The Cryosphere Discuss.,
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The Cryosphere
Discussions

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Interactive comment

Interactive comment on "Constraints on post-depositional isotope modifications in East Antarctic firn from analysing temporal changes of isotope profiles" *by* Thomas Münch et al.

Anonymous Referee #1

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General comments

This article presents new measures of isotopic compositions (d18O, d-excess) in the first 2 meters of snow at Kohnen (Antarctica). These measurements are used to evaluate how the isotopic signal is modified with time (over a two-year interval), after deposition, at this site. The authors also present a simple model including 3 post-deposition processes, and use it to simulate the evolution of d18O values for the same period of time. The model and data results are coherent with each other. The authors conclude that no other processes (besides these three) are necessary to account for d18O evolution in the snow layers. Besides this study of post-deposition, the authors compare the spatially averaged d18O profile in the snow to measured temperature evolution

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(AWS) and note a strong discrepancy. Since post-deposition processes do not explain this discrepancy, they propose that processes before or during deposition have to be investigated.

I recommend that this paper be accepted with moderate revisions.

1) The data presented here are crucially needed at the moment. They not only represent a huge amount of field work and analysis, but also respect a carefully designed set-up to ensure the quality of the signal retrieved by minimization of horizontal noise. Such high-quality data are exactly what is required to evaluate quantitatively the impact of post-deposition processes.

2) The quantitative evaluation of the three processes studied through minimization of RMSD is clear, and the magnitudes obtained are coherent with independent estimates.

3) However, the articulation between the strategy of the field experiment and the broader issue of the discrepancy between interannual temperatures and interannual d18O could be more detailed in Introduction.

4) The authors could nuance their conclusion that post-deposition processes are unable to produce the interannual variability of d18O observed. Only three processes have been evaluated quantitatively, the others are rejected based only on qualitative observations (and are still subject of research).

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_____________________________Specific comments_____________________

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ABSTRACT

O_____‘Here we reject the hypothesis of post-depositional change within the open-porous firn beyond diffusion and densification.’ This sentence is unclear. Is it possible to use affirmative form?

O_____‘These results show that the discrepancy between local temperatures and isotopes most likely originates from spatially coherent processes prior to or during deposition, such as precipitation intermittency or systematic isotope modifications acting on drifting or loose surface snow.’ Why did you choose to evaluate post-deposition processes and not precipitation intermittency in this study? The latter is a strong candidate for the observed discrepancy. Is it due to a lack a measurements?

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INTRODUCTION

O_____When you say that diffusion and condensation ‘only smooth and compress the original signal’, you should precise that you are talking about vapor diffusion against isotopic gradients.

O_____ ‘In contrast, the low local annual accumulation rates and potential seasonal intermittency of precipitation increase the time the surface is exposed to the atmosphere (Town et al., 2008; Hoshina et al., 2014) and therefore to processes that might alter

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the snow's original isotopic composition.' The intermittency of precipitation does not only favor post-deposition processes through exposition to the atmosphere; it can also shape the d18O signal because of irregular accumulation.

O_____'These processes can act either on loose snow in the post-condensational phase (falling or drifting snow), . . .' Could you precise which processes are active then? It is not wind redistribution, since these processes have to be spatially coherent.

O_____'This discrepancy stresses the importance of contributions other than regional temperature alone to the formation of the isotope signal. /// In this study, we investigate whether post-depositional isotope modifications in the open-porous firn contribute to the observed discrepancy between isotopes and local temperature at Kohnen Station.' This transition is very short. Could you indicate briefly what are the other contributions and why this study is dedicated to post-deposition?

Figure 1.

O_____Do you have information on precipitation amounts over this period? Or on summer d18O in the snowfall? Does the summer d18O in the snowfall follow the evolution of summer temperatures? If precipitation amounts are unknown, please state it here, not later in the Discussion. . . It will be easier to understand why you focus on post-deposition processes.

O_____'. . .we have designed our study such that it allows for the first time to quantitatively follow the isotopic changes and thus to test for post-depositional effects over a time span of 2 years.' What do you expect for the evolution of the variability over 2 years? An attenuation or an amplification? If you expect only an attenuation, then post-deposition is obviously not responsible for the discrepancy between temperature and d18O interannual variations (attenuating a flat profile will not lead to increased variability). If you expect amplification, then why do you simulate only 'attenuating' post-deposition processes?

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RESULTS

Table 2.

O_____ ‘The higher variances in vertical direction of the T15 records are partly expected for autocorrelated data in combination with a larger record length,’ It seems also stronger for the horizontal variability. Do you have an explanation for that? There is also a strong increase of the signal-to-noise ratio. Does it mean that the mean profile in 2013 is less well known?

Figure 3.

O_____Considering only the part of the profiles that is complete, there seems to be an increase of d18O with depth. The shallowest winter (24 cm) has a very low value compared to the deepest winter (153 cm). There is a similar trend for summers (-37‰ for the summer at 173 cm and -44‰ for the summer at 33 cm). Is it possible to test this trend with a linear regression? Do you have information on the continuation of this trend at greater depths? If this trend is verified, what process could be responsible of such an increase?

Figure 4.

O_____It is really difficult to compare quantitatively the two curves on this figure, because they are not superposed. Could you put them on the same d18O scale, and shift the 2013 curve ‘optimally’?

«<Figure 4: superposed»> see attached figure (Figure 1)

O_____ ‘In the 2 years, the T13 isotope profiles are advected downwards, compressed

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by densification and smoothed by firn diffusion.' Attenuation is not very clear here. There is attenuation between 75 and 120 cm depth (blue zone). However, between 60 and 75 cm depth and also between 125 and 150 cm depth the profile after two years (2015) has larger amplitude (red zones). Adding attenuation to the initial d18O profile from T13 would increase the agreement in the blue zone, but decrease the agreement in the red zones.

Figure 5

O_____ 'For the downward-advection, we apply vertical shifts between Δ = 40 and 60 cm,' This range is too large to stay within the bounds of the first winter minimum (47-53 cm would be enough) and too small to permit the shifting of the curve by one cycle (shift of 25-75 cm required). How is it possible that 60 cm become an optimum (it should lead to anti-correlation)?

O_____ Compression higher than 6 cm or diffusion length higher 4 cm leads to RMSD higher than 'doing nothing' (1.05 at the point of origin). This is interesting as it gives an upper bound for the impact of these processes. It also confirms the estimates from independent datasets.

Figure 6

O_____ 'We obtain the best agreement (RMSD = 0.92h, Fig. 5; r = 0.93) between the T15 and the modified T13 mean profile (= T13*) for the optimal parameters Δopt = 50.5cm, σopt = 2.3cm and γopt = 3.5cm (Fig. 6).' Even if adding attenuation generally increases agreement with 2015, is it really the best scenario to apply here (considering red zones)? If the diffusion length was computed only on the zone where attenuation is evident (between 75 and 120 cm) would it have the same value?

O_____ Did you try to move the profile of T13 vertically (more or less enriched in heavy isotopes) to get a better fit? Of course the processes tested here would not lead to a change in the mean value, but it could give information on other processes (maybe for discussion).

O_____ Could you give us an estimation of the attenuation due to diffusion? It could be useful for future comparisons (to other data or models). Roughly from the graph (T13*), the half-attenuation seems to be of ∼0.6 ‰ and the initial half-amplitude of about 2.2 ‰ which would correspond to a quite strong attenuation, of the order of 25 % over two years. What would be the attenuation in the 'blue zone': 75-120 cm depth?

O_____ p10 l20: 'can be seen' and l21: 'clearly': It would be easier to see the improvement if there were somewhere a figure showing T13 (unmodified) and T15 superposed. Without this figure, the term 'seen' should be avoided/replaced.

O_____ 'Nevertheless, both processes play a significant role in explaining part of the temporal changes. This can be seen if we only shift the T13 mean profile vertically to find the maximum correlation with T15...' Is the RMSD of 'only compression' different from the one of T13*? How much improvement is obtained by adding the diffusion to the 'compression only' experiment?

O_____ 'deviations especially remain around the isotopic extreme values, in particular for the first overlapping cycle and the depths around 100 and 125–140 cm.' As expected, the deviation after post-deposition is high mostly in the red zones (first cycle, 125-140 cm), where the amplitude in 2015 is larger than the amplitude in 2013. For these zones adding diffusion leads to higher deviations than doing nothing (and the term 'remaining difference' is maybe not the best adapted).

O_____ What do you call 'extreme values'? All the extremums? Or only the summer at 175 cm and the winter at 70 cm? If you are talking about the extremums, then there is a contradiction with p. 14: 'Furthermore, the difference curve (Fig. 6b) does not show any clear seasonal timing...'

O_____ 'This gives a best shift of 48.5 cm, but clearly the agreement is less pronounced (RMSD = 1.1‰ r = 0.88) compared to...' On the Figure 5, at the point of origin (no diffusion, no densification), the RMSD is 1.05. It reaches 0.92 ‰ for optimal compression and diffusion. Thus these two processes are a step in the right direction, but finally do not improve the RMSD very much.

O_____ p. 10, l25: 'Taking these processes into account leads to a good match of the trench mean profiles (Fig. 6b). However, deviations on the order of 0.9–1‰ remain.' What were the deviations before taking them into account?

O_____ 'These can have two causes: firstly, additional temporal changes driven by unaccounted post-depositional processes;' Could you precise what other processes you are thinking about? Or maybe just make a note toward the section where these unaccounted processes are discussed? Listing possible processes could help to research specific features expected in the remaining variability.

O_____ 'secondly, remaining spatial variability since we average a large but finite number of records which do not originate from the exact same position.' It seems coherent to evaluate the remaining variability as spatial noise, if this variability is random. However, it may not be the case here (slight trend toward higher values with depth, see below).

O_____ 'The agreement of both estimates indicates that the remaining profile differences between the modified T13 mean profile and T15 (Fig. 6b) can be entirely explained by spatial variability through stratigraphic noise. We note however that the squared RMSD lies at the upper end' If there is still a doubt in your mind after the mathematical demonstration, why do you use the term 'entirely' in the first sentence? This term also seems in contradiction with the end of the paragraph. To facilitate reading, you could add a layer of uncertainty such as: 'At first order, the agreement of both estimates indicates'

Figure 7

O_____ 'We find that the distributions of the spatial differences between the mean profiles of each trench campaign (T13–1 vs. T13–2 and T15–1 vs. T15–2, Fig. 7a) are statistically indistinguishable' Could you explicit the results of these tests with simple words? What is the more general conclusion of this first test? That the sampling strategy has no influence on the results? That the uncertainty is the same for T13 and T15?

O_____ 'More importantly, the combined distribution of spatial variability is also indistinguishable from the distribution of the temporal differences between the T15 and the modified T13 mean profile' Does this test evaluate if the difference between T13** and T15 is more than just the difference between T13** and T15 that comes from having a different location?

O_____ How do you 'combine' spatial differences between trenches? The distances considered are not exactly the same (∼350 m between T13-1 and T13-2; ∼500 meters between T15-1 and T15-2; ∼200 m between the mean T13 position and the mean T15 position). Do you apply a weighting by distance?

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DISCUSSION

________Densification, diffusion and stratigraphic noise________

O_____ 'We found a strong resemblance...' This 'strong resemblance' is largely brought by moving downward the profile (advection). The impact of compression and diffusion, even if it is significant, is still very small.

O_____ 'our assumption of a linear profile compression with depth is certainly a rough approximation given the actually observed seasonal firn density variation (Laepple et al., 2016).' In what direction would that process intervene? Preferential compression of summers or winters?

O_____ 'In detail, the diffusion correction improves the match of the trench mean profiles in the medium depth range but also results in higher deviations of the profile minima at the top and bottom part of the overlap (Fig. 6).' This observation is much welcome but should have come earlier in the manuscript, when the deviations are first described.

O_____ 'Part of this mismatch might be reduced by accounting for the seasonally varying firn temperature resulting in stronger (weaker) diffusion for summer (winter) seasons (Simonsen et al., 2011).' How exactly? Does this mean that summers would be more attenuated than winters (due to stronger attenuation when they are still at the surface)? What about temperature gradients? They might not only favor attenuation, but also redistribute heavy and light isotopes vertically.

______________Additional post-depositional modifications________

O_____ '. . .any additional post-depositional changes of the isotopic composition of the firn, below 10 cm, must be on average clearly below the residual stratigraphic noise level, thus « 1‰.' Thus the change can be of more than 1 ‰ as long as it goes on opposite directions at top and at bottom (the average being zero)?

O_____ 'This conclusion is also supported by comparing the qualitative nature of the differences between the mean profiles (Fig. 6b)' Regarding this difference (violet curve): is it possible to add the zero line, to discriminate between positive and negative differences? Is it possible to add the difference T15-T13 (with optimum downward advection), to see where the post-deposition has been most effective?

O_____ 'the T15 mean profile shows, if anything, more depleted 18O values compared to the T13** record (Fig. 6b).' Is this negative difference significant (see below d-excess)? If it is significant, does this mean that post-deposition, at this site, is characterized by a decrease of d18O values? What process could be responsible of this decrease?

O_____ ‘Specifically for South Pole conditions (annual-mean temperature −50°C, accumulation rate 84mmw.eq.yr−1, surface wind speed 5ms−1), the firn isotopic composition showed annual-mean enrichment by firn ventilation after several years of ∼3‰ (Town et al., 2008).’ In as much as the first cycle of T15 reflects undisturbed isotopic cycle (-44 to -52‰ and annual average of -48‰), the annual average value after post-deposition (between 70 and 150 cm depth) is indeed enriched (-45 to -46‰) by nearly 3 ‰

O_____ ‘For the first overlapping annual cycle, T15 exhibits an average difference from T13** of −1.6‰ for the other annual cycles the averages are −0.4, ±0 and −0.1‰’ There seems to be an increase in values with depth, with the difference between T15 and T13** getting closer to zero. Is that trend significant?

____i____ The T13 profile, and its derivatives (T13* and T13**) do not show this trend. If it is significant, it could mean that this trend is a result of a post-deposition process yet unknown, that could also be responsible for the overall depletion of T15 relative to T13 (or T13*, T13**). This process would be oriented, and would bring preferentially light isotopes to the top and/or heavy isotopes to the bottom.

____i____ Qualitatively, sublimation (Sokratov and Golubev, 2009) is unlikely to produce this result; it would instead bring enrichment in the top layers. Oriented diffusion is also unlikely, because when it is active in summer, vapor moves downward, and would bring light isotopes to the bottom.

____i____ The ventilation process as described by Town et al. (2008) could contribute to this trend: Town et al. (2008) show that the winters become more and more enriched after burial, at least until the influence of the wind becomes null (40 cm). Looking at Figure 6b, there seems to be indeed a trend toward higher winter values when depth increases (especially in the original ‘first 40 cm’ located between 60 and 100 cm depth).

_____i_____ Regarding the summers values, they are too low for the first two summers (T15 relative to T13*) and too high for the next (deeper) summers. This could be explained by ventilation too. The summers at shallow depth are first depleted because of condensation of 'winter' vapor during the winters. But later on, they can be enriched again by 'summer' vapor entering during subsequent summers. Since more vapour is available in summer, this influence would become preponderant when layers are buried more deeply. (In winter the atmospheric air would contain only little vapour that would condensate quickly/entirely in shallow layers and not reach these deeper layers).

_____i_____ Of course all of this is very theoretical as long as we ignore the vapor isotopic composition in the atmosphere, and the direction of air fluxes.

O______ 'We note that the RMSD corresponding to the first value is above our stated detection limit.' See above («1‰

O______ 'Furthermore, the difference curve (Fig. 6b) does not show any clear seasonal timing which might be expected for a systematic post-depositional modification.' This affirmation could be nuanced. The maximum deviations (from zero) generally occur in phase with the extremums. The only case where the maximum deviation is not in phase (in front of the T15 extremums) is when the two curves T13** and T15 are not in phase with each other (110-120 cm) probably due to linear compression.

«<Figure 6b: annotated»> See attached figure (Figure 2)

O______ 'We nevertheless note the possibility that post-depositional changes by wind-driven firn ventilation are present at Kohnen Station but that their effect is unexpectedly weak and thus masked by the stratigraphic noise level.' See above («1‰

O______ 'Finally, we note the small tendency towards negative values of the differences between the T15 and T13** mean profiles (Fig. 6), What do you mean by 'negative tendency'? Is it the increase with depth or just the average of the differences between T15 and T13**?

O______ '. . .we cannot reject the null hypothesis that both spatial and residual temporal differences originate from the same distribution,' This sentence is unclear, could you be more explicit ?

O______ On Figure 7b, the 'spatial' difference and 'temporal' difference seem to have the same mean value (which seems negative). Did you made a test to evaluate if the average value is statistically different from zero, for the two variables? The fact that they 'originate from the same distribution' does not really prove that the average value is null for both, just that their averages are not statistically different from each other.

O______ Is the negative difference between T15 and T13** significant? (See above). If it is the case, then there is a contradiction between the two tests. If not, this negative difference cannot be used as an argument to select processes.

O______ On Figure 7b, the 'spatial' difference appears to have wider distribution than the 'temporal' difference. Does your statistical test include the width of the distribution?

O______ 'the histogram of the temporal differences is even more symmetric than for 18O.' This clearly supports the absence of new deposition processes. Is there a trend with depth for the d-excess values?

O______ '(1) Seasonal variation and intermittency of precipitation cause the discrepancy between isotope and local temperature data (Sime et al., 2009, 2011; Persson et al., 2011; Laepple et al., 2011).' This hypothesis could have come earlier (in the introduction or when the discrepancy was described).

O______ 'At Kohnen Station, a large part of the annual accumulation is assumed to occur in winter since little or no precipitation is observed in the summer field seasons. However, the exact seasonal and inter-annual variation of accumulation is still unclear due to the lack of sufficiently precise, year-round observations (Helsen et al., 2005).' Idem

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CONCLUSIONS

O_____ ‘The trench records show a pure downward-advection of the isotope signal within the open-porous firn, further influenced only by firn diffusion and densification, with no evidence for substantial additional post-depositional modification.’ This conclusion is largely supported by the data, and the statistics. Quantitatively, the remaining difference can be accounted for by spatial noise, and thus there is no proof of another process active (and no need for it). Qualitatively, ventilation may still be happening.

O_____ ‘Year-long isotope studies (e.g. in seasonal intervals) focusing on the near-surface would help to constrain isotope modifications at the interface of surface snow and atmosphere.’ Yes, more field campaigns, especially at this interface are acutely needed to understand what is happening.

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________________Technical comments________________________

p8 line 7: ‘T15-2 profile’.

p10, l16: ‘deviations especially remain’ remove ‘especially’ p10, l30: “variability” miss an ‘a’

p12, l28: ‘occured during the 2 years’ misses a ‘r’.

p12, l3: ‘modified T13’ which one? Is it T13* like in the previous sentence or T13** like on the figure 6b? If it is T13**, could you also check the previous sentence, and give RMSD for T13** (for consistency)?

P16, l2: verify ‘focussing’

p 16, l8: ‘averaging’ needs a second ‘a’

Figure 2. The labelling is too small for longitude, latitude, and for the core and trench names. Is it possible to add the general wind direction?

Figure 5.

O_____ ‘For each parameter set of compression and diffusion, we record the minimum root-mean square deviation of the profiles (contour lines) for the optimal downward-advection value (colour scale).’ From this legend it seems that only the (diffusion; compression) couples were tested (while in the main text it seems that all the parameters are varied independently). Could you clarify this point? Is the downward advection the parameter with the less impact on RMSD? This is suggested by not treating the parameters equally in this figure.

Interactive comment on The Cryosphere Discuss., doi:10.5194/tc-2017-35, 2017.

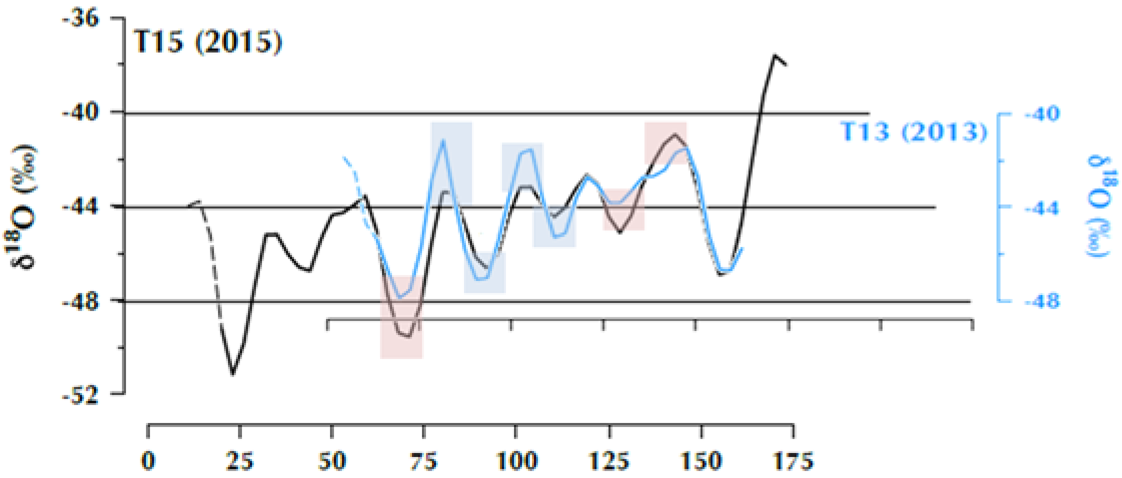

Fig. 1.

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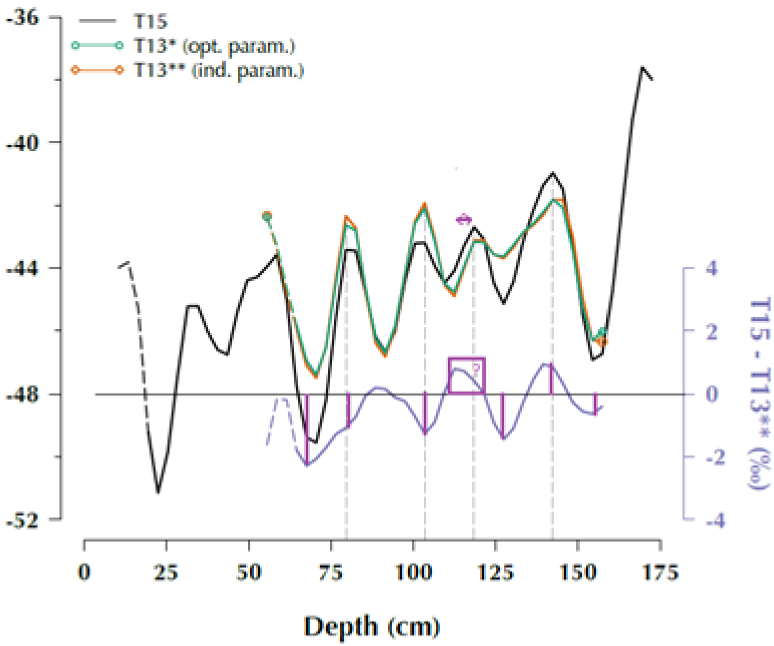

Fig. 2.

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