**Climate
of the Past**

Discussions

Interactive comment on "Analytical constraints on layered gas trapping and smoothing of atmospheric variability in ice under low accumulation conditions" *by* Kévin Fourteau et al.

Anonymous Referee #2

Received and published: 5 August 2017

This study presents a high quality, novel data set consisting of ultra-high resolution methane measurements across Dansgaard-Oeschger event 17 in the low accumulation Vostok ice core from East Antarctica. The incredible detail of this record reveals rapid, anomalous signals that do not reflect past atmospheric changes, but are instead related to the process of time-varying gas trapping in the firn column. The authors develop a simple but effective numerical model to simulate the formation of these gas trapping artifacts, facilitating their removal and obtainment of a solely atmospheric signal. The Vostok atmospheric signal contains more high frequency information than would be expected from existing firn model-based predictions. A revised, much narrower, estimate of the gas age distribution at Vostok is produced. Although more work

is needed to confirm these findings, the implication is that more detailed atmospheric records can be obtained from the older ice located in the Antarctic interior.

The paper will be of interest to many in the ice core community and its implications are particularly relevant for the future development of CFA gas measurements and the search for the oldest ice. It is well written with excellent figures. I include many comments, but they should be straightforward for the authors to address.

Understanding gas trapping Can any more information be provided about the frequency of the gas trapping artifacts in depth and ice age domain? The signals reported by Rhodes et al. 2016 were annual – is the variability closer to decadal here and what does this suggest about the physical heterogeneity responsible? Is any comparison with high resolution chemistry possible across this interval?

Simple model of layered trapping Section 4.3. - Please provide more explanation of how extrapolation of Hörhold data to obtain density variability is carried out. What does the range in density variability obtained represent?

- Pg. 11, lines 20, 22-25: is the "closure depth shift" the difference in depth of pore closure between adjacent layers of different density? Please state clearly if so. And is the "age shift" of 207 yrs equivalent to the age difference between the gas trapped in adjacent layers? Does this value change as a result of subsequent tests? Pg. 13, line 4: are "age anomalies" the same as "age shift"?

- A series of tests are conducted to illustrate the sensitivity of the model to input parameters. This is important and interesting but not that clear. Add some paragraphs please. Line 3 – make it clear that the extreme values used are the max and min of ranges already stated. A table including the parameters used and the resulting age and depth shifts would be informative.

- Can anything be said about the relative importance of accumulation rate and density variability in causing gas trapping? Sites like Vostok have low accumulation, causing

higher CH4 anomalies than high accumulation sites, but cold, low accumulation sites also tend to have lower density variability at depth (Fig. 7F, Horhold et al. 2012), which would cause lower CH4 anomalies.

Estimation of Vostok GAD Section 5.2 - Needs an existing high(er) resolution CH4 record. No record exists beyond ~100 ka (NEEM), which limits application of this technique. Abstract (line 14) should be modified to state need for higher resolution record. Still, it will be really interesting to see method applied to other sites for the Last Glacial.

- Pg. 17, line 10-11. WD also experiences stable conditions over this time period. What if the reference atmospheric scenario was from NEEM where accumulation and temperature change greatly across DO events? Would method need to be adapted?

- Related to this, how valid is the assumption that WD represents the atmosphere? Why isn't this record also biased by gas trapping effects (high accumulation so faster trapping? more CFA smoothing?)?

- Pg. 19, line 2. Is the impact of layering on GAD really "unknown". Mitchell et al. (2015) state "total net effect of layering on gas trapping and the width of the age distribution of gases are unquestionably to narrow the age distribution" and your results seem to support this. Some discussion of the modelling work in Mitchell et al. (2015) might help the discussion here.

Also on Pg. 21, line 18 – a sentence or two summarizing the findings of Mitchell et al. (2015) would help will the argument that firn models currently do a poor job (or don't attempt) at dealing with layered gas trapping.

Specific comments: Pg. 2, Lines 3-10: Consider stating that this is the 'traditional' description of the firn column. There is evidence, including the gas trapping anomalies presented here, that contradict the idea of bubble closure only occurring in the lock-in zone.

Pg. 3, line 27: Clathrate relaxation cavities are not mentioned again until Pg. 10. line 15. Sentence 'samples showed small clathrate relaxation cavities, the CFA sticks did not reveal visual anomalies'. Isn't this statement contradictory? In which direction would clathrate relaxation affect the CH4 signal and why?

Pg. 3, line 7: 'in periods of fast atmospheric variations...' Be clearer about what this means. Atmospheric variation must occur over the time frame of the gas trapping process (not seasonal variability for example), which will change with ice core analyzed.

line 10: WAIS Divide information in Rhodes et al. (2016) is from a model only.

Pg. 9 & Fig. 3: Great figure. Could an arrow be added to indicate the direction of time (right to left)? In discussion about relative influence of early and late closure on final signal, do you mean proportion of early trapped layers will be greater than later trapped layers? Or, do you mean the amplitude of the early layer signals will be greater than the later layer signals? Could this hypothesis be illustrated on the figure?

Pg. 12 & Pg. 16: Buizert et al. (2012) does not convert gas ages to AICC2012. Do you mean GICC05 here?

Figure 5 & Pg. 15: Yes, the tiny sub-centennial variation is smoothed out in Vostok, but multi-centennial information is preserved, e.g., feature 58.7-58.4 ka. This is more detail than we would expect from Dome C GAD estimation and worth mentioning. It would help justify statement on Pg. 19, line 9 that at the moment is tenuous.

Pg. 20, line 1: Can you be more specific about the 'bias' possibly introduced by gas trapping artifacts? Does the 7 ppbv refer to a positive or negative bias? Wouldn't the direction of bias change with the atmospheric trend and so even itself out over the relatively short timescales of gas trapping (compared to length of record compressed within small depth of ice)?

Supplement, Pg. 1, line 13: statement about WAIS data being scaled to discrete measurements is not accurate.

Technical notes: Pg. 1, Line 13: Add "numerical" method.

Pg. 1, Line 21 and repeatedly through manuscript: "gases get enclosed within bubbles...and allow reconstructing..." "Allow reconstructing" is not grammatically correct and should be changed to something like "allow us to reconstruct..." or "allowing reconstruction of...".

Pg. 2, line 11: change "atmospheric composition events" to "atmospheric variability"

Pg. 2 line 12: "dampening" should read "damping" = the decrease in the amplitude of an oscillation or wave motion with time.

Pg. 3, line 4: define or explain "short scale physical variability"

Pg. 3, line 5: insert "physical" before heterogeneities

Pg. 4, line 2-3 repeats what is said on previous page

Pg. 4, line 12: state volume of debubbler

Pg. 6, line 5 onwards: separate into two paragraphs

Pg. 6, line 15: does 2.1m represent one instance of kerosene contamination or it is the sum of many?

Fig. S3: Add indication of depth range represented.

Fig. 1: increase sub-figure size

Fig. S11 caption and elsewhere: be specific - 'WD2014' gas chronology

Pg. 6, Line 21: change to "atmosphere relevant" of atmospheric history relevant?

Pg. 6, line 28: 50 ppbv amplitude and 2 cm wavelength

Pg. 8, line 26: 'the closure of such a layer is likely progressive' – please clarify meaning

Pg. 9, line 4: clarify 'significant atmospheric variations'. Again, quantify.

Pg. 11, line 9: replace 'later' with 'latter'

Pg. 13, line 21: a signal that is representative of only atmospheric variability

Pg. 13, line 28: be specific here, artifacts already removed are due to breaks or kerosene.

Pg. 14, line 3: provide details on spline fit

Pg. 14, line 27: 'high frequency atmospheric variability'

Pg. 19, line 23: be specific here, "anomalous layers" are 'gas trapping artifacts' or artifacts

also due to other things like kerosene?

Pg. 21, line 21: delete "or infirm"

Strictly, the WAIS Divide ice core should be referred to as WD, not WAIS (the ice sheet).