

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

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Capron et al. present an impressive compilation (including new data) of $\delta^{15}\text{N}$ data from firn cores in Antarctica. Those data are in conflict with what $\delta^{15}\text{N}$ should be according to firn densification models during glacial periods. They offer three hypotheses for the origin of this mismatch: faulty input parameters to the model, convective zone, and snow to ice metamorphosis susceptible to impurities in the snow. Several options to solve the problem are discussed. The manuscript reads very hard. The discussion of reasons for the model data mismatch is not very clear. Several points are taken up in different sections. The manuscript needs to be written much more to the point and

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shortened.

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

1-We follow the reviewer's suggestion and put all the methodological details about Δ depth 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 $\delta^{15}\text{N}$ profiles displayed on an age scale (Figure 4 and Figure 5). 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.

-We have now an estimate of the β parameter from Equation (4) for JRI and BI through the glaciological modelling, so that, we do not present and discuss anymore two scenarios of past accumulation rate in the main manuscript. This enables us to present a clearer and shorter description of the modelled results, together with the comparison with the datasets for those two sites.

3-Section 5.3 has been modified as well as the conclusion and hopefully, we now highlight better what are the important finding of our study. We hope that the reviewer will be satisfied with this shorter version of the manuscript. In the following, we answer point by point to his other comments/suggestions.

The nomenclature is confusing. Speaking about $\delta^{15}\text{N}$ as data and as a model parameter needs to be clearly distinguished. I suggest using 'diffusive column height' as the model parameter and then adding another axis to the figures.

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->We do not feel comfortable with this suggestion. Indeed, gravitational $\delta^{15}\text{N}$ follows the isobaric equation (Equation 1 in the manuscript) and thus, it is not simply proportional to the diffusive column height (noted z , in the equation) but is also affected by the temperature (noted T) in addition to the temperature effect on the diffusive column height itself. As a result, we can only compare the measured $\delta^{15}\text{N}$ with a modelled $\delta^{15}\text{N}$ on Figure 4 and Figure 5. However, to make it clearer in the text which $\delta^{15}\text{N}$ we are referring to, we introduced two notations: we systematically refer to DATA- $\delta^{15}\text{N}$ when describing $\delta^{15}\text{N}$ measurements and MODEL- $\delta^{15}\text{N}$ when mentioning $\delta^{15}\text{N}$ simulated with the firn densification model. We hope that it is a clearer way to describe and discuss our results.

There are too many figures in the manuscript; figures 4, 5 and 6 can be combined.

->We have combined Fig 4, 5, 6 and 7 from the CPD manuscript into one single figure (which is now Figure 5, see below our answers to the comments) in the revised manuscript. Figure 9 from the CPD manuscript is not anymore in the main manuscript and has been moved to the Appendix.

Specific remarks Page 6054, line 21: 'continuous snow material' should maybe be replaced with 'homogeneous'.

->Done

Page 6059, lines 18-26: How big is the effect of where the diffusion stops? Why take 21%?

->We have run the Goujon model for the EDML site with 3 different closed porosity thresholds to define the base of the LID: 13%, 21% and 37%. These values have been defined through total gas and firn air measurements (Goujon et al., 2003). Considering this range of closed porosity in the three simulations, we have observed that the effect of where the diffusion stops is not large considering the $\delta^{15}\text{N}$ levels and variations we are discussing in the paper. Indeed, the mean standard deviation on the LID definition

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based on those three values along the EDML record is 1.7m and it leads to a change in $\delta^{15}\text{N}$ values of 0.009 permil. As the lack of data unable us to set precisely for each site a closed porosity threshold to define the LID and considering that the sensitivity tests show such a small impact, we arbitrarily decided to apply to the model the 21% value which has been defined at the Vostok site. To be clearer on that in the new manuscript, we have rewritten the paragraph in the revised manuscript.

Page 6060, line 3: 'configuration of the BI drilling site'. I guess what is meant is the flow regime of BI.

->Yes it does but the sentence including "configuration of the BI drilling site" has now been removed in the new manuscript.

Page 6061, line 15: Typo Dd18O should be d18O.

->Done.

Equation 1: Delta mass should have the unit of kg/mol not g/mol. The delta value is given in per mil which is not obvious. Per mil is a prefix; therefore delete the factor of 1000 in the equation.

->Done.

Page 6055, line 17: the Goujon and Arnead models are no longer the 'most recent' once. Replace 'most recent' with e.g. 'state of the art'.

->Done.

Section 5.2: The title of this section is confusing. Also the entire section can go into the appendix and be replaced with the last sentence referring to Parrenin et al., 2012b.

->In the revised manuscript, the section is now named: "5.2. Absence of a deep glacial convective zone at EDML". We also follow the suggestion of Reviewer 2 and we now have put all the methodological details on the Δ depth determination in the Appendix at the end of the paper.

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On several occasions there is claimed that 'the successive patterns of $\delta^{15}\text{N}$ trends during the deglaciation' is similar in the $\delta^{15}\text{N}$ data and model output. That is hard to see and I would like to see an in depth analysis of that statement.

->By such a statement "the successive patterns of $\delta^{15}\text{N}$ trends during the deglaciation", we mean that, on some particular sections of the deglaciation, the model is able to reproduce the same trend that the one measured even if the absolute $\delta^{15}\text{N}$ levels are not the same, except for TALDICE. For example during phase 1 and phase 3 in the new Figure 5.d, the model predicts increases of $\delta^{15}\text{N}$ and we do measure $\delta^{15}\text{N}$ increases. For TALDICE, the $\delta^{15}\text{N}$ tendencies over the 3 phases and the Early Holocene (EH) are predicted by the model. Over the EH, phase 2 and phase 3, the absolute TALDICE DATA- $\delta^{15}\text{N}$ levels are reproduced as well. We have changed the text in the revised manuscript and we hope that it is clearer now.

One of the main points of the discussion is the different response of the firnification models to accumulation and temperature changes. This very important point (including figure 8) should be introduced early on in the manuscript.

->We have followed this suggestion and we introduce now the different responses of the LID in firnification models to accumulation and temperature changes in the introduction. Consequently, we have also moved forward Figure 8 from the CPD manuscript, which is now referred as Figure 2 in the revised version. We have added onto the figure two arrows to emphasise on the respective impact of temperature (horizontal black arrow) and accumulation rate (vertical black arrow) on the LID and thus on the $\delta^{15}\text{N}$ (please, see the revised figure 2 below).

We are grateful to the reviewer for his valuable comments and recommendations on how to improve our paper.

New Figure 2 caption: $\delta^{15}\text{N}$ evolution (‰ versus accumulation rate and temperature calculated by the Arnaud model (2000). Scenarios of past temperature and accumulation rate evolution used as model inputs (see Section 3.3 for details) are plotted for

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EDML (blue), EDC (turquoise), TALDICE (green) and BI (purple). Present climatic surface conditions are indicated for each site (black marker). Note that in response to an increase in accumulation rate, the LID and consequently the $\delta^{15}\text{N}$ increase (vertical arrow) while in response to an increase in temperature, the LID and consequently $\delta^{15}\text{N}$ decrease (horizontal arrow).

New Figure 4 caption: Experimental and modelled results on the JRI ice core. Left panel: all new $\delta^{15}\text{N}$ measurements on a depth scale. Right panel: δD (grey, Mulvaney et al., 2012), MODEL- $\delta^{15}\text{N}$ (red, this study) and DATA- $\delta^{15}\text{N}$ (blue, this study) over the time interval 7-30 ka. Note that the water stable isotope variation suggests an unrealistically fast deglaciation compared to all other Antarctic records, related to an unconformity present in the early deglacial interval in the JRI ice core (Mulvaney et al., 2012). This prevents us to discuss the MODEL- $\delta^{15}\text{N}$ along the deglaciation and as a result, we only comment on the mean MODEL- $\delta^{15}\text{N}$ levels for LGM (Last Glacial Maximum) and EH (Early Holocene) climatic conditions.

New Figure 5 caption: 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)TALDICE, Left panel, from top to bottom on the TALDICE1 age scale (Buiron et al., 2011): δD profile (grey; Stenni et al., 2011, new $\delta^{15}\text{N}$ data (black diamonds), modelled TALDICE $\delta^{15}\text{N}$ (red curve), "Acc- $\delta^{15}\text{Nmod}$ " curve (pink) which represents $\delta^{15}\text{N}$ simulated in response to accumulation changes only, and "Temp- $\delta^{15}\text{Nmod}$ " 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 $\delta^{15}\text{N}$ data (black diamonds).

b)EDML, Left panel, from top to bottom on the Loulergue et al. (2007) age scale: δD profile (grey, Stenni et al., 2010), published $\delta^{15}\text{N}$ data (black diamonds, Landais et al.,

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2006), new $\delta^{15}\text{N}$ data (blue diamonds) and modelled $\delta^{15}\text{N}$ (purple curve). Right panel, from top to bottom on a depth scale: Dust concentration profile (light green; Ruth et al., 2008) and Ca^{2+} concentration (dark green; Fischer et al., 2007), $\delta^{15}\text{N}$ data (black diamonds; Landais et al., 2006) and new $\delta^{15}\text{N}$ data (blue diamonds). Red rectangle highlights $\delta^{15}\text{N}$ data used to infer Δdepth estimates (from 1363.2 m to 1387.8 m).

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 $\delta^{15}\text{N}$ data (black diamonds) and modelled $\delta^{15}\text{N}$ with Scenario A (β equal to 0.0156; violet curve) and with Scenario B (β equal to 0.0065; pink 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 $\delta^{15}\text{N}$ 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), $\delta^{15}\text{N}$ data (Dreyfus et al., 2010) and modelled $\delta^{15}\text{N}$ (purple curve) Right panel, from top to bottom on the depth scale over Termination I (TI): Dust concentration profile (green, Lambert et al., 2012), $\delta^{15}\text{N}$ data (Dreyfus et al., 2010).

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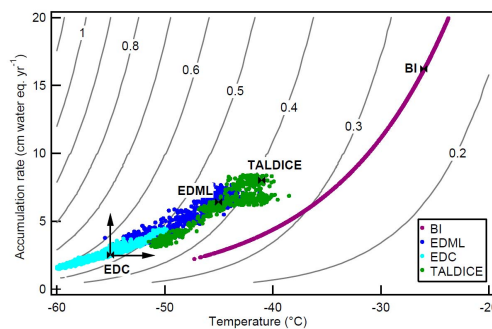


Fig. 1. New Figure 2

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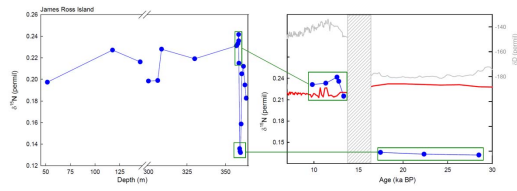


Fig. 2. New Figure 4

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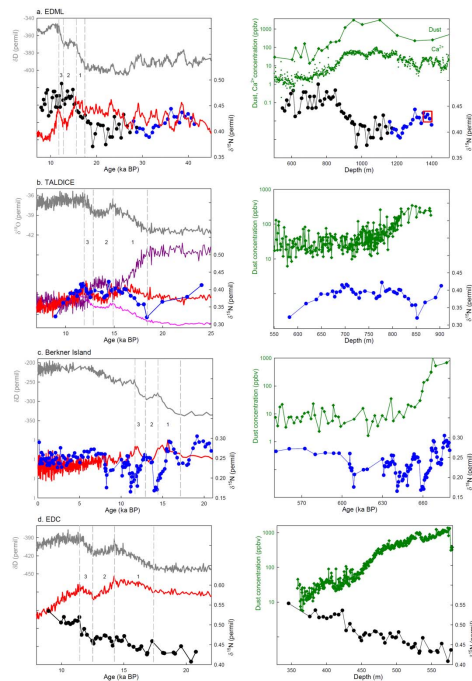


Fig. 3. New Figure 5

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