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Climate
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Discussions

Interactive comment on “Glacial-interglacial dynamics of Antarctic firn columns: comparison between simulations and ice core air-δ^{15}N measurements” *by* E. Capron et al.

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(FYI I have not seen other reviews and replies) This manuscript presents new d15N data from Antarctic ice cores and discusses origins of discrepancies between the data and model predictions (assuming no change in convective zones) during the last glacial maximum and subsequent climatic transition into the current interglacial. The problem of firn thickness in glacial periods is one of unsolved issues in ice-core paleoclimatology and glaciology for the last few decades. The topic is well suited for CP and this special issue, and the authors made good efforts in collecting data from different ice cores. However, interpretations of the data and discussion of mechanisms for firn thickness

variations are sometimes weak and difficult to follow, thus the conclusions are not well supported at least in the current form. Before the manuscript can be published, the authors should analyze the data and conduct model experiments more extensively to draw solid and useful conclusions, or they should greatly reduce the manuscript to simply present the data and describe the (in)consistency between data and model, and make basic discussion/speculations for each sites without bold statements.

Major comments: There are a few major points in the abstract and associated text.

P6053 L12. This sentence does not make sense. d15N during the last termination at EDC and EDML are qualitatively consistent with model outputs where dD increases, but the modeled magnitudes are underestimated. Modeled DCH, under the assumption of no change in convective zone, drifts away during relatively stable climatic conditions, making the overall change of firn thickness over the termination opposite to estimations from d15N.

»» The sentence starting at the line P6053L12 has been removed in the abstract of the revised manuscript.

It would be necessary to investigate what caused the slow and large changes of modeled DCH in ACR and EH by conducting sensitivity tests of the model with only temperature or accumulation change (while fixing the other), or different coefficients for converting dD to the climatic variables. In the current manuscript such exercises are done for very limited cases, thus they don’t support the authors’ arguments.

»» We have followed the reviewer’s suggestions and we have now performed a set of sensitivity tests for EDML, TALDICE, EDC and BI sites with the Goujon model.

Test 1: While previously done only for the case of TALDICE, we now have compared, for each site, two simulations from the Goujon model forced with:

a. A scenario of surface temperature fixed to the present surface temperature associated with the original scenario of accumulation rate deduced from Equation (4) with the β value given in Table 1 of the revised manuscript. Forced with those inputs, the model simulates an "Acc_MODEL-δ15N" curve representing MODEL-δ15N simulated in response to accumulation changes only.

b. A scenario of surface accumulation rate where the later is fixed to the present accumulation rate associated with the original scenario of surface temperature deduced from Equations (2) or (3) with the αD and αO values given in Table 1 of the revised manuscript. Forced with those inputs, the model simulates a "Temp_MODEL-δ15N" curve representing MODEL-δ15N simulated in response to surface temperature changes only. This first test illustrates systematically the opposite influence of surface temperature and accumulation rate on firnification processes. However, the total MODEL-δ15N curve is not simply the average of the two δ15N simulations considering each single factor. This is due to non-linear interactions because the accumulation rate influence is different for different temperature levels, and vice versa. To better investigate the complex interaction between the two, we have performed for each four sites a second test:

Test 2: For each site, we have run the Goujon model forced by inputs parameters deduced from water isotopic profiles but with slightly different coefficients αD, αO and β in Equations (2), (3) and (4) to convert them into the past surface temperature and accumulation rate respectively.

a. We have run the Goujon model with an accumulation rate scenario deduced such as the LGM accumulation rate was (i) 50% larger (Acc_high_MODEL-δ15N curve) or (ii) 50% smaller (Acc_low_MODEL-δ15N curve) than the original LGM accumulation rate, keeping the original surface temperature scenario.

b. We have run the Goujon model with a surface temperature scenario such as the LGM surface temperature was (i) 3°C warmer (Temp_high_MODEL-δ15N curve) or (ii) 3°C colder (Temp_low_MODEL-δ15N curve) than the estimated LGM surface temperature in the original scenario, keeping the original accumulation rate scenario.

These two tests and the associated results are described partly in the main text and mostly in the Appendix 2. New modelled curves are displayed on Figure A1 in the revised manuscript (Figure 1 below).

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The observation of small convective zone is only made for MIS 3, which is not exactly LGM, and only for EDML. This cannot really support the statement that convective zone did not develop at EDML in LGM which is the studies period for d15N. Even with additional published suggestion for EDC, the generalized conclusion that there were no changes in the size of convective zone at all sites is not supported by these observations. Maybe the authors could strengthen the case for EDML in LGM by conducting similar delta-depth exercise as done by Parrenin and colleagues for EDC.

»» It was not our intention to say that there was no changes in the size of the convective zone at all sites and we are sorry if this is the idea that came through in the CPD manuscript. We have modified a few sentences in the new manuscript to make it clear that (1) we do not generalize the conclusion for the EDML site to the other sites and that (2) further evidences are necessary to strengthen our results for the EDML site and to assess the presence or not of a deep convective zone at other Antarctic sites.

Parrenin et al. (2012, 2013) proposed four different methods to estimate Δdepth at EDC:

- One method purely based on modelling (firn densification and ice flow models);

- One method based on δ15N measurements and ice flow modelling to estimate the thinning function under the assumption that δ15N purely represents a gravitational signal and that there was never the development of a significant convective zone in the firn;

- One method based on the synchronisation of the EDC ice core to the EDML and the

TALDICE records using gas and ice stratigraphic constraints. Indeed, because of much higher accumulation rate at these sites, the uncertainty on the age difference between a concomitant event in the gas and in the ice phase as deduced from firnification model is relatively small.

- One method using the bipolar seesaw prediction that the maximum in Antarctic temperature (hence in δD record in the ice phase) is synchronous with the abrupt temperature increase in Greenland (also recorded in the abrupt CH4 increase in the gas phase of Antarctic ice cores).

We have tried to use these different methods to get more constraints to test the deep convective zone hypothesis at EDML over the LGM and the glacial period in general. We have added in the revised manuscript a figure (Figure 2 here, and Figure 5 in the new manuscript) which presents Δdepth estimates based on the two first methods described previously:

- First, we represent one Δdepth estimate that we deduced by combining information from the firn densification model together with an estimate of the thinning;

- Second, the diffusive column height can be estimated from DATA-δ15N converted to Δdepth using the same thinning function as above and the assumption that there is no significant convective zone (this method was already described in the CPD manuscript). We observe a general good agreement between the Δdepth estimates based on the two methods within the uncertainty range however, it is not possible to firmly conclude on the thickness of the convective zone at EDML during the LGM. We have added a short discussion in the new manuscript for the depth interval corresponding to the LGM.

Unfortunately, we cannot apply the two other approaches to deduced Δdepth that are used by Parrenin et al. (2012, 2013). As for the seesaw based method, the EDML water isotopic profile presents squared shapes for the Antarctic Cold Reversal (ACR) and the previous Antarctic Isotopic Maxima (AIM) (Buiron et al., 2012) while the EDC

water isotopic profile presents an ACR and AIM events with a triangular shape. It is also observed that the maximum of the surface temperature (or δD) at EDML is reached much sooner than the maximum in δD over the triangular AIM over Dome C (Veres et al., 2012). As a result, we do not feel comfortable with using the bipolar seesaw hypothesis to synchronise the water isotopic record of EDML with the gas CH4 record to deduce some Δdepth estimates as it is impossible to define precisely when the maximum temperature occurred for each millennial scale event in the EDML ice core. As for estimating a Δdepth based on ice and gas synchronisation of the EDML ice core to a higher accumulation ice core, we would need an ice core with numerous gas and ice stratigraphic links to EDML and a higher accumulation rate or direct gas and ice stratigraphic links between the EDML ice core and the NorthGRIP ice core. To our knowledge, there does not exist any high accumulation rate Antarctic ice core with numerous ice and gas stratigraphic links to EDML. Then, if some ice stratigraphic links exist for the later part of the Holocene between EDML and NorthGRIP, there are only a few gas stratigraphic link between the two ice cores over the deglaciation. The impossibility to use a similar method that Parrenin et al. is illustrated by the Figure 3 below: we can observe that various gas and ice stratigraphic markers are available over the glacial period and the deglaciation between the EDC, TALDICE and EDML ice core which enabled Parrenin et al. (2012) to produce some Δdepth estimates. Unfortunately, only some gas stratigraphic links are available between NorthGRIP and EDML over the time period of interest.

Note that the methodological details and uncertainty determination linked to the different approaches to obtain Δdepth constraints are now given in an Appendix following the main manuscript.

I think it is fine to include the speculation that the origin to may lie within accumulation rates, but it should only be written as speculation (not as definitive conclusion as the current manuscript reads) because I don't think they provide enough support for it.

»» We have rewritten a few sentences in the abstract and in the revised main text accordingly.

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A significant conclusion is made against the hypothesis of major effect of impurities on firn densification rate, but I don't think that the materials in this study are strong enough to reject such hypothesis. In fact the text describes uncertainty associated with magnitude and scaling of dust content, which makes the quantitative discussion of dust effect almost impossible. When plotted on a log scale, the profiles of dust content and dD become very similar, making it hard to separate the effects of temperature, accumulation rate and dust (as acknowledged in the text) without knowing the actual physics of dust effects. The presented study does not provide information to solve this, thus the statement in the abstract is too bold.

»» We agree with the reviewer that in the previous manuscript the conclusions drawn in the abstract about the role of impurity content of the snow on the firn structure did not exactly reflect the discussion that we have in the main text. Consequently we have changed the abstract. We agree that we do not provide a quantitative discussion and that the available datasets do not allow drawing firm conclusions about the role of impurities on the firn structure. Note that there is no clearer visual link when the impurity marker is displayed on a linear scale (Figure 4) than when it is displayed on a log scale (Figure 5). We can actually clearly see that above 655 m, the dust concentration is very low at Berkner Island and do not show any significant variations while millennial-scale δ15N variations occur in the mean time. Also, we feel like it is important to mention that our new δ15N datasets from TALDICE and Berkner Island show glacial δ15N level almost equal to interglacial- δ15N while there is a significant variation of dust concentration from glacial –interglacial that is measured for both sites. Still, we agree with the reviewer that we should have mentioned in a clearer way the limitations of our approach. So in the new manuscript, we have added/modified a few sentences in the corresponding section and the conclusions. We hope that the reviewer

will be satisfied.

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Minor comments: It should be made clear in the abstract and text that this study ignores any temperature effects on the d15N signal. This may be not correct (read papers by Severinghaus and colleagues).

»» This is now done both in the abstract and in the main manuscript

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In general, the manuscript is too long and unfocused with observations and arguments scattered around.

»» We did our best to shorten and, hopefully, to provide a clearer and shorter manuscript. For that purpose:

1-We put all the methodological details about Δdepth determination in the Appendix of the revised manuscript. As a result, it reduces considerably Section 5.2 in the revised manuscript.

2- Both JRI and BI ice cores now benefit from some glaciological modelling to derive their respective chronologies. It enables: -To propose more coherent manuscript and figures with all the δ15N profiles displayed on an age scale (Figure 3and Figure 4). It enables also to perform modelling only with the Goujon model. -The section 3.2 on ice core timescale has been shortened and details on how JRI and BI timescales have been derived are given in the Appendix:

3- Section 5.3 has been modified as well as the conclusion and hopefully, we now highlight better what are the important findings of our study.

4- We remove Figure 8 and associated comments.

We hope that the reviewer will be satisfied with this shorter version.

Fig 8 presents the steady state solutions of the Goujon model for different climatic parameters, so they don’t reflect real (transient) change in d15N. So there seems little meaning to present the figure

»» Done.

We thank Referee 3 for his comments and suggestions

References :

Bazin, L., A. Landais, B. Lemieux-Dudon, H. Toyé Mahamadou Kele, D. Veres, F. Parrenin, P. Martinerie, C. Ritz, E. Capron, V. Lipenkov, M.-F. Loutre, D. Raynaud, B. Vinther, A. Svensson, S. O. Rasmussen, M. Severi, T. Blunier, M. Leuenberger, H. Fischer, V. Masson-Delmotte, J. Chappellaz, and E. Wolff, An optimized multi-proxy, multi-site Antarctic ice and gas orbital chronology (AICC2012): 120–800 ka, Clim. Past Discuss., 8, 5963-6009, 2012.

Buiron, D., Chappellaz, J., Landais, A., Baumgartner, M., Bonazza, M., Capron, E., Frezzotti, M., Kageyama, M., Lemieux-Dudon, B., Masson-Delmotte, V., Parrenin, F., Schilt, A., Selmo, E., Severi, M., Stenni, B., Swingedouw, D., and Udisti, R. Regional imprints of millennial variability during the MIS3 period around Antarctica. QSR, 48, 99-112, 2012.

Goujon, C., Barnola, J.-M., and Ritz, C.: Modeling the densification of polar firn including heat diffusion: Application to close-off characteristics and gas isotopic fractionation for Antarctica and Greenland sites, Journal of Geophysical Research 108(D24), 4792, doi:10.1029/2002JD003319, 2003.

Parrenin, F., Barker, S., Blunier, T., Chappellaz, J., Jouzel, J., Landais, A., Masson-Delmotte, V., Schwander, J., and Veres, D.: On the gas-ice depth difference (delta depth) along the EPICA Dome C ice core, Climate of the Past 8, 1239–1255, 2012.

Parrenin, F., Masson-Delmotte, V., Kölher, P., Raynaud, D., Paillard, D., Schwander, J., Barbante, C., Landais, A., Wegner, A., and Jouzel, J.: Synchronous change in atmospheric CO2 and Antarctic temperature during the last deglacial warming, Science, 339, 1060-1063, doi: 10.1126/science.1226368.

Veres, D., L. Bazin, A. Landais, H. Toyé Mahamadou Kele, B. Lemieux-Dudon, F. Parrenin, P. Martinerie, E. Blayo, T. Blunier, E. Capron, J. Chappellaz, S. O. Rasmussen, M. Severi, A. Svensson, B. Vinther, and E. W. Wolff, The Antarctic ice core chronology (AICC2012): an optimized multi-parameter and multi-site dating approach for the last 120 thousand years, Clim. Past Discuss., 8, 6011-6049, 2012.

Figure 1. (Figure 5 in the revised manuscript). EDML Δdepth estimates from the Goujon et al. (2003) model (red curve), from δ15N data (black diamonds) and from the 10Be-CH4 empirical constraints over the Laschamp event (green triangle) and associated uncertainties (See details in Appendix 3).

Figure 2. (Figure A1 in the revised manuscript). Sensitivity tests performed with the Goujon Model. Left panels, for each site : DATA-δ15N (black diamonds), MODEL-δ15N (red curve), “Acc_MODEL-δ15N”curve (blue) which represents δ15N simulated in response to accumulation changes only, and “Temp_MODEL-δ15N” curve (green) simulated when considering only the effect of temperature change. Right panels, for each site: DATA-δ15N (black diamonds), MODEL-δ15N (red curve),”Acc_high_MODEL-δ15N” curve (dark blue),”Acc_low_MODEL-δ15N” curve (light blue), “Temp_high_MODEL-δ15N” curve (dark green), “Temp_low_MODEL-δ15N” curve (light green).

Figure 3. Water isotopic profiles of the NorthGRIP (δ18Oice), TALDICE (δ18Oice), EDML (δ18Oice) and EDC (δD) ice cores on the AICC2012 dating (Bazin et al., 2012). Available stratigraphic links between the different ice cores are represented. Note that the green bars represent the available gas stratigraphic link between the NorthGRIP, TALDICE and EDML ice cores and the red bars represent the available ice stratigraphic

links between the NorthGRIP, and EDML ice cores.

Figure 4. (Figure 4 in the revised manuscript). Experimental and model results for EDML, TALDICE, BI and EDC ice cores. Three phases over the deglaciation (1. from the LGM to the ACR; 2. the ACR; 3. from the end of the ACR to the EH) are indicated by vertical dashed light grey lines.

a. EDML, Left panel, from top to bottom on the Loulergue et al. (2007) age scale: δD profile (grey, Stenni et al., 2010); Published δ15N data (black diamonds, Landais et al., 2006), new δ15N data (blue diamonds) and modelled δ15N (purple curve); Right panel, from top to bottom on a depth scale: Dust concentration profile (light green; Ruth et al., 2008) and Ca2+ concentration (dark green; Fischer et al., 2007); δ15N data (black diamonds; Landais et al., 2006) and new δ15N data (blue diamonds). Red rectangle highlights δ15N data used to infer Δdepth estimates (from 1363.2 m to 1398.8 m).

b. TALDICE, Left panel, from top to bottom on the TALDICE1 age scale (Buiron et al., 2011): δD profile (grey; Stenni et al., 2011); New DATA-δ15N (blue diamonds), TALDICE MODEL-δ15N (red curve), "Acc_MODEL-δ15N"curve (pink) which represents δ15N simulated in response to accumulation changes only, and "Temp_MODEL-δ15N" curve (purple) simulated when considering only the effect of temperature change. Right panel, from top to bottom on the depth scale: Dust concentration profile (green; Albani et al., 2012); New δ15N data (black diamonds);

c. Berkner Island, Left panel, from top to bottom on an age scale (F. Parrenin, perso. comm.): δD profile (grey, R. Mulvaney, pers. comm.); New δ15N data (black diamonds) and modelled δ15N (purple curve); Right panel, from top to bottom on the depth scale: Dust concentration profile (light green; this study, see Lambert et al., 2008 for experimental details for dust concentration measurements); New δ15N data (black diamonds);

d. EDC: Left panel, from top to bottom over Termination I (TI) on the EDC3 age scale (Parrenin et al., 2007a); δD profile (grey, Jouzel et al., 2007); δ15N data (Dreyfus et al.,

2010) and modelled δ15N (purple curve); Right panel, from top to bottom on the depth scale over Termination I (TI); Dust concentration profile (green, Lambert et al., 2012); δ15N data (Dreyfus et al., 2010).

Figure 5. Same caption as Figure 4 but the impurity markers are displayed on a linear scale.

Interactive comment on Clim. Past Discuss., 8, 6051, 2012.

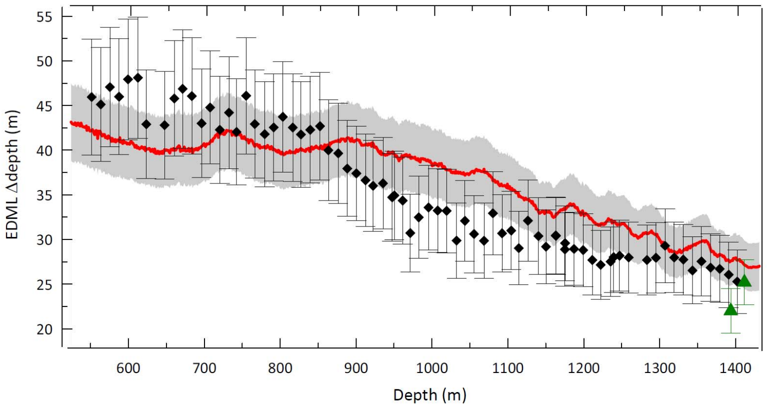

Fig. 1. Figure 5 in the revised manuscript.

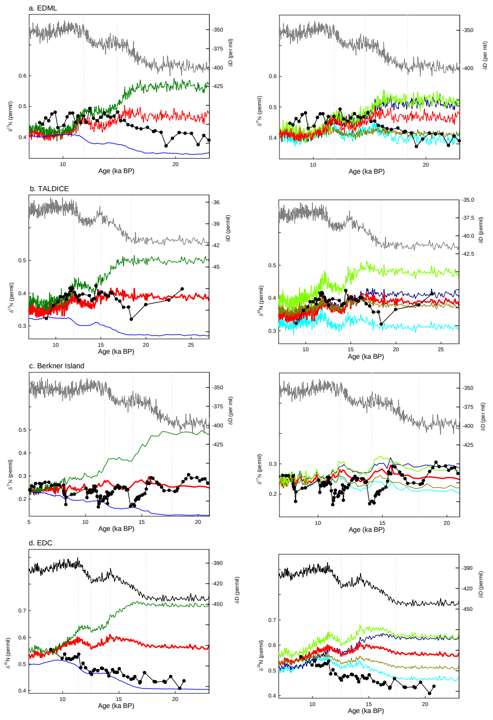

Fig. 2. Figure A1 in the revised manuscript.

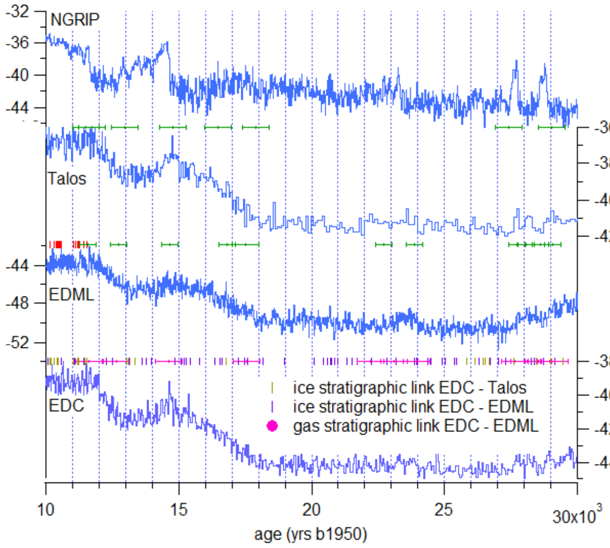

Fig. 3. Stratigraphic links between the EDC, EDML, TALDICE and NorthGRIP ice cores.

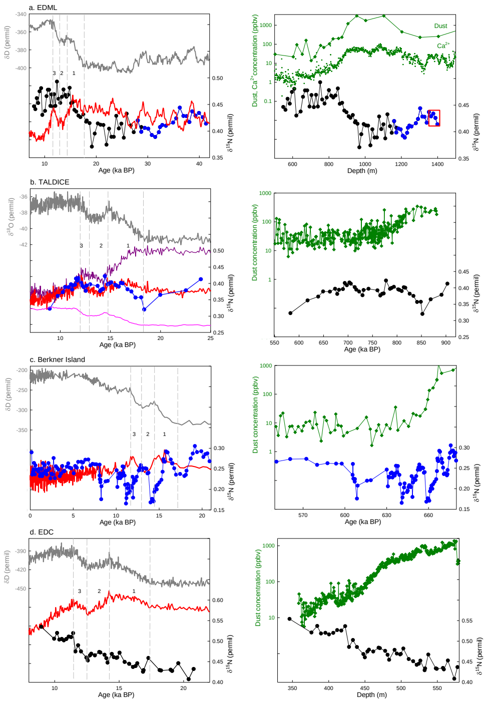

Fig. 4. Figure 4 in the revised manuscript.

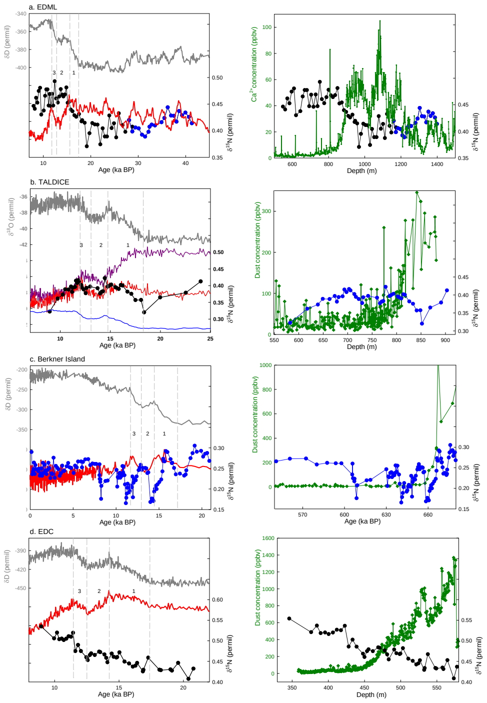

Fig. 5. Same as Figure 4 but the impurity markers are displayed on a linear scale.