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Interactive comment on "Bipolar volcanic synchronization of abrupt climate change in Greenland and Antarctic ice cores during the last glacial period" *by* Anders Svensson et al.

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COMMENT: This paper is addressing a really great concept: that of synchronising Greenland and Antarctic climate records precisely through volcanic signals. The concept is bold: until recently most of us would have considered this too hard to attempt. And it is used to do an important task of refining the relationship between hemispheres across bipolar seesaw events. While the alignment done here may be improved in the future, this is likely the best that can be done for now, and it opens up a number of very interesting possibilities around global synchronisation, understanding firn dynamics, and addressing variability between D-O events. The paper is written very clearly,

and although I have a rather large concern I need to raise, it was a pleasure to read. Because my concern is quite significant (but I believe addressable) I will tick the "major revisions" box, but this does not mean I think the paper is generally flawed in any way – on the contrary it's great, but I think it lacks one major caveat that readers need to be more aware of.

REPLY: We thank the reviewer for appreciating our efforts and will try to respond to the concerns in the following.

COMMENT: It is very challenging to safely match up volcanic records from distant locations, as those of us who have been involved in comparisons across Antarctica know. This is even more the case between hemispheres because there will be numerous additional volcanic peaks in Greenland (less so in Antarctica) that do not have a bipolar signal. As the authors explain, the secret is to get a pattern of several peaks with an identical spacing. An advantage the authors have is that the methane matching already done allows them to home in on the right section with a century or so. The authors aim to achieve the pattern match by using layer counting between volcanic peaks in two cores: NGRIP and EDML. We all know this can be done at NGRIP, as it was the basis for GICC05; while it has its issues, over short intervals the uncertainties should be quite small. However, it is a huge leap to accept that it can be done at EDML, and I find it very strange that this is glossed over, and even more so that we are not shown any examples.

The only example I am aware of where layer counting has been attempted at EDML was in Sommer et al (2002, not referenced in this paper), where layers were counted for the top 2000 years. With only about 7 cm we/yr, the example given in Sommer et al makes it clear this is tricky (and required matches to known dated volcanic peaks for verification, something that would be circular in this case), but the authors nonetheless claimed an accuracy of around 3%. But now in this paper we enter the much harder realm of doing the same thing in the last glacial: where some of the key records used by Sommer are not available and where the snow accumulation rate is as low as 3 cm we/year (range 3-5 in the sections used). The authors justify their ability to count at EDML by saying (line 142) "for the investigated time interval the annual layer thicknesses are comparable to those of NGRIP (Veres et al., 2013) and layer counting can be done in a similar way". However this misses the point. Whether annual layers can be distinguished and counted relies on two different factors. One is whether the analysis method is well enough resolved to give several samples per year in layers that may be (in this case) only 1.5 cm thick – this is actually quite dubious (Sommer gives the true EDML resolution as 0.7 cm, implying 2 samples/year for chemistry) and it would be nice to see examples to understand this. However more important is whether annual layers were ever present, and our experience at Dome C and Dome Fuji would suggest that, at somewhere with 3 cm we accumulation, they are not (or at least not reliably), with a certainty of missing some years due to redistribution (sastrugi) that occurs at scales greater than the approximately 8 cm scale of the snow depth deposited each year.

REPLY: There were a few examples of layer counting in the EDML glacial ice presented in Svensson et al., CP, 2013 (full reference in manuscript), but never mind, there is no reason not to provide some examples of annual layer counting also for this work, where it indeed forms the basis of the volcanic bipolar synchronization.

In the supplementary figures, we now provide examples of annual layer counting in NGRIP and EDML across four intervals applied to match up patterns of bipolar volcanic eruptions:

- Fig. S17A-D shows the layer counting across the four prominent volcanic spikes that occur right before the onset of the GS-1 / Younger Dryas (Fig. 2 left in manuscript). For NGRIP the annual layers are marked in the liquid conductivity record and for EDML the marks are set in the Calcium concentration record. 'Certain' annual layers are marked with black dots and 'uncertain' layers are marked with white dots following the notation introduced in Rasmussen et al., JGR, 2006 and Andersen et al., QSR, 2006 (full references in manuscript).

- Fig. S18A-B shows the layer counting between a pair of significant volcanic spikes in GS-5.1 that represents a section of low accumulation for both NGRIP and EDML. For NGRIP the annual layers are marked in the liquid conductivity record and for EDML the marks are set in the dust concentration record. The annual layer thickness in this interval is around 1.4 cm and 1.9 cm for NGRIP and EDML, respectively.

- Fig. S19A-D shows the layer counting across the onset of GI-8 (Fig. 2 right in manuscript). In NGRIP the annual layer thickness increases from ~1.7 cm to ~2.9 cm across the onset, whereas EDML has an annual layer thickness close to 2 cm for the entire interval.

- Fig. S20A-D shows the layer counting between the deepest two eruptions applied in this study (in GS-16, Fig. S14A). In this interval, the annual layer thickness of EDML (~2 cm) is approximately two times that of NGRIP (~1 cm). In NGRIP the annual layers are only countable in the line-scan grey-scale intensity profile as all the chemistry records have too low resolution to resolve the annual layers.

The above examples cover some 20 m out of the more than 1 km ice core that has been layer counted for this study, and the shown sections are representative of sections with 'thick' and 'thin' annual layers as well as 'high' and 'low' accumulation periods. There are shorter sections in both cores where one or several records are missing or where data quality is too low for annual layer counting to be possible. In those sections, the annual layers have been interpolated based on adjacent sections.

As it was noticed for the counting of the GICC05 time scale, the distribution of annual layer thicknesses is fairly narrow (Andersen et al., QSR, 2006, Fig. 7). In other words, it is unlikely to find an annual layer with half the thickness of the average or with two times the thickness of the average. This appears to be true also for the EDML dataset, and this 'regularity' of the annual pattern can be applied as guidance for layer picking over shorter intervals where data are missing or disturbed somehow.

For both NGRIP and EDML, most of the chemistry records cannot resolve the annual layers when the thickness is below 2-3 cm depending on the resolution of individual records. In that case, the grey-scale of the visual-stratigraphy record is necessary for counting the annual layers. The record has millimeter resolution and was obtained by the same instrument for both cores. The visual stratigraphy does not provide as clear an annual signal as the (smoothed) chemistry records, but the annual signal is visible in both NGRIP and EDML.

COMMENT: I would have expected to see a number of strategies to overcome this: a) Knowing the estimated accumulation rate at EDML (which is embedded in the AICC2012 age model), one could estimate the distance between volcanic peaks without counting;

REPLY: We have been using the AICC2012 annual layer thicknesses for guidance, but the time scale is too imprecise to match up the volcanic eruptions.

COMMENT: b) WAIS Divide is actually counted to 31 ka. Why was this not used at least to GI5? Intrinsically the chances of counting layers below that are still better at WD than at EDML because the accumulation rate at WD was higher so signals were at least formed and may be decipherable with higher resolution analysis (which could in theory be done).

REPLY: The WD2014 time scale has been applied for guidance and for most of the intervals younger than 31 ka there is agreement within error estimates between the EDML and WDC interval durations. We now mention this in the manuscript. The right hand side of Table 1 now shows a comparison of interval durations between bipolar match points as determined in GICC05 and WD2014 and in this work. Independent layer counting in several cores allows us to better identify critical sections whenever a grand unified bipolar ice core chronology will be constructed next time.

COMMENT: c) If the authors really think they can count layers in EDML glacial ice then they should show us some extended examples, and explain how counting is possible at a site with such low accumulation rate. Personally I suspect this cannot be done at

any level better than just using the average accumulation rate, and that probably the counters are kidding themselves that small oscillations represent decipherable years. However I am willing to be convinced if the authors provide examples at different sections that they have used.

REPLY: We now provide counting examples in Fig. S17-S20. We will leave it to the reader to judge how well the annual layers can be identified in NGRIP and EDML.

COMMENT: I do not see this as fatal to the paper. Strategy (a) (checked by strategy (b) until GI5) would likely yield a reasonable result, but the authors need to be clear about what is possible. As things stand the reader who is not familiar with EDML would imagine some rather routine piece of layer counting, and it is therefore essential to explain that it is far from routine and indeed would, if successful, represent a breakthrough most of us would consider could not be achieved with any useful accuracy.

REPLY: Indeed, we need to provide those counting examples. However, we are maintaining the viewpoint that the layer counting in EDML can be performed in much the same way as was done for the NGRIP ice core. The CFA and line scan datasets for the two cores are very similar in terms of measured records and depth resolution. The datasets were obtained by very similar instrumentation and to some degree also by the same group of people.

It is true that EDML is a lower accumulation site than NGRIP. AICC2012 states 3-5 cm ice eq. accumulation at EDML for the 15-60 ka period, as compared to 5-7 cm ice eq. accumulation at NGRIP for the coldest intervals. Nevertheless, it appears that by far the majority of the annual layers are well preserved in the EDML core throughout the investigated period. This is seen for the annual layer counting where there is agreement within error of interval durations for the NGRIP and EDML layer counting over longer sections. It is also expressed by the preservation of the volcanic signal that is very similar for the EDML core and higher-accumulation WDC core. All of the bipolar events identified in this study are identified in both EDML and WDC. If there would have been a loss of annual layers in EDML that would have resulted in a loss of volcanic spikes as well. As mentioned by the reviewers, and as discussed in several studies, EDC and DF appear to sometimes lose part or all of the volcanic signal, which is explained by the low accumulation at those sites (examples are seen in Svensson et al., CP, 2013, Fig. 8). For EDML, this seems not to be the case, likely because the EDML accumulation is greater than that of EDC by a factor of two (according to AICC2012).

COMMENT: Apart from this, I have only very minor comments: Line 21: "The last glacial period is characterized by a number of abrupt climate events that have been identified in both Greenland and Antarctic ice cores". This is a bit imprecise as they are abrupt in Greenland and in d_ln in Antarctica but not in Antarctic climate. How about "The last glacial period is characterized by a number of millennial climate events that have been identified in both Greenland and Antarctic ice cores, and that are abrupt in Greenland climate". Line 23 and elsewhere "Hemispheres" should be lower case. Line 146: for clarity it would be helpful to spell out that published AICC2012 ages are in bp (1950), and so b2k ages will be 50 years greater than those in AICC2012. It's not really my concern as a reviewer but it seems a little strange that the acknowledgment calls out all the participants in NEEM (which is not the prime Greenland core used here) but not NGRIP or EPICA.

REPLY: All the suggested changes have been implemented.

Please also note the supplement to this comment:
https://cp.copernicus.org/preprints/cp-2020-41/cp-2020-41-AC2-supplement.pdf

Interactive comment on Clim. Past Discuss., https://doi.org/10.5194/cp-2020-41, 2020.