 value range) is simply a scaling factor that represents the uncertainty range for ^{14}C production rate by neutrons from prior studies (see Section 3.2.1 as well as line 452 in the manuscript). The range of atmospheric ^{14}CO histories used in the model (Section 4.3.2) is intended to be conservative (as broad as possible) considering possible variations in the main ^{14}CO sink (OH radicals) and stratosphere to troposphere transport. The broad range of ^{14}CO histories chosen ensures that the range of accepted $f_{\mu f}$ and f_{μ^-} values is also conservative.

The $R_1 - L_1$ parameter ranges are determined based on the firn matrix ^{14}CO profile (Figure 4; lines 431 – 439 already explain this in the manuscript) and are insensitive to the choice of f_{μ^-} and $f_{\mu f}$, as the manuscript already also already explains on lines 453 – 457. So here we are only determining two parameters at once, and provide feasible ranges for both.

The $f_{\mu^-} - f_{\mu f}$ parameter ranges are determined based on ^{14}CO measurements in lock-in zone (LIZ) firn air and in ice below the LIZ (already stated on lines 440 – 442). As Section 4.3.1 in the manuscript explains, in the model we trial all $f_{\mu^-} - f_{\mu f}$ parameter pairs from Dyonisius et al. (2023), together with several options of atmospheric ^{14}CO histories as well as combinations of F_n , R_1 and L_1 that yield the full possible range of resulting ^{14}CO (from maximum to minimum).

Trialing a wide range of scenarios for atmospheric ^{14}C history and the full possible range of values for F_n , R_1 and L_1 (as determined in Section 4.2 of the manuscript) allows for a conservative (broad) range of f_{μ} -- $f_{\mu f}$ values to be accepted.

We can add a further clarification in the manuscript that we are only ever constraining two tunable parameters at a time.

With “processes and mechanisms at play” I hereby refer to the physical and chemical processes involved and happening in the ice. For the different species, both in the gaseous (e.g. CO, CO₂, CH₄) and liquid phase (e.g. DOC) the following come to mind: (i) the specific chemical reaction mechanisms and reaction kinetics on ice surfaces/in quasi-liquid-layers, maybe associated with fractionation and considering equilibria in the partitioning of in-situ ^{14}C into different species (e.g. CO, CO₂, CH₄, DOC) potentially also temperature dependent, (ii) the diffusion of gases in ice, which is certainly different from the diffusion of DOC (and also its releases into the porous open space of the firn), (iii) snow and firn metamorphism (i.e. recrystallisation), (iv) the potential effect of impurities in ice on ^{14}C production rates, (v) the gas transport in the firn and firn ventilation, etc.. Some of these points are more or less thoroughly addressed and discussed in the current manuscript while others are not mentioned. For this reason, I suggest that a revised version of the manuscript aims to better clarify and distinguish the level of process/mechanism understanding and the likelihood that a lack thereof might (or might not) explain the observed discrepancy, e.g. between the observed ^{14}C in ice and the one expected based on previous determinations of ^{14}C production rates from studies in quartz.

The authors should note that for in-situ cosmogenic ^{14}C analysis in quartz the analytical procedures and techniques are very well established and a very large number of studies exist, the use of reference standard reference materials for inter-laboratory comparison is common practice (e.g. Lupker et al., 2019; Nichols et al., 2022). Generally, the analysis in quartz is likely a more direct measurement than in ice, because potential processes in the archive (i.e. quartz) are assumingly less and easier to understand compared to the many (not fully understood factors) in firn and ice discussed in the manuscript and supplemented in the paragraph above. Therefore, statements like in line 614 ff. “...our results also indirectly confirm ... that muogenic ^{14}C production rates in ice are several times lower than what would be predicted from studies in quartz – a puzzle that currently lacks a good explanation.” should be put a bit more into context (also see line 42 in the abstract or L 647 ff in the conclusions). Obvious to me, the by far most likely explanation seems to be that the processes in firn and ice are still not fully understood yet.

For this manuscript, the only in situ cosmogenic ^{14}C species that we have characterized is ^{14}CO . Prior studies (van der Kemp et al., Tellus B, 2002, Dyonisius et al., Cryosphere, 2023) indicated that approximately twice as much of the in situ ^{14}C in ice forms $^{14}\text{CO}_2$ as compared to ^{14}CO . $^{14}\text{CO}_2$ in Greenland Summit ice and firn is strongly dominated by the trapped atmospheric component, unfortunately precluding precise determination of the in situ cosmogenic $^{14}\text{CO}_2$ component. Since we are at most examining $\approx 1/3$ of the total in situ cosmogenic ^{14}C in Summit ice and firn, we intentionally did not focus too strongly on the disagreement between our findings for muogenic ^{14}C production rates in ice and the prior estimates in quartz. Dyonisius et al 2023, in

contrast, measured $^{14}\text{CO}_2$, ^{14}CO and $^{14}\text{CH}_4$ and were therefore better positioned to make the comparison to the quartz estimates.

Regarding the specific mechanisms the referee mentions above as possible explanations for why muogenic ^{14}C production rates in ice may disagree with estimates in quartz:

- (i) *In situ chemical reactions effect on ^{14}CO would indeed be expected to be temperature and possibly impurity-dependent. There are now 3 studies from 3 different locations (Dyonisius et al., 2023 – Taylor Glacier, Antarctica; van der Kemp et al., 2023 – Scharffenbergbotnen, Antarctica; this study – Greenland Summit) that have different ice temperatures and impurity loadings. Muogenic ^{14}CO production rates for all of these studies agree within uncertainties, arguing against such reactions destroying in situ ^{14}CO to a significant extent. Partitioning of ^{14}C among different species (e.g., ^{14}CO , $^{14}\text{CO}_2$) is due to “hot” (high energy) atom reactions and as such would not be expected to be affected by ice temperature or differences in concentration of trace impurities. We will add some brief discussion of this in the revised manuscript*
- (ii) *Diffusion of gases through the ice lattice has already been considered (see discussion in Section 4.2)*
- (iii) *Firn metamorphism likely affects the release of ^{14}CO from ice grains into firn porosity, but it would not be expected to destroy ^{14}CO . Further, ^{14}CO released into porosity can be detected by our firn air measurements. So this cannot be the mechanism that results in lower total ^{14}C content. We will add brief discussion of this in the revised manuscript*
- (iv) *This is related to our response in (i) above. Impurities in ice in interior Greenland and Antarctica are generally present at very low (part per million) levels. They would therefore not significantly affect the abundance of ^{16}O target nuclei for muogenic ^{14}C production, nor would they be expected to affect the partitioning of in situ ^{14}C between species, as the “hot” ^{14}C atoms will encounter mainly O and H atoms. We will add brief discussion of this in the revised manuscript*
- (v) *Gas transport in the firn / exchange with the atmosphere is already fully included in our model.*

We agree that overall ^{14}C measurements in quartz are better established than ^{14}C measurements in ice. However, we do not agree that muogenic ^{14}C production rates in quartz are better characterized than muogenic ^{14}C production rates in ice in the published literature, particularly when ^{14}CO in ice is concerned. For quartz, there are the Heisinger et al (2002a, 2002b references in our manuscript) laboratory irradiation studies. However, the muon fluxes and energies used were not representative of fluxes / energy spectra in natural settings for rock and ice. There is also the Lupker et al 2015 study in a 15m deep rock core (also already cited in our manuscript) that had 9 samples in the depth zone ($> \approx 800 \text{ g cm}^{-2}$) where muogenic ^{14}C is expected to be dominant over neutron-produced ^{14}C . These samples had an average relative uncertainty of 64% (based on comparing total ^{14}C content with overall uncertainty in their Table 2). The Lupker et al analysis found that production rate via negative muon capture was in agreement with Heisinger et al (2002a) within uncertainties. For the fast muon mechanism production rate, Lupker et al. (2015) found a best-estimate value of zero, although their uncertainty range was large and included the Heisinger (2002b) value. We have also been

informed (Greg Balco, open peer review process for Dyonisius et al., 2023) that there are further unpublished measurements in quartz that also support the Heisinger production rates.

In ice, the Dyonisius et al (2023) study had 10 depth levels where muogenic ^{14}C was dominant over neutron-produced ^{14}C and the 2-sigma relative uncertainty in results was 15%. The Hmiel et al study (this manuscript) examines ^{14}CO only, with 3 additional samples in ice and 6 in firn air lock-in zone where the muogenic signal is dominant, with much lower relative measurement uncertainties still. There are additional unpublished ^{14}CO data in ice and firn air from Law Dome, Antarctica from our collaborative group (currently in interpretation; Petrenko et al., 2023, AGU Fall Meeting) that are consistent with the Dyonisius et al and Hmiel et al muogenic ^{14}CO production rates. Finally, there was a study done by a different group (van der Kemp et al., 2002 reference in the manuscript) that measured $^{14}\text{CO}_2$ and ^{14}CO in ablating ice at Scharffenbergbotnen, Antarctica, using an entirely independent method (dry vs wet extraction, different facility and procedure for graphitization and ^{14}C measurement). Van der Kemp et al used much smaller sample sizes and their relative uncertainties are larger, but their results for muogenic production rates agreed well with those derived from Taylor Glacier (see Dyonisius et al., 2023). We would also note that the mass-depth range of ice studies is currently larger (to $\approx 10,000 \text{ g cm}^{-2}$ in this manuscript) than from published studies in quartz ($\approx 4,000 \text{ g cm}^{-2}$) which is important for constraining the muogenic production rates.

To conclude, we would argue that ice ^{14}C measurements are well enough established at this point that the measurements themselves are not in doubt. There is no simple explanation for the discrepancy between observed muogenic ^{14}C production rates in quartz and in ice. Because this study only considers ^{14}CO (at most 1/3 of total ^{14}C), we think that a comprehensive discussion of the muogenic production rate discrepancy between quartz and ice is not appropriate for this manuscript. Dyonisius et al 2023 (who measured ^{14}CO , $^{14}\text{CO}_2$ and $^{14}\text{CH}_4$) provided more of this discussion and suggested that a dedicated study to investigate the discrepancy is needed. We will add some brief discussion of this issue into the manuscript, and clarify that while our ^{14}CO results support the Dyonisius et al production rates, they do not refute the production rates from quartz studies. Rather, it seems that transferring production rates from quartz to ice using the Heisinger et al framework may not be appropriate.

Detailed:

L 54 ff. "The in situ produced ^{14}C mainly forms $^{14}\text{CO}_2$ and ^{14}CO , with a smaller fraction forming $^{14}\text{CH}_4$ and possibly other simple organics such as formaldehyde (Dyonisius et al., 2023; Hoffman, 2016; van der Kemp et al., 2002; Fang et al., 2021)." Of the total number of in-situ produced ^{14}C atoms per gram ice, Hoffmann (2016) found a fraction of 11-25 % incorporated into the DOC fraction when performing a neutron irradiation experiment on Alpine ice core samples. The incorporation of cosmogenic in-situ ^{14}C into DOC has later been supported by measurements in environmental samples (Fang et al., 2021). In Dyonisius et al., 2023 (and obviously all studies before 2022 or at least 2016) this partition has not been considered and is obviously also missing in the reviewed study here (see next point). Unlike $^{14}\text{CH}_4$ this does not seem to be a minor fraction and should be considered (maybe needed therefore: DOC

concentrations, around 5 $\mu\text{g C / kg ice}$ for polar ice; Preunkert et al. 2011). As you assume for CO, same partitioning for the n and muon mechanism needs to be similarly assumed here. Important might also be that the cosmogenic produced ^{14}C incorporated into DOC is likely to behave differently in the firn/ice than the gaseous species (CO etc) in terms of diffusion and release into the porous firn (and transport therein), basically being fixated after incorporation (removed ^{14}C partition in subsequent modeling of firn gas transport/retention/leakage). *We will clarify in the manuscript that ^{14}C partitioning into organics is supported by multiple studies now, and may be a substantial fraction. However, even at the maximum value of 25%, the organic fraction of in situ ^{14}C would be insufficient to explain the discrepancy in muogenic production rates between quartz and ice (an increase of $\approx 400\%$ rather than 25% is needed for this). Since this study focuses on ^{14}CO only, more detailed consideration of the organic ^{14}C fraction is beyond the scope of this work.*

L 319 ff. “We use a value of $\Omega_{\text{CO}} = 0.31$ for the fraction of total in situ ^{14}C in ice that forms ^{14}CO (Dyonisius et al., 2023; van der Kemp et al., 2002).” In Dyonisius et al. (2023), the value for Ω_{CO} seems to be 33.7 % associated with an uncertainty of $\pm 11.4\%$. Has an uncertainty for Ω_{CO} been considered and propagated here? This seems relevant considering the narrow range of μ - and μ_f and the difference compared to earlier values (see Table 2). If not, this should not be too difficult to be introduced for example in a similar way as done for the uncertainty of the n production rate (introduction of an additional, adjustable “uncertainty factor” like F_n in L 326). Also see above regarding the missing partition which is incorporated into DOC. *The f_{μ} - and f_{μ_f} dimensionless factors account for both the fraction of ^{14}C that forms ^{14}CO and the reduction in muogenic production rates from the Heisinger values. This was already stated in the manuscript on lines 364 – 365. The f -value uncertainty ranges thus already incorporate any uncertainty in Ω_{CO} . We will clarify this further in the revised manuscript.*

L 356,357 “...(we use $\alpha = 0.75$, consistent with Dyonisius et al., 2023 and Heisinger et al., 2002b),...”. Heisinger et al. (2002b) considered uncertainties in the muon energy and flux to be in the range of 10% each. It does not seem you similarly considered and propagated these uncertainties. Aiming for a comprehensive study, propagating all uncertainties will finally be more useful, resulting in the most realistic range estimates. Especially if there still persist a number of unknowns (i.e. a detailed understanding of all process and mechanisms involved). If not considered, the factors or uncertainties should at least be summarized in the discussion (reference to suggested additional table?), providing a possible tie-point for future studies. *The referee is correct that we did not consider uncertainties in the muon fluxes and mean energies. However, as the referee mentions, these uncertainties are expected to be relatively small as there is a good amount of observations available from muon detectors underground, underwater and under ice. As we use the same parameterizations of these fluxes / energies as studies in quartz (model from Balco et al., 2008), this could not explain the ice – quartz discrepancy in muogenic ^{14}C production rates. We will mention exploring these uncertainties as a point of improvement for future studies, as the referee suggests.*

L 378 ff. “We introduce these two reservoirs because a preliminary analysis showed that using a single ice grain reservoir does not provide a good fit to the observations.” Is there any

hypothesis of a possible mechanism/process to justify this partitioning into two reservoirs?
What is considered as a good fit (especially if considering all other uncertainties, including the ones mentioned above and some of the points mentioned below), i.e. how bad would the fit be?

Please see our detailed response to referee 1 on this point.

Section 4.2, L 481 ff. Is ventilation not part of gas transport/movement in the firn? Since you are using a firn transport model, I do not see why your proposed mechanism would not also (to some extent at the least) include ventilation. Further, snow metamorphism (the most common type of recrystallization of snow and the uppermost firn) is a very fast process (days to weeks); e.g. Pinzer et al., 2012. With depth and higher density of the firn, the recrystallization process will become slower, probably in the order of a few years at the LIZ (e.g. Duval et al., 1995). Thus, would it not be more appropriate to, in the model, combine the processes of diffusion and metamorphism / recrystallization, essentially leading to an “enhanced diffusion” (strong enhancement in the upper firn and much less close/at the LIZ)? Maybe a partitioning of the model into two reservoirs could then be avoided?

*We thank the referee for pointing this out – this was not phrased as clearly as it could have been in the manuscript. Prior studies discussed processes such as recrystallization and sublimation **in combination with** wind ventilation to explain ^{14}C loss from ice grains in the firn. We will clarify this in the revised manuscript. Gas diffusion by itself (even without recrystallization) predicts such rapid loss of ^{14}CO that ^{14}CO content of ice grains in the firn would be expected to be essentially zero all the way through the firn column. So the second reservoir is needed to ensure some ^{14}CO retention, consistent with the measurements. While we agree that a model that is based fully on physical processes would be better, so far we just have a few data points from a single site to guide the interpretation of this process. More data, from multiple sites in future studies would be needed to confirm the results and better identify the ^{14}C loss processes. We will note this in the revised manuscript.*

Minor issues

L 187, equation 1. Definition of $x\text{CO}$ seems to be missing in the text.

This was defined on lines 104 – 105 in the manuscript.

L 188 “...pMC is the sample or blank ^{14}C activity in pMC units...”. pMC denotes percent modern carbon, a pMC unit does not exist (as the name tells, it is a percentage).

We will make this slight edit in the revised manuscript

L 191 (& equation 1) “ 1.1694×10^{-12} is the $^{14}\text{C} / (^{13}\text{C} + ^{12}\text{C})$ ratio corresponding to the absolute international ^{14}C standard activity (Hippe and Lifton, 2014), ...” pMC is defined based on a half life of 5730 (as you mention elsewhere, the half life you used), but Hippe and Lifton, in their reformulation, from which your value of 1.1694×10^{-12} results, considered a half-life of 5700. Note that their reformulation is performed for two main reasons: (i) to omit a necessary correction in activity for the decay from 1950 to the year of measurement of the international ^{14}C standard used for AMS calibration (yielding the number for the activity to be used with

1.1694 × 10⁻¹²) and (ii) to account for the conventionally introduced ¹³C normalization for AMS measurements (to -25 per mil; not to be confused with the additionally performed normalization of the standard to -19 per mil to account for the switch to a new material of the international AMS reference standard; see e.g.

<https://www.hic.ch.ntu.edu.tw/AMS/A%20guide%20to%20radiocarbon%20units%20and%20calculations.pdf>). In any case, the reformulation eventually leads to their Eq 22, which in principle corresponds to your Eq 1 (without the terms accounting for CO molecules per volume). Your equation misses one important term (since this is one of the two main reasons to perform the reformulation in the first place), $\Delta^{13}C$, which results from accounting/correcting for ¹³C normalization. I suggest checking carefully (maybe using the activity of the reference standard and correcting to the year of measurement might be more appropriate for your data anyhow; not that all that matters much with regards to all other uncertainties, I think...).

We have re-checked Equation 1 and think that it is the correct form to use for our samples. The full derivation of this equation is available in the Supplement to the Petrenko et al., 2016 reference in the manuscript. pMC is commonly used for reporting ¹⁴C results, and is how ANSTO reports theirs. A decay correction from 1950 is needed to get from pMC to absolute ¹⁴C abundance (exponential term in our Equation 1), and using a half-life of 5700 vs 5730 years in this decay correction changes the result by less than 0.01%.

L 297 “Figure 1 illustrates total ¹⁴C production rates by each mechanism versus depth at Summit, ...”. The term “each mechanism” might not be ideal with regards to the previous sentence where also the mechanism of “loss of this ¹⁴C from the ice grains via leakage into the open porosity (firn air) or closed porosity (air bubbles).” is mentioned. Maybe clearer would be, “Figure 1 illustrates total ¹⁴C production rates by secondary cosmic ray neutrons and muons versus depth at Summit, ...”, even though not the most pretty due to repetition.

We will make this edit in the revised manuscript to clarify

L 355 “... $\beta(h)$ is a unitless depth dependence factor...”. Shouldn’t that be mass-depth dependence factor?

We will make this edit in the revised manuscript to clarify

References

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