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Climate
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Discussions

Interactive comment on “Rapid changes in ice core gas records – Part 2: Understanding the rapid rise in atmospheric CO_2 at the onset of the Bølling/Allerød” *by* P. Köhler et al.

P. Köhler et al.

peter.koehler@awi.de

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This review points to several parts of the manuscript under discussion, which were not clearly described and therefore left some open question to the reader. We apologise that for that. However, we feel able to satisfactory reply to all the comments in details and we furthermore performed all the tests suggested by the reviewer to see, if and how our filter function can be understood. We can therefore clarify all open questions relatively easily and will incorporate improvements in a revised version.

Our responses in detail are:

- Reviewer comment: *1) There are several serious scientific issues that this paper presents that warrant some further examination. One is that the atmospheric methane record from the same ice core, the Dome C ice core, contains a rather well-preserved signal of the Younger Dryas and Bølling atmospheric methane variations, which are well known from high-accumulation rate ice cores such as the Byrd ice core, Siple Dome ice core, Law Dome core, and the Greenland cores. These atmospheric signals therefore contain an invaluable testbed with which to check the author's postulated age distribution probability density function. I suggest that the authors use this methane record, smoothed with their pdf as a filter, to compare with the actual methane data from the Dome C core. Without actually doing the exercise, I can guess that the results may well require a substantial revision of the pdf.*

  The upshot of this revision of the pdf may very well substantially change the conclusions of the manuscript, as the authors infer such a large magnitude transient peak in atmospheric mixing ratios. This inference is entirely a product of the age distribution pdf that the authors adopt, which is based on a glaciological bubble formation model. The breadth of this pdf requires that a much higher atmospheric peak have occurred, to explain the sharpness of the rather sudden change (but lower magnitude change) observed in the bubble record.

  Of particular importance in this context is the fact that the observed age distributions of gases in trapped air often deviate substantially from modeled age distributions. The reasons are not completely understood. It is possible that the process whereby air is separated from mixing with the atmosphere, effectively sealing it off, is not directly and simply related to the bubble close-off process. Instead, it may be that horizontal ice layers seal off the gas mixing prior to bubble formation. A variety of firn air pumping studies hint at this mechanism, with these studies showing an absence or near-absence of anthropogenic gases such as chlorofluorocarbons in the air in open pores from near the bubble close-off re-

gion. [If instead the closure of bubbles were the relevant event that removed gases from contact with the atmosphere, then one would expect the full burden of anthropogenic gases to be observed in all open pores.]

Also of possible relevance is the well-known fact that as climate warms, the densification process of polar firn accelerates with an Arrhenius-type exponential dependence on temperature. The enhanced densification means that the horizon at which gas is separated from the atmosphere travels through more than one annual layer per year. This has the effect of reducing the gas age-ice age difference during times of warming. For example, the gas age-ice age difference may be 2000 years during a cold period. After 1000 years of warming, the gas age-ice age difference may have been reduced to 1000 years, for the sake of argument. This implies that the closure surface migrated upward through two annual snow layers per year during this time of warming. Because the event studied by the authors occurs during a time of strong Antarctic warming, it is quite possible that this process has narrowed the age distribution of the gases.

Of potential further relevance is the fact that strong layering in polar snow is often observed in warm climates with moderate accumulation rate but not in cold climates with very low accumulation rate. Therefore the climate change itself may induce a qualitative change in the gas occlusion process, that leads to narrowing of the age distribution of the trapped gases as ice layers begin to seal off gases prior to bubble formation.

All of these unknowns caution us not to rely too heavily on a model calculation. Instead, empirical and observational constraints are of much greater value. That is why it is key to utilize the Dome C methane record, with the known atmospheric forcing function (i.e. methane record from high-accumulation cores), to validate the age distribution pdf.

Our reply: We performed the key test suggested by the reviewer, which is,

that we took CH_4 from high accumulation sites as a surrogate of the atmospheric signal, and smoothed it with the filter functions used for CO_2 in EPICA Dome C (EDC) (which is our log-normal function with $E = 400$ yr). This is a useful exercise because the filter function of the gas enclosure process are very similar for both CO_2 and CH_4 (Joos and Spahni, 2008).

The results are attached as figure (Fig. 1, right). We took as examples for high accumulation ice cores EPICA DML (EDML), Byrd and Greenland composite. Methane is plotted for EDC, EDML and Greenland on the most recent synchronized age scale (Lemieux-Dudon et al., 2010) and for Byrd as in Ahn and Brook (2008). Recent accumulation rates are with 65 (EDML), 110 (Byrd), 211 (GRIP) mm (water eq.) yr^{-1},) significant high than for EPICA Dome C (25 mm (water eq.) yr^{-1}). The compilation of accumulation rates is taken from the companion paper (Köhler, 2010). Before we discuss our results one should be aware, that this exercise has still two limitations:

1. The methane signals of the high accumulation ice cores are still not identical to the atmospheric signal. The accumulation rate for GRIP, for example, would suggest a mean width of a filter function of about 50 years for the Bølling/Allerød warm period (Köhler, 2010).
2. This comparison is not entirely correct if we use Greenland ice cores, because of the existing interhemispheric gradient in CH_4 (Dällenbach et al., 2000). However, slopes during rapid changes should be comparable.

The hypothesis to be tested with this exercise is the following: If our filter function used to deconvolve CO_2 is useful and meaningful, then the same filter should be able to deconvolve the CH_4 signal. In other words, our log-normal filter with a mean width $E = 400$ yr applied to the CH_4 signal during onset of the the B/A warm interval measured in high accumulation ice cores should produce a signal which is comparable to the CH_4 signal measured in situ in EDC. This exercise, of course, heavily depends on the temporal resolution of the ice core data and the correctness of the gas age models. Furthermore, the comparison should only be applied for the slope of rapid changes in CH_4, not for the exact timing of events, because rapid changes in CH_4 measured in situ in ice cores are wiggle-matched onto each other in synchronisation efforts, which were used in the development of gas age chronologies (Lemieux-Dudon et al., 2010).

The slopes of rapid rise in CH_4 around 14.6 kyr BP measured in situ in the ice cores and after filtering with the log-normal function with $E = 400$ yr are as follows (Fig. 1):

ice core	original	filtered
	(ppbv/century)	
Greenland	171	27
Byrd	53	21
EDML	48	22
EDC	target:	**39**

This follows very closely our expectations:

1. CH_4 measured in situ in ice cores changes more rapidly in high accumulation sites (Greenland $>$ Byrd $>$ EDML $>$ EDC).
2. After the filtering those records with highest accumulation rates (with presumably a record of CH_4 most closely to the atmospheric CH_4) are closest to the target slope of EDC. The slope in filtered data in Byrd and EDML are very similar, but Byrd had nearly half the temporal resolution of EDML here and thus the result heavily depends on the sampling.
3. Because of the mentioned limitation (1) above (no ice core CH_4 in high accumulation sites is identical to the atmospheric record) we can not expect, that

the slope of the filtered time series is identical to the slope in EDC. We expected what we found. Slopes in the ice core records are already smoothed in comparison to atmospheric CH_4 and therefore the slopes in the filtered time series (based on these ice core CH_4 data) should be smaller than the slope in the original CH_4 data in EDC: the smaller the accumulation rates the larger the offset of the filtered CH_4 records from CH_4 measured in situ in EDC.

There is another way to qualitatively check if our approach and understanding of the gas age distribution PDF is consistent with expectation from the CH_4 record. The filtering procedure should lead for very short and very rapid changes (as observed during D/O events in MIS 3) to smaller amplitudes in ice core CH_4 in low accumulation sites (see also companion paper: Köhler, 2010). Again, the comparison with Greenland is difficult due to the interhemispheric gradient in CH_4. We indeed observe these smaller CH_4 amplitudes in EDC if compared with EDML during the last 50 kyr (Fig. 1, left).

Given these analyses we think our approach is relatively robust. It passed the test suggested by the reviewer and a substantial revision of the PDF is not necessary.

Concerning other not well understood physical processes (sealed off layers, densification, etc) which might have caused alternatively that the CO_2 signal in EDC looks like it is: We agree, that we can not entirely exclude such mechanisms, but the test of our filter function for CH_4 convinced us that our hypothesis is within our limited understanding at least possible. However, we will in the revision of our manuscript extend the discussion of our results by these potential uncertainties. We furthermore like to highlight, that the CO_2 data from other ice cores, as plotted in Fig. 4a (Taylor Dome, Siple Dome) support our approach and results. A final judgment is probably only possible if CO_2 was measured on an ice core with even higher accumulation rates, e.g. on the West Antarctic Ice Sheet (WAIS) Divide ice core, which has a recent accumulation rates of more than 200 mm (water eq.) yr^{-1}, and is thus in the expected temporal resolution comparable with Greenland ice cores (Banta et al., 2008). Our hypothesis, that the atmospheric CO$_2$ rise at the onset of the B/A warm event was a factor of $2 - 3.5$ larger than measured in EDC, will therefore be validated by these new CO$_2$ data in the future.

- Reviewer comment: *2) With their term "width" the authors seem to be describing the second moment of the pdf. Why not use this metric? The description of the expected value E as a metric for the width of the age distribution is odd and confusing. Several well-known methods for calculating the second moment, or "spectral width", are available in the literature:*

  C. Trudinger, D. Etheridge, P. Rayner, I. Enting, G. Sturrock, R. Langenfelds, Reconstructing atmospheric histories from measurements of air composition in firn, Journal of Geophysical Research 107 (D24). doi:10.1029/2002JD002545.

  T. Hall, R. Plumb, Age as a diagnostic of stratospheric transport, Journal of Geophysical Research 99 (D1) (1994) 1059-1070.

  T. Hall, D. Waugh, Timescales for the stratospheric circulation derived from tracers, Journal of Geophysical Research 102 (D7) (1997) 8991-9001.

  A. Andrews, K. Boering, B. Daube, S. Wofsy, E. Hintsa, E. Weinstock, T. Bui, Empirical age spectra for the lower tropical stratosphere from in situ observations for co2: Implications for stratospheric transport, Journal of Geophysical Research 104 (D21) (1999) 26581-26595.

  Our reply: The metrics suggested by the reviewer refer to a method, in which the age distribution PDF is described by a Green function. Here, we decided to fit a log-normal function to the output of a firn densification model (Spahni et al., 2003; Joos and Spahni, 2008) and therefore stick to the metrics normally taken for this kind of function. Our choice for a log-normal function

was motivated by their easy implementation (depending only on one parameter, the width, which could be obtained from the physical firn densification models) and very good fit to the model output ($r^2 \sim 0.9$). A similar approach would in principle also be possible if we would have chosen to take the Green function used in the cited literature above. This alternative approach and its use in previous literature should be discussed in the revised version of the article.

- Reviewer comment: *3) Furthermore, the idea that the dating of the core using methane synchronisation was biased by the broad age distribution is a bit odd and not well explained. This seems to assume that the beginning of the methane rise was the tie point used during methane synchronisation. Yet my understanding is that the process of methane synchronisation uses midpoints, not the beginning of the methane rise. These assumptions need to be explicitly stated, whatever they are. Midpoints may indeed lead to a small error due to the non-Gaussian nature of the pdf, but this needs much clearer explanation.*

  Our reply: In this context we would like to refer to the details in the companion paper (Köhler, 2010). But in general we are open to an extension of this topic in a revised version.

- Reviewer comment: *4) Generally it is common practice to normalise the age of a filter so that it has a centroid of zero. In other words, such a filter does not bias the age. One good test of a filter, to see if it is unbiased, is to pass a linear trend through it. An unbiased filter will not change a linear trend at all. The authors instead have a value of E, their expected value, that is measured in the hundreds of years. This is odd and confusing and possibly represents a major error, although I cannot tell from the text whether the authors account for their* *nonzero value of E in a separate step.*

Our reply: Our filter follows the criteria necessary, e.g. it does not bias age. We have chosen not to normalise the age of the filter in the presentation of our article (there: Fig. 2), in order to make it comparable to the output from firn densification models (e.g. Joos and Spahni, 2008). However, after the filtering procedure the age is corrected by E, because this age correction is performed in the development of the gas age chronologies (R. Spahni (Uni Bern), personal communication). Our intention was to describe these different effects in Fig. 7 in the article. This might need some more detailed descriptions in a revised version of the MS. We show the correct (unbiased) representation of age by the test suggested by the reviewer, filtering a linear trend (Fig. 2).

- Reviewer comment: *5) The authors have not discussed, from my reading, the assumptions they must have made in order to come up with the shape of the atmospheric history. While it is true that a perfectly known filter can enable the deconvolution of a record uniquely, the error in the filter in this case is quite large. This error produces substantial non-uniqueness in a situation like this. The resulting shape of the atmospheric history that is inferred from a deconvolution is therefore quite non-unique, in addition the amplitude.*

Our reply: The shape of the potential atmospheric CO_2 time series (Fig. 4a) was derived by injecting 125 PgC into the atmosphere and calculating with the carbon cycle box model the atmospheric concentration and its variability over time. In the article we described how we derived by analytical (airborne fraction estimate) and numerical (box model simulations) methods at our carbon injection target of 125 PgC to explain the rapid rise in CO_2 measured in situ in EDC. We performed many simulation scenarios, in which these 125 PgC were injected in 50 to 300

yr (in 50, 100, 150, 200, 250, 300 yr), corresponding to constant injection fluxes of 125 PgC/50 yr = 2.5 PgC yr^{-1} to 125 PgC/300 yr = 0.42 PgC yr^{-1} over the whole injection periods. The fastest injection (in 50 yr) has been motivated by the abruptness in the climate signals recorded in NGRIP (Steffensen et al., 2008). We have to acknowledge that this was not clearly motivated in the methods section. We then tested various longer scenarios. The scenarios with injection times longer than 200 yr seems to be inconsistent with the ice core record, therefore no longer injection times were taken into consideration.

References

Ahn, J. and Brook, E. J.: Atmospheric CO_2 and climate on millennial time scales during the last glacial period, Science, 322, 83–85, doi: 10.1126/science.1160 832, 2008.

Banta, J. R., McConnell, J. R., Frey, M. M., Bales, R. C., and Taylor, K.: Spatial and temporal variability in snow accumulation at the West Antarctic Ice Sheet Divide over recent centuries, Journal of Geophysical Research, 113, D23 102, doi:10.1029/2008JD010235, 2008.

Dällenbach, A., Blunier, B., Flückiger, J., Stauffer, B., Chappellaz, J., and Raynaud, D.: Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the last glacial and the transition to the Holocene, Geophysical Research Letters, 27, 1005–1008, 2000.

Joos, F. and Spahni, R.: Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years, Proceedings of the National Academy of Science, 105, 1425–1430, doi: 10.1073/pnas.0707386 105, 2008.

Köhler, P.: Rapid changes in ice core gas records. Part I: On the accuracy of methane synchronisation of ice cores, Climate of the Past Discussions, 6, 1453–1471, 2010.

Lemieux-Dudon, B., Blayo, E., Petit, J.-R., Waelbroeck, C., Svensson, A., Ritz, C., Barnola, J.-M., Narcisi, B. M., and Parrenin, F.: Consistent dating for Antarctic and Greenland ice cores, Quaternary Science Reviews, 29, 8 – 20, doi:10.1016/j.quascirev.2009.11.010, 2010.

Spahni, R., Schwander, J., Flückiger, J., Stauffer, B., Chappellaz, J., and Raynaud, D.: The attenuation of fast atmospheric CH_4 variations recorded in polar ice cores, Geophysical Research Letters, 30, 1571, doi: 10.1029/2003GL017 093, 2003.

Steffensen, J. P., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Fischer, H., Goto-Azuma, K., Hansson, M., Johnsen, S. J., Jouzel, J., Masson-Delmotte, V., Popp, T., Rasmussen, S. O., Rothlisberger, R., Ruth, U., Stauffer, B., Siggaard-Andersen, M.-L., Sveinbjörnsdóttir, A. E., Svensson, A., and White, J. W. C.: High-resolution Greenland ice core data show abrupt climate change happens in few years, Science, 321, 680–684, doi: 10.1126/science.1157 707, 2008.

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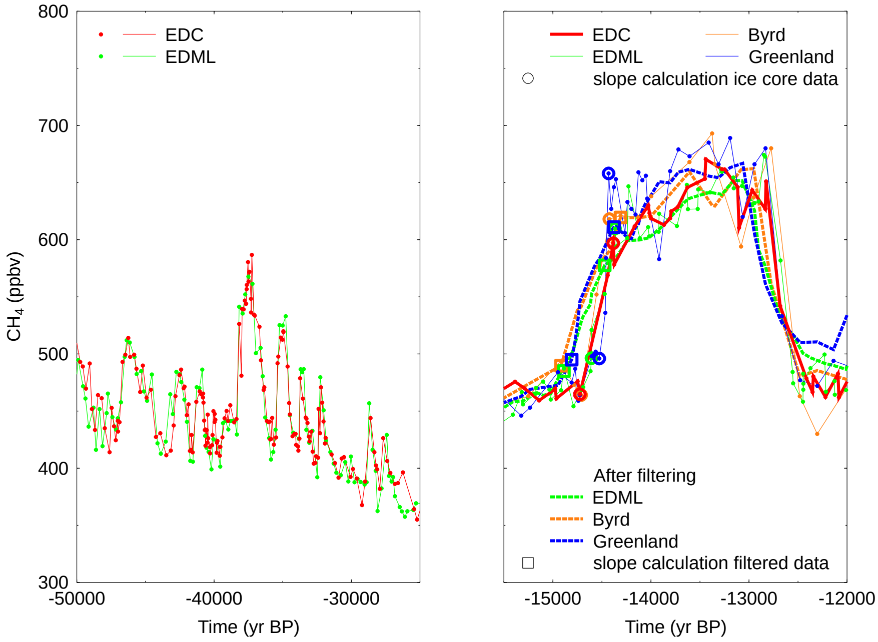

Fig. 1. Left: A qualitative understanding of the gas enclosure by comparing methane in EDC and EDML in MIS 3. Right: Testing our filter function with methane from various ice cores.

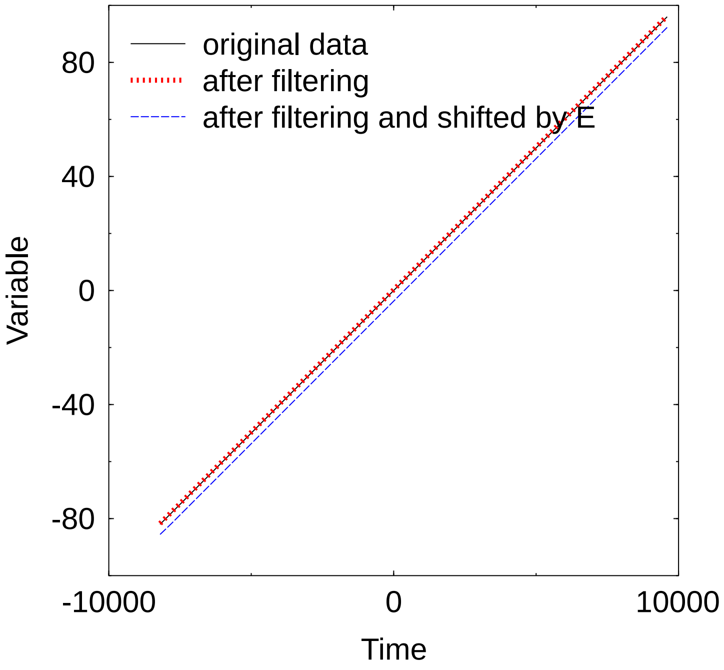

Fig. 2. Testing our filter by filtering a linear trend.