Reply to review 1

COMMENT:
The paper presents the first comprehensive attempt to link ice core from both hemispheres on a common timescale at high resolution, based on volcanic matching in addition to the now "traditional" method of using gas records (e.g. methane). I find the paper very well written, and the analysis is convincing. I wish to congratulate the authors on a very very important contribution to ice core dating, and to our understanding of abrupt climate change. I have three concerns.
First, citations for data are not consistent, and are incorrect for those data sets that I am familiar with. This should be corrected.
Second, the discussion of the relationship between deuterium excess and oxygen 18 (d18O) is confusing; I think those who have worked closely with these data (including me) will understand the arguments, but others will not.
Third, overall, I think the paper is written for an audience that already knows all the issues very well, but it will be difficult to follow for those that are not already in the ice core research community. Following are my corrections and suggestions on each point.

REPLY:
We thank the referee for the positive review and the constructive comments that we will reply to in the following.

COMMENT:
1. Citations:
A. Reference is made to both Fudge et al. 2013 and WAIS Divide Project Members, 2013, which are the same paper. Reference is also made to Buizert et al., 2015, and WAIS Divide Project Members, 2015, which are also the same paper. The correct citations are the WAIS Divide Project Members, 2013 and WAIS Divide Project Members, 2015. Fudge et al. 2013 and Buizert et al. 2015 should not be used. This was agreed upon by the WAIS community at the time those papers were written. Note that there is a different Buizert et al., 2015 (https://doi.org/10.5194/cp-11-153-2015) which should be cited when discussing the WAIS Divide timescale, but not the synchronization work nor the isotope data. This is not the same paper as WAIS Divide Project Members 2015.

REPLY:
Corrected.

COMMENT:
B. Several of the citations to data are wrong. Please correct these both in the main text and in the Supplement Table. I am sure it would be appreciated by all those who produced the data if the original works were cited.
i) For WAIS Divide sulfate and conductivity, the references are WAIS Divide Project Members 2013, and Sigl et al., 2016. (As noted above, Fudge et al., 2013 is not a correct citation.)

REPLY:
Corrected.

COMMENT:
ii) For GISP2, the original reference is Grootes et al., 1993, not Stuiver and Grootes, 2000.

REPLY:
We now cite both references. The applied GISP2 dataset appears to be updated in 1999.

COMMENT:
iii) The d18O and deuterium excess data for WAIS Divide is ascribed to Buizert et al. 2018 in various places. This is incorrect. (For example, line 167.) The correct citations for theWAIS Divide d18O (not dxs) areWAIS Divide Project Members 2013 and Steig et al,. 2013. The correct citation for WAIS Divide dxs is Markle et al. 2017. This is the sole reference that should be used.

REPLY:
Corrected, except that the Steig et al., Nature Geoscience, 2013, publication appears to be mostly concerned with the last 2000 years and is not cited.

COMMENT:
iv) I encourage the authors to double-check references for Dome C, etc. that may also be incorrect.

REPLY:
The references for the Antarctic ice cores have been updated.

COMMENT:
2. In general, I find the discussion of the relationship between d18O and dxs incomplete and confusing.
A. In the abstract, you write that "During abrupt transitions, we find more coherent Antarctic water isotopic signals (d18 O and deuterium excess) than was obtained from previous gas-based synchronizations." I don't understand this statement. You find that the phase relationship between dxs and d18O is shorter than was found by Markle et al. 2017, and later by Buizert et al., 2018. But you do not show that the records are more coherent. (If you do find greater *coherence*, this is interesting but would require further analysis).

REPLY:
Abstract text now changed to "In response to Greenland abrupt climatic transitions, we find a response in the Antarctic water isotope signals (δ^{18}O and deuterium excess) that is both more immediate and more abrupt than found with previous gas-based interpolar synchronizations."

COMMENT:
B. Also in the abstract, you say that "The time difference between Antarctic signals in deuterium excess and d18O, which is less sensitive to synchronization errors, suggests an Antarctic d18O lag of 152 ± 37 years." For those not familiar with this subject, it is not clear what "an Antarctic d18O lag" refers to. This is the lag between d18O and dxs, both in Antarctica. I think what you are trying to say is that because dxs is in phase with Greenland d18O, then the phase lag between d18O and dxs in Antarctica provides an independent estimate of the phase between d18O in Antarctica and Greenland d18O. This has to be spelled out or no one will understand it!

REPLY:
The formulation in the abstract is now changed to: 'The time difference between Antarctic signals in deuterium excess and δ^{18}O, which likewise reflects the interpolar phasing of the bipolar seesaw yet is less sensitive to synchronization errors, suggests an Antarctic δ^{18}O lag behind Greenland of 152 ± 37 years.'

COMMENT:
C. Throughout the paper, too little credit is given to the first paper (Markle et al. 2017) that showed how the lag between dxs and d18O in Antarctica is connected with the lag between d18O in Greenland and d18O in Antarctica. Prior to that, dating quality was insufficient to make this argument. Buizert et al., 2018 did not make this discovery; in that paper, we extended the findings of Markle et al., to other Antarctic ice cores. Markle is cited at the moment only for suggesting that: "Antarctic warming response to the

Greenland warming is likely to be associated with fast atmospheric changes", and "It was suggested that the gradual dln trends before and after the transition follow the gradual source-water sea-surface-temperature trends of the SH via the bipolar seesaw." Those things are true, but were not the main subject of Markle et al.! To give credit where it is due, I would suggest the following rewrite.
Replace the following:
Besides d18O, we also stack records of Antarctic deuterium excess using the logarithmic definition (dln) introduced by (Uemura et al., 2012). Previous work has found d ln to abruptly increase (decrease) in synchrony with the onset (termination) of GIs at multiple Antarctic sites (Buizert et al., 2018; Markle et al., 2017; Masson-Delmotte et al., 2010), which has been attributed to shifts of the Southern Hemisphere (SH) subpolar jet and westerly winds (e.g. Schmidt et al. (2007)).
With
Besides d18O, we also stack records of Antarctic deuterium excess using the logarithmic definition (dln) introduced by (Uemura et al., 2012). Markle et al. (2017) showed that in the WAIS Divide ice core, dln abruptly increases in synchrony with the onset of GIs; at the termination of GIs, dln abruptly decreases. Markle et al. (2017) used a climate model simulation with moisture tagging to show that this relationship could be explained by north-south shifts in the location of moistures sources associated with changes in the shifts of the Southern Hemisphere (SH) subpolar jet and westerly winds. This is consistent with work of Schmidt et al. (2007) who had previously shown with climate model simulations that the deuterium excess should be inversely correlated with the Southern Annular Mode (SAM) index. Masson-Delmotte et al. (2010) made a similar argument on the basis of the Dome C core, but without sufficient dating precision to demonstrate the close relationship found by Markle et al. (2017). These findings were later extended to multiple Antarctic sites by Buizert et al. (2018).
Please note also that the use of parentheses to mean opposites is very difficult to read, and should be avoided. There is no reason to do this. "abruptly increase (decrease) in synchrony with the onset (termination)"

REPLY:
We thank the referee for contributing to the writing of the manuscript. The suggested text has been adopted.

COMMENT:
3. A. In general, a clearer discussion of the relationship between CH4, d18O, and dxs is needed. I am missing a clear explanation of this for the non expert. I think the following points are important to make clear. Consider, for example, how you would explain Figure.5 to a non-expert.
First, the relationship between CH4 and d18O in Greenland is well established, and the lag is short. Second, cores have been linked mostly by matching methane, but there is uncertainty in the ice timescales because of uncertainy in DeltaAge. Third, the WAIS Divide core has a small enough DeltaAge that it was possible to show a clear lag of 200 years between abrupt warming AND abrupt CH4 increases in Greenland and the changepoint of d18O in Antarctica. Fourth, also with WAIS Divide, it was shown that dxs is is close to being in phase with CH4, and therefore in phase with d18O in Greenland. Fifth, this has been extended to other Antarctic cores by volcanic synchronization within Antarctica. Sixth, the current paper adds volcanic synchronization between Greenland and Antarctica, further refining the relationships among dxs, CH4, and d18O in both Greenland and Antarctica.

REPLY:
The present work is independent of previous gas and cosmogenic bipolar synchronizations, except that we use them as a starting point for the volcanic synchronization. The reader should therefore be able to read Fig. 5 without any detailed knowledge of the history of bipolar synchronizations. In the introduction, we are referring to the main papers that details the complications of existing synchronization efforts; we are mentioning issues with Delta Age, the 200 yr Antarctic lag, and the Greenland and Antarctic internal

volcanic synchronizations. Furthermore, we are now making ample reference to the Markle et al., 2016, Buizert et al., 2018, and the WAIS Divide project members 2013 and 2015 papers.

COMMENT:
B. A few other small things.
i) In the statement on line 52, DO events are believed to originate in the North Atlantic, but have a global climatic impact that is documented in a wide range of paleoclimate archives across the Northern Hemisphere (Voelker and workshop participants, 2002).
I would say:
DO events are believed to originate in the North Atlantic, but have a global climatic impact that is documented in a wide range of paleoclimate archives across the Northern (Voelker and workshop participants, 2002) and Southern Hemispheres (Pedro et al. 2015).

REPLY:
The suggested formulation is adopted.

COMMENT:
ii) Line 71, "Modeling past Deltaage requires assumptions about past accumulation and temperature variations, introducing substantial age uncertainties associated with the synchronization." This isn't quite true for WAIS Divide or central Greenland, where we know the accumulation extremely well. Consider changing this to make it clear that the chief uncertainty for WAIS Divide (and for Greenland) is the firn physics, not the lack of knowledge of T and accumulation.

REPLY:
The text is now formulated as: 'Modeling past Δage requires an understanding of the physical processes taking place in the firn as well as knowledge or assumptions about past accumulation and temperature variations, introducing substantial age uncertainties associated with the synchronization.'

Reply to review 2

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.

Reply to review 3

COMMENT:
The paper presents the results of bipolar volcanic synchronization, which is a challenging task, and discusses bipolar phasing of DO events. Utilizing 80 volcanic eruptions during the second half of the last glacial period recorded in both Greenland and Antarctic ice cores, age control of the multiple bipolar ice cores is greatly improved. The paper confirms the previously proposed centennial-scale lag of Antarctic temperatures after abrupt Greenland temperature changes during DO events. The improved age control provided by this study significantly reduces the duration of the lag. This new important finding will give better constraints to climate modeling and contribute to further understanding of the mechanisms of DO events. The improved age control will also have a wide range of applications not only in ice core studies but also in other fields of geophysics and geochemistry.

REPLY:
We very much appreciate the positive mentioning and we will reply to the concerns in the following.

COMMENT:
I have a concern about how the bipolar volcanic signals are pinpointed. The criteria need to be more clearly explained. I have the following questions and comments regarding this.
1. Lines 201-203: To my eyes, the inner two spikes are not very clear. The second one from the left does not seem to be seen in the EDC core.

REPLY:
It is sometimes the case that eruptions identified in WDC and EDML are not visible in the EDC record. This is probably because EDC is a low accumulation site, where 1) some events are not archived due to the intermittency of snow fall and snow drift and 2) that the EDC sulfate record has comparable low temporal resolution. In this specific case, the second EDC spike from the left is present in the DEP record and the 3rd EDC spike from the left is visible in the sulfate record (Fig. 2).

COMMENT:
2. Lines 209-211: I don't see the 12.17ka peak in the EDC core.

REPLY:
This is another example of a minor peak that is hard to identify in the lower-resolution EDC ice core. The peak has been identified in the Antarctic volcanic synchronization of Buizert et al., 2018, so the EDC depth is included in the bipolar list as well. For this work, the Antarctic eruptions are pinpointed mostly in EDML and WDC, whereas EDC is mainly applied to support the major eruptions. However, when the corresponding EDC depth is known from the Antarctic synchronization it is included in the bipolar list for completeness.

COMMENT:
3. Line 236: "the bipolar volcanic matching pattern is easily recognized". I'm not convinced. Please explain how the bipolar volcanic signals are selected. For example, why is the spike around 16.3 ka not selected?

REPLY:
The main focus of this study has been to determine the exact bipolar phasing in the neighborhood of the abrupt Greenland warming and cooling transitions. Away from the transitions there are additional bipolar volcanic events not identified in this study. We have now included the 16.3 ka peak in the bipolar volcanic list (Table 1).

COMMENT:
4. Lines 241-242. In the WDC core, there are small acidity peaks around 15.63 ka and 15.71ka. Couldn't one of these peaks correspond to the 15.68 ka peak in Greenland? Are these peaks too far from 15.68ka?

REPLY:
Those links are prohibited by the layer counting constrains. Assuming the bipolar link at 15.56 b2k GICC05 is correct, then it would require a counting uncertainty of some (15.71-15.68)/(15.68-15.56)*100 = 25% to allow for the suggested match. That is far more than the counting uncertainty can allow. There is however another pair of minor peaks in the WDC sulfur record that fit with the 15.68 ka peaks in Greenland that we now included in the bipolar volcanic list (Table 1).

COMMENT:
I have other minor comments and questions.
1. Lines 32-34: Where in the main text is "more coherent Antarctic water isotopic signals" discussed?

REPLY:
The sentence in the abstract is now reformulated: 'In response to Greenland abrupt climatic transitions, we find a response in the Antarctic water isotope signals ($\delta^{18}O$ and deuterium excess) that is both more immediate and more abrupt than found with previous gas-based interpolar synchronizations.' Figure 5 shows the more immediate response of the Antarctic water isotopic signal for the volcanic synchronization as compared to the gas synchronization.

COMMENT:
2. Line 65: Does Steinhilber et al paper really use 36Cl for bipolar synchronization? The paper does use 10Be. But 36Cl measurement needs large samples and it is usually difficult to use 36Cl for synchronization. Am I wrong?

REPLY:
Indeed, 36Cl is not applied in the cited references and is now removed from the text.

COMMENT:
3. Line 164: Please give more details about "high-resolution. What are the resolutions of the stable water isotope records?

REPLY:
The sample depth resolution of the water isotopic records vary from core to core and is provided in the cited references. Timewise, the sample resolution will depend on the accumulation and the layer thinning with depth. The term 'high-resolution' has been removed.

COMMENT:
4. Lines 175-179: I think wind-scouring is another factor affecting the low accumulation Antarctic sites particularly during colder periods.

REPLY:
The wind-scouring effect is now mentioned in this context.

COMMENT:
5. Line 190: It would be nice to show GI-2 in Fig. 1 for readers who are not so familiar with GIs.

REPLY:
The position of GI-2 is now indicated in the figure.

COMMENT:
6. Line 216: To my eyes, the EDML water isotope data seems to be increasing during 12.75-13.10 ka.

REPLY:
The comment on the Antarctic water isotopes has been removed.

COMMENT:
7. Lines 227-232: I agree that this study gives no support for the Hiawatha crater to have formed around the onset of YD/GS-1. But I don't understand that undisturbed stratigraphy can deny the Hiawatha crater hypothesis. Is the stratigraphy at NEEM really expected to be disturbed by the Hiawatha event which was 378 km away from NEEM? I'm not very sure about this.

REPLY:
The study by Kjær et al., 2018, does not suggest that the Hiawatha crater was formed at the onset of the Younger Dryas event, so the discussion of the crater has been removed.

COMMENT:
8. Line 244: It is difficult to see from Fig. S3A that the spike is a triplet.

REPLY:
There is now an inset in Fig. S3A showing the triplet in NGRIP and EDML.

COMMENT:
9. Lines 246-247: I could not understand this sentence. Is this a typo?
10. Lines 255-257: I could not understand this sentence. Please explain in more detail.
11. Line 280: Figure numbers seem to be wrong. Do you mean "such as GI-8 and GI-12 (Figs.S7B and S10B). For the GI-9 onset (Fig.S8B)"?

REPLY:
Corrected.

COMMENT:
12. Lines 291-296: Larger variability in Antarctic ice cores could be also due to wind scouring. At low accumulation interior sites, wind scouring increases the noise in water isotope records.

REPLY:
The effect is now mentioned.

COMMENT:
13. Lines 324-327: Please explain how the local cycle of sublimation-condensation affects the alignment of the water isotope records.

REPLY:
The following text has been added to the manuscript: 'Sublimation affects the isotope concentration and the deuterium excess of snow through kinetic fractionation. Snow sublimation requires large amounts of energy

and it is controlled by the relative humidity, which in turn is linked to the large-scale atmospheric circulation. Sublimation effects are poorly constrained on the East Antarctica plateau.'

COMMENT:
14. Line 337: Please explain more about the logarithmic definition of deuterium excess for readers who are not so familiar with water isotopes.

REPLY:
There is now a reference to Markle et al., NatGeo, 2016, where the logarithmic definition is discussed and applied to match Antarctica to the abrupt Greenland climate events.

15. Line 363: I'm confused. Why is there small uncertainty in the relative phasing? Isn't the uncertainty zero if oxygen and hydrogen isotopes were measured in the same samples? If they were measured in different samples, I would expect almost negligible uncertainty.

REPLY:
The sentence is now formulated as: 'The Antarctic d_{ln} and $\delta^{18}O$ signals (Fig. 5) are recorded in the same physical ice cores, and therefore the uncertainty in their relative phasing is small and only related to the stacking of the Antarctic cores and the change point determinations.'

Bipolar volcanic synchronization of abrupt climate change in Greenland and Antarctic ice cores during the last glacial period

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Abstract

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 records. The mechanisms governing this climate variability remain a puzzle that requires a precise synchronization of ice cores from the two hemispheres to be resolved. Previously, Greenland and Antarctic ice cores have been synchronized primarily via their common records of gas concentrations or isotopes from the trapped air and via cosmogenic isotopes measured on the ice. In this work, we apply ice-core volcanic proxies and annual layer counting to identify large volcanic eruptions that have left a signature in both Greenland and Antarctica. Generally, no tephra is associated with those eruptions in the ice cores, so the source of the eruptions cannot be identified. Instead, we identify and match sequences of volcanic eruptions with bipolar distribution of sulfate, i.e. unique patterns of volcanic events separated by the same number of years at the two poles. Using this approach, we pinpoint 82 large bipolar volcanic eruptions throughout the second half of the last glacial period (12-60 ka before present). This improved ice-core synchronization is applied to determine the bipolar phasing of abrupt climate change events at decadal-scale precision. In response to Greenland abrupt climatic transitions, we find a response in the Antarctic water isotope signals ($\delta^{18}O$ and deuterium excess) that is both more immediate and more abrupt than found with previous gas-based interpolar synchronizations, providing additional support for our volcanic framework. On average, the Antarctic bipolar seesaw climate response lags the midpoint of Greenland abrupt $\delta^{18}O$ transitions by 122 ± 24 years. The time difference between Antarctic signals in deuterium excess and $\delta^{18}O$, which likewise informs on the time needed to propagate the signal as described by the theory of the bipolar seesaw, but is less

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sensitive to synchronization errors, suggests an Antarctic $\delta^{18}O$ lag behind Greenland of 152 ± 37 years. These estimates are shorter than the 200 years suggested by earlier gas-based synchronizations. As before, we find variations in the timing and duration between the response at different sites and for different events suggesting an interaction of oceanic and atmospheric teleconnection patterns as well as internal climate variability.

1. Introduction

Greenland and Antarctic ice cores provide high-resolution records of abrupt climate events occurring throughout the last glacial period (11.7-115 ka BP). In Greenland ice cores, Dansgaard-Oeschger (DO) events describe a series of characteristic climate events (Dansgaard et al., 1993; North Greenland Ice Core Project members, 2004) that involve warming transitions of up to 16.5 degrees (Kindler et al., 2014) occurring within decades (Erhardt et al., 2019). Each DO event consists of a relatively mild climatic period, referred to as a Greenland Interstadial (GI) that is followed by a cold climatic period, known as a Greenland Stadial (GS). The duration of GIs and GSs range from centuries to millennia. Detailed investigation of the stratigraphy of the 25 major DO events originally identified has revealed that some of the events are composed of several separate warming and cooling events, leading to a total of 31-33 abrupt warming events during the last glacial period depending on the definition employed (Rasmussen et al., 2014). Whereas the onset of a GI event is abrupt and occurs in less than a century, the cooling transitions from GI to GS are more gradual and typically occur over several centuries. DO events are believed to originate in the North Atlantic, but have a global climatic impact that is documented in a wide range of paleoclimate archives across the Northern (Voelker and workshop participants, 2002) and southern hemispheres (Pedro et al., 2018). In Antarctic ice cores, the corresponding Antarctic Isotopic Maxima (AIM) are characteristic warm events that are more gradual and of smaller amplitude than the Greenland events (EPICA community members, 2006). The AIMs are believed to be related to the DO events through the so-called bipolar seesaw mechanism (Bender et al., 1994; Stocker and Johnsen, 2003), but the detailed mechanism is a matter of debate (Landais et al., 2015; Pedro et al., 2018). Knowledge of the exact phasing of climate in the two hemispheres is crucial for deciphering the driving mechanism of the abrupt climate variability of the last glacial period and the climatic teleconnection patterns that connect the two hemispheres.

Three different techniques have been applied to progressively improve the synchronization of Greenland and Antarctic ice cores: globally well-mixed atmospheric gases, in particular the methane concentration (Blunier et al., 1998; Lemieux-Dudon et al., 2010; Rhodes et al., 2015; WAIS Divide Project Members, 2015) and the isotopic compositions of O_2, $\delta^{18}O_{atm}$ (Bender et al., 1994; Capron et al., 2010), cosmogenic isotopes such as ^{10}Be (Raisbeck et al., 2017; Steinhilber et al., 2012), and identification of large volcanic eruptions with bipolar sulfate deposition (Sigl et al., 2013; Svensson et al., 2013). A strength of the bipolar methane matching approach is that atmospheric methane concentrations change almost in phase with abrupt Greenland climate change allowing for those events to be synchronized in ice cores. A weakness of the bipolar gas matching approach is the dependency on a precise determination of the so-called Δage that refers to the offset in age between the ice and the air enclosed in an ice core at a given depth (Blunier et al., 2007; Schwander and Stauffer, 1984). Modeling past Δage requires an understanding of the physical processes taking place in the firn as well as knowledge or assumptions about past accumulation and temperature variations, introducing substantial age uncertainties associated with the synchronization.

Cosmogenic isotope production rates are modulated by the Earth's magnetic field and by solar variability, and they therefore carry a global signal that is shared by Greenland and Antarctic cosmogenic ice core records.

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Bipolar ice core synchronization using cosmogenic isotopes has mostly been done in the Holocene (Mekhaldi et al., 2015; Sigl et al., 2015; Steinhilber et al., 2012) and around the geomagnetic Laschamps event that occurred some 41 ka ago (Raisbeck et al., 2017; Raisbeck et al., 2007). Furthermore, the ice core cosmogenic signal enables the comparison with ^{14}C records of other archives, such as dendrochronologies (Adolphi and Muscheler, 2016; Sigl et al., 2016) and stalagmites (Adolphi et al., 2018). Weaknesses of this technique include the sparsity of significant events, climatic influences on radionuclide transport and deposition masking the cosmogenic signal, and the very costly and time-consuming analyses that limit the possibility of obtaining continuous high-resolution records. Furthermore, archive noise in the ice core records hampers unambiguous peak detection and synchronization.

This study focuses on volcanic bipolar synchronization of ice cores in the second half of the last glacial period (12-60 ka BP). The volcanic record of the last glacial period in Greenland ice cores includes more than a hundred confirmed Icelandic and high-latitude eruptions that have left predominantly cryptotephra (invisible to the naked eye) deposits in the ice (Abbott and Davies, 2012; Bourne et al., 2015) (Cook et al, in prep 2020); and presumably many more Icelandic eruptions that have not been identified as such. In addition to those, a large number of more distant eruptions have left an acidity signature in the ice cores but no tephra (Zielinski et al., 1997). In fact, during the last glacial only tephra from mid and high latitude eruptions have been identified in Greenland, whereas, to date, there is no evidence of tropical, low latitude or even continental European tephra in Greenland. Whether the lower latitude tephras never make it to Greenland or whether they are too small to be identified by conventional optical microscopy techniques and thus masked by more abundant, similar-sized background dust of continental origin is an open question.

In Antarctica, there are many visible tephra layers of Antarctic origin as well as a large number of acidity spikes associated with more distant eruptions (Narcisi et al., 2017; Severi et al., 2007). It has been proposed that tephra of tropical origin is present in the WAIS Divide ice core, but the evidence is solely based on dust size distributions and not on geochemical fingerprinting (Koffman et al., 2013). A pioneering study has suggested to have identified a bipolar tephra at around A.D. 1257 (Palais et al., 1992) and there is recent support for that conclusion suggesting that the source is the Indonesian Samalas volcano (Lavigne et al., 2013).

Although the ice-core records lack bipolar tephra layers they do hold evidence of volcanic eruptions that are powerful enough to leave sulfuric acid in the stratosphere from where it may be distributed to both Greenland and Antarctica. More than 80 such events have been identified for the last 2500 years (Sigl et al., 2015). For the earlier part of the Holocene, which has been less intensely studied, some 75 bipolar events have been found (Veres et al., 2013), and from around the time of the Indonesian Toba eruption occurring in Sumatra some 74 ka ago, a handful of bipolar volcanic events have been identified (Svensson et al., 2013). Recently, there has been progress in identifying stratospheric volcanic peaks in ice cores based on their sulfur isotopic fingerprints (Burke et al., 2019; Gautier et al., 2019). In this work, we expand the bipolar volcanic matching approach systematically throughout the 12-60 ka time interval.

2. Methods

The approach taken to synchronize Greenland and Antarctic ice cores is to identify large volcanic eruptions with a bipolar acidity or sulfur/sulfate signature. Because such events generally do not leave tephra in ice cores from both polar regions, individual eruptions cannot be matched geochemically between the two hemispheres, as there is no way to verify that they have the same source. What can be matched up, however, are sequences of eruptions that show the same relative timing in both Greenland and Antarctica. To determine the time interval between eruptions, and thereby the relative timing of events, annual layer counting is carried out over the volcanic sequence in both Greenland and Antarctic ice cores. When identical volcanic peak patterns are identified in north and south, it is seen as a strong indication for a bipolar link. There is, however, always a risk of making an incorrect link, because an assumed volcanic sequence could consist of regional (non-bipolar) eruptions with coincidental similar temporal spacing.

The peak heights of the recorded eruption intensities in a bipolar volcanic ice-core sequence cannot be expected to be similar at the two poles, because the strength of the recorded signal depends on the geographical location of the eruption, the atmospheric circulation at the time of the eruption, and the variability in deposition of acids at the ice coring sites (Gautier et al., 2016). Furthermore, the annual layer counting comes with an uncertainty that adds to the possibility of making an incorrect bipolar match (Rasmussen et al., 2006). On the other hand, the bipolar timing of Greenland and Antarctic ice core records is already well constrained by existing gas- and ^{10}Be-based bipolar synchronizations. At the onset of each GI, the uncertainty in the bipolar methane matching between the Greenland NGRIP and the Antarctic WDC ice cores is around a century (WAIS Divide Project Members, 2015), which constrains the time windows for matching of bipolar volcanic sequences. Similarly, the cosmogenic isotope link around the time of the Laschamps event firmly constrains the volcanic matching in that time period (Raisbeck et al., 2017). Therefore, the risk of making false bipolar volcanic matches is strongly reduced by the existing bipolar synchronization.

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We perform annual layer counting in sections of the Greenland NGRIP (North Greenland Ice Core Project members, 2004) and the Antarctic EPICA (European Project for Ice Coring in Antarctica) Dronning Maud Land (EDML) (EPICA community members, 2006) ice cores using high-resolution records of chemical impurities (Bigler, 2004; Ruth et al., 2008), dust (Ruth et al., 2003; Wegner et al., 2015), and visual grey-scale intensity (Faria et al., 2018; Svensson et al., 2005). The approach is the same as that applied for the glacial section of the Greenland Ice core Chronology 2005 (GICC05) (Andersen et al., 2006; Svensson et al., 2008). For this study, most sections of the NGRIP ice core have been recounted, and the Greenland time scale has been slightly modified as the bipolar matching allows for obtaining an improved precision from annual counting in both NGRIP and EDML. For most of the glacial period, the EDML ice core has not previously been layer-counted, but 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. Examples of annual layer counting in NGRIP and EDML across four intervals applied to match up patterns of bipolar volcanic eruptions are shown in Fig. S17-S20. The WAIS Divide ice core chronology 2014 (WD2014) time scale has been applied for guidance, and for most of the intervals within the layer-counted section of WD2014 there is agreement within error estimates between the EDML and WDC interval durations. The bipolar layer counting is not continuous, but is focused on periods of abrupt climate variability or high volcanic activity. In order to allow for comparison to published records, ages in all tables and figures have been converted to GICC05 ages using the year 2000 CE as datum (referred to as 'b2k'). We note that ages published on the Antarctic Ice Core Chronology 2012 (AICC2012) or the WD2014 time scale use the year 1950 CE as datum, and so ages reported relative to b2k will be 50 years greater than those in AICC2012 and WD2014.

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In order to obtain a robust identification of volcanic sequences in the ice cores, all available acidity records from the Greenland GRIP (Wolff et al., 1997), GISP2 (Mayewski et al., 1997; Taylor et al., 1997), NGRIP (Bigler, 2004), and NEEM (Schüpbach et al., 2018) ice cores have been included. For Antarctica, records from the EDML ice core from the Atlantic sector (EPICA community members, 2006), the EDC core from the East Antarctic plateau (EPICA community members, 2004), and the West Antarctic Ice Sheet Divide (WDC) (Fudge et al., 2016; Sigl et al., 2016; WAIS Divide Project Members, 2013) ice core are used. Records of sulfur, sulfate, chloride, and Electrical Conductivity Measurements (ECM) of the ice (Hammer et al., 1980), Dielectric Profiling (DEP) (Moore et al., 1989; Wilhelms et al., 1998) and the liquid conductivity of melt water are also employed as good indicators of volcanic signals in ice cores. With the inclusion of those records, the ability of distinguishing large global volcanic events from more regional eruptions is improved, in particular for Antarctica.

The Greenland ice cores used here previously have been synchronized by volcanic events (Rasmussen et al., 2013; Seierstad et al., 2014). Likewise, the Antarctic ice cores have been linked internally by volcanic matching (Buizert et al., 2018; Ruth et al., 2007). In addition to the published volcanic match points made for Antarctica, some 25 additional Antarctic match points have been identified in the present study to strengthen the synchronization in the neighborhood of Greenland abrupt climate change events. The non-bipolar or 'local' volcanic matching applied here is in agreement with the published synchronizations for Greenland and Antarctica, respectively.

To investigate the bipolar climate signal, we employ stable water isotopes ($\delta^{18}O$) from the GRIP (Dansgaard et al., 1993; Johnsen et al., 2001), GISP2 (Grootes et al., 1993; Stuiver and Grootes, 2000), NGRIP (Gkinis et al., 2014; North Greenland Ice Core Project members, 2004), and NEEM (Vinther et al., in prep, 2020) ice cores, as well as $\delta^{18}O$ and deuterium excess from the EDML (EPICA community members, 2006; Stenni et al., 2010b), EDC (EPICA community members, 2004; Stenni et al., 2010b), WDC (Markle et al., 2016; WAIS Divide Project Members, 2013), Dome Fuji (DF) (Kawamura et al., 2007; Watanabe et al., 2003) and Talos Dome (TAL) (Landais et al., 2015; Stenni et al., 2010a) ice cores. The sources of the employed datasets are listed in Table S1.

3. Results

The bipolar volcanic match points identified in the 12-60 ka interval are shown in Fig. 1 and listed in Table S2. Of the 87 bipolar match points listed, five are previously published cosmogenic match points associated with the Laschamps geomagnetic excursion occurring in the 40.5-42.0 ka interval (Raisbeck et al., 2017). For the interval 16.5-24.5 ka, roughly corresponding to the Last Glacial Maximum (LGM), the ice cores are notoriously difficult to match up, and no bipolar match points are reported. We note that most of the identified bipolar match points fall within Greenland interstadial periods and rather few are located in stadials. The main reasons for this are the elevated dust concentrations in the colder periods that mutes the ice conductivity signal as well as the elevated sulfuric background signal of colder periods that obscures the volcanic signal of the ice (Seierstad et al., 2014). Besides this, precise annual layer counting is also more difficult in the colder periods where accumulation is lower (Andersen et al., 2006). Wind-scouring is another factor affecting low-accumulation Antarctic sites particularly during colder periods.

All of the bipolar volcanic match points are identified in the Greenland NGRIP and the Antarctic EDML ice cores, and most of them are also identified in the Antarctic WDC and EDC ice cores. About half of the bipolar match points are also identified in the Greenland GRIP, GISP2, and NEEM ice cores, but the lower resolution of available sulfate and conductivity records for those cores is often insufficient for precise identification of weaker volcanic events. The Greenland ice cores are however internally synchronized throughout the last glacial period (Rasmussen et al., 2013; Seierstad et al., 2014) by northern hemispheric eruptions, typically Icelandic in origin,

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that leave a stronger fingerprint in Greenland. Therefore, for most of the bipolar match points all of the Greenland ice cores are precisely matched by interpolation between Greenland match points.

The bipolar match points are unevenly distributed over the 12-60 ka interval, but bipolar volcanic events have been identified within a range of 500 years of all major onsets and terminations of Greenland interstadials (GIs) with the exception of GI-2 (Fig. 1). All of the Greenland abrupt climate-change events in that period (except for GI-2) are thus synchronized with the Antarctic climate at high precision. The derived depths and ages for the onsets and terminations of GI events are shown in Table 1. Based on the 5% average counting uncertainty during the last glacial period (Svensson et al., 2008), the relative uncertainty of the bipolar linking related to the GI events is taken as 10% of the distance to the nearest bipolar match point (Table 1). On average, this relative uncertainty is less than 15 years and reaches a maximum of 50 years. The definition of GI onsets and terminations applied in this study are the midpoints of the NGRIP isotopic transitions as identified in WAIS Divide Project Members (2015), except for the onset of GI-1 (the Bølling-Allerød) which is taken from Steffensen et al. (2008).

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In the following sections, we provide examples of the bipolar synchronization from selected time intervals. In the supplementary material detailed figures are provided for all the DO events (Fig. S1-S14).

3.1 The termination of GI-1 / Onset of the Younger Dryas

The onset of the Younger Dryas (GS-1) is synchronized between the two hemispheres by four large acidity spikes clustered around 13 ka and spanning 110 years (Fig. 2). The two outermost spikes are most significant, but all four spikes are present in all investigated cores. All four volcanic eruptions are interpreted as bipolar and they are therefore most likely associated with low-latitude eruptions. This is in conflict with the hypothesis that one of them should be related to the German Laacher See eruption (Baldini et al., 2018) that is believed to have a primarily Northern Hemispheric fingerprint (Graf and Timmreck, 2001). A tephra layer in the NGRIP ice core occurring close to the oldest of the four spikes has previously been tentatively associated with a Hekla eruption (Mortensen et al., 2005), but with the clear bipolar signature there is likely a temporal overlap between this Icelandic and an additional lower-latitude eruption. We notice that the eruption associated with the very significant North Atlantic Vedde Ash layer (Lane et al., 2012; Mortensen et al., 2005) located at 12.17 ka in the Greenland ice cores (Rasmussen et al., 2006) potentially has left a weak acidic signal in Antarctica.

Our bipolar volcanic linking allows for synchronizing the climate signal of the investigated cores (Fig. 3). The four Greenland cores show quite variable climate patterns for the termination of GI-1, making it difficult to define the duration of the transition, but they all have the most significant drop in isotopic values in the interval constrained by the two bipolar events at 12.75 ka and 12.92 ka, respectively.

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It has been proposed that the Younger Dryas period/GS-1 was initiated by a cosmic impact for which there is indirect and debated evidence in a large number of sites in the NH surrounding the North Atlantic region (Kennett et al., 2015). A very significant Platinum (Pt) spike has been identified in the GISP2 ice core (Petaev et al., 2013) and at several North American sites (Moore et al., 2017) that potentially originate from the same impact event. The Pt spike occurs about 45 years after the volcanic quadruplet, i.e. after the Greenland cooling has initiated but before it has reached its minimum (Fig. S1B). The hypothesis of the YD initiation by a cosmic impact is currently debated (Holliday et al., 2020).

Deleted: , and it recently took an exciting twist with the discovery of the (undated) Hiawatha impact crater in NW Greenland (Kjær et al., 2018). Based on ice radar profiles and other evidence, the crater, which is located 378 km from the NEEM drill site, has been suggested to be the origin of the YD impact event. From an ice core point of view, however, we would expect the ice core stratigraphy to be significantly affected by such a dramatic event occurring in Greenland. Yet, we do not find any signs of disturbances of the ice core stratigraphy at the time of the GISP2 Pt spike. The annual layers are well preserved in all Greenland cores, and there is no abnormal layer thickness nor any elevated concentrations of dust or other impurities. Our study thus gives no support for the Hiawatha crater to have formed close to the onset of YD/GS-1; nor for the onset of the YD to have been triggered by this impact.¶

The onset of Greenland Interstadial 1 (GI-1) / Bølling-Allerød

The very steep Greenland onset of the GI-1 / Bølling-Allerød period is preceded by a 1.8 ky-long period of strong global volcanic activity (Fig. S2A). The bipolar phasing is well constrained by several significant eruptions leading up to the onset, and the bipolar volcanic matching pattern is easily recognized. In agreement with Steffensen et al. (2008), we note that NGRIP appears to be the Greenland ice core with the steepest $\delta^{18}O$ transition at the GI-1 onset (Fig. S2B). The Antarctic ice cores are all peaking close to 200 years after the Greenland mid-transition in agreement with the methane matching of NGRIP and WDC (WAIS Divide Project Members, 2015). The very strong volcanic double spike in NGRIP close to 15.68 ka is associated with tephra from the explosive caldera-forming Towada-H eruption (Bourne et al., 2016) located in present-day Japan close to 40°N. This eruption appears to have no significant Antarctic imprint.

3.2 Greenland Stadial 3 (GS-3)

In the late GS-3, at 24.67 ka, there is a characteristic volcanic triplet spike that constitutes a strong bipolar link (Fig. S3A). The three spikes are separated by 20±1 and 10±1 years, respectively, making the match point unique (Fig. S3A inset). At 25.46 ka (b2k GICC05 age) we hypothesize to record traces from the Oruanui eruption from the Taupo volcano in present-day New Zealand in the Greenland record. Tephra of this eruption has been previously identified and dated to 25.37 ka (b2k WD2014 age) in the WDC ice core (Dunbar et al., 2017). There appears to be a major Greenland acidity spike associated with this eruption despite its latitude being close to 40°S. Unfortunately, there are no adjacent bipolar eruptions within several hundreds of years making the bipolar Oruanui link somewhat uncertain. The nearest pair of bipolar eruptions is found at 25.76 and 25.94 ka, respectively, leaving enough room in the layer counting uncertainty for the Greenland acidity spike to potentially be a 'false match' offset by up to 30 years from the Antarctic Oruanui spike. The link needs to be investigated by the bipolar sulfur isotopes method to rule out a coeval local source for the NGRIP event (Burke et al., 2019). Besides being relevant for comparing Greenland and Antarctic ice core time scales (Sigl et al., 2016), the Oruanui eruption constitutes an important comparison point for ^{14}C ages and ice core chronologies as tephra from the eruption is widely distributed (Muscheler et al., Accepted, June 2020).

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3.3 The onset of Greenland Interstadial 8 (GI-8)

The very prominent onset of GI-8 is associated with four significant bipolar eruptions within a 400 yr period (Fig. 2). The eruption occurring at 38.13 ka, close to a century after the onset, shows a very significant signal in all acidity proxies of all investigated ice cores, and it appears to be one of the largest eruptions of the last glacial period. We thus see it as a potential candidate for the H1 horizon identified in Antarctica by radio-echo sounding (Winter et al., 2019). Other prominent bipolar events are situated at 37.97, 38.23, and 38.37 ka, respectively. The 38.23 ka event occurs right at the initiation of the GI-8 onset.

In the climate records across the GI-8 onset, the Greenland records behave quite similarly, whereas the Antarctic records show rather distinct patterns (Fig. 3). EDC expresses a prominent warming coinciding with the Greenland warming; WDC also shows a warming although much less significant. Both EDC and WDC exhibit a cooling trend initiating some decades after the Greenland onset. In contrast, EDML shows a century-long cooling period starting right at the Greenland onset. Being rather noisy, it is hard to separate signal from noise in the Antarctic records based on just one warming event. However, the stacking exercise across several warming events discussed below reveals that the pattern expressed by the Antarctic records at the GI-8 onset is an archetypical expression of an Antarctic response to a major GI onset.

3.4 Greenland interstadials 9 and 10 (GI-9 and GI-10)

For the period 40-43 ka that covers GI-9 and GI-10, the bipolar matching is very well constrained by 16 bipolar match points (Fig. S8A), five of which are independent cosmogenic match points related to the Laschamps geomagnetic excursion (Raisbeck et al., 2017). The volcanic match presented here is in agreement within uncertainties with the cosmogenic matching, and it replaces the existing bipolar volcanic matching in this region (Svensson et al., 2013) that has been shifted by some 30 years.

The onsets of GI-9 and GI-10 provide examples of less prominent GI-events where the Antarctic isotopic response pattern is different from that of the larger events, such as GI-8 and GI-12 (Figs. 2 and S10B). For the GI-9 onset, it is practically impossible to distinguish a bipolar seesaw response in the adjacent periods in the Antarctic climate records. For the GI-10 onset, EDC has a small spike and EDML has a dip, but none of them stand out from the background. WDC appears to enter GI-10 without any climatic response. For the smaller/weaker GI events the response pattern in Antarctica is likewise smaller, making it harder to identify it within the isotopic background variability (Fig. 1).

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4. Bipolar phasing of abrupt climate change

The characteristics of the climate record of the individual GI onsets may vary from event to event, from ice core to ice core and from proxy to proxy both in Greenland and in Antarctica. In Greenland, the main pattern associated with a GI onset is similar for all deep ice cores, but transition durations and the relative phasing of individual parameters, such as water isotopes and impurity concentrations, vary between events and to a lesser degree between cores (Erhardt et al., 2019; Rasmussen et al., 2014; Steffensen et al., 2008). In Antarctica, the investigated cores are located further apart, they are exposed to the climatic influence from different ocean basins, and they do in general show greater variability in relation to the Greenland GI onsets than is the case for the more closely located Greenland coring sites. In addition to the noise in water isotope records caused by wind-driven redeposition at low accumulation sites, millennial-scale climate variability in Antarctica has a profoundly lower signal-to-noise ratio than that in Greenland, contributing to the difficulty of interpreting individual events.

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Keeping in mind this variability among individual GI events, we find it useful to extract a general pattern across the GI onsets and terminations by aligning the individual events and stacking (or compositing) them, as it has been done using bipolar methane synchronization (Buizert et al., 2018; WAIS Divide Project Members, 2015). The stacking provides us with an overall phasing relation that may be helpful in unravelling the governing mechanisms of the abrupt climate change, for example by comparison to model experiments that typically do not capture the details of individual events (Buizert et al., 2018). We stress that the associated underlying assumption of the stacking approach, that the complete temporal progression of all events is the result of the same underlying process, may not be fully justified.

In Fig. 4, we show the $\delta^{18}O$ records of NGRIP together with five Antarctic ice cores stacked across all of the GI onsets and terminations in the 12-60 ka interval (except for GI-2), centered at the Greenland transition midpoint as defined in Table 1. Besides the EDML, EDC and WDC ice cores applied for the bipolar synchronization in this study, we expand the geographical coverage by including the Antarctic Dome Fuji (DF)(Kawamura et al., 2007) and Talos Dome (TAL) (Stenni et al., 2010a) records applying the existing Antarctic volcanic synchronization (Buizert et al., 2018; Fujita et al., 2015; Severi et al., 2012). Fig. 5 shows the stacking of the five Antarctic ice cores from Fig. 4, thus a stack of 21 events in five Antarctic ice cores totaling 105 events. We note that the Greenland

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onsets are aligned according to the midpoint of the warming transition (set to *t*=0), implying that the initiation of the Greenland event occurs earlier than the alignment point. A recent study suggests that the abrupt NGRIP $\delta^{18}O$ and Calcium (Ca) transition onsets on average precede the $\delta^{18}O$ transition midpoint by 25±7 and 33±15 years, respectively (Erhardt et al., 2019); in Fig. 4 and Fig. 5 this places the Greenland $\delta^{18}O$ and Ca event onsets at *t* = -25 and *t* = -33 years, respectively.

For Antarctica, the stacked EDC, WDC and EDML records show distinct $\delta^{18}O$ patterns similar to those identified for the onset of GI-8 (Fig. 3). EDC, WDC and TAL show a peak of accelerated warming, the onset of which is synchronous with Greenland warming and that lasts for close to a century. DF likewise shows an accelerated warming, albeit somewhat later than the aforementioned cores. This direct Antarctic warming response to the Greenland warming is likely to be associated with fast atmospheric changes on a global scale (Markle et al., 2016). In particular, it has been proposed that a northward shift in the SH westerlies in response to NH warming (Lee et al., 2011; Pedro et al., 2018) may drive a warming anomaly in most of the Antarctic continent through enhanced zonal heat transport in the atmosphere (Buizert et al., 2018; Marshall and Thompson, 2016).

Another process that is likely to contribute to the alignment of the water isotope records at the GI onsets is the local cycle of sublimation-condensation in summer on the Greenland and Antarctic ice sheets that is currently under investigation (Kopec et al., 2019; Pang et al., 2019). Sublimation affects the isotope concentration and the deuterium excess of snow through kinetic fractionation. Snow sublimation requires large amounts of energy and it is controlled by the relative humidity, which in turn is linked to the large-scale atmospheric circulation. Sublimation effects are poorly constrained on the East Antarctica plateau.

EDML, however, shows an immediate cooling response that is distinct among the cores investigated (Fig. 4 and Fig. S15), perhaps reflecting regional effects such as wind-driven changes to the Weddell Sea stratification, gyre circulation, sea-ice extent or polynya activity.

Based on the volcanic bipolar synchronization, the general Antarctic response time (Fig. 5) to a Greenland warming event is shorter than that obtained from bipolar methane linking (WAIS Divide Project Members, 2015). Instead of the 200 year lag found in the methane-based synchronization, we find an average response time of 122 ± 24 years (2σ uncertainty) using the same fitting routine as used in WAIS Divide Project Members (2015) (see discussion of uncertainty estimates below). This difference is mostly due to uncertainty in the WDC Δage calculation; the new synchronization suggests that the glacial Δage was too small by around 70 years on average (Fig. S16).

Besides $\delta^{18}O$, we also stack records of Antarctic deuterium excess using the logarithmic definition (d_{ln}) introduced by (Uemura et al., 2012). Markle et al. (2016) showed that in the WAIS Divide ice core, d_{ln} abruptly increases in synchrony with the onset of GIs; at the termination of GIs, d_{ln} abruptly decreases. Markle et al. (2016) used a climate model simulation with moisture tagging to show that this relationship could be explained by north-south shifts in the location of moistures sources associated with changes in the shifts of the southern hemisphere (SH) subpolar jet and westerly winds. This is consistent with work of Schmidt et al. (2007), who had previously shown with climate model simulations that the deuterium excess should be inversely correlated with the Southern Annular Mode (SAM) index. Masson-Delmotte et al. (2010) made a similar argument on the basis of the EDC core, but without sufficient dating precision to demonstrate the close relationship found by Markle et al. (2016). These findings were later extended to multiple Antarctic sites by Buizert et al. (2018).

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Stacks using a methane-based synchronization show a d_{ln} transition that takes ~220 years, followed by a broad peak (Fig. 5); in contrast, our volcanic synchronization suggests a shorter transition (152 ± 37 years) and a much sharper d_{ln} transition. Any chronological errors in the bipolar synchronization will misalign the events being composited, thereby broadening the climatic features in the stacked record. The fact that our volcanic synchronization yields sharper features is thus indirect evidence that it is more accurate than existing gas-based synchronizations. The duration of the d_{ln} transition we observe in our stack is still an upper bound on its true duration, given that our event alignment includes uncertainties due to annual layer counting to the nearest volcanic tie point, as well as potentially incorrectly identified volcanic tie points. It was suggested that the gradual d_{ln} trends before and after the transition follow the gradual source-water sea-surface-temperature trends of the SH via the bipolar seesaw (Markle et al., 2016).

Deleted: Besides $\delta^{18}O$, we also stack records of Antarctic deuterium excess using the logarithmic definition (d_{ln}) introduced by (Uemura et al., 2012). Previous work has found d_{ln} to abruptly increase (decrease) in synchrony with the onset (termination) of GIs at multiple Antarctic sites (Buizert et al., 2018; Markle et al., 2017; Masson-Delmotte et al., 2010), which has been attributed to shifts of the Southern Hemisphere (SH) subpolar jet and westerly winds (e.g. Schmidt et al. (2007)).

Our volcanic bipolar synchronization also shifts the onset of the d_{ln} transition towards older ages, placing it at t = -30 ± 29 years (2σ uncertainty) relative to the Greenland $\delta^{18}O$ transition midpoint. Such an early onset may seem surprising, but is actually in very good agreement with other Greenland proxies that suggest that low-latitude changes precede the Greenland $\delta^{18}O$ signals. In particular, changes in Greenland dust / Ca concentrations appear to lead the Greenland $\delta^{18}O$ by a decade at the onset of the transitions (Erhardt et al., 2019), which has been attributed to early changes in the ITCZ position and atmospheric circulation (Steffensen et al., 2008). Meridional shifts in the SH eddy-driven jet and westerlies are suggested to be dynamically linked to the ITCZ position (Ceppi et al., 2013). The onset of the Greenland Ca transition (presumably reflecting NH atmospheric circulation shifts) precedes the Greenland $\delta^{18}O$ transition midpoint (which we set as t=0) by 33 ± 15 years on average (Erhardt et al., 2019), in good agreement with the 30 ± 29 years we find for the onset of SH atmospheric circulation changes.

The Antarctic d_{ln} and $\delta^{18}O$ signals (Fig. 5) are recorded in the same physical ice cores, and therefore the uncertainty in their relative phasing is small and only related to the stacking of the Antarctic cores and the change point determinations. Errors in the bipolar synchronization will blur the abruptness of their transitions, but should not alter their relative phasing; by contrast, the phasing relative to Greenland proxies is very sensitive to bipolar synchronization errors. The 152 ± 37 year duration between the onset of the d_{ln} response, and the breakpoint in the $\delta^{18}O$ curve therefore represents a robust estimate of the climatic lag of the mean Antarctic temperature response behind the first atmospheric manifestation of the GI event in the southern hemisphere high latitudes.

At the terminations of GI events, the stacked NGRIP $\delta^{18}O$ shows a less prominent but still sharp transition over a ~100 year interval (Fig. 4). For $\delta^{18}O$, all of the stacked Antarctic cores reach a minimum in the interval 100-150 year following the Greenland termination with the strongest response seen for TAL. For d_{ln}, EDC and DF show a significant response related to the Greenland terminations, whereas the other Antarctic cores express a less coherent signal. Note that EDML has its coldest temperatures near t=0, suggesting again a fast response at this site of opposite sign as in the DO warming case.

4.1 Uncertainty estimate of stacked records

To estimate the uncertainty in the change-point analysis of the stacked records (Fig. 5) we use a Monte Carlo scheme with 1,000 iterations (WAIS Divide Project Members, 2015). In each iteration, the alignment of the individual events is shifted randomly prior to the stacking, and the change-point is identified in the new stack using an automated algorithm. The applied time shifts are randomly drawn from normal distribution with widths corresponding to the following event-specific uncertainties; (1) the uncertainty in the NGRIP event midpoint detection (WAIS Divide Project Members, 2015); (2) the uncertainty in the Antarctic layer count from the bipolar eruption to the event (Table 1a); (3) the uncertainty in the Antarctic volcanic synchronization (Buizert et al., 2018). In each iteration, the user-specified parameters of the fitting algorithm (such as the time interval used in the fitting) are likewise perturbed randomly. The stated 2σ uncertainty values therefore reflect uncertainty in the bipolar synchronization, stacking procedure, and change-point detection.

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The Antarctic delay times and uncertainties identified for δ^{18}O and d_{ln}, respectively, are valid for the stacked (averaged) transitions (Fig. 5), but are not representative for the variation among individual transitions. When performing an event-by-event fitting of the Antarctic 5-core average we find a much greater range of delay times. For the δ^{18}O change point, the mean and standard deviation of the individual-event timings is t =138 ± 89 years; for the d_{ln} it is -6 ± 78 years and 116 ± 80 years for transition beginning and end, respectively. This larger variability reflects both differences in timing between individual events, as well as the much smaller signal-to-noise ratio when fitting individual events.

5. Conclusions and outlook

Overall, our new bipolar volcanic synchronization confirms the centennial-scale delay of the mean Antarctic bipolar seesaw temperature response behind abrupt Greenland DO variability (WAIS Divide Project Members, 2015); however, the improved age control offered by volcanic synchronization significantly reduces the estimated duration of this delay compared to previous work based on CH_4 synchronization. Our reduced estimates are more in line with, but still larger than, results from climate model simulations (Pedro et al., 2018; Vettoretti and Peltier, 2015), that typically give an oceanic response on multi-decadal timescales.

WAIS Divide Project Members (2015) interpreted the 208 ± 96 year delay they observed as characteristic of an oceanic teleconnection. The reduced delay timescale we infer here (122 ± 24 years) is still consistent with the original interpretation. However, the new observations urge some caution. Despite our best efforts, the new bipolar volcanic framework likely contains some incorrect matches, and as the bipolar synchronization continues to be refined, the inferred Antarctic delay may be reduced further. The divergent climate response at various sites (Fig. 4, Fig. S15 and WAIS Divide Project Members (2015)), as well as the relatively gradual transition in d_{ln} over ~145 years (suspiciously similar to the updated timescale Antarctic temperature delay presented here) perhaps suggest a more complex interplay of atmospheric and oceanic processes that is currently very poorly understood (see e.g. Kostov et al. (2017)). We suggest future work along two parallel lines of inquiry.

First, further refinement and confirmation of our bipolar synchronization is called for. Analysis of sulfur mass-independent isotopic fractionation (Burke et al., 2019) is needed for the proposed bipolar volcanic events. For low-latitude eruptions to show up in both the Arctic and Antarctic almost certainly requires injection of materials into the stratosphere, which is reflected in Δ^{33}S. High-resolution records of ^{10}Be can further refine bipolar matching (Adolphi et al., 2018) in critical intervals where the volcanic record is ambiguous. Second, climate modeling studies are needed to better understand the interaction between atmospheric and oceanic changes during the D-O cycle. In particular the anomalous response of the EDML site during both Heinrich (Landais et al., 2015) and Dansgaard-Oeschger (Buizert et al., 2018) abrupt climate change calls for detailed investigation.

The volcanic bipolar synchronization has a wide range of potential applications that go beyond the objectives of this paper. Those include the development of consistent bipolar ice core time scales, constraining ice-core delta-gas ages, investigation of impacts of volcanism on abrupt climate change, quantification of the last glacial global volcanic eruption record, and the discussion of solar variability through synchronization of cosmogenic isotopes. Furthermore, the precise bipolar synchronization should allow for an improved understanding of the mechanisms governing the glacial climate through comparison to model studies and non-ice core records.

Author contribution

All authors contributed to obtaining the applied datasets. AS prepared the manuscript with contributions from all co-authors. CB prepared Fig. 4 and 5.

Competing interests

The authors declare that they have no conflict of interest.

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TABLE CAPTIONS:

Table 1a + 1b: Bipolar onsets and terminations

Depths of the Greenland interstadial onsets (a) and terminations (b) in the NGRIP, NEEM, GRIP, GISP2, EDML, EDC, and WDC ice cores based on volcanic matching. The NGRIP onsets are defined as the mid-points of the $\delta^{18}O$ transitions and are identical to those applied in WAIS Divide Project Members (2015) except for the onset of GI-1. The Greenland match points are from Seierstad et al. (2014), Antarctic match points are from Buizert et al. (2018), and the bipolar match points are from Table S2. Corresponding GICC05 ages are provided with reference to year 2000 CE. 'Distance' refers to the temporal distance to the nearest bipolar match point in Table S2 with negative values signifying the match point occurring before the onset/termination. The relative uncertainty of the bipolar matching is stated as 10% of the 'distance' assuming a 5% maximum counting error of the annual layer counting in both Greenland and Antarctica. 'YD-PB' refers to the Younger Dryas – Preboreal transition (the onset of the Holocene) and 'BA-YD' refers to the Bølling-Allerød – Younger Dryas transition (the onset of GS-1). All EDC depths are on the EDC99 depth scale.

Table S1: Data sources

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Table S2: Bipolar match points

Depths and ages of bipolar volcanic and cosmogenic match points. GICC05 and WD2014 (Sigl et al., 2016) ages are provided with reference to year 2000 CE. Fields are empty when no match point has been identified. Five match points around GI-10 (BeA – BeE) are based cosmogenic bipolar matching (Raisbeck et al., 2017), all other match points are volcanic match points of this study. All EDC depths are on the EDC99 depth scale. On the right hand side of the table, the annual layer counting between bipolar match points as determined in this work is compared to those of the GICC05 and WD2014 time scales. Interval durations of some longer intervals were not counted for this work.

FIGURE CAPTIONS:

Figure 1:

Greenland (NGRIP) and Antarctic (EDML, WDC, and EDC) climate records ($\delta^{18}O$) throughout the 10-60 ka time period based on volcanic matching. Ages are on the GICC05 time scale relative to the year 2000 CE ('b2k'). Grey vertical lines show the position of bipolar volcanic match points identified in this study (Table S2) together with five match points based on cosmogenic isotopes around 41 ka (Raisbeck et al., 2017). Blue-shaded intervals indicate the Greenland Interstadial (GI) periods according to the definition of Rasmussen et al. (2014). The bipolar synchronization for the 16.5-24.5 ka interval is tentative as there are no bipolar match points in that interval.

Figure 2:

Bipolar volcanic synchronization of the investigated ice cores across the transition from GI-1 / Bølling-Allerød (BA) to GS-1 / Younger Dryas (YD) (left panel) and the onset of GI-8 (right panel). Grey vertical lines are bipolar volcanic match points (Table S2). The records have different units, some are uncalibrated and peak heights are not comparable on an absolute scale, which is the reason why no scales are provided.

Figure 3:

Synchronized climate records of the investigated ice cores across the GS-1 onset (left panel) and the GI-8 onset (right panel) applying the volcanic synchronization shown in Fig. 2. The acidity records in the bottom of the figure are for reference and are also shown in Fig. 2. All other records are $\delta^{18}O$ in ‰ (see Fig. 1 for scales). Grey vertical lines are bipolar volcanic match points (Table S2).

Figure 4:

Stacks of isotopic records across GI onsets (left) and terminations (right) for the events listed in Table 1a and 1b, respectively, applying the bipolar volcanic synchronization. The time '*t*=0' refers to the midpoint of the NGRIP onset for each GI-event as defined in Table 1. **Top**: Stack of NGRIP $\delta^{18}O$ (blue; left axis) and WDC CH_4 (green; right axis). **Center**: Stack of Antarctic $\delta^{18}O$ at the indicated locations and the average curve (mean). **Bottom**: Stack of Antarctic d_{ln} at the indicated locations and the mean. The figure is modified from Buizert et al. (2018), Extended data Fig. 3. See Fig. S15 for Antarctic core site locations.

Figure 5:

Top: Stack of Greenland NGRIP isotopes and CH_4 for the onsets of GI events listed in Table 1a. **Center:** Antarctic 5-core mean $\delta^{18}O$ (stack of 5 x 21 warming events). Black curve is the same as 'mean' in Fig. 4 center; grey curve

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is applying the bipolar methane synchronization of WAIS Divide Project Members (2015). **Bottom:** Antarctic 5-core mean deuterium excess (d_{ln}) . Black curve is the same as 'mean' in Fig. 4 bottom; grey curve is applying the bipolar methane synchronization of WAIS Divide Project Members (2015). Orange curves are fitting functions using the change-point analysis applied in WAIS Divide Project Members (2015). The stated 2σ uncertainty estimates are obtained from a Monte Carlo sampling (see main text). When the same uncertainty estimate is made for the GI terminations (Fig. 4) the $\delta^{18}O$ timing is at 101 ± 29 years, the d_{ln} transition onset is at -59 ± 58 years, the d_{ln} transition end is at 95 ± 34 years; the duration between the d_{ln} onset and the $\delta^{18}O$ change-point is 160 ± 65 years. The earlier d_{ln} onset for the GI termination is probably reflecting that the GI terminations are generally more gradual than the GI onsets.

REFERENCES:

Abbott, P. M. and Davies, S. M.: Volcanism and the Greenland ice-cores: the tephra record, Earth-Sci. Rev., 115, 173-191, 2012.

Adolphi, F. and Muscheler, R.: Synchronizing the Greenland ice core and radiocarbon timescales over the Holocene - Bayesian wiggle- matching of cosmogenic radionuclide records, Clim. Past., 12, 15-30, 2016.

Adolphi, F., et al.: Connecting the Greenland ice-core and U/Th timescales via cosmogenic radionuclides: testing the synchroneity of Dansgaard-Oeschger events, Clim. Past., 14, 1755-1781, 2018.

Andersen, K. K., et al.: The Greenland Ice Core Chronology 2005, 15-42 ka. Part 1: constructing the time scale, Quaternary Science Reviews, 25, 3246-3257, 2006.

Baldini, J. U. L., Brown, R. J., and Mawdsley, N.: Evaluating the link between the sulfur-rich Laacher See volcanic eruption and the Younger Dryas climate anomaly, Clim. Past., 14, 969-990, 2018.

Bender, M., Sowers, T., Dickson, M.-L., Orchardo, J., Grootes, P., Mayewski, P. A., and Meese, D. A.: Climate correlations between Greenland and Antarctica during the last 100,000 years, Nature, 372, 663-666, 1994.

Bigler, M.: Hochauflösende Spurenstoffmessungen an polaren Eisbohrkernen: Glazio-chemische und klimatische Prozessstudien, 2004.Ph.D. dissertation, Physics Institute, University of Bern, Switzerland, 2004.

Blunier, T., et al.: Asynchrony of Antarctic and Greenland climate change during the last glacial period, Nature, 394, 739-743, 1998.

Blunier, T., Spahni, R., Barnola, J.-M., Chappellaz, J., Loulergue, L., and Schwander, J.: Synchronization of ice core records via atmospheric gases, Clim. Past., 3, 325-330, 2007.

Bourne, A. J., Abbott, P. M., Albert, P. G., Cook, E., Pearce, N. J. G., Ponomareva, V., Svensson, A., and Davies, S. M.: Underestimated risks of recurrent long-range ash dispersal from northern Pacific Arc volcanoes, Scientific Reports, 6, 2016.

Bourne, A. J., Cook, E., Abbott, P. M., Seierstad, I. K., Steffensen, J. P., Svensson, A., Fischer, H., Schupbach, S., and Davies, S. M.: A tephra lattice for Greenland and a reconstruction of volcanic events spanning 25-45 ka b2k, Quaternary Science Reviews, 118, 122-141, 2015.

Buizert, C., et al.: Abrupt ice-age shifts in southern westerly winds and Antarctic climate forced from the north, Nature, 563, 681-685, 2018.

Burke, A., Moore, K. A., Sigl, M., Nita, D. C., McConnell, J. R., and Adkins, J. F.: Stratospheric eruptions from tropical and extra-tropical volcanoes constrained using high-resolution sulfur isotopes in ice cores, Earth Planet. Sci. Lett., 521, 113-119, 2019.

Capron, E., et al.: Synchronising EDML and NorthGRIP ice cores using delta O-18 of atmospheric oxygen (delta O-18(atm)) and CH4 measurements over MIS5 (80-123 kyr), Quaternary Science Reviews, 29, 222-234, 2010.

Ceppi, P., Hwang, Y. T., Liu, X., Frierson, D. M. W., and Hartmann, D. L.: The relationship between the ITCZ and the Southern Hemispheric eddy-driven jet, Journal of Geophysical Research Atmospheres, 118, 5136-5146, 2013.

Dansgaard, W., et al.: Evidence for general instability of past climate from a 250-kyr ice-core record, Nature, 364, 218-220, 1993.

Dunbar, N. W., Iverson, N. A., Van Eaton, A. R., Sigl, M., Alloway, B. V., Kurbatov, A. V., Mastin, L. G., McConnell, J. R., and Wilson, C. J. N.: New Zealand supereruption provides time marker for the Last Glacial Maximum in Antarctica, Scientific Reports, 7, 2017.

EPICA community members: Eight glacial cycles from an Antarctic ice core, Nature, 429, 623-628, 2004.

Field Code Changed

EPICA community members: One-to-one coupling of glacial climate variability in Greeland and Antartctica, Nature, 444, 195-198, 2006.
Erhardt, T., Capron, E., Rasmussen, S. O., Schupbach, S., Bigler, M., Adolphi, F., and Fischer, H.: Decadal-scale progression of the onset of Dansgaard-Oeschger warming events, Clim. Past., 15, 811-825, 2019.
Faria, S. H., Kipfstuhl, S., Lambrecht, A., Faria, S. H., Kipfstuhl, S., and Lambrecht, A.: EPICA-DML Deep Ice Core: A Visual Record. In: Epica-Dml Deep Ice Core: A Visual Record, Frontiers in Earth Sciences, 2018.
Fudge, T. J., Taylor, K. C., Waddington, E. D., Fitzpatrick, J. J., and Conway, H.: Electrical stratigraphy of the WAIS Divide ice core: Identification of centimeter-scale irregular layering, Journal of Geophysical Research: Earth Surface, 121, 1218-1229, 2016.
Fujita, S., Parrenin, F., Severi, M., Motoyama, H., and Wolff, E. W.: Volcanic synchronization of Dome Fuji and Dome C Antarctic deep ice cores over the past 216 kyr, Clim. Past., 11, 1395-1416, 2015.
Gautier, E., Savarino, J., Erbland, J., Lanciki, A., and Possenti, P.: Variability of sulfate signal in ice core records based on five replicate cores, Clim. Past., 12, 103-113, 2016.
Gautier, E., et al.: 2600-years of stratospheric volcanism through sulfate isotopes, Nature Communications, 10, 2019.
Gkinis, V., Simonsen, S. B., Buchardt, S. L., White, J. W. C., and Vinther, B. M.: Water isotope diffusion rates from the NorthGRIP ice core for the last 16,000 years - Glaciological and paleoclimatic implications, Earth Planet. Sci. Lett., 405, 132-141, 2014.
Graf, H. F. and Timmreck, C.: A general climate model simulation of the aerosol radiative effects of the Laacher See eruption (10,900 B.C.), Journal of Geophysical Research Atmospheres, 106, 14747-14756, 2001.
Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S. J., and Jouzel, J.: Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores, Nature, 366, 552-554, 1993.
Hammer, C. U., Clausen, H. B., and Dansgaard, W.: Greenland ice sheet evidence of post-glacial volcanism and its climatic impact, Nature, 288, 230-235, 1980.
Holliday, V. T., Bartlein, P. J., Scott, A. C., and Marlon, J. R.: Extraordinary Biomass-Burning Episode and Impact Winter Triggered by the Younger Dryas Cosmic Impact ∼12,800 Years Ago, Parts 1 and 2: A Discussion, The Journal of Geology, 128, 69-94, 2020.
Johnsen, S. J., DahlJensen, D., Gundestrup, N., Steffensen, J. P., Clausen, H. B., Miller, H., Masson-Delmotte, V., Sveinbjornsdottir, A. E., and White, J.: Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP, J. Quat. Sci., 16, 299-307, 2001.
Kawamura, K., et al.: Northern Hemisphere forcing of climatic cycles in Antarctica over the past 360,000 years, Nature, 448, 912-U914, 2007.
Kennett, J. P., et al.: Bayesian chronological analyses consistent with synchronous age of 12,835-12,735 Cal B.P. for Younger Dryas boundary on four continents, Proc. Natl. Acad. Sci. U. S. A., 112, E4344-E4353, 2015.
Kindler, P., Guillevic, M., Baumgartner, M., Schwander, J., Landais, A., and Leuenberger, M.: Temperature reconstruction from 10 to 120 kyr b2k from the NGRIP ice core, Clim. Past., 10, 887-902, 2014.
Koffman, B. G., Kreutz, K. J., Kurbatov, A. V., and Dunbar, N. W.: Impact of known local and tropical volcanic eruptions of the past millennium on the WAIS Divide microparticle record, Geophysical Research Letters, 40, 4712-4716, 2013.
Kopec, B. G., Feng, X., Posmentier, E. S., and Sonder, L. J.: Seasonal Deuterium Excess Variations of Precipitation at Summit, Greenland, and their Climatological Significance, Journal of Geophysical Research: Atmospheres, 124, 72-91, 2019.
Kostov, Y., Marshall, J., Hausmann, U., Armour, K. C., Ferreira, D., and Holland, M. M.: Fast and slow responses of Southern Ocean sea surface temperature to SAM in coupled climate models, Climate Dynamics, 48, 1595-1609, 2017.

Landais, A., et al.: A review of the bipolar see-saw from synchronized and high resolution ice core water stable isotope records from Greenland and East Antarctica, Quaternary Science Reviews, 114, 18-32, 2015.

Lane, C. S., Blockley, S. P. E., Mangerud, J., Smith, V. C., Lohne, Ø., Tomlinson, E. L., Matthews, I. P., and Lotter, A. F.: Was the 12.1ka Icelandic Vedde Ash one of a kind?, Quaternary Science Reviews, 33, 87-99, 2012.

Lavigne, F., et al.: Source of the great A.D. 1257 mystery eruption unveiled, Samalas volcano, Rinjani Volcanic Complex, Indonesia, Proc. Natl. Acad. Sci. U. S. A., 110, 16742-16747, 2013.

Lee, S. Y., Chiang, J. C. H., Matsumoto, K., and Tokos, K. S.: Southern Ocean wind response to North Atlantic cooling and the rise in atmospheric CO_2: Modeling perspective and paleoceanographic implications, Paleoceanography, 26, 2011.

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, 2010.

Markle, B. R., et al.: Global atmospheric teleconnections during Dansgaard-Oeschger events, Nature Geoscience, 10, 36-40, 2016.

Marshall, G. J. and Thompson, D. W. J.: The signatures of large-scale patterns of atmospheric variability in Antarctic surface temperatures, Journal of Geophysical Research, 121, 3276-3289, 2016.

Masson-Delmotte, V., et al.: Abrupt change of antarctic moisture origin at the end of termination II, Proc. Natl. Acad. Sci. U. S. A., 107, 12091-12094, 2010.

Mayewski, P. A., Meeker, L. D., Twickler, M. S., Whitlow, S., Yang, Q. Z., Lyons, W. B., and Prentice, M.: Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series, Journal of Geophysical Research-Oceans, 102, 26345-26366, 1997.

Mekhaldi, F., et al.: Multiradionuclide evidence for the solar origin of the cosmic-ray events of 774/5 and 993/4, Nature Communications, 6, 2015.

Moore, C. R., et al.: Widespread platinum anomaly documented at the Younger Dryas onset in North American sedimentary sequences, Scientific Reports, 7, 2017.

Moore, J. C., Mulvaney, R., and Paren, J. G.: Dielectric stratigraphy of ice: A new technique for determining total ionic concentrations in polar ice cores, Geophysical Research Letters, 16, 1177-1180, 1989.

Mortensen, A. K., Bigler, M., Grönvold, K., Steffensen, J. P., and Johnsen, S. J.: Volcanic ash layers from the Last Glacial Termination in the NGRIP ice core, J. Quat. Sci., 20, 209-219, 2005.

Muscheler, R., Adolphi, F., Heaton, T. J., Ramsey, C. B., Svensson, A., Plicht, J. v. d., and Reimer, P. J.: Testing and improving the IntCal20 calibration curve with independent records, Radiocarbon, Accepted, June 2020. Accepted, June 2020.

Narcisi, B., Petit, J. R., and Langone, A.: Last glacial tephra layers in the Talos Dome ice core (peripheral East Antarctic Plateau), with implications for chronostratigraphic correlations and regional volcanic history, Quaternary Science Reviews, 165, 111-126, 2017.

North Greenland Ice Core Project members: High-resolution record of Northern Hemisphere climate extending into the last interglacial period, Nature, 431, 147-151, 2004.

Palais, J. M., Germani, M. S., and Zielinski, G. A.: Inter-hemispheric transport of volcanic ash from a 1259 AD volcanic eruption to the Greenland and Antarctic ice sheets, Geophysical Research Letters, 19, 801-804, 1992.

Pang, H., et al.: Influence of Summer Sublimation on δD, δ18O, and δ17O in Precipitation, East Antarctica, and Implications for Climate Reconstruction From Ice Cores, Journal of Geophysical Research: Atmospheres, 124, 7339-7358, 2019.

Pedro, J. B., Jochum, M., Buizert, C., He, F., Barker, S., and Rasmussen, S. O.: Beyond the bipolar seesaw: Toward a process understanding of interhemispheric coupling, Quaternary Science Reviews, 192, 27-46, 2018.

Petaev, M. I., Huang, S., Jacobsen, S. B., and Zindler, A.: Large Pt anomaly in the Greenland ice core points to a cataclysm at the onset of Younger Dryas, Proc. Natl. Acad. Sci. U. S. A., 110, 12917-12920, 2013.

Raisbeck, G. M., et al.: An improved north-south synchronization of ice core records around the 41 kyr Be-10 peak, Clim. Past., 13, 217-229, 2017.

Raisbeck, G. M., Yiou, F., Jouzel, J., and Stocker, T. F.: Direct north-south synchronization of abrupt climate change records in ice cores using beryllium 10, Clim. Past., 3, 541–547, 2007.

Rasmussen, S. O., et al.: A first chronology for the north greenland eemian ice drilling (NEEM) ice core, Clim. Past., 9, 2713-2730, 2013.

Rasmussen, S. O., et al.: A new Greenland ice core chronology for the last glacial termination, Journal of Geophysical Research, 111, D06102, doi:06110.01029/02005JD006079, 2006.

Rasmussen, S. O., et al.: A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: Refining and extending the INTIMATE event stratigraphy, Quaternary Science Reviews, 106, 14-28, 2014.

Rhodes, R. H., Brook, E. J., Chiang, J. C. H., Blunier, T., Maselli, O. J., McConnell, J. R., Romanini, D., and Severinghaus, J. P.: Enhanced tropical methane production in response to iceberg discharge in the North Atlantic, Science, 348, 1016-1019, 2015.

Ruth, U., et al.: Proxies and measurement techniques for mineral dust in antarctic ice cores, Environmental Science and Technology, 42, 5675-5681, 2008.

Ruth, U., et al.: "EDML1": a chronology for the EPICA deep ice core from Dronning Maud Land, Antarctica, over the last 150 000 years, Clim. Past., 3, 475-484, 2007.

Ruth, U., Wagenbach, D., Steffensen, J. P., and Bigler, M.: Continuous record of microparticle concentration and size distribution in the central Greenland NGRIP ice core during the last glacial period, Journal of Geophysical Research, 108, 4098, doi:4010.1029/2002JD002376, 2003.

Schmidt, G. A., LeGrande, A. N., and Hoffmann, G.: Water isotope expressions of intrinsic and forced variability in a coupled ocean-atmosphere model, Journal of Geophysical Research-Atmospheres, 112, 2007.

Schwander, J. and Stauffer, B.: Age difference between polar ice and the air trapped in its bubbles, Nature, 311, 45-47, 1984.

Schüpbach, S., et al.: Greenland records of aerosol source and atmospheric lifetime changes from the Eemian to the Holocene, Nature Communications, 9, 2018.

Seierstad, I. K., et al.: Consistently dated records from the Greenland GRIP, GISP2 and NGRIP ice cores for the past 104 ka reveal regional millennial-scale delta O-18 gradients with possible Heinrich event imprint, Quaternary Science Reviews, 106, 29-46, 2014.

Severi, M., et al.: Synchronisation of the EDML and EDC ice cores for the last 52 kyr by volcanic signature matching, Clim. Past., 3, 367-374, 2007.

Severi, M., Udisti, R., Becagli, S., Stenni, B., and Traversi, R.: Volcanic synchronisation of the EPICA-DC and TALDICE ice cores for the last 42 kyr BP, Clim. Past., 8, 509-517, 2012.

Sigl, M., et al.: The WAIS Divide deep ice core WD2014 chronology - Part 2: Annual-layer counting (0-31 ka BP), Clim. Past., 12, 769-786, 2016.

Sigl, M., et al.: A new bipolar ice core record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last 2000 years, Journal of Geophysical Research Atmospheres, 118, 1151-1169, 2013.

Sigl, M., et al.: Timing and climate forcing of volcanic eruptions for the past 2,500 years, Nature, 523, 543-+, 2015.

Steffensen, J. P., et al.: High-resolution Greenland ice core data show abrupt climate change happens in few years, Science, 321, 680-684, 2008.

Steinhilber, F., et al.: 9,400 years of cosmic radiation and solar activity from ice cores and tree rings, Proc. Natl. Acad. Sci. U. S. A., 109, 5967-5971, 2012.
Stenni, B., et al.: Expression of the bipolar see-saw in Antarctic climate records during the last deglaciation, Nature Geoscience, 4, 46-49, 2010a.
Stenni, B., Masson-Delmotte, V., and Selmo E, O. H., Meyer H, Röthlisberger R, Jouzel J, Cattani O, Falourd S, Fischer H, Hoffmann G, Iacumin P, Johnsen SJ, Minster B, Udisti R: The deuterium excess records of EPICA Dome C and Dronning Maud Land ice cores (East Antarctica), Quaternary Science Reviews, 29, 146-159, 2010b.
Stocker, T. F. and Johnsen, S. J.: A minimum thermodynamic model for the bipolar seesaw, Paleoceanography, 18, 1087, doi:1010.1029/2003PA000920, 2003.
Stuiver, M. and Grootes, P. M.: GISP2 oxygen isotope ratios, Quaternary Research, 53, 277-284, 2000.
Svensson, A., et al.: A 60 000 year Greenland stratigraphic ice core chronology, Clim. Past., 4, 47-57, 2008.
Svensson, A., et al.: Direct linking of Greenland and Antarctic ice cores at the Toba eruption (74 ka BP), Clim. Past., 9, 749-766, 2013.
Svensson, A., Nielsen, S. W., Kipfstuhl, S., Johnsen, S. J., Steffensen, J. P., Bigler, M., Ruth, U., and Röthlisberger, R.: Visual stratigraphy of the North Greenland Ice Core Project (NorthGRIP) ice core during the last glacial period, Journal of Geophysical Research, 110, D02108, doi:02110.01029/02004JD005134, 2005.
Taylor, K. C., Alley, R. B., Lamorey, G. W., and Mayewski, P.: Electrical measurements on the Greenland Ice Sheet Project 2 Core, Journal of Geophysical Research, 102, 26511-26517, 1997.
Uemura, R., Masson-Delmotte, V., Jouzel, J., Landais, A., Motoyama, H., and Stenni, B.: Ranges of moisture-source temperature estimated from Antarctic ice cores stable isotope records over glacial-interglacial cycles, Clim. Past., 8, 1109-1125, 2012.
Veres, D., et al.: The Antarctic ice core chronology (AICC2012): An optimized multi-parameter and multi-site dating approach for the last 120 thousand years, Clim. Past., 9, 1733-1748, 2013.
Vettoretti, G. and Peltier, W. R.: Interhemispheric air temperature phase relationships in the nonlinear Dansgaard-Oeschger oscillation, Geophysical Research Letters, 42, 1180-1189, 2015.
Voelker, A. H. L. and workshop participants: Global distribution of centennial-scale records for Marine Isotope Stage (MIS) 3: A database, Quaternary Science Reviews, 21, 1185-1212, 2002.
WAIS Divide Project Members: Onset of deglacial warming in West Antarctica driven by local orbital forcing, Nature, 500, 440-444, 2013.
WAIS Divide Project Members: Precise interpolar phasing of abrupt climate change during the last ice age, Nature, 520, 661-U169, 2015.
Watanabe, O., Jouzel, J., Johnsen, S., Parrenin, F., Shoji, H., and Yoshida, N.: Homogeneous climate variability across East Antarctica over the past three glacial cycles, Nature, 422, 509-512, 2003.
Wegner, A., Fischer, H., Delmonte, B., Petit, J. R., Erhardt, T., Ruth, U., Svensson, A., Vinther, B., and Miller, H.: The role of seasonality of mineral dust concentration and size on glacial/interglacial dust changes in the EPICA Dronning Maud Land ice core, Journal of Geophysical Research-Atmospheres, 120, 2015.
Wilhelms, F., Kipfstuhl, J., Miller, H., Heinloth, K., and Firestone, J.: Precise dielectric profiling of ice cores: A new devise with improved guarding and its theory, J. Glaciol., 44, 171-174, 1998.
Winter, A., Steinhage, D., Creyts, T. T., Kleiner, T., and Eisen, O.: Age stratigraphy in the East Antarctic Ice Sheet inferred from radio-echo sounding horizons, Earth System Science Data, 11, 1069-1081, 2019.
Wolff, E. W., Moore, J. C., Clausen, H. B., and Hammer, C. U.: Climatic implications of background acidity and other chemistry derived from electrical studies of the Greenland Ice Core Project ice core, Journal of Geophysical Research, 102, 26325-26332, 1997.

Zielinski, G. A., Mayewski, P. A., Meeker, D., Grönvold, K., Germani, M. S., Whitlow, S., Twickler, M. S., and Taylor, K.: Volcanic aerosol records and tephrachronology of the Summit, Greenland, ice cores, Journal of Geophysical Research, 102, 26625-26640, 1997.

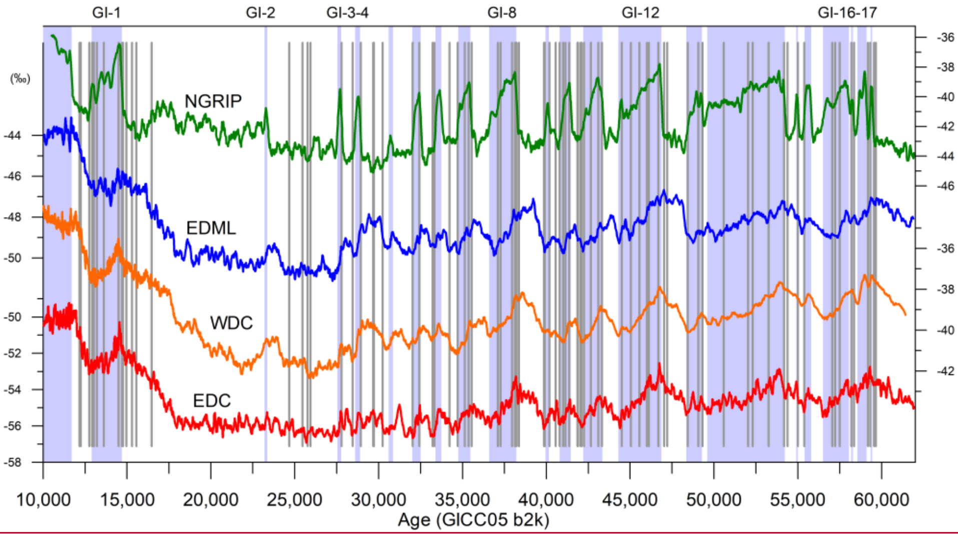
Table 1a.

GI-event	Greenland interstadial onset depth (m) NGRIP	NEEM	GRIP	GISP2	EDML	EDC	WDC	GICC05 age (yr b2k)	Distance (yr)	Uncertainty (yr)
YD-PB	1490.89	1418.75	1622.08	1675.61	676.46	356.32	1962.70	11669	-20	2
1	1604.64	1489.26	1753.34	1797.78	792.70	421.58	2238.95	14693	-13	1
3	1869.00	1640.94	2025.32	2056.57	1123.54	586.08	2742.16	27776	-20	2
4	1891.27	1654.11	2045.81	2076.33	1145.97	598.37	2782.83	28888	-51	5
5.1	1919.48	1671.51	2070.21	2099.96	1179.08	619.07	2835.50	30781	498	50
5.2	1951.66	1690.04	2098.82	2127.52	1207.26	637.16	2874.01	32500	68	7
6	1974.48	1703.17	2118.52	2147.03	1229.98	650.73	2903.17	33737	409	41
7	2009.62	1723.26	2148.80	2177.90	1260.99	670.24	2949.01	35487	-71	7
8	2069.88	1758.82	2200.19	2232.03	1312.67	702.32	3012.40	38215	-20	2
9	2099.50	1777.43	2223.52	2255.87	1354.20	726.08	3057.51	40154	-24	2
10	2123.98	1791.21	2243.22	2276.30	1378.51	741.14	3085.75	41457	83	8
11	2157.58	1810.16	2270.82	2304.00	1412.29	762.45	3123.76	43346	18	2
12	2221.96	1846.28	2323.98	2358.79	1465.79	800.57	3188.00	46843	-177	18
13	2256.73	1865.21	2350.38	2385.39	1506.61	828.05	3231.20	49271	-48	5
14	2345.39	1911.86	2420.68	2454.73	1583.95	882.69	3307.14	54213	36	4
15.1	2355.17	1917.40	2427.86	2461.37	1596.44	891.17	3317.75	54990	-15	2
15.2	2366.15	1923.24	2435.93	2469.02	1609.21	900.36	3326.36	55787	406	41
16.1	2398.71	1940.25	2460.18	2491.91	1643.43	925.25	3347.52	58037	-152	15
16.2	2402.25	1942.05	2462.74	2494.33	1647.22	928.01	3349.52	58258	-103	10
17.1	2414.82	1948.37	2472.05	2503.02	1660.55	937.91	3356.71	59067	-125	12
17.2	2420.35	1951.08	2476.15	2506.86	1667.53	942.84	3360.52	59435	-132	13

Table 1b.

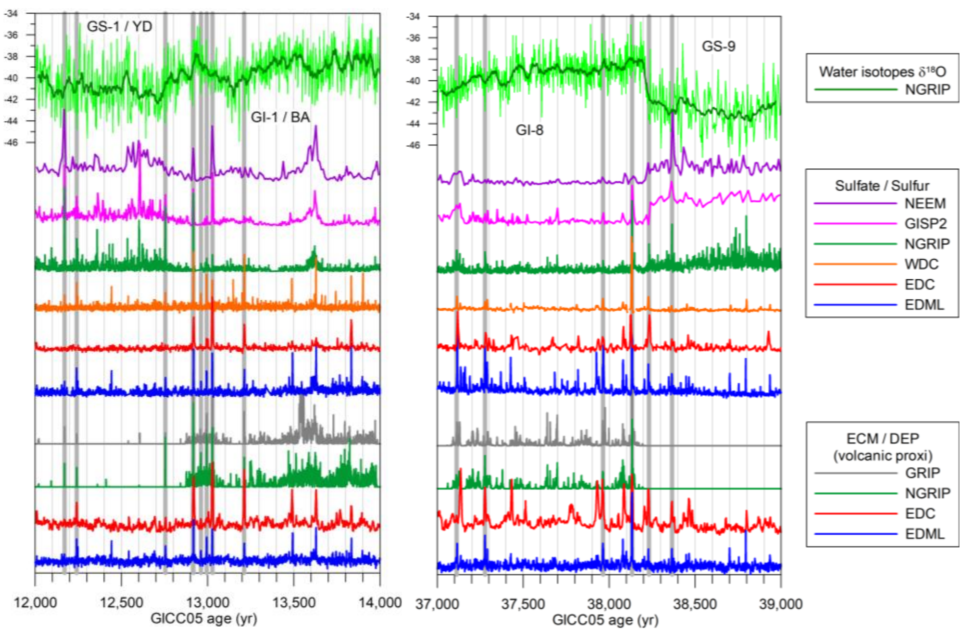
	Greenland interstadial termination depth (m)							GICC05 age	Distance	Uncertainty
GI-event	NGRIP	NEEM	GRIP	GISP2	EDML	EDC	WDC	(yr b2k)	(yr)	(yr)
BA-YD	1524.21	1442.83	1659.79	1710.70	728.33	385.53	2074.86	12826	70	7
3	1861.91	1636.91	2018.50	2050.17	1118.41	583.69	2733.94	27548	-247	25
4	1882.59	1649.04	2037.69	2068.53	1140.75	595.17	2773.18	28599	144	14
5.1	1916.45	1669.74	2067.61	2097.44	1176.51	617.40	2831.89	30621	354	35
5.2	1939.71	1683.41	2087.98	2117.21	1199.75	632.37	2863.36	32042	9	1
6	1964.52	1697.55	2109.93	2138.17	1223.04	646.48	2894.41	33374	47	5
7	1990.58	1712.44	2132.00	2160.68	1248.60	662.24	2929.30	34753	36	4
8	2027.43	1733.94	2163.25	2193.23	1282.58	683.27	2976.19	36620	-504	50
9	2095.51	1775.13	2220.41	2252.62	1351.26	724.27	3054.08	39955	40	4
10	2112.53	1784.96	2233.80	2266.44	1369.94	735.89	3075.84	40968	-39	4
11	2135.66	1798.19	2252.48	2285.68	1394.25	750.63	3103.22	42281	31	3
12	2171.17	1818.25	2281.50	2314.92	1429.09	773.57	3142.52	44358	-144	14
13	2242.85	1857.83	2339.54	2374.51	1494.80	819.77	3219.51	48490	48	5
14	2261.49	1867.76	2354.09	2389.14	1511.69	831.58	3236.02	49602	282	28
15.1	2353.66	1916.55	2426.76	2460.35	1595.02	890.21	3316.61	54901	-101	10
15.2	2359.92	1920.06	2431.35	2464.59	1603.35	896.01	3322.51	55419	35	4
16.1	2375.88	1928.41	2442.94	2475.66	1621.92	908.87	3333.90	56605	-444	44
16.2	2400.56	1941.21	2461.50	2493.16	1645.82	927.02	3348.82	58174	-8	1
17.1	2406.52	1944.20	2465.91	2497.28	1652.67	932.01	3352.41	58594	243	24
17.2	2417.77	1949.85	2474.23	2505.06	1665.07	941.18	3359.21	59307	-9	1

Figure 1:



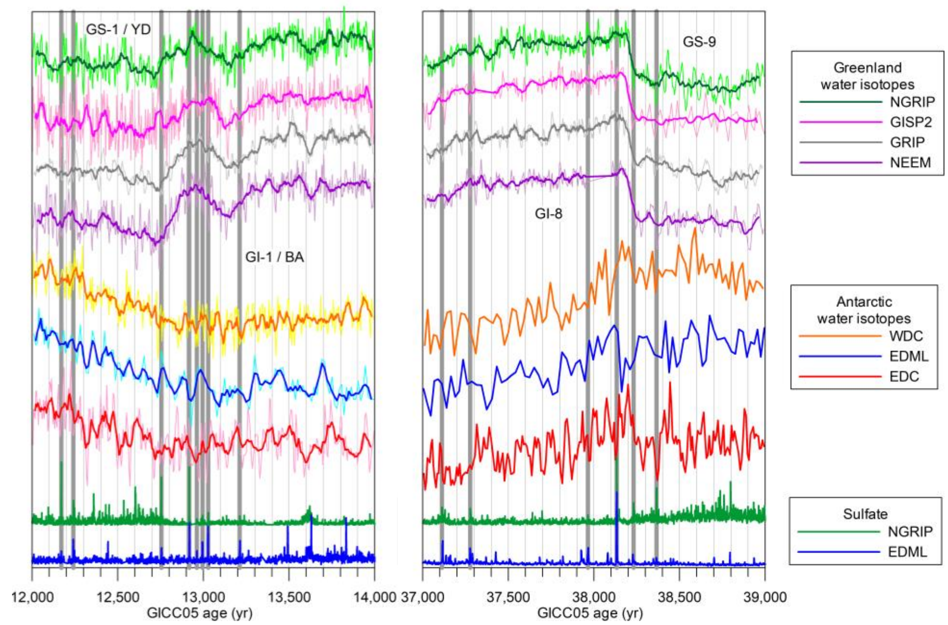
GI-1
GI-2
GI-3-4
GI-8
GI-12
GI-16-17
(‰)
NGRIP
EDML
WDC
EDC
-44
-46
-48
-50
-50
-52
-54
-56
-58
-36
-38
-40
-42
-44
-46
-36
-38
-40
-42
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
50,000
55,000
60,000
Age (GICC05 b2k)

Figure 2:

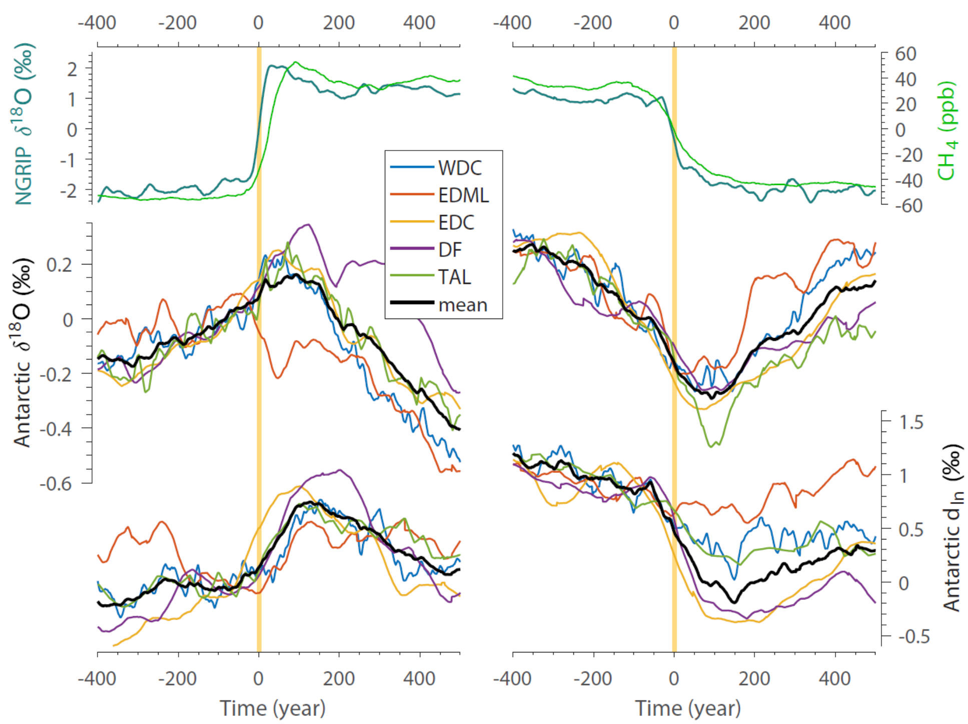


GS-1 / YD
GI-1 / BA
GI-8
GS-9
-34
-36
-38
-40
-42
-44
-46
Water isotopes δ18O
NGRIP
Sulfate / Sulfur
NEEM
GISP2
NGRIP
WDC
EDC
EDML
ECM / DEP
(volcanic proxi)
GRIP
NGRIP
EDC
EDML
12,000
12,500
13,000
13,500
14,000
37,000
37,500
38,000
38,500
39,000
GICC05 age (yr)
GICC05 age (yr)

Figure 3:

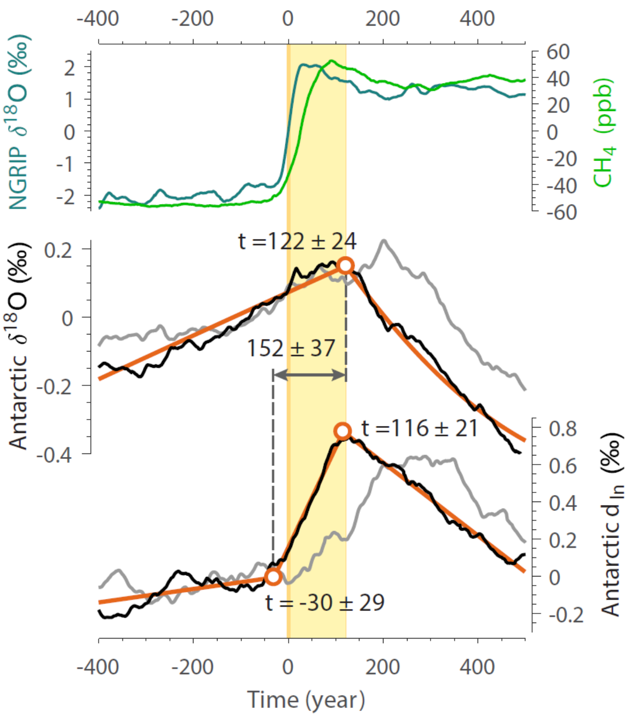

GS-1 / YD
GI-1 / BA
GS-9
GI-8
Greenland water isotopes
NGRIP
GISP2
GRIP
NEEM
Antarctic water isotopes
WDC
EDML
EDC
Sulfate
NGRIP
EDML
12,000
12,500
13,000
13,500
14,000
37,000
37,500
38,000
38,500
39,000
GICC05 age (yr)
GICC05 age (yr)

854 **Figure 4:**



855

Figure 5:


NGRIP δ18O (‰)
CH4 (ppb)
Antarctic δ18O (‰)
Antarctic d_ln (‰)
t =122 ± 24
152 ± 37
t =116 ± 21
t = -30 ± 29
-400
-200
0
200
400
Time (year)