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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Model calculations of the age of firn air across the Antarctic continent" *by* K. A. Kaspers et al.

K. A. Kaspers et al.

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J. Barnola

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Let me first of all thank you for your time and effort to give me your constructive comments. In the new version of this manuscript you find that your comments have been addressed, resulting in an improved manuscript. Please find below the answers to your specific questions.

Best Regard

Karsten Kaspers

Antarctic firn contain large amount of air which is several decades old and in some place area could be older than one century. By sampling this air it is thus possible

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to get large amount of pre-industrial air. This paper deal to the prediction of the best place to sample the oldest air. The approach is to model the firn densification and the air diffusion through the open pores down to the close- off with the results of a climate model as input.

My main concern is the choice of the densification model. The authors have chosen to use the Herron-Langway model and only it and in my mind they should also have used at least the Pimienta model to test the sensitivity of the prediction. The reason is that the H-L model tends to over estimate the close-off depth in the area of relatively high accumulation rates where the Pimienta model do a better job. This is true not only for South Pole as mentioned but also and more obviously for DE08 (note that unfortunately, this site is missing in the figure 7). For this test, the Pimienta model has the advantage on the Arnaud model that the same input parameters than the Herron Langway model have to be included. I donŠt think it will change the location of the oldest air but I am pretty sure that it will reduce the close off depth and thus the age of the air at the bottom and it will allow to give a better envelope to the predictions.

Indeed the depth of PCOD and therefore also the age of the firn air at PCOD is slightly less when the density model of Pimienta is used. We have incorporated the Pimienta model into the diffusion model and show the results in this version of the manuscript as a comparison to the use of the Herron and Langway (1980) model. Overall for the deep PCODs and locations of old firn air (at The Antarctic plateau), the use of the Pimienta model resulted in a 2-14 m less deep PCOD and approximately 10 year younger firn air (CO2 effective age) at PCOD.

Concerning the tortuosity in Fabre et al (2000), the authors have misinterpreted the linear relationship between the open porosity and the tortuosity. This unique linear relationship had been established on small individual samples and the conclusion of the paper is that it cannot be used on real firn. For real firn inverse or tuned method has to be used has proposed here. Thus I suggest to delete the first paragraph of part

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We have partly deleted and rephrased is paragraph.

Finally note that firn results have been published for Vostok (Bender et al GRL, 1994) and Dome F (K. Kawamura Thesis) which could be used for comparison. Looking at the figure 6 it seems that the predicted close off depth should be too large also.

We have incorporated the results for Vostok (Bender et al., 1994) in this study. This resulted in newly parameterizations for the Tortuosity and pore close-off density, yielding newly results for the PCOD and firn air age at PCOD across the Antarctic continent.

C. Trudinger (Referee)

Received and published: 13 May 2004

Dear Cathy Trudinger,

Like Jean-Marc Barnola I would also like to thank you for your constructive comments, which had helped to improve the new version of the manuscript. Your idea to incorporate the mean age and age-distribution was an important one and gave a great contribution to the new version. I have answered the specific questions and comments our have made below.

Best Regard,

Karsten Kaspers

General comments This paper describes the development of parameterisations for pore close-off depth (PCOD) and the age of CO2 in firn air at the PCOD in terms of meteorological conditions. The authors use relationships between the physical properties of polar firn and meteorological conditions, and a firn diffusion model, to develop these parameterisations, which they then apply to the whole Antarctic continent. Their motivation for creating the parameterisations is to allow them to be used in the field to predict the pore close-off depth and corresponding age of CO2, from knowledge of the meteorological conditions, without having to tune a firn diffusion model. This idea of

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parameterising the PCOD and CO2 age in terms of the meteorology is an interesting one, but I would like some indication of how widely applicable the equations are, and how reliable they are for other sites, to know whether they really are useful in the field.

In the study, the oldest CO2 is found for conditions of deep PCOD, low temperature and relatively high atmospheric pressure and accumulation rate. It would be useful if, in addition to predicting the age of CO2 at the PCOD, the authors could also predict some measure of the width of the age distribution at PCOD. The age spread can be specified as the spectral width of the age distribution (defined in Trudinger et al., 2002) or the full width at half height (e.g. Saltzman et al., 2003). This would make the study much more useful for researchers in the field. It is good to be able to obtain very old air, but knowing where to go to obtain old air with the smallest age spread would be even more useful.

We agree with the referee, that the age distribution will provide valuable information for future firn air analysis. We have therefore calculated the age distribution as defined by Saltzman et al., 2003 as the full width of the age spread at PCOD at half height, across the Antarctic continent. In the end of this manuscript we have parameterized the results of the age distribution as a function of meteorological quantities. Although the parameterizations for PCOD, the mean age at PCOD and the age distribution are valuable for the use in the field, this was not the main aim of this paper. Here the main aim is the combination of a firn diffusion model with climate data, so that the diffusion model could be used across the entire Antarctic continent.

Specific comments:

It seems that observed values of the meteorological variables were used for the density and tortuosity parameterisations, but modelled values for the PCOD and CO2 age parameterisations. Could observed meteorology have been used for both cases to develop the parameterisations, then the modelled meteorology used to extrapolate to the entire continent? This seems to me like the better approach, but maybe there are

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reasons not to do this, or I have misunderstood what was done.

Developing parameterizations for the PCOD and the firn air age at PCOD is not the main aim of this paper. In this paper we would like to show the reader that a firn air diffusion model could be combined with a climate dataset, yielding the modelled PCOD and firn air age at PCOD across the Antarctic continent. However we have tried to parameterize the derived PCODs and mean ages of firn air at PCOD from the ten measured firn air sites to meteorological quantities, but this appears not to be so straightforward and those parameterizations contained large 1s uncertainties. We have therefore chosen to parameterize the results from the combined model because 1. This way we had more data, approximately 8000 in stead of only 10 and therefore increased the accuracy of the parameterized main results and 2. One can now use the RACMO-ANT dataset directly, before going into the field.

If the authors suggest that these parameterisations can be used in the field, they need to give a good indication of where and how they are applicable. Are the equations applicable at any site in Antarctica for which the meteorological conditions are known?

We have rephrased parts of this section. Because the parameterizations described in section 3.4 are derived from the main results of section 3.1 and 3.2 and are parameterized to RACMO-ANT meteorological conditions, these parameterizations can be used widely in the field.

Can researchers expect the parameterisations to give a reasonable approximation for the PCOD and CO2 age anywhere in Antarctica? Is the fact that the parameterisations seem to be for modelled meteorological conditions on a 55 km resolution a limitation? Should observed or modelled meteorological conditions be used to calculate PCOD and CO2 age? Have the authors verified their parameterisations at a site other than the ones used to generate these equations? Could DSS be used, as this was not used in generating the parameterisations, or DSSW20K (described by Sturrock et al., 2002), with observed values of the meteorological conditions to verify the equations?

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The derived parameterizations of Section 3.4 can be widely used in the field and are derived with modelled RACMO-ANT meteorological quantities. The limitation of the RACMO-ANT resolution is no more a limitation for the parameterization. In section 3.4 we have incorporated a paragraph in which we compared the parameterized PCOD and mean age of firn air at PCOD using measured meteorological input data to the values directly derived from the ten firn air sites. This comparison indicates a correlation of r2 = 0.83 for the PCOD comparison and r2 = 0.55 for the mean age comparison.

The authors should carefully define what they mean by pore close-off depth. Some people have used the term Špore close-offŠ to refer to the depth range over which the pores gradually close, rather than a particular depth, so a clear definition is important.

Indeed, we have added this remark in the Introduction of this manuscript.

The authors chose to use DE08-2 but not DSS on Law Dome because the horizontal resolution of the meteorological fields was too coarse to resolve the area. Why did they choose DE08-2, is there a reason why the parameterisation would work for one site but not the other? Do the modelled meteorological conditions for the region reflectobserved conditions at DE08-2?

We have resolved this problem and all ten firn air sites are now used for this comparison.

Is Temperature in Table 1 from observations or RACMO?

Observed, we have checked all values again because some errors appeared to be made in the previous version of this paper.

The equations 8, 9 and 10 refer to constants in Table 3, but there are no values of Phi2 or Phi3 in this table, instead there are epsilon2 and epsilon3, should these refer to the same thing? The legend for Table 3 says the constants refer to equations 7, 8 and 10, should this be equations 8, 9, and 10? To avoid this confusion, could the constants be written directly into the equations?

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These errors have been corrected

Assuming the epsilon and Phi in equations 8, 9 and 10 and Table 3 are the same, these equations give me a PCOD of 114m and CO2 age of 29 yrs for DE08-2, and PCOD of 102m and CO2 age of 59 yrs for South Pole. Have I implemented the equations correctly? If so, these values (particularly for DE08-2) do not seem right to me. Is there a way to show readers that they are implementing the equations correctly, like providing some test values, or labeling the points on Figure 4?

Due to the recalculations of section 3.1 and 3.2 because of the incorporation of the Vostok data, the constants of the parameterizations 8,9 and 10 have slightly changed. To provide the reader some indication of the accuracy of these parameterizations, we have placed a paragraph in section 3.4 where we compare the results from the parameterizations with the ten measured firn air sites.

This study, by using a CO2 ice core record to determine CO2 ages at PCOD, is calculating the ŠeffectiveŠ age of CO2, rather than the ŠmeanŠ age (see Trudinger et al., 2002). The effective age depends on the growth rate of CO2 in the atmosphere, and the degree to which this matters will depend on the width of the age distribution. This is a minor point, and the difference may not be large for CO2. The mean age would be older than the effective age for CO2 (as the growth rate has increased with time). Alternatively, the authors should define what they mean by mean age.

We have included the results for the mean age of firn air at PCOD in section 3.2 and improved the distinguishing between results based on effective age and mean age.

There are other features that might affect the suitability of a site for collection of firn air, such as melt layers, dunes, or wind-blown snow. This might be worth mentioning.

Because the climate model does not account for such features, a small note has been added concerning the effect of such features on the mean age results in section 2.

Technical corrections

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All these Technical corrections are taken into account.

Page 1820 line 5: ŠWe constructedŠ does not make it clear that you used the model to calculate the depth profile. Wording could be improved.

Page 1820 line 8: Specify that it was by comparison with the input atmospheric record that you obtained the ŠeffectiveŠ age.

Page 1829 line 2: What does Šfewer chocks between moleculesŠ mean?

Appendix: Accumulation for DSS is wrong (it is correct in Table 1). Some other values differ between the Appendix and Table 1. The units for accumulation are missing ŠaŠ. Siple - should this be Siple Dome?

Fig 4: Could you be more specific in the figure caption whether the x-axis refers to ages estimated by the studies quoted? The text suggests this, but from the figure caption is not clear to me whether it is something you have calculated. Perhaps the CO2 age at PCOD from the quoted studies could be added to Table 1.

Fig 7: Are we supposed to be able to compare the dots with the lines in this figure?

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