

## Author's response

*Reviewer's and editor's comments are in italic, author's response in plain characters.*

### Editor's comment

*Dear Ms. Philippe,*

*I now received two reviews for your revised manuscript, which are available for you at the journal web site. The reviewer #1 recommended accepting the manuscript with minor revisions. The reviewer #2 acknowledges that estimating past SMB using the timescale is largely improved, but argued that the timescale presented in the revised manuscript is not convincing enough.*

*I am unable to accept this paper in the current form but happy to see another revised version as a possible contribution to the journal *The Cryosphere*. Please submit a revised manuscript together with point-to-point responses to all comments brought by the reviewers. Some additional guidance can be found below.*

*1. I agree with the reviewer #1 that the isotope/chemistry sampling was made not at high enough resolution (Figure R1 in the response letter), and that uncertainty in age control using volcanic events and its consequences should be more clearly shown in the manuscript.*

We believe that the uncertainty was already well acknowledged in the manuscript, as it was stated p.8, lines 21-23: "it is very likely that our oldest estimate is closer to the real age-depth relationship than the youngest estimate. However, we will keep both of them as an evaluation of the influence of the dating uncertainty on our accumulation rates reconstruction."

All numbers and trends in the rest of the manuscript take the largest uncertainty into account, since we agreed already with the reviewers who said that the volcanic identifications were ambiguous. We only left Tambora in order to give the reader a good reason to believe that the correct timescale lies within the range identified between the oldest and the youngest estimates.

This does not affect our conclusions because:

- the increased accumulation trend begins in the end of the 2<sup>nd</sup> half of the 20<sup>th</sup> century, where the dating is literally "flawless" (max. 2-3 years difference between oldest and youngest estimates).
- Both the youngest and oldest estimates show an increasing trend.

However, we understand the reviewer's argument regarding the Tambora matching and decided to be even more cautious in our interpretation, in accordance with the editor's recommendations.

The example between 103 and 104 meters did not lead to an ambiguity in the annual layer counting since at least four parameters agree in showing three annual cycles (ECM,  $\delta^{18}\text{O}$ , nssSO<sub>4</sub>, MSA). Even if SO<sub>4</sub>/Na is less clear in this case, it is not a sufficient argument to find this layer ambiguous.

This is also a very isolated case. The full range from 101 to 108 m for example shows 22 years with, in our opinion, no ambiguity at all between the  $\delta^{18}\text{O}$  and the Na/SO<sub>4</sub> ratio datasets. More interestingly, very close to the bottom of the core, the section between 112.3 m and 115 m shows 13 isotopically defined annual layers in the oldest estimate and 10 in the youngest estimate. However, the Na/SO<sub>4</sub> signal unambiguously reproduces 13 annual layers.

We actually use this excellent match between  $\delta^{18}\text{O}$  and the  $\text{Na}/\text{SO}_4$  ratio throughout the whole core including the deepest sections to confirm our range of estimate. We also believe this clearly shows that using a technique such as subtracting 1 or 2 more years every 20 or 10 years down from 40 m depth, as suggested by the reviewer would clearly overestimate the potential error on dating. It would be at the most 1/22 years below 100 m, a depth below which there is no obvious trend in SMB anyway.

*2. This reviewer informed me after the review was submitted that the reviewer misunderstood the uncertainty mentioned in the manuscript (0.6%, though it is said 6%). So, the authors do not need to address the comments directly related to this misunderstanding, but respond to the age control and uncertainty issues brought by the reviewer.*

Agreed

*3. I echo reviewer's view on the Tambora identification. Main concerns are: (1) the unknown 1809 event is not found, (2) Tambora and 1809 events do not sustain for several years as typically seen in many cores, and (3) low sulfate and high ECM peaks (or any other data properties) are not convincingly presented to support author's identification of the Tambora event, and (4) isotope data are unavailable from 100-101 m (see the review for the full argument by the reviewer). If the authors maintain the current argument on the Tambora identification and age control in general, please fully respond to the comments and provide argument that is more rigorous in the manuscript.*

We removed the sentence about Tambora in the abstract: “and the identified Tambora 1815 volcanic horizons confirms the oldest age-depth estimate” and reset Figure 5 as the original suggestion of all the volcanic events with a potential match. However, we do not use it to refine our depth-age scale anymore and instead use it to conclude that the background noise on ECM due to the coastal location is too strong. We consider the oldest and youngest estimates as representing our full range of uncertainty (see above).

*(1) the unknown 1809 event is not found.*

This event was found in version 1 at 104 m (New Fig. 5). Note that (i) the relative level of difference is from simple to double, as in the WAIS divide ice core mentioned by the referee (ii) unknown is just above  $2\sigma$ , a threshold recognized in previous literature.

*(2) Tambora and 1809 events do not sustain for several years as typically seen in many cores*

First, the WAIS divide ice core shown by the reviewer is from 1766 m a.s.l. and 500 km away from the coast, while IC12 is typically coastal. Volcanic peaks are therefore less prominent compared to the background signal in our core. However, we agree that there are other peaks, especially in the  $\text{nssSO}_4$  record that do not allow us to use Tambora as a strict tie point for our depth scale. This is why we chose to refrain from this interpretation in the revised manuscript.

*(3) low sulfate and high ECM peaks (or any other data properties) are not convincingly presented to support author's identification of the Tambora event*

We compare the raw ECM signal to the normalized signal in Fig. A1 below. Both are very similar, so we are convinced that our treatment of the ECM data did not affect our conclusions.

Density correction was not based on optical televiewer measurements but on a best fit through gravimetric measurements. We made that point clearer in the text. We now provide the manuscript explaining that density correction. We hope that it is now

clearer why we made this correction, and that it did not bring more noise in the dataset.

(4) *isotope data are unavailable from 100-101 m.*

This is unfortunately due to a missing ice core section (fell back in the borehole) and this drilling default is now mentioned in the text: “The ice core is complete, except for the 100-101 m section which fell back in the borehole and was recovered in broken pieces.”

*4. I found that the data presented in this manuscript is of high interest and can be publishable even if the Tambora event isn't convincingly identifiable. If the authors pursue such publication, please fully address uncertainties in the timescale and provide a realistic range of uncertainty or possible alternative interpretations of the past SMB (does the revised timescale really support the increasing SMB?).*

Agreed and amended

*5. Many of reviewer #2's comments are associated with inaccurate or incomprehensive information on previous work in DML. For example, the current manuscript only mentions that Altnau found positive SMB trend in the interior DML. However, Altnau also found a negative trend in the ice shelves. Both should be mentioned to give the full picture of previous findings. Similarly, there are many firn cores collected in DML coast (not very few, see reviewer's comment on P3L20 of the revised manuscript), but most of them cover only up to several decades and the DIR ice core is one of only a few that covers nearly a century. Please revise the manuscript so that the manuscript articulates the current understanding in DML coastal region and emphasizes what's exactly new in this manuscript.*

Agreed and amended.

*6. I am afraid that some of Reviewer #2's comments refer wrong page/line numbers (e.g. a comment on P2L20 of the revised manuscript is probably on P3L4 of the revised manuscript). However, the authors are probably able to identify the statements that the reviewer concerned in most cases. If it is unfeasible for some specific comments, please say so in the response letter.*

Agreed. We believe we found and addressed all comments of referee #2

*7. Your manuscript cites Fig. 10 (P13L6ff), but the manuscript includes only 9 figures.*

Amended

*Editorial comments:*

*- I think that the authors use “accumulation” and “surface mass balance” interchangeably. Please distinguish them and use these terms consistently through the manuscript.*

Amended

*- Does the depth axis show physical depth or depth in water/ice equivalent? Table 2 shows that 2011 SMB is 0.98 m w.e./a, and Figure S1 shows that the 2011 layer is to about 1 m depth (I assume that the surface density is below 500 kg/m<sup>3</sup>).*

All figures show physical depth except Fig. 2, which is in ice equivalent, as we have now clearly indicated in Fig. 2.

The 2011 layer is the one between 1.07 m and 3.14 m so it is 2.07 m thick. With snow density of 473 kg/m<sup>3</sup> at that depth, this gives 0.98 m w.e.

The 2012 layer is incomplete since the ice core was drilled in November 2012.

- Figure 2: all depths should be positive.

Amended

- Figure 6: it's hard to distinguish curves in different colors. Please use more distinct colors.

Amended

- Figure 7: is the ERA-Interim record shown relative to the 1980s record, while CESM and ice core data are relative to the 1860s record? Is it better to show all of these data relative to the latest years?

Agreed and amended

Thank you for submitting the manuscript to TC/TCD. Both reviewers and I found significant improvements in your manuscript through the review process, and I encourage you to submit a revised manuscript for further consideration.

Sincerely,

Kenny Matsuoka  
TC/TCD editor

### **Report 1 and author's response**

*Philippe et al. TCD*

*The authors put a lot of work into the revised version and the manuscript has been greatly improved. However, some points remain, which I will address in the following.*

*First a remark: the font size of the manuscript pdf file is a bit of an imposition, it was completely unnecessary to keep the formatting info on the right side. Especially with all the marked changes it was very hard to read. I suggest to avoid that in the future.*

*Comments to reply to specific comments (line numbers refer to the original manuscript:*

*P2, l23: you still do not mention that Altnau et al. found a negative trend for SMB at the coast at this point. Why?*

We mentioned it in section 4.3 but forgot to do so in the introduction. It is now included in both sections.

*P6, L3: your reply should be discussed in the text.*

We added to the text: "The CESM simulated sea-ice extent in the observational period is very realistic compared to observations (Lenaerts et al., 2016) and does not show any trend in the Atlantic sector, which gives us confidence that the sea ice is treated realistically."

*P10, L5: I still think that an SMB of 0.3 is difficult to use as a threshold since many sites at the coast have SMBs just around 0.3. so slightly above or below 0.3 would not mean a systematic difference here. (I am not sure why Massimo Frezzotti chose it in the first place.)*

Agreed. Although we already mentioned in the manuscript that these high accumulation sites were not all coastal, we now show the difference between coastal and inland sites in Fig. 9, using a distance of less than 100 km from the coast and below 1500 m a.s.l. to define coastal sites.

*P12, L20: Please, discuss this in the text, too. The high SMB in 2009 and 2011 found by Lenaerts was mainly due to the atmospheric circulation patterns during those years. Those patterns have a much stronger influence on SMB than a couple of days longer or shorter sea*

*ice coverage. (and keep in mind that sea ice extent refers to 15% sea ice concentration, so plenty of open water available for evaporation.)*

We agree that the atmospheric circulation largely determines the variability, and sea-ice and sea-surface temperature conditions play a secondary role. We have included this before the last paragraph before the conclusions:

“Atmospheric circulation exhibits a primary role in determining temporal and spatial SMB variability. Sea-ice and ocean surface conditions play a secondary role, and could contribute to a higher SMB in a warmer climate. A more recent study....”

*From now on, the line numbers refer to the revised version*

*P2*

*L19: what does it mean that this is the only record that supports model results?? Are all the other cores not representative and the DIR core is the only representative one? This is not self-evident.*

We think that the line numbers are wrong here but if you refer to the abstract, we removed “thereby supporting model predictions”.

*L20: this is not consistent evidence: e.g. Fudge et al. found that SMB and temperature are not always positively correlated.*

*Fudge, T. J., B. R. Markle, K. M. Cuffey, C. Buizert, K. C. Taylor, E. J. Steig, E. D. Waddington, H. Conway, and M. Koutnik (2016), Variable relationship between accumulation and temperature in West Antarctica for the past 31,000 years, Geophys. Res. Lett., 43, 3795–3803, doi:10.1002/2016GL068356.*

Amended

*P3*

*L 18: see above, negative trend in SMB in coastal cores in Altnau et al.*

Amended

*L20: I would not call this “very few”, there are quite a few investigations of DML cores from German, Scandinavian and Indian expeditions.*

We modified the sentence and other instances where such confusion was made: “few studies focused on ice cores spanning more than 100 years”

*L21: higher than the interior (a comparative needs something to compare to)*

Amended

*P4*

*L15: ice rises are too small to “block” atmospheric circulation. (this would mean that the air flows AROUND the ice rise rather than over it. Blocking is a clearly defined term in meteorology.*

We changed it to ‘disrupt’

*L18-22: good!*

*P9*

*L3: this is not correct, there is ERA20C (ECMWF) meanwhile, which covers the entire 20th century.*

Correct, but ERA-20C suffers from severe data gaps in the early 20th century over the Southern Ocean (Titchner et al., 2014), which makes it useless for this purpose.

Titchner, H. A. & Rayner, N. A. The Met Office Hadley Centre sea ice and sea surface temperature data set, version 2: 1. Sea ice concentrations. *J. Geophys. Res. Atmos.* 119, 2864–2889 (2014).

P12

L7: delete “is”

Amended

P17

L4. Better: source region of atmospheric moisture for DIR.

Amended

Fig. 8 should be described as part of the results section.

Amended

L2-8: sea ice is only one factor. The same factor that causes high accumulation might influence the sea ice extent without changes in sea ice being the reason for the accumulation deviations. I still do not find this paragraph very convincing. E.g. high sea ice extent related to lower air temperatures might be caused by a generally more zonal atmospheric circulation pattern, which at the same time could be the reason for low accumulation due to lack of meridional moisture transport (as Lenaerts et al. showed for 2009 and 2011. These things should be discussed in the text.

We agree with the reviewer, which is why added to the text (see above): “Atmospheric circulation exhibits a primary role in determining temporal and spatial SMB variability. Sea-ice and ocean surface conditions play a secondary role, and could contribute to a higher SMB in a warmer climate.”

L18: see above. Does it not make you think that no other coastal core in DML shows an increase in SMB?

Yes, even if we consider shallow cores, all of them show a decrease or no significant change.

L27: see above, please explain the physical reason for the choice of the threshold.

We don't use anymore SMB threshold but rather define coastal sites as those situated less than 100 km away from the coast and below 1500 m a.s.l.

L31: if we compared

Amended

P20

L1-7: see above, maybe quote Fudge et al. here, too.

The sentence was changed to: “However, both Altnau et al. (2015) and Fudge et al. (2016) found that SMB and changes in ice  $\delta^{18}\text{O}$  are not always correlated. They hypothesized that changes in synoptic circulation (cyclonic activity) have more influence than thermodynamics, especially at the coast.”

L8ff: this is still not clear. Atmospheric rivers don't occur for the whole year, just for certain events. Precipitation at the coast is usually event-type, but the events occur during the whole year, whereas in the interior those events happen not very often, but are related to amplified Rossby waves.

This paragraph was changed by “In the presence of a blocking anticyclone at subpolar latitudes, an amplified Rossby wave invokes the advection of moist air (Schlosser et al., 2010;

Frezzotti et al., 2013). On these rare occasions, meridional moisture transport towards the interior in DML is concentrated into atmospheric rivers. Two recent manifestations of these short-lived events, in 2009 and 2011, have led to a recent positive mass balance of the East Antarctic ice sheet (Shepherd et al., 2012; Boening et al., 2012). It was also observed in situ, at a local scale, next to the Belgian Princess Elisabeth base (72 °S, 21 °E) (Gorodetskaya et al., 2013; 2014). Several of these precipitation events in a single year can represent up to 50 % of the annual SMB away from the coast (Schlosser et al., 2010; Lenaerts et al., 2013). At the coast, precipitation is usually event-type, but the events occur during the whole year. However, the 2009 and 2011 events are also observed in our data as two notably higher than average SMB years (2009 and 2011, Table 2).”

*L25: 2009 and 2011*

Amended

*P21*

*L8: wind is certainly a very important factor, but e.g. the interannual variability in the years 2009-2011 was definitely not mainly caused by the wind. Be careful with general statements like this. Of course, in years with fairly “average” flow patterns, the wind is the main factor, that is correct.*

Amended

*L21: why should there be a decrease at the coast then?*

Because the moisture is transferred inland.

*L24ff: see comment on P1*

Already answered above

*Parts of the discussion actually belong into the results section.*

Amended

*p23*

*l16ff: see above.*

We changed the sentence « Our analysis based on CESM output suggests that accumulation variability is also potentially explained by changes in sea ice cover combined with regional atmospheric changes. » to “Our analysis suggests that atmospheric circulation to a great extent determines SMB variability, with a potential secondary role of changes in sea ice cover”.

## **Report 2**

*Review of Revised Phillippe et al., 2016 manuscript:*

*The revised manuscript by Phillippe et al. has notable improvements, particularly in regards to the ice-flow modeling and reconstruction of the accumulation rate history. The collaboration with other researchers doing ice-dynamics work has led to a robust and convincing correction of strain thinning.*

*Unfortunately, the development of the timescale remains flawed. The attempt to identify Tambora is unconvincing and undermines the entire development of the timescale. A critique of the timescale development is below.*

*Overall, the authors need to admit that they:*

- cannot reliably identify any volcanic events and thus have no age control beyond annual layer counting  
- did not sample the core at high enough resolution and may thus be overcounting, predominantly in the deep core  
- and thus the interpretation of an increase in recent accumulation is tentative and more work is needed to answer this interesting question definitively.

This work can become published, but only after giving up on identifying volcanic peaks and giving an honest and detailed assessment of the annual layer interpretation and the likelihood of overcounting in the deeper part of the core. The type of questions that needs to be answer is: What would the record look like if you subtracted 1 year in every 20 below 40 m depth? Or 1 year in every 10? And then discuss whether your annual layer count is reliable at that level. One approach could be to use automated techniques (such as Mai Winstrup's stratcounter: <https://github.com/maiwinstrup/StratiCounter>) on the different data sets to get a sense of the uncertainty. My guess is that the real uncertainty is closer to 6% than 0.6%.

### **The Timescale:**

The paper hinges upon accurate interpretation of the depth-age relationship. The main conclusion is that the accumulation rate has increased in recent decades compared to the previous couple of centuries. This interpretation relies both the timescale and the corrections for density and ice-flow induced thinning. The authors have greatly improved the corrections, which can now be both understood and trusted. However, the timescale remains both poorly described and untrustworthy.

The magnitude of the inferred accumulation rate depends directly upon the thickness of the identified annual layers. Thus, supporting the interpretation of increased recent accumulation requires showing that the annual cycles are properly identified. The authors attempt to do this in two ways: 1) the presentation of data with distinct seasonal cycles to convince the reader that the seasonal cycles at all depths of the core are unambiguous (or at least nearly unambiguous) and 2) identify horizons (such as volcanic events) that can be tied to other cores (or other paleoclimate records) that confirm the annual cycle interpretation.

### **-Tambora**

I recommended focusing on Tambora in my previous review but am deeply frustrated by the revised manuscript. It is worth discussing here why Tambora is so distinctive in Antarctic ice core records. Tambora is indeed the largest event in the past few hundred years. But part of the reason it is so distinctive is that is preceded by the second largest event of the past few hundred years, yielding distinctive double peak. I've attached a figure of Tambora and the unknown events as shown by Sigl et al. (2013) from the WAIS Divide ice core. It is worth noting that both events have durations of 3 years.

The purported Tambora in IC12 lacks all resemblance to this event found elsewhere.

1) the authors make no attempt to identify the preceding event (commonly know as the unknown 1809 event).

2) The sulfate peak associated with Tambora is not even the largest in the figure. The authors do not explain why the ECM is so anomalously high while the source of acidity, H<sub>2</sub>SO<sub>4</sub>, does not result in high SO<sub>4</sub> levels.

3) The figure starts at 101 m, conveniently hiding the fact there is no data from 100 to 101 m – something that I do not believe is discussed in the text.

4) The lack of chemistry measurements of the full core means there is no ability to reliably identify and compare SO<sub>4</sub> peaks along the core

5) The ECM data is heavily filtered, indicating it has major quality-control issues and reducing any confidence that it can reliably detect volcanic events. Further, the filtering methods are unclear with the techniques used reference (Karlov et al. 2000) being more



complicated than what is described in this text (just the Savitsky-Golay filter and normalization) – I'm still not sure what was done to the ECM data presented here. Further again, the ECM data is corrected for density based on borehole optical televiewing that is likely not that well depth-referenced (the methods are not described except for an unprovided in review manuscript) and regardless, is not appropriate for ~10 cm scale variations anyway, as explicitly stated in the given reference, Hubbard et al., 2013. This technique likely just introduced a bunch of noise at annual-to-volcanic frequencies into an already noisy record.

6) The authors claim that the ECM peak occurs in wintertime, despite being in an Na trough with a clear  $\text{SO}_4/\text{Na}$  peak (and hence  $\text{SO}_4$ ). Though the water isotopes are indeed unusual, there is a shoulder which may indicate a lack resolution to identify peaks. This seems more likely to be a thin year than volcano, let alone Tambora. Further, the logic of a wintertime peak is faulty. Tambora is a multi-year event such that the peak should be highest in summertime when there is both volcanic deposition and ocean-derived deposition. I guess the authors could argue that the coastal characteristics of deposition could truncate the duration of Tambora - but they would need to do that and be convincing with climate model output and observational data.

My biggest issue with the “identification” of Tambora is that it is so far from convincing I simply have no trust in the authors development of any part of the timescale. This is particularly important because the timescale was clearly developed iteratively; the chemistry measurements were only made in areas of uncertain annual layering indicating that the annual layers (of  $\text{d}18\text{O}$  and ECM) were interpreted prior to the chemistry measurements clarifying the annual layer interpretation. It is likely that the volcanic matching was also done before, and thus the annual layer interpretation may have (consciously or subconsciously) been interpreted to get the right age at Tambora. While this sort of issue is not uncommon producing annual timescales, the lack of awareness of this issue in the manuscript is troubling especially given the propensity to pick too many years in undersampled data.

See response to editor's question 3

#### **- Annual layer interpretation**

Evaluating annual interpretation in publications has to be based largely on trust since it is difficult to present that data and interpretation in a manageable way. The authors do a good job of presenting the data with the addition the supplementary figures. However, the authors fail to convince me of their uncertainty, and hence the underlying timescale. This is in part because of the unconvincingly attempt to identify Tambora, but also because the measurements are just not of sufficient quality and continuity to get 0.6% accuracy. Some of the issues:

- The stable isotopes, the primary parameter used to identify annual layers, are of insufficient resolution much of the time. The histogram in Figure R1 shows that the mode of the number of data points per annual layer is 4, with a significant number of layers identified with 3, 2, and even 1 data point. 4 data points is not enough for annual layer interpretation, less alone fewer. The authors may say that the other data sets define these layers, so I address that below:

- The ECM data is heavily filtered with a 301-point window and unclear other techniques (see above). The authors do not describe how this impacts the annual interpretation, which is a major shortcoming. But what I see of the ECM data suggests to me that it is of questionable reliability for interpreting annual layers, with an uncertainty of 10% not less than 1%.

- The chemistry data is sporadic with samples sizes that appear larger than for the stable isotopes (it's hard to see in Figure S2), such that the same criticisms of the stable isotope record apply to the chemistry records.

*For instance, between 103 and 104 meters, there is a sequence of 3 thin years which is interpreted exactly the same in the oldest and youngest scenarios (1837-1835 or 1813-11). Yet the Na/So4 looks like there are only two years. In both cases, the sampling frequency is too low to be sure peaks and troughs are being resolved. This type of interpretation may be finding an extra year, biasing the annual layer thickness low, and underestimating the accumulation rate. While individual interpretations can always be nit-picked, the real concern here is that the authors do not even acknowledge the uncertainty.*

See response to editor's question 1.

Globally, we have now abandoned the use of volcanic markers to refine our relative dating uncertainty. We still believe that our oldest estimate is the best one, since it shows coherent synchronicity of  $\delta^{18}\text{O}$  and Na/SO<sub>4</sub> signatures all the way down to the deepest part of the core. However, we now make it clearer that we treat our data set as an "uncertainty" range (see e.g. Fig. 7).

In our opinion, using the technique of ignoring 1 out of 10 or 20 layers below 40 m, as suggested by the reviewer, would bring us away from the one-to-one  $\delta^{18}\text{O}$  - Na/SO<sub>4</sub> synchronicity observed for the oldest estimate even in the deep layers, therefore overestimating the errors.

Also, clearly, using our "uncertainty range" does not jeopardize the main conclusion of the paper that there exists a trend of increasing SMB, at least from the mid-20<sup>th</sup> century.

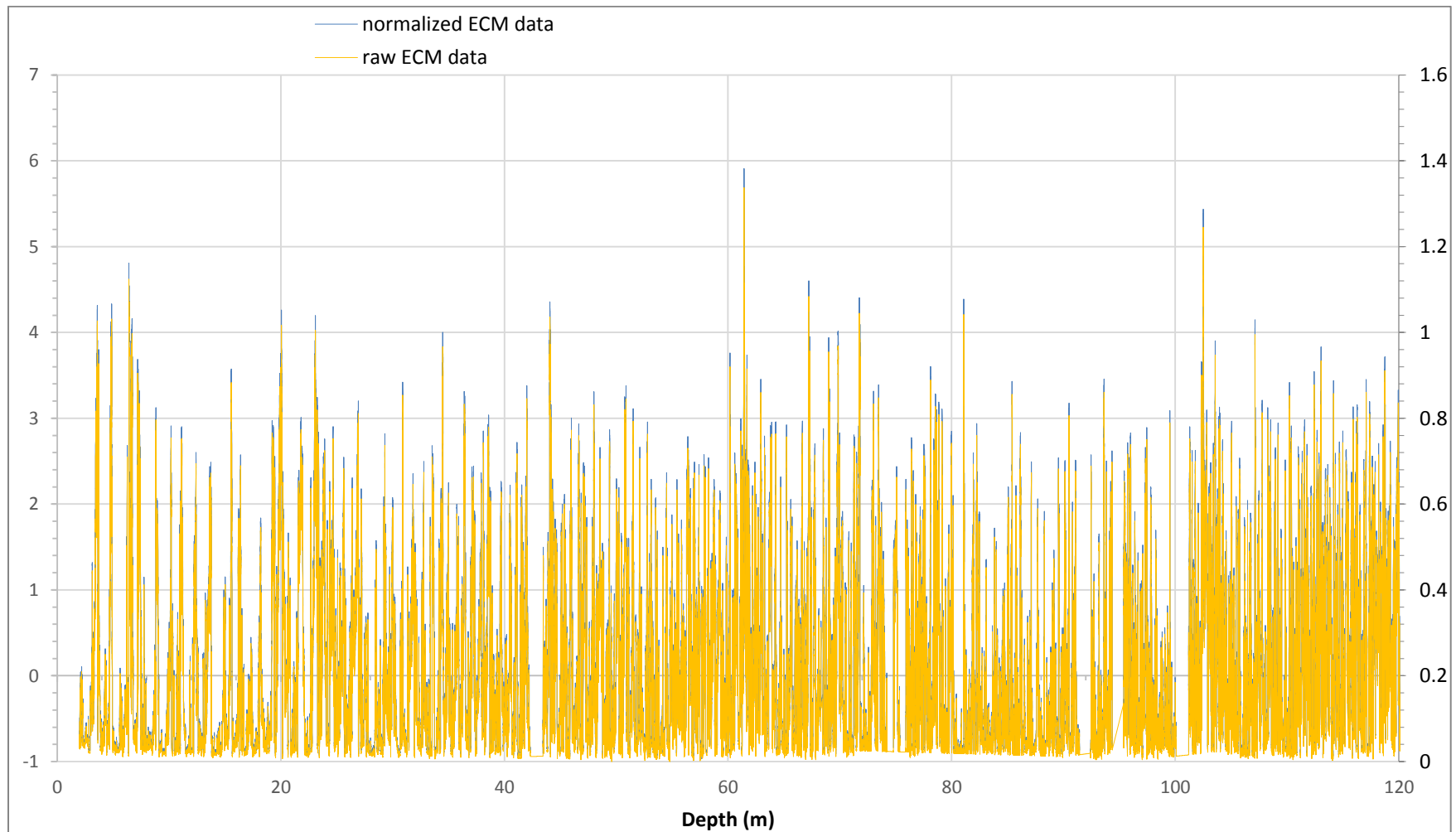


Fig. A1. Raw ECM data (10 mm running average, left axis) and normalized ECM data (right axis), respectively before and after “density correction, normalizing and Savitsky-Golay filtering”.

# Ice core evidence for a **recent-20<sup>th</sup> century** increase in **snow accumulation surface mass balance** in coastal Dronning Maud Land, East Antarctica

Morgane Philippe<sup>1</sup>, Jean-Louis Tison<sup>1</sup>, Karen Fjøsne<sup>1</sup>, Bryn Hubbard<sup>2</sup>, Helle A. Kjær<sup>3</sup>, Jan T. M. Lenaerts<sup>4</sup>, [Reinhard Drews<sup>5</sup>](#), Simon G. Sheldon<sup>3</sup>, Kevin De ~~Bondt<sup>5</sup>~~ [Bondt<sup>6</sup>](#), Philippe Claeys<sup>6,5</sup>, Frank Pattyn<sup>1</sup>

<sup>1</sup>Laboratoire de Glaciologie, Département des Géosciences, Environnement et Société, Université Libre de Bruxelles, BE-1050 Brussels, Belgium

<sup>2</sup>Centre for Glaciology, Department of Geography and Earth Sciences, Aberystwyth University SY23 3DB, United Kingdom

<sup>3</sup>Centre for ice and climate, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100, Copenhagen, Denmark

<sup>4</sup>Institute for Marine and Atmospheric research Utrecht, Utrecht University, Princetonplein 5, 3584 CC Utrecht, Netherlands

<sup>5</sup>[Bavarian Academy for Sciences and Humanities, Alfons-Goppel-Strasse 11, 80539 Munich, Germany](#)

<sup>6</sup>Department of Analytical Environmental and Geo-Chemistry, Vrije Universiteit Brussel, Pleinlaan 2, BE-1050 Brussels, Belgium

Correspondence to: M. Philippe (mophilip@ulb.ac.be)

**Abstract.** Ice cores provide temporal records of ~~snow accumulation~~ [Surface Mass Balance \(SMB\)](#), a crucial component of Antarctic mass balance. Coastal areas [have relatively high and sensitive SMN but](#) are ~~particularly~~ under-represented in ~~such~~ records [spanning more than 100 years, despite their relatively high and sensitive accumulation rates.](#) Here we present records from a 120 m ice core drilled on [the](#) Derwael Ice Rise, coastal Dronning Maud Land (DML), East Antarctica in 2012. [Water stable isotopes \( \$\delta^{18}\text{O}\$  and  \$\delta\text{D}\$ \) stratigraphy is supplemented by discontinuous major ion profiles and continuous electrical conductivity measurements \(ECM\).](#) [The ice core and the identified Tambora 1815 volcanic horizons confirm the dating](#) We date core bottom is dated ~~the ice core bottom~~ back to [1759 ± 16 A.D.](#) ~~1745 ± 2 AD~~ [and the identified Tambora 1815 volcanic horizons confirm the oldest age depth estimate.](#)  $\delta^{18}\text{O}$  and  $\delta\text{D}$  stratigraphy is supplemented by discontinuous major ion profiles, and verified independently by electrical conductivity measurements (ECM) to detect volcanic horizons. The resulting annual ~~layer-layer thickness~~ history is combined with the ~~core gravimetric~~ density profile to ~~calculate-reconstruct~~ [SMB accumulation](#) history, corrected for the influence of ice deformation. The mean long-term ~~accumulation~~ [SMB](#) is  $0.4725 \pm 0.0235$  m water equivalent (w.e.) a<sup>-1</sup> ~~(average corrected value)~~. Reconstructed annual ~~accumulation rates~~ [SMB](#) show an increase ~~from 1955 onward~~ [in at least the last 50 years](#) to a mean value

of  $0.61 \pm 0.012$  m\_w.e. a<sup>-1</sup> between 1962 and 2012. This trend is compared with other reported accumulationSMB data in Antarctica, generally showing a high spatial variability. Output of the fully coupled Community Earth System Model demonstrates that sea ice and atmospheric patterns largely explain the accumulation variability. This is the first record from a coastal ice core in East Antarctica showing a steady increase during the 20<sup>th</sup> and 21<sup>st</sup> centuries, thereby supporting modelling predictions. Output of the fully coupled Community Earth System Model suggests that, although atmospheric circulation is the main factor influencing SMB, variability in sea surface temperatures and sea ice cover in the precipitation source region also explain part of the variability in SMB, along with a likely significant impact of local snow redistribution. The latter which likely has a significant impact on interannual variability but not on long-term trends. This is the first record from a coastal ice core in East Antarctica showing a steady increase of accumulation ratesSMB during the 20<sup>th</sup> 20<sup>th</sup>-and 21<sup>st</sup> 21<sup>st</sup>-centuries, thereby supporting modelling predictions.

## 1 Introduction

In a changing climate, it is important to know the Surface Mass Balance (SMB, i.e. precipitation minus evaporation, sublimation, meltwater runoff, and/or erosion) of Earth's ice sheets as it is an essential component of their total mass balance, directly affecting sea level (Rignot et al., 2011). The average rate of Antarctic contribution to sea level rise is estimated to have increased from 0.08 [-0.10 to 0.27] mm a<sup>-1</sup> for 1992–2001 to 0.40 [0.20 to 0.61] mm a<sup>-1</sup> for 2002–2011, mainly due to increasing rising ice discharge from coastal West Antarctica (Vaughan et al., 2013), where the present-day warming seems to be confined (Turner et al., 2005; Bromwich et al., 2014; Ludescher et al., 2015). (Vaughan et al., 2013). This Some studies suggested that this increase in dynamic ice loss could be partly balanced by a warming-related increase in precipitation in East Antarctica (e.g. Polvani et al., 2011; Krinner et al., 2007, Palerme et al., 2016) by the end of the 21<sup>st</sup> century, but this is subject to debate. For example, Frieler et al. (2015) showed that past Antarctic (used as a synonym for SMB) were positively correlated with past air temperature during glacial–interglacial changes, using ice core data and modelling. However, Fudge et al. (2016) found that SMB and temperature are not always positively correlated in West Antarctica. There has been no significant long-term trend in the SMB over the continent during the past few decades (Van de Berg et al., 2006; Monaghan et al., 2006; van den Broeke et al., 2006; Bromwich et al., 2011; Lenaerts et al., 2012; Wang et al., 2016).

In East Antarctica, ~~s~~There is consistent evidence that past Antarctic snow accumulation rates were positively correlated with past air temperature, as recently shown by Frieler et al. (2015) using ice core data and modelling. Similarly, satellite radar and laser altimetry suggest recent mass gain in East Antarctica (Shepherd et al., 2012), Dronning Maud Land (DML) in particular, ~~L~~ which has experienced several high ~~accumulation~~SMB years since 2009 (Boening et al., 2012; Lenaerts et al., 2013). ~~C~~, in particular in DML, which has experienced several high ~~accumulation~~ years since 2009 (Boening et al., 2012; Lenaerts et al., 2013). However, although recent alibrated regional atmospheric climate models indicate higher ~~accumulation~~SMB during 1980–2004 along the coastal sectors than in previous estimates (e.g. Van de Berg et al., 2006), they show and Wang et al. (2016) found that climate models generally underestimate SMB in coastal DML. This region is therefore of particular interest. ~~DML, which has experienced several high accumulation years since 2009 (Boening et al., 2012; Lenaerts et al., 2013).~~ no long term trend in the total accumulation over the continent during the past few decades (Monaghan et al., 2006; van den Broeke et al., 2006; Bromwich et al., 2011; Lenaerts et al., 2012).

Ice cores provide temporal records of ~~SMB~~snow accumulation, which ~~These~~ are essential to calibrate internal reflection horizons in radio-echo sounding records (e.g. Fujita et al., 2011; Kingslake et al., 2014), to force ice sheet flow and dating models (e.g. Parennin et al., 2007) and to evaluate regional climate models (e.g. Lenaerts et al., 2014). However, records of ~~accumulation~~SMB are still scarce relative to the size of Antarctica. While ~~est~~ the majority ~~lack~~ show no significant trend in ~~SMB snow accumulation~~ over the last century (e.g. Nishio et al., 2002), some ~~do~~ show an increase (e.g. Karlof et al., 2005), and others show a decrease (e.g. Kaczmarek et al., 2004). Frezzotti et al. (2013) compiled ~~surface accumulation~~SMB records for the whole of Antarctica and Altnau et al. (2015) for ~~Dronning Maud Land (DML)~~ more specifically. Frezzotti et al. (2013) showed no significant SMB changes over most of Antarctica since the 1960s, except for an increase in coastal regions with high SMB and in the highest part of the East Antarctic ice divide. Altnau et al. (2015) found a statistically significant positive trend in SMB for the interior DML and a negative trend at the coast. ~~Both authors concluded that the trends are insignificant.~~

However, there is still a clear need for data from the coastal areas of East Antarctica (ISMASS Committee, 2004; van de Berg et al., 2006; Magand et al., 2007; Wang et al., 2016), where ~~very few~~ studies ~~have~~ focused ~~ded~~ on ice cores, ~~and few of those have~~ spanned ~~ed~~ more than 20–100 years. Coastal regions allow higher temporal resolution than the interior as ~~SM~~accumulation ~~r~~Bates generally decrease with both ~~altitude~~ elevation and distance from the coast (Frezzotti et al., 2005). Ice rises are ideal locations for paleoclimate studies (Matsuoka et al., 2015) as they are undisturbed by up-stream topography, ~~since~~ and lateral flow is almost negligible. Melt events are also likely to be much less frequent than on ice shelves (Hubbard et al., 2013).

In this paper we report on water stable isotopes (~~continuous ice~~  $\delta^{18}\text{O}$  and  $\delta\text{D}$ ) measurements (5–10 cm resolution) along a 120 m ice core drilled on the Derwael Ice Rise (DIR) (~~(70°14'44.88'' S, 26°20'5.64'' E)~~), in coastal DML. This record is complemented by major ions and continuous electrical conductivity measurement (ECM) profiles to improve the resolution of the seasonal cycles wherever necessary. ~~Dating is checked independently using volcanic horizons detected from continuous electrical conductivity measurements (ECM) along the core (Hammer et al., 1994).~~ After correcting for dynamic vertical thinning, we derive annual ~~accumulation~~SMB, and average ~~accumulation~~SMB and trends over the last  $254 \pm 1667$  years, i.e. across the Anthropocene transition. These are compared ~~with~~ other reported trends in Antarctica, including DML, over the last ~~decades~~20 and 50 years.

## 10 2 Field site and methods

### 2.1 Field site

The study site is located in coastal DML, East Antarctica. A 120 m ice core, named IC12 after the project name IceCon, was drilled in 2012 on the divide of the DIR (70°14'44.88''S, 26°20'5.64''E, 450 m a.s.l., Fig. 1). This ice rise is 550 m thick and the recent SMB has been estimated to 0.50 m w.e. a<sup>-1</sup> from preliminary ice core analysis (Drews et al., 2015; Callens et al., 2016).

Ice rises provide scientifically valuable drill sites because they are located close to the ocean (and hence sample coastal precipitation regimes) and because ~~remote sensing~~ ground-penetrating radar data can easily identify drill sites on a local dome that are relatively undisturbed by horizontal flow ~~can be identified easily from remote sensing data~~. However, a number of regional factors complicate the interpretation of ice-core records on ice rises: ice rises form topographic barriers with the capacity to ~~block~~ disrupt atmospheric circulation on otherwise flat ice shelves. Orographic precipitation can thereby result in significantly high SMB values on the upwind sides of such ice rises, with corresponding precipitation shadows on the downwind side (Lenaerts et al., 2014). For the DIR in particular, the SMB on the upwind side is up to 2.5 times higher than on the downwind side (Callens et al., 2016). On top of this larger scale (~10 km) asymmetry, Drews et al. (2015) identified a small scale (km) SMB oscillation near the divide, tentatively attributed to erosion at the crest, and subsequent redeposition on its downwind side. The observed SMB maximum is therefore offset by ~4 km from the topographic divide where the ice core was drilled. This means that the absolute values of the ice-core derived ~~accumulation rates~~SMB sample a regime where the SMB varies on short spatial scales. Moreover, Drews et al. (2015) identified isochrone arches (a.k.a. Raymond Bumps) beneath the divide. This characteristic flow pattern causes ice at

shallow to intermediate depths beneath the divide to be older than at comparable depths in the ice-rise flanks, necessitating a specific strain correction for the ice-core analysis, which we discuss below. Both Drews et al. (2015) and Callens et al. (2016) suggested that the DIR has maintained its local ice divide for the last thousands of years and possibly longer. By matching the radar stratigraphy to an ice-flow model, Drews et al. (2015) suggested that the DIR divide elevation is close to steady-state and has potentially undergone modest surface lowering in the past. Both studies used a temporally constant SMB. Here we focus on the temporal variability and argue that, because the DIR has been stable in the past, we can draw conclusion with respect to the larger-scale atmospheric circulation patterns.

The study site is located in coastal DML, East Antarctica. A 120 m ice core was drilled in 2012 on the divide of Derwael Ice Rise, named IC12 after the project name IceCon (70°14'44.88''S, 26°20'5.64''E Figure 1), which is 486 m thick and has a local ice flow (Drews et al., 2015). Due to its coastal location, the accumulation rate is high and allows dating by seasonal peak counting. Only a few very thin melt layers are present. A continuous density profile was obtained by calibrating optical televiewer (OPTV; Hubbard et al. 2008) luminosity records in the borehole with discontinuous gravimetric measurements (Hubbard et al., 2013).

## 2.2 Ice coring and density analyses

The IC12 ice core was drilled with an Eclipse electromechanical ice corer in a dry borehole. The mean length of the core sections recovered after each run was 0.77 m and the standard deviation 0.40 m. The ice core is complete, except for the 100-101 m section, which fell back in the borehole and was recovered in broken pieces. Immediately after drilling, temperature (Testo 720 probe, inserted in a 4 mm diameter hole drilled to the centre of the core, precision  $\pm 0.1$  °C) and length were measured on each core section, which was then wrapped in a PVC bag and stored directly in a refrigerated container at -25 °C, and kept at this temperature until analysis at the home laboratory. The core sections were then split bisected lengthwise in two, in a cold room at -20 °C. One half of the core section was used for ECM measurements and then kept as archive, while and the other half was sectioned for continuous water stable isotope sampling and discontinuous major ion analysis. Only a few very thin (1 mm) ice layers are present. A continuous density profile A best was obtained by calibrating optical televiewer (OPTV; Hubbard et al. 2008) luminosity records through discrete gravimetric density measurements, previously published (Hubbard et al., 2013), is used here to convert measured annual layer thicknesses to meters



~~water equivalent (w.e.) (Sect. 2.3) s in the borehole with discontinuous gravimetric measurements (Hubbard et al., 2013).~~

## 2.3 Annual layer counting and dating

### 2.3.1 Water stable isotopes and ~~major ions~~ major ion

5 Half of each core section was resampled as a central bar of 30 mm x 30 mm square section with a clean band saw. The outer part of the half-core was melted and stored in 4 ml bottles for  $\delta^{18}\text{O}$  and  $\delta\text{D}$  measurements, completely filled to prevent contact with air. For ~~major ions~~ major ion measurements, the inner bar was ~~then~~ placed in a Teflon holder and further decontaminated by removing ~2 mm from each face under a class-100 laminar flow hood, using a methanol-cleaned microtome blade. Each 5 cm -long decontaminated section was  
10 then covered with a clean PE storage bottle, and the sample cut loose from the bar by ~~hitting~~ striking it perpendicularly to the bar axis. Blank ice samples prepared from milliQ water were processed before every new core section and analysed for contamination.

Dating was achieved by annual layer counting identified from the stratigraphy of the  $\delta^{18}\text{O}$  and  $\delta\text{D}$  isotopic composition of  $\text{H}_2\text{O}$  measured ~~sured (10 cm resolution in the top 80 m and 5 cm resolution below)~~ with a  
15 PICARRO L 2130-i Cavity Ring Down Spectrometer (CRDS) (precision,  $\sigma = 0.05 \text{ ‰}$  for  $\delta^{18}\text{O}$  and  $0.3 \text{ ‰}$  for  $\delta\text{D}$ ). This composition was measured at 10 cm resolution in the top 80 m and 5 cm resolution below (See Fig. S1 for exact resolution). ~~The annual layer was identified by the  $\delta^{18}\text{O}$  summer maximum value.~~

For sections of unclear isotopic seasonality, major ion analysis ( $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$  and methylsulonic acid (MSA))  ~~$\text{NO}_3^-$ ,  $\text{Cl}^-$~~  was ~~performed with~~ additionally carried out using a Dionex-ICS5000 liquid chromatograph, at  
20 5 cm resolution. The system has a standard deviation of 2 ppb for  $\text{Na}^+$  and  $\text{SO}_4^{2-}$ , 8 ppb for  $\text{Cl}^-$ , 7 ppb for  $\text{NO}_3^-$ , and 1 ppb for MSA ~~8 ppb for  $\text{Cl}^-$~~ . Non sea-salt sulfate was calculated as  $nss\text{SO}_4 = [\text{SO}_4^{2-}]_{\text{tot}} - 0.052 * [\text{Cl}^-]$ , following Mulvaney et al. (1992) and represents all  $\text{SO}_4^{2-}$  not of a marine aerosol origin. The ratio ~~R~~  $\text{Na}^+/\text{SO}_4^{2-}$  was also calculated as an indicator of seasonal  $\text{SO}_4^{2-}$  production.

### 2.3.2 ECM ~~and volcanic horizons~~ measurements

25 ECM measurements were ~~made~~ carried out in a cold room at  $-18^\circ\text{C}$  at the Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, with a modified version of the Copenhagen ECM described by Hammer (1980). Direct current (1250 V) was applied at the surface of the freshly -cut ice and electrical conductivity was measured at -a ~~1~~ mm resolution. The DC electrical conductivity of the ice, once corrected for temperature,

depends principally on ~~its impurity content located at the crystal boundaries~~ its acidity ( $\text{SO}_4^-$ ,  $\text{NO}_3^-$ ,  $\text{Cl}^-$ , etc.) (Hammer, 1980; Hammer et al., 1994). This content varies seasonally and usually shows longer term localized maxima associated with sulfate production from volcanic eruptions. ECM can therefore be used both as a relative and an absolute dating tool.

5 As measurements were principally made in firn, we applied a novel technique described by Kjær et al. (in review) to correct for the effect of the firn porosity on the ~~noise~~ amplitude of the signal. As the ~~noise~~ ECM current is ~~lower~~ enhanced for higher air content, we multiplied the high resolution ECM signal by the inverse of the ice volume fraction, i.e. the ratio of the ice density to firn density ( $\rho_{\text{ice}}/\rho_{\text{firn}}$ ), ~~us~~ following the gravimetric density best fit from Hubbard et al. (2013).

10 ECM data were smoothed with a 301 point ~~wide~~ first-order Savitsky–Golay filter (Savitsky and Golay, 1964) which eliminates peaks due to random noise and small-scale variations in material chemical composition while preserving the larger peaks, including those due to volcanic eruptions. ~~As measurements were principally made in firn, we multiplied the signal by the ratio of the ice density to firn density following Kjær (2014).~~ Finally, the ECM data were normalized by subtracting the mean and dividing by the standard deviation following Karlof et al. (2000).

15 ~~We selected potential volcanic peaks as those above the  $2\sigma$  threshold, following standard practice (e.g. Kaczmarek et al., 2004).~~

#### 2.4. Corrections for ice flow

20 ~~Snow burial~~ The compression of snow under its own weight not only involves density changes along the vertical, but also involves ~~involves~~ lateral deformation of the underlying ice. Failure to take the latter process into account would provide an underestimation of reconstructed initial annual layer thickness, and therefore of the ~~accumulation–SMB~~ rate, especially within the oldest part of the record. ~~Commonly~~ In this paper, three–two different models are used to represent vertical strain rate evolution with depth: (i) strain rates derived from a full Stokes model that represents the full Raymond effect measured at the ice divide (Drews et al., 2015); and (ii) a modified Dansgaard–Johnsen model (Dansgaard and Johnsen, 1969) based on the description given in Cuffey and Paterson (200X2010).

25 The Drews et al. (2015) strain rate profile accounts for the best fit with the radar layers at depth, taking into account a small amount of surface thinning ( $0.03 \text{ m a}^{-1}$ ) and anisotropy (although the former is not essential). From a hexagonal strain network, we calculated horizontal strain rates ( $\epsilon_{xx} + \epsilon_{yy}$ ) to be  $0.002 \text{ a}^{-1}$ . Mass conservation then gives a vertical strain rate at the surface of  $-0.002 \text{ a}^{-1}$ . The vertical velocity profile was then

30

scaled to match this measured value measured vertical strain rate at the surface. A best fit to the measured radar layers was obtained with a value of a mean accumulationSMB-rate of  $0.55 \text{ m a}^{-1}$  ice equivalent (Fig. 2).

From an octagonal strain network, we inferred horizontal strain rates ( $E_{xx} + E_{yy}$ ) being equal to  $0.002 \text{ a}^{-1}$ , which from mass conservation leads to a vertical strain rate at the surface of  $-0.002 \text{ a}^{-1}$ . The vertical velocity profile was then scaled to match the measured vertical strain rate at the surface. A best fit was obtained with a value of a long term mean accumulation rate of  $0.55 \text{ m a}^{-1}$  ice equivalent (see Figure xx).

Alternatively, we used the Dansgaard-Johnsen (D-J) model to fit the characteristics at the ice divide, exhibited by the Raymond effect. Assuming that the horizontal velocity is zero, the vertical velocity is maximum at the surface and equals the accumulationSMB-rate (with negative sign) and is zero at the bed. Assuming a vertical surface strain rate of  $-0.002 \text{ a}^{-1}$  at the surface, we can determine the kink point (between constant strain rate above and a strain rate linearly decreasing with depth below) that obeys these conditions (Cuffey and Paterson, 2010). This approach indicates that the kink point lies at  $0.9H$ , where  $H$  is the ice thickness. As seen in Fig. 2b, this method yields a vertical strain pattern that is consistent with that of Drews et al. (2015), especially in the first 120 m corresponding to the length of the ice core.

Both strain rates (Drews/D-J) were then used to correct the ice equivalent annual layer thickness for strain thinning. Annual layer thicknesses were then converted from ice equivalent to w.e. for easier comparison with other studies.

Alternatively, we used the Dansgaard-Johnson (D-J) model to fit the characteristics at the ice divide, exhibited by the Raymond effect. Assuming that the horizontal velocity is zero, the vertical velocity is maximum at the surface and equal to the accumulation rate (with negative sign) and is zero at the bed, and assuming a vertical surface strain rate of  $-0.002 \text{ a}^{-1}$ , we can determine the kink point that obeys these conditions (see Cuffey and Paterson). It follows that it lies at  $0.9H$ , where  $H$  is the ice thickness. As seen in Figure xx, this fits well with the strain rate profile of Drews et al. (2015): (i) a power law model (Lliboutry, 1979), (ii) a piece-wise linear model (Dansgaard and Johnsen, 1969) and (iii) a fully linear model (Nye, 1963).

(i) The power law model requires measurements of the borehole horizontal displacement, which are unfortunately not available. (ii) the Nye model corrects the layer thickness  $L$  by assuming ice is incompressible, with a linear decrease from a constant annual layer thickness at the surface to zero at the ice bedrock interface (which implies a constant total ice thickness). In that case,  $L_z = L_s (z/H)$ , where  $H$  is the total ice thickness in m w.e., and subscripts  $s$  and  $z$  represent the values at the surface and at a height  $z$  (in m w.e.) above the bed. The piece-wise model assumes a constant vertical strain rate between the surface and a given depth, which in our case is below the zone of interest since the ice core is drilled in the first quarter of the total ice rise thickness (486

m, Drews et al., 2015), and then a quadratic decrease to zero at the ice bedrock interface. The constant strain rate in the upper part of the ice sheet can be inferred from the slope of water equivalent (w.e.) annual layer thickness versus depth, also in m w.e., assuming a constant long term snow accumulation (equal to annual layer thickness at the surface, Roberts et al., 2014). (iii) Finally, the Nye model corrects the layer thickness  $L$  by assuming ice is incompressible, with a linear decrease from a constant annual layer thickness at the surface to zero at the ice bedrock interface (which implies a constant total ice thickness). In that case,  $L_s = L_s(z/H)$ , where  $H$  is the total ice thickness in m w.e., and subscripts  $s$  and  $z$  represent the values at the surface and at a height  $z$  (in m w.e.) above the bed.

The last two ~~Bothe~~ corrections were applied separately and are compared in the results section.

## 10 2.5 Community Earth System Model (CESM)

~~Atmospheric reanalyses and regional climate models extend back to 1979, which means that they cover only a subset~~ small proportion of the ice core record. ~~Instead, to interpret our ice core derived SMB record and relate it to the large-scale climate conditions, we use output from the Community Earth System Model (CESM).~~ To interpret our ice core derived accumulation record and relate it to the large scale atmospheric and ocean conditions, we use outputs of the Community Earth System Model (CESM). CESM is a global, fully coupled, CMIP6-generation climate model with an approximate horizontal resolution of 1°-degree, and has recently been used successfully to shown to realistically simulate present-day Antarctic climate and SMB (Lenaerts et al., ~~in press~~ 2016). We use the historical time series of CESM (156 years, 1850–2005) that overlaps with most of the ice core record, and group the 16 single ~~(~10%)~~ years (i.e. ~10 %) with the highest accumulationSMB and lowest accumulationSMB in that time series. We take the mean accumulationSMB of the ice covered CESM grid points of the coastal region around the ice core (20–30 °degrees–East, 69–72 degrees–°South) as a representative value. For the grouped years of highest est and lowest est accumulationSMB, we take the anomalies (relative to the 1850–2005 mean) in near-surface temperature, and sea-ice fraction and surface pressure as parameters to describe the regional ocean and atmosphere conditions corresponding to these extreme years. The CESM simulated sea-ice extent in the observational period is very realistic compared to observations (Lenaerts et al., 2016) and does not show any trend in the Atlantic sector, which gives us confidence that the sea ice is treated realistically.

### 3 Results

#### 3.1 Dating

##### 3.1.1 Relative dating (seasonal peak counting)

~~with 1 year difference at 20 m depth~~ Figures 2-3, S1 and S2 illustrate how the high-resolution water stable isotopes ( $\delta^{18}\text{O}$ ,  $\delta\text{D}$ ), smoothed ECM, chemical species and their ratios are used in combination to ~~identify deeper~~ annual layer boundaries. All of these physico-chemical variables generally show a clear seasonality, undisturbed by the few very thin ice layers (white dots in Fig. 3). The summer peak in water stable isotopes is obvious in most cases. The boundary between annual layers was identified as the middle depth of the range of values of the peak above the mean  $\delta^{18}\text{O}$  value (thin black line in Fig. 3), considered as the “summer season”. Major ions ~~Major ion~~ such as  $\text{nssSO}_4^-$ ,  $\text{SO}_4^-/\text{Na}^+$ ,  $\text{NO}_3^-$ , and especially the ratio  $\text{Na}^+/\text{SO}_4^-$  generally help to distinguish ambiguous peaks in the isotopic record.  $\text{SO}_4^-$  is one of the oxidation products of Dimethyl Sulfide (DMS), a degradation product of DMSP (dimethylsulfoniopropionate) which is synthesized by sea ice microorganisms (sympagic) as an antifreeze and osmotic regulator (e.g. Levasseur, 2013). Both  $\text{nssSO}_4^-$  and  $\text{Na}^+/\text{SO}_4^-$  ~~vary seasonally and are also strong indicators of volcanic eruptions.~~  $\text{NO}_3^-$  also shows a seasonal signal, but the processes controlling its seasonality are not yet ~~fully well~~ understood (Wolff et al., 2008). For ECM, there is also a regular seasonal signal, ~~but only to a depth of which is sometimes blurred below 80 m,~~ although some seasonal cycles can still be seen, for example between 115 and 118 m ~~80 m.~~ (Fig. S2). ~~The two different extreme age-depth profiles (youngest and oldest) resulting resulted from this counting procedure, taking the remaining ambiguities into account (Fig. S2). The mean age-depth profile is~~ presented in ~~Figure Fig. 43~~ with the ranges associated with the two extreme age-depth estimates. ~~No ambiguity in layer counting is detectable above 62.38 m depth (i.e. 1933 A.D.).~~ Between 249-237 and 269-269 annual cycles ~~we~~ are identified between the reference surface (2012 A.D.) and the bottom of the core, which is ~~accordingly consequently preliminarily~~ dated to  $17594 \pm 160$  A.D. ~~before absolute dating.~~

~~In the oldest estimate, e and in a deep part of the record, for example between 101 and 110 m, or between 112 and 115 m, each  $\text{Na}^+/\text{SO}_4^-$  can~~ generally be associated with a trough in  $\delta^{18}\text{O}$ , even in the deep parts of the record. This is the case between 101 and 110 m or between 112 and 115 m, for example (Fig. S2) ~~while our,~~ while in the youngest estimate, ~~leaves some~~ these years ~~years with~~ show a double ~~trough~~ peak in  $\text{Na}^+/\text{SO}_4^-$ , ~~suggesting the latter underestimates the number of years. We will now see if we can find a confirmation for trusting this oldest estimate from volcanic signals in the ECM record.~~

### 3.1.2 Absolute dating Can we identify volcanic horizons to refine our depth-age scale?

Volcanic indicators (ECM,  $\text{nssSO}_4$ ,  $\text{SO}_4^{2-}/\text{Na}^+$ ) can be used to identify specific, dated volcanic eruptions, allowing us to reduce the uncertainties resulting from the relative dating procedure. However, unambiguous eruption identifications are challenging in ice cores from coastal regions, where the ECM and  $\text{nssSO}_4$  background signals are commonly highly variable due to the proximity of the ocean and ocean-related MSA products (Fig. S1).

Given the preliminary dating of  $1759 \pm 16$  A.D. made on the basis of our relative core dating (Section 3.1.1 above), we have looked for volcanic horizons at the depths corresponding to the oldest estimate to try and refine this timescale (Figure 5). The Tambora eruption seems to appear at 102.35 m, with an ECM signature above the  $4\sigma$  threshold and a consecutive peak above the  $2\sigma$  threshold, which could be attributed to the ~~No other peak in this depth range shows high values in the three indicators. Therefore, it is very likely that our oldest estimate is closer to the real age-depth relationship than the youngest estimate. However, 1809 eruption (unknown volcano, Traufetter et al., 2004). Although this is much less pronounced than in other cores, more inland, such as WAIS divide (Sigl et al., 2013), this threshold is usually considered as sufficient (e.g. Kaczmarek et al., 2004) and allows potential matching of 13 volcanoes. However, many other peaks above that threshold could not be associated with any known volcanic eruption. Therefore, we concluded that the background is too noisy to refine the relative time scale in this core. As a result, we will keep both of the estimates resulting from our relative dating process as an evaluation of the influence of the dating uncertainty on our SMB reconstruction.~~

In order to further improve our annual layer estimates and the depth-age relationship, we have used the ECM signal (which is mainly inherited from the  $\text{SO}_4^{2-}$  profile) to detect volcanic eruptions using a threshold from the background signal of  $2\sigma$  (Figure 4). The best depth-age match (corresponding to the closest age match at the base of the core) was obtained with the "oldest estimate", for which 12 peaks out of 33 could be assigned to known volcanic eruptions and one more from the chemistry alone (Krakatau—1883). Following this absolute dating recalibration, the bottom of the core is dated to 1745. The year of deposition of each volcanic peak allowed us to reduce the uncertainty of the depth-age relationship in the IC-12 core to  $\pm 2$  years. This is the precision usually associated with volcanic horizons, due to the time lapse between eruption and deposition (see sources in Table 1). The characteristics of these peaks are summarized in Table 1. The 1815 Tambora eruption has a clearly identifiable peak (Figure 4), which is expected from its high Volcanic Explosivity Index of 7 (Table 1) and its signal is detected up to two years after its eruption (e.g. Traufetter et al., 2004). Some eruptions, such as the 1762 Planchon Peteroa eruption (assigned as unknown in Sigl et al., 2012) are recorded in both hemispheres (Sigl et al., 2012).

### 3.2 ~~Snow accumulation rate~~ Surface Mass Balance history record

~~Annual layer thicknesses in m w.e. for the oldest estimate: using full Stokes Drews et al. (2015) model (black line) and corrected annual layer thickness blue line, undistinguishable from the black line at this scale; using Drews et al. (2015) model with error bars (thin black line) and 11 years running mean (thick black line) for the oldest estimate; (c) same as (b) (green lines); (d) Comparison of youngest (green) and oldest (black) estimates 11 years running mean.~~ Combining the annual layer thickness data set with the ~~continuous gravimetric IC12 density best fit profile~~ (published in Hubbard et al., 2013), we reconstructed the ~~accumulation rate SMB record history~~ at the summit of ~~Derwael Ice Rise the DIR~~ from 1744~~5~~ to 2011~~2~~. ~~The cumulative thickness in w.e. is 91.8 m (Figure 5).~~ Without correction for layer thinning, the mean annual layer thickness is  $0.36 \pm 0.024 \pm 0.003$  m w.e., ~~the lowest annual accumulation is  $0.14 \pm 0.05$  m w.e. in 1834 and the highest is  $1.05 \pm 0.05$  m w.e. in 1989 (Figure 6).~~

We applied ~~two two~~ corrections: ~~the modified the piece-wise linear model (Dansgaard and Johnsen model, 1969) and the adapted full Stokes model (Drews et al., 2015) the fully linear model (Nye, 1963)~~ (see ~~Section Sect.~~ 4.2) to investigate the influence of ice deformation on annual layer thicknesses, ~~both techniques~~ assuming a constant ~~SMB accumulation rate~~ and a steady state. ~~The piece-wise model approach cannot therefore be applied to the whole data set, since plotting annual layer thickness against depth in m w.e. reveals two trends with different slopes (Figure 5), suggesting an increase in accumulation rates. The transition occurs at ~49 m w.e., corresponding to 1900 A.D. Hypothesizing that, if accumulation rates have increased under the intensification of the hydrological cycle in response to the industrial revolution, we can consider the pre 1900 A.D. slope ( $0.003 \text{ a}^{-1}$ , Figure 5) as representative of the rate of thinning associated with the constant long term 'pre industrial' rate of surface accumulation. We therefore used this strain rate value to correct annual layer thicknesses when applying the Dansgaard Johnsen model.~~

Figure 6a shows the reconstructed history of annual layer thicknesses accumulation rates at IC12 from 1744~~5~~ to 2011~~2~~, ~~with associated error bars~~ without ice deformation (~~grey line~~) and with the two different ice-deformation models (~~modified D-J model, blue line and Drews et al., 2015, black line~~), which overlie each other at this scale. ~~From now on, we will only consider the correction of Drews et al. (2015) as it is both similar to the modified D-J model and more closely guided by field measurements. field real~~ As interannual variability is high, 11 years running means are also shown (thick lines in Figure 6a). As expected, ~~the annual layer thicknesses accumulation rate~~ without ice deformation (~~blue lines in Figure 6a~~) ~~are~~ underestimated in the oldest part of the ice core ~~as relative to that with ice deformation taken compared to the other two reconstructions taking ice deformation into account.~~ ~~Figure 6 (b-d) shows both the oldest and the youngest estimates resulting from absolute dating to~~

evaluate the influence of the dating uncertainty. The mean annual SMB, i.e., the mean corrected annual layer thickness, is  $0.47 \pm 0.02 \text{ m w.e. a}^{-1}$ . As interannual variability is high, the 11 year running means are also shown. The uncorrected curve shows a constant increase in accumulation, with multiple step increases at 1902, 1955 and 1994 A.D. The constant increase in accumulation rates before 1902 attenuates with the correction based on the Nye approach for taking deformation into account (green lines in Figure 6a and 6b) and becomes insignificant with the Dansgaard-Johnsen model (D-J, black lines in Figure 6a and 6b). However, all curves show a clear increasing positive trend in accumulation rates SMB since the early from at least the second half of the 20<sup>th</sup> century.

Table 1 shows average SMB accumulation rates for three different periods (chosen mainly for easier comparison to with previous studies) starting from there are calculated on the basis of deformation corrections (Nye and D-J) and averaged over various periods framed averaged over three different periods between by Tambora eruption and Cerro Azul volcanic horizons and the surface (1816–2011); the last 111 years compared to the full period of time (i.e. 1900–2011 cf. 1816–1900), the last 50 years compared to the previous full period of time (i.e., 1962–2011 cf. 1816–1961), and the last 20 years compared to the previous full period of time (i.e. 1992–2011 cf. 1816–1992); for the youngest and oldest estimates and average between both (Table 1 (e.g. Kaczmarek et al., 2004, Sigl et al. 2012; bold years in Table 1) are shown in Figure 6b and summarized in Table 2). The long term annual accumulation, starting from the oldest volcanic layer identified: From 1768–1816 to 2011, the average accumulation SMB rate is between 0.39 and 0.46  $0.49 \pm 0.02 \text{ m w.e. a}^{-1}$  depending on the correction applied. For the last 111 years, the SMB is  $0.55 \pm 0.02 \text{ m w.e. a}^{-1}$ , representing a  $26 \pm 1 \%$  increase compared to the previous period. For the last 50 years (Table 2). The recent (1955–2011), the accumulation rate SMB is between 0.60–0.61 and  $0.63 \pm 0.01 \text{ m w.e. a}^{-1}$  with, as expected, less impact from the different deformation corrections, representing a. The sharpest increase occurs between the periods 1902–1955 and 1955–1992 (36% to 45% increase). With a 31 years running mean, the rate of accumulation change between 1902 and 1992 is  $0.21 \text{ m w.e. a}^{-1}$  (data not shown).  $32 \pm 4 \%$  increase compared to the previous period. For the last 20 years (1992–2011), the accumulation rate SMB is  $0.64 \pm 0.01 \text{ m w.e. a}^{-1}$  and the increase compared to the previous period is  $32 \pm 3 \%$ .

Table 3 shows the detailed annual accumulation rates for the last 10 years for both corrections. The highest accumulation of the last 10 years occurred in 2009 and 2011, which belong to the 3% and 1% highest



accumulation years of the whole record, respectively. Table 2 shows the detailed annual accumulation rates SMB for the last 10 years for our oldest and youngest estimates. In both the oldest estimates, the highest accumulation SMB during the last 10 years occurred in 2011 and 2009, which belong to the 1 % and 3 % highest accumulation SMB years of the whole record, respectively. In the youngest estimate, 2002 is higher than 2009.

### 3.3 Sources of uncertainties

Surface Mass Balance rates reconstructed from ice cores can be characterized by substantial uncertainty (Rupper et al., 2015). The accuracy of reconstructed snow accumulation rates depends on the dating accuracy, which, in our case, is determined by the oldest and youngest estimates. Also, given our vertical sampling resolution of  $\delta^{18}\text{O}$ , the location of summer peaks is only identifiable to a precision of 0.05 m where no other data are available, but this error only affects inter-annual accumulation rates at an annual resolution, as shown by error-bars in Fig. 6. Note also that it is very unlikely that we have overestimated the number of years due to the  $\delta^{18}\text{O}$  sampling resolution, since a one-to-one correspondence subsists, in the deepest part of the core, between the  $\delta^{18}\text{O}$  and the  $\text{Na}^+/\text{SO}_4^-$  ratio. SMB reconstructions are also influenced by density measurement error (2 % error) and small-scale variability in densification. The influence on SMB is very small. Callens et al. (2016) for example, used a semi-empirical model of firn compaction (Arthern et al., 2010) adjusting its parameters to fit the discrete measurements instead of using the best fit from Hubbard et al. (2013). Using the first model changes our reconstructed SMB values by less than 2 %.

Average SMB on longer time periods are therefore in all cases more robust than reconstructed annual SMB because they are less affected by uncertainties. These average estimates are also useful to reduce the influence of inter-annual variability.

Vertical strain rates also represent a potential source of error. A companion paper will be dedicated to a more precise assessment of this factor using repeated borehole optical televiewer stratigraphy. However, the present study uses a field-validated strain rate models which is as close as possible to reality, and shows that the using the simpler modified Dansgaard-Johnsen model changes the reconstructed SMB accumulation rates by maximum 0.001 m w.e.  $\text{a}^{-1}$ . Therefore, we are confident that refining knowing the exact strain rate profile will not change our main conclusions.

Average accumulation rates on longer time periods are therefore more robust than reconstructed annual accumulation rates because they are less affected by uncertainties. These average estimates are also useful to reduce the influence of inter-annual variability.

Uncertainties are also influenced by density measurement error 2 % and small scale variability in densification. The influence on accumulation rates is very small. Callens et al. (2016) for example, used a semi-empirical model of firn compaction (Arthern et al., 2010) adjusting its parameters to fit the discrete measurements instead of using the best fit from Hubbard et al. (2013). Using the first model changes our reconstructed accumulation values by less than 2 %. Another possible source of possible error is the potential migration of the ice divide. Indeed, radar layers show accumulation SMB asymmetry next to the DIR divide, therefore, had induced non-climatic rates. However, rRh However, two recent analyses Drews et al (2015) found that the ice divide of the DIR must have remained laterally stable for thousands of years to explain the comparatively large Raymond arches in the ice stratigraphy. Callens et al. (2016) find a similar argument by using the radar stratigraphy in the ice-rise flanks. The possibility for an ice-divide migration is therefore small indicate that there is a very low probability that such a migration occurred as the DIR has been stable for at least the last thousands of years (Drews et al., 2015; Callens et al., 2016). Temporal variability of accumulation rates SMB at certain locations can also be due to the presence of surface undulations upstream (e.g. Kaspari et al, 2004), but this effect is minimised at ice divides.

Average accumulation rates on longer time periods are therefore more robust than reconstructed annual accumulation rates because they are less affected by uncertainties. These average estimates are also useful to reduce the influence of inter-annual variability.

### **3.43 Relation to atmospheric and sea ice patterns Comparison with climate models**

Figure 7 compares the trend in our IC12 SMB record with outputs from two atmospheric models: ERA-Interim reanalysis (Dee et al., 2009) and the CESM model. ERA-Interim shows no trend in the Interestingly, in the relatively short overlapping period (1979–2012) it covers, which is not surprising since it is too short to be of climatic significance. The ice core derived SMB correlates rather poorly/moderately to ERA-Interim reanalysis (Dee et al., 2009) and RACMO2 (Lenaerts et al., 2014), yielding —(both correlation coefficient  $R^2 = 0.36$  and  $0.5-0.4$ , respectively—not shown). This much poorer correlation than that compared to ice cores collected on West Antarctica (Medley et al., 2013 (GRL); Morris et al., 2015 (Nat Geo)) is presumably explained by the strong impact of local wind induced snow redistribution and sublimation on the SMB on the wind exposed ridge of the Derwael ice rise (Lenaerts et al., 2014). For a longer overlapping period, we used the output of the CESM model, although it is a freely evolving model that does not allow a direct comparison with

measured data. The average SMB at Derwael in CESM (closest grid point) is too low ( $0.295 \pm 0.061 \text{ m a}^{-1}$ ) because the orographic precipitation effect is not well simulated ~~with the low model resolution~~. Figure 8 shows the relative trends in CESM output and ERA Interim compared to the IC12 record. However, ERA Interim shows no trend in the short period 1979–2015 but the period is too short to explore the mechanisms. Instead, ~~CESM~~ does reproduce (much of) the observed trend. Subtle small-scale variations in wind speed and direction, typically not resolved by reanalyses or regional climate models, might disrupt the inter-annual variability of SMB, although we assume that it does not ~~impaenflucet~~ the positive SMB trend found in the ice core record. Unfortunately, our method does not allow for an explicit partitioning of the SMB explained by precipitation as opposed to wind processes. Instead, we focus on the drivers of precipitation at the ice core site using the output of CESM (Fig. 8), and we discuss it in Sect. 4.1.

In anomalously high ~~accumulation~~ SMB years, sea ice coverage is substantially lower than average (20–40 fewer days with sea-ice cover, fig. 8) in the Southern Ocean northeast of the ice core location, which is the prevalent source region of atmospheric moisture for DIR (Lenaerts et al., 2013). This is associated with considerably higher near-surface temperatures (1–3 K). In low-~~accumulation~~ SMB years (not shown), we see a reverse, but less pronounced signal, with higher sea ice fraction (10–20 days), and slightly lower temperatures at the oceanic source region of precipitation. 9). In anomalously high accumulation years (top panel), , the sea ice coverage is significantly lower than average (20–40 fewer days with sea ice cover) in the Southern Ocean northeast of the ice core location, which is the prevalent source region of the atmospheric flow (Lenaerts et al., 2013). This is associated with significantly higher near surface temperatures (1–3 K). In low accumulation years (not shown), we see a reverse, but less pronounced (not significant) signal, with higher sea ice fraction (10–20 days), and slightly lower temperatures and the oceanic source region of precipitation.

~~Figure 9. Large scale atmospheric, ocean and sea ice anomalies in high accumulation (10% highest) years in the CESM historical time series (1850–2005). The colours show the annual mean near surface temperature anomaly (in °C), and the hatched areas show the anomaly in sea ice coverage (>20 days less sea ice cover than the mean). The green area shows the location of the ice core.~~

Figure 7 shows a summary of the output from the CESM as described in Section 2.5. In anomalously high accumulation years (top panel), the sea ice coverage is very low (20–40 fewer days with sea ice cover) in the Southern Ocean northeast of the ice core location, which is the prevalent source region of the atmospheric flow (Lenaerts et al., 2013). This is associated with higher near surface temperatures (1–3 K), and a strengthening of

the low climatological low pressure system ( $>1$  hPa lower surface pressure), located offshore the ice core location (Lenaerts et al., 2013). In low accumulation years (bottom panel), we see a reverse, albeit less strong, signal, with higher sea ice fraction, lower temperatures and higher core pressure of the low pressure system.

## 4 Discussion

### 4.1 Regional-scale ~~Small-scale~~ variability

Output of the CESM show that, along with atmospheric circulation, sea-ice ~~Sea ice cover and near-surface temperatures at the ice core location also have an influence on precipitation at a regional scale, as shown by the output of the CESM (Fig. 8).~~

~~Figure 9. Large scale atmospheric, ocean and sea ice anomalies in high accumulation (10% highest) years in the CESM historical time series (1850-2005). The colours show the annual mean near surface temperature anomaly (in °C), and the hatched areas show the anomaly in sea ice coverage ( $>20$  days less sea ice cover than the mean). The green area shows the location of the ice core.~~

~~Small scale spatial variability in cyclonic activity and atmospheric rivers could both explain why our results are different from others in the same region, and why they correlate only moderately to the climate reanalyses (ERA-Interim and RACMO2). Orography can also greatly affect spatial variability in SMB snow accumulation variability (Lenaerts et al., 2014). Local wind phenomena are important factors of interannual and spatial variability. Indeed, the low ~~poor~~ correlation with ERA-Interim and RACMO2 in our study, as compared to ice cores collected on West Antarctica (Medley et al., 2013; MorrisThomas et al., 2015) is presumably explained by the strong ~~influence~~ ~~impact~~ of local wind-induced snow redistribution and sublimation on the SMB on the wind-exposed ridge of the ~~Derwael ice rise~~ DIR (Lenaerts et al., 2014).~~

~~However, Callens et al. (2016) showed that this spatial pattern has been constant for the last thousands of years. Therefore, our ~~the~~ observed trend of increasing annual ~~accumulation~~ SMB is highly unlikely to be explained by a different orographic precipitation pattern caused by a change in local wind direction or strength, which would cause a different orographic precipitation pattern.~~

~~This argument, along with the existing correlations with ERA-Interim and RACMO2, suggests that the ~~observed~~ ~~these~~ trends ~~is~~ ~~are~~ not only representative ~~limited~~ of the climate on to the DIR ~~the Roi-Baudouin ice shelf~~~~

but that ~~they are~~ it is also representative of at least the Roi Baudouin ice shelf, surrounding the DIR ~~typical of a wider area~~. More studies are needed in the area to confirm this.

~~Sea ice cover and near surface temperatures at the ice core location also have an influence on precipitation, as shown by the output of the CESM (Fig. 8).~~

~~The output of the CESM (Figure 9.) can be used as a preliminary indicator of the drivers of precipitation at the ice core location. In anomalously high accumulation years, the sea ice coverage is substantially significantly lower than average (20-40 fewer days with sea ice cover) in the Southern Ocean northeast of the ice core location, which is the prevalent source region of the atmospheric flow (Lenaerts et al., 2013). This is associated with significantly considerably higher near surface temperatures (1-3 K). In low accumulation years (not shown), we see a reverse, but less pronounced (not significant) signal, with higher sea ice fraction (10-20 days), and slightly lower temperatures and the oceanic source region of precipitation.~~ **4.21 Spatial and temporal Continental Large-scale variability**

Our results show an increase in ~~accumulation~~SMB on the ~~Derwael Ice Rise~~the DIR in coastal DML from 1955 onward during the 20<sup>th</sup> and 21<sup>st</sup> centuries. This confirms ~~the~~ studies that show a ~~current~~ recent increase in precipitation in coastal East Antarctica on the basis of satellite data and regional climate models (Davis et al., 2005, Lenaerts et al., 2012). Using a new glacial isostatic adjustment model, King et al. (2012) estimated that a  $60 \pm 13 \text{ Gt a}^{-1}$  mass increase ~~for~~of the East Antarctic Ice Sheet during the ~~most recent period~~last 20 years was concentrated along coastal regions, particularly in DML. However, until now, no ~~change~~increase had been detected in ice cores from the area. Our study is the first ~~in situ validation of~~to detect in situ an ~~climate related~~ increase in coastal Antarctica precipitation, which is expected to occur mainly in the peripheral areas at surface elevations below 2250 m (Krinner et al., 2007; Genthon et al., 2009).

However, not all of Antarctica would be expected to have the same ~~accumulation~~SMB trend. Figure 1 and Table A1 summarize results on ~~accumulation~~SMB trends from previous studies based on ice cores, extended with a few studies based on stake networks and radar. The colours of the sites ~~position indicated on Figure~~Fig. 1 ~~refers to show~~ the ~~accumulation~~SMB change at that site. The reference period ~~refers to~~corresponds to the last ~200 years, ~~the recent period and it was compared to two recent periods of different lengths, corresponding approximately to~~ the last ~50 years and ~~to the most recent period to~~the last ~20 years. The exact periods are given in Table A1.

~~Although the~~The ISMASS Committee (2004) pointed out the importance of analysing coastal records, ~~only~~ ~~Twenty-three~~25 of the temporal records found in the literature concern ice cores drilled ~~at less than 100 km from the coast and below 1500 m above sea level, among which, and only~~176 of them are located in DML. ~~However,~~

o Only two of those records cover a period longer than ~~20-100~~ years: S100 (Kaczmarska et al., 2004) and B04 (Schlosser and Oerter, 2002). They both show a small ~~decreasing-negative~~ trend (Figure Fig. 1).

5 ~~For the whole continent, m~~ Most studies (69 % of those comparing the last ~50 years with the last ~200 years) show ~~no~~ lack a significant trend (< 10 % change). ~~When we consider only the studies comparing the last 20 years to the last 200 years, the percentage reporting no significant trend falls from 69 % to 46 %, for all Antarctica, but the trends revealed are both positive and negative.~~ For example, Isaksson et al. (1996) found <-3 % change at ~~the~~ EPICA drilling site (Amundsenisen, DML) between 1865-1965 and 1966–1991. No trend was found on most inland and coastal sites (e.g. B31, S20) in DML, for the second part of the 20<sup>th</sup> century (Isaksson et al., 1999; Oerter et al. 1999, 2000; Hofstede et al., 2004; ~~) or for the recent period (Fernandoy et al., 2010).~~ When we consider only the studies comparing the last 20 years to the last 200 years, the percentage reporting no significant trend falls from 69 % to 46 %. The trends revealed are both positive and negative and concern the whole Antarctic continent.

15 A few studies ~~(9% for the larger period and 18% for the shorter, more recent period)~~ show a decrease of more than 10 % ~~(9 % of the studies observed this decrease during for the last ~50 years and 18 % during for the last ~20 years)~~. This is the case for several inland sites in DML (e.g. Anschutz et al., 2011), but also coastal sites in this region (Kaczmarska et al., 2004: S100; Isaksson ~~&and~~ Melvold, 2002: Site H; Isaksson et al., 1999: S20; Isaksson et al., 1996: Site E; Isaksson et al., 1999: Site M).

20 Twenty-one percent of the studies record an increase of >10 % of ~~accumulation~~ SMB-rates starting during the last ~50 years from the middle of the 20<sup>th</sup> century, and 36 % of the studies show such an increase during the most recent period starting during the last ~20 years. In East Antarctica, ~~increasing-positive~~ trends were only recorded at inland sites, e.g. in DML (Moore et al., 1991; Oerter et al., 2000), at South Pole Station (Mosley ~~&and~~ Thompson, 1999), Dome C (Frezzotti et al., 2005), and around Dome A (Ren et al., 2010; Ding et al., 2011).

25 Other ~~increasing-positive~~ trends were found on the Antarctic Peninsula in coastal West Antarctica (Thomas et al., 2008; Aristarain et al., 2004). For some sites, the increase only started ~~during the last ~20 years ago the most recent period~~ (Site M: Karlof et al., 2005). ~~The only other coastal site in East Antarctica potentially showing an increase in snow accumulation rates is Talos Dome, where Frezzotti et al. (2013) reported a 19% decrease during the period 1966-1996 (compared to 1816-2001), while Stenni et al. (2002) reported an increase by 11% during 1992-1996 (compared to 1816-1996).~~

30 ~~between ,to the ion of, which is R~~

Following Frezzotti et al. (2013), a pattern arises when we compare the sites with low accumulationSMB ( $< 0.3 \text{ m w.e. a}^{-1}$ ) sites with to the sites with higher accumulationSMB and found that most of the high SMB sites show an increase in SMB sites. However, Fig. 9 shows that coastal sites (below 1500 m a.s.l. and less than 100 km from the ice shelf) do not all behave similarly. (not all coastal), setting the threshold at  $0.3 \text{ m w.e. a}^{-1}$ , following Frezzotti et al. (2013) (Figure 8). The 11 sites above  $0.3 \text{ m w.e. a}^{-1}$  show an average increase of accumulationSMB of  $34.33.8\%$  Most of the sites with high accumulation (coastal or not) show an increase in SMB between the last ~50 years and the reference period (last ~200 years), whereas the sites with lower accumulationSMB show no trend, even if they are coastal (FigureFig. 8a9a). This increase is more important (75%) if we compare the figure also shows that only two other coastal sites can be used to compare the last ~200 years with the last 20 years (Fig. 9b). same reference period with the most recent period (last ~20 years) but this only covers two high accumulationSMB sites, including IC12 (Figure 8b). Comparing the most recent period last ~20 years with to the last ~50 years, the 12 high accumulationSMB sites show an average increase of  $9.910.1\%$  (Figure 8c)-increase is less important (Fig. 9c).

#### 4.2 Sources of uncertainties

It is important to keep in mind that the trends, reported in this study (and others) have considerable uncertainties (Rupper et al., 2015). The accuracy of reconstruction of past snow accumulation rates depends on the dating exactness. Volcanic horizons are sometimes difficult to identify in coastal ice cores due to the ECM peaks associated with the presence of marine components. Also, given our vertical sampling resolution, the location of any single summer peak is only identifiable to a precision of 0.1 m. However, annual layer counting is easier than on inland sites, due to higher accumulation rates. Average accumulation rates on longer periods are preferred, since they are less affected by uncertainties than annual accumulation rates. These average estimates are also useful to reduce the influence of inter-annual variability.

Vertical strain rates are also a potential source of error. A companion paper will be dedicated to a more precise assessment of this factor using repeated borehole optical televiewer stratigraphy. However, the present study, by using a range of available strain rate models, shows that knowing the exact strain rates should not affect our main conclusions. Uncertainties are also influenced by the error on density and small scale variability in densification but these are assumed to be very small. For example, Callens et al. (submitted) used a semi-empirical model of firn compaction (Arthern et al., 2010) adjusting its parameters to fit the discrete measurements instead of using the best fit in Hubbard et al. (2013). Using the first model changes accumulation values by less than 2% (data not shown). Another source of possible error is the potential migration of the ice

divide. Indeed, radar layers show accumulation asymmetry next to the Derwael ice Rise divide; if the divide migrated, it could have affected the change in accumulation. However, recent data indicate that there is a very low probability that such a migration occurred (Drews et al., 2015). Temporal variability at certain locations can also be due to the presence of surface undulations up glacier (e.g. Kaspari et al., 2004), but this is not the case for ice divides.

#### 4.33 Causes of spatial and temporal variability

The ~~increasing positive~~ temporal trend in ~~snow accumulation~~SMB measured here and in ice cores from other areas, ~~as well as the apparent and the observed~~ spatial contrast, ~~observed~~ could be the result of ~~variable forcing~~: thermodynamic ~~forcing~~ (temperature change), dynamic ~~forcing~~ (change in atmospheric circulation) or both.

~~Increasing~~ Higher temperature ~~increases~~ induces higher saturation vapor pressure ~~the capacity of the air to hold vapour~~, generally enhancing precipitation. Oerter et al., (2000) ~~demonstrates~~ showed a correlation between temperature and ~~accumulation~~SMB rates in DML. On longer timescales (~~glacial-interglacial~~), using ice cores and models, Frieler et al., (2015) found a correlation between temperature and ~~accumulation rates~~SMB for the whole Antarctic continent. However, ~~both~~ Altnau et al. (2015) ~~and~~ Fudge et al. (2016) found ~~no correlation between that snow accumulation~~SMB and changes in ice  $\delta^{18}\text{O}$  ~~in coastal cores are not always correlated~~. They hypothesized that changes in synoptic circulation (cyclonic activity) have more influence ~~at the coast~~ than thermodynamics, ~~especially at the coast, alone~~.

~~In the presence of a blocking anticyclone at subpolar latitudes, an amplified Rossby wave invokes the advection of~~ The increased frequency of blocking anticyclone and amplifying Rossby waves leads to the advection of moist air ~~from the warmer middle and low latitudes~~ (Schlosser et al., 2010; Frezzotti et al., 2013). ~~On these rare occasions, meridional moisture transport towards the interior in DML is concentrated into “atmospheric rivers”.~~ ~~Two recent manifestations of these short-lived events, in 2009 and 2011, have led to a recent positive mass balance of the East Antarctic ice sheet (Shepherd et al., 2012; Boening et al., 2012). It was also observed in situ, at a local scale, next to the Belgian Princess Elisabeth base (72 °S, 21 °E) (Gorodetskaya et al., 2013; 2014).~~ ~~Several of these~~ Multiple of these precipitation events in a single year can represent up to 50 % of the annual SMB ~~further~~ away from the coast (Schlosser et al., 2010; Lenaerts et al., 2013). At the coast, precipitation is usually event-type, but the events occur during the whole year. However, the 2009 and 2011 events are also observed in our data as two notably higher than average SMB years (2009 and 2011, Table 32). ~~This moisture transport is sometimes concentrated into “atmospheric rivers” of which two recent manifestations, in 2009 and 2011, have led to a positive anomaly in the net mass balance of East Antarctica (Shepherd et al., 2012; Boening~~



et al., 2012) which was also observed in situ, at a local scale, next to the Belgian Princess Elisabeth base (72 °S, 21 °E) (Gorodetskaya et al., 2013; 2014). Such individual precipitation events can represent up to 50% of the annual accumulation (Schlosser et al., 2010; Lenaerts et al., 2013). These two highly variable accumulation events are also observed in our data as two notably higher than average accumulation years (2009 and 2011, Table 3). Our record ~~puts places~~ these extreme events ~~within an~~ historical perspective. ~~Despite the fact that higher SMB years exist in the recent part of record, confirming that they 2009 and 2011 are amongst the 3+ % and to 13 % highest accumulation SMB years of the last two centuries, respectively, despite the fact that higher accumulation years exist in the recent part of record.~~

A change in climate modes could also partly explain recent changes in ~~accumulation SMB~~. The Southern Annular Mode (SAM) has shifted to a more positive phase during the last 50 years (Marshall, 2003). This has led to increasing cyclonic activity, but also increasing wind speed and sublimation. Kaspari et al. (2004) also established a link between periods of increased ~~accumulation SMB~~ and sustained El Niño events (negative Southern Oscillation Index (SOI) anomalies) in 1991–95 and 1940–42. ~~We compared our detrended data set with SOI and SAM time series (KNMI, 2015) and found no correlation with either of those two indexes, yielding respective R<sup>2</sup> value of 0.0016 and 0.0026. In the~~ ~~In our~~ detrended dataset (not shown), mean ~~accumulation SMB~~ is indeed 5% higher during 1991–95 than the long-term average and 17% higher during 1940–42. However, high ~~accumulation SMB~~ is also recorded during 1973–75 (19% higher than average) while that period is characterized by positive SOI values. Therefore, climate modes seem to have little influence ~~(or an influence of unconstrained complexity)~~ on inter-annual variability of ~~accumulation SMB rates~~ at IC12.

~~Highest snowfall and highest trends in predicted snowfall are expected in the escarpment zone of the continent, due to orographic uplift (Genthon et al., 2009). Wind ablation represents one of the largest sources of uncertainty in modelling SMB. This is an important factor generating spatial and interannual variability. Highest snowfall and highest trends in predicted snowfall are expected in the escarpment zone of the continent, due to orographic uplift (Genthon et al., 2009). For example, in the escarpment area of DML, low and medium precipitation amounts can be entirely removed by the wind, while high precipitation events lead to net positive accumulation SMB (Gorodetskaya et al., 2015). An increase in accumulation SMB coupled with an enhanced wind speed could result in increased SMB where the wind speed is low and decreased SMB in the windier areas (90 % of the Antarctic surface, Frezzotti et al., 2004). Frezzotti et al. (2013) suggested that snow accumulation SMB has increased at low altitude sites and on the highest ridges due to more frequent anticyclonic blocking events, but has decreased at intermediate altitudes due to stronger wind ablation in the escarpment areas. In DML, however, Altnau et al. (2015) reported an accumulation SMB increase on the plateau (coupled to~~

an increase in  $\delta^{18}\text{O}$ ) and a decrease on coastal sites, which they associated with a change in circulation patterns. Around Dome A, Ding et al. (2011) also reported an increase in accumulationSMB in the inland area and a recent decrease towards the coast. Their explanation is that air masses may transfer moisture inland more easily due to climate warming. ~~A combination of the wind spatial variability and the local nature of the atmospheric phenomenon potentially involved can explain the spatially contrasting trends observed.~~

Atmospheric circulation exhibits a primary role in determining temporal and spatial SMB variability. Sea-ice and ocean surface conditions play a secondary role, and could contribute to a higher SMB in a warmer climate. A more recent study using a fully coupled climate model (Lenaerts et al., 2016) suggests that DML is the region most susceptible to an increase in snowfall in a present and future warmer climate. The snowfall increase in the coastal regions is particularly attributed to loss of sea ice cover in the Southern Atlantic Ocean, which in turn enhances atmospheric moisture uptake by evaporation. This is further illustrated in Fig. 8, which suggests that extremely high accumulationSMB years are associated with low sea ice cover. The longer exposure of open water leads to higher near-surface temperatures and enhances evaporation and moisture availability for ice sheet precipitation (Lenaerts et al., 2016).

~~Small scale spatial variability in cyclonic activity and atmospheric rivers could explain why our results are different from others in the same region. Orography can greatly affect spatial variability in snow accumulation (Lenaerts et al., 2013). Highest snowfall and highest trends in predicted snowfall are expected in the escarpment zone, due to orographic uplift (Genthon et al., 2009). The main factor generating spatial variability, however, is commonly the wind; wind ablation represents one of the largest sources of uncertainty in modelling SMB. For example, in the escarpment area of DML, low and medium precipitation amounts can be entirely removed by the wind, while high precipitation events lead to net accumulation (Gorodetskaya et al., 2015). An enhanced wind speed coupled with an increase in accumulation could only increase SMB where the wind speed is low, while decreasing SMB in the windier areas (90% of the Antarctic surface (Frezzotti et al., 2004)). Frezzotti et al. (2013) suggested that snow accumulation has increased at low altitude sites and on the highest ridges due to more frequent anticyclone blocking events, but has decreased at intermediate altitudes due to stronger wind ablation in the escarpment areas. In DML however, Altnau et al. (2015) reported an accumulation increase on the plateau (coupled to an increase in  $\delta^{18}\text{O}$ ) and a decrease on coastal sites, which they associated with a change in circulation patterns. Around Dome A, Ding et al. (2011) also reported an increase in accumulation rate in the inland area and a recent decrease towards the coast. Their explanation is that air masses may transfer moisture inland more easily due to climate warming.~~

A more recent study using a fully coupled climate model (Lenaerts et al., in press) suggests that DML is the region most susceptible to an increase in snowfall in a present and future warmer climate. The snowfall increase in the coastal regions is particularly attributed to loss of sea ice cover in the Southern Atlantic Ocean, which in turn enhances atmospheric moisture uptake by evaporation. This is further illustrated in Figure 7, which shows that extremely high accumulation years are associated with low sea ice cover. The longer exposure of open water leads to higher near surface temperatures and enhances evaporation and moisture availability for ice sheet precipitation (Lenaerts et al., in press). Additionally, the low pressure system, located offshore the ice core location (Lenaerts et al., 2013) is strengthened and invigorates meridional heat and moisture transport towards the ice sheet. The opposite is true for extremely low accumulation years.

## 5 Conclusions

A 120 m ice core was drilled on the divide of the DIRerwael ice rise, and dated back to  $1759 \pm 16$  A.D. ~~1745  $\pm$  2 A.D.~~ using  $\delta^{18}\text{O}$ ,  $\delta\text{D}$ , ~~major ions~~~~major ion where necessary~~, and ~~volcanic horizons identified from ECM data.~~ Due to the coastal location of the ice core, the identification of volcanic horizons is hampered by high background acidity. Therefore, we rely on a range of estimates between an oldest and a youngest depth-age scale to ~~18~~of the bottom of the ice core to the oldest estimate. To calculate the mean-average ~~accumulation~~SMB and temporal trends at this site and their uncertainties. The average ~~accumulation~~SMB between 1816–2011 is  $0.47 \pm 0.02$ ~~0.425  $\pm$  0.035~~ m w.e.  $\text{a}^{-1}$  after corrections for densification and dynamic layer thinning. An ~~increasing trend~~  $32 \pm 4$  % increase in ~~SMB~~accumulation rate is ~~reconstruct~~observed from 1955 onwards during the 20<sup>th</sup> and 21<sup>st</sup> centuries, confirming the relative trend calculated by the CESM for this area, ~~as expected from climate models.~~ Wind redistribution may well have a substantial impact on interannual variability of ~~accumulation~~SMB rates at the DIR, but it is unlikely that it has an influence on the temporal trend.

The trends in ~~accumulation~~SMB observed in other records all over Antarctica are spatially highly variable. In coastal East Antarctica, our study is the only to show an increase in ~~accumulation~~SMB during the 20<sup>th</sup> and 21<sup>st</sup> centuries. Many studies point to a difference in the behaviour of coastal and inland sites, due to a combination of thermodynamics and dynamic processes. ~~A combination of spatial variability in snowfall and snow redistribution by the wind explain the observed spatial variations and the poor correlation between our record and the climate reanalyses (ERA-Interim and RACMO2)~~~~A combination of the wind spatial variability and the local nature of the atmospheric phenomenon potentially involved can explain the spatially contrasting trends observed.~~ ~~Spatial variability in wind patterns, cyclonic activity and atmospheric rivers could explain why our results are different~~

5 ~~from others in the same region, and why they correlate only moderately to the climate reanalyses (ERA Interim and RACMO2). Our analysis suggests that atmospheric circulation to a great extent determines SMB variability, with a potential secondary role of changes in sea ice cover. Our results of the analysis based on CESM output suggests that accumulation variability is potentially largely explained by changes in sea ice cover combined with regional atmospheric changes, and atmospheric patterns.~~ More studies are ~~however still clearly~~ clearly needed at other coastal sites in East Antarctica to determine how representative this result is.

10 Long time-series ~~of annual accumulation SMB rates~~ are scarce in coastal East Antarctica. ~~The divide of Derwael Ice Rise is a suitable drilling site for deep drilling. It has a high accumulation rate, and appropriate ice conditions (few thin ice layers) for paleoclimate reconstruction. With a 486 m ice thickness, drilling to the bedrock could reveal at least 2000 years of a reliable climate record with high resolution, a priority target of the International Partnership in Ice Core Science (IPICS, Steig et al., 2005).~~ ~~The divide of Derwael Ice Rise is a suitable drilling site for deep drilling. It has a high SMB accumulation rate, and appropriate ice conditions (few thin ice layers) for paleoclimate reconstruction. According to the full Stokes model (Drews et al., 2015), drilling to 350 m could~~  
15 ~~reveal at least 2000 years of a reliable climate record with high resolution, which would address one of the priority targets ("IPICS-2k array", Steig et al., 2005) of the International Partnership in Ice Core Science (IPICS).~~

## 20 **Data Availability**

~~Age depth~~ ~~Age depth~~ data and uncorrected ~~accumulation SMB~~ ~~rates~~ are available online (doi:10.1594/PANGAEA.857574).

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## Tables

Table 1. Characteristics of the 12 volcanic peaks found in the IC12 core, and used to constrain the depth-age relationship to an uncertainty of  $\pm 2$  year. Bold years were used as reference for average accumulation calculations by period in Figure 6. Ref.: references: 1) Traufetter et al., 2004 and references therein ; 2) Kaczmarzka et al., 2004 ; 3) Nishio et al., 2002 ; 4) Stenni et al., 2002 ; 5) Kohno and Fuji, 2002 ; 6) Zhang et al., 2002 ; 7) Moore et al., 1991 ; 8) Langway et al., 1994. \*identified from ion chromatography.

| Probable source volcano | Year of eruption | Year of deposition             | VEI | Depth (m) | Difference between assigned age and year of deposition | Ref.  |
|-------------------------|------------------|--------------------------------|-----|-----------|--|-------|
| Unknown                 |                  | 2009                           |     | 4.822     |  |       |
| Unknown                 |                  | 1995                           |     | 20.01     |  |       |
| Pinatubo                | 1991             | <b>1992 <math>\pm 1</math></b> | 6   | 23.095    | 0  | 1     |
| El-Chichon              | 1982             | 1982 $\pm 1$                   | 4   | 33.63     | -2   | 1     |
| Unknown                 |                  | 1976                           |     | 36.42     |  |       |
| Unknown                 |                  | 1973                           |     | 38.58     |  |       |
| Unknown                 |                  | 1966                           |     | 44.08     |  |       |
| Agung                   | 1963             | 1964 $\pm 1$                   | 4   | 45.95     | -1   | 1     |
| Unknown                 |                  | 1961                           |     | 47.15     |  |       |
| Carran Los Venados      | 1955             | <b>1955 <math>\pm 1</math></b> | 4   | 50.79     | 0  | 2,3   |
| Unknown                 |                  | 1945                           |     | 56.37     |  |       |
| Unknown                 |                  | 1940                           |     | 59.24     |  |       |
| Unknown                 |                  | 1936                           |     | 61.445    |  |       |
| Cerro Azul              | 1932             | 1932 $\pm 1$                   | 5   | 62.92     | 0  | 1     |
| Unknown                 |                  | 1930                           |     | 63.81     |  |       |
| Unknown                 |                  | 1922                           |     | 67.26     |  |       |
| Unknown                 |                  | 1918                           |     | 69.05     |  |       |
| Unknown                 |                  | 1916                           |     | 69.82     |  |       |
| Unknown                 |                  | 1912                           |     | 71.745    |  |       |
| Unknown                 |                  | 1908                           |     | 73.49     |  |       |
| Santa Maria             | 1902             | <b>1902 <math>\pm 1</math></b> | 5   | 75.03     | 1  | 2,4,5 |
| Unknown                 |                  | 1892                           |     | 78.84     |  |       |
| Krakatau                | 1883             | <b>1884 <math>\pm 1</math></b> | 6   | 82.237*   | 0  | 1     |
| Unknown                 |                  | 1844                           |     | 94.98     |  |       |
| Coseguina               | 1835             | 1835 $\pm 1$                   | 5   | 97.34     | 0  | 1     |
| Galunggung              | 1822             | 1822 $\pm 1$                   | 5   | 101.3     | -1   | 2,5,6 |
| Tambora                 | 1815             | <b>1816 <math>\pm 1</math></b> | 7   | 102.4     | 2  | 1     |
| Unknown                 | 1809 $\pm 2$     | 1809 $\pm 3$                   | ?   | 104       | 2  | 1     |
| Cotopaxi                | 1768             | <b>1768 <math>\pm 1</math></b> | 4   | 115.3     | -1   | 2,7,8 |
| Planchon Peteroa        | 1762             | 1762 $\pm 1$                   | 4   | 116.2     | 1  | 1     |
| Unknown                 |                  | 1759                           |     | 117.4     |  |       |
| Unknown                 |                  | 1750                           |     | 119.2     |  |       |
| Unknown                 |                  | 1747                           |     | 119.9     |  |       |

Table 1. Mean [accumulation SMB-rates](#) at IC12 for different time periods

| <u>Period (years A.D.)</u> | <u>SMB (m w.e. a<sup>-1</sup>) (oldest estimate)</u> | <u>SMB (m w.e. a<sup>-1</sup>) (youngest estimate)</u> | <u>Mean SMB (m w.e. a<sup>-1</sup>)</u> |
|----------------------------|--|--|---|
| <u>1816–2011</u>           | <u>0.476</u>   | <u>0.513</u>   | <u>0.495</u>                            |
| <u>1816–1900</u>           | <u>0.401</u>   | <u>0.441</u>   | <u>0.421</u>                            |
| <u>1900–2011</u>           | <u>0.532</u>   | <u>0.568</u>   | <u>0.550</u>                            |
| <u>1816–1961</u>           | <u>0.432</u>   | <u>0.476</u>   | <u>0.454</u>                            |
| <u>1962–2011</u>           | <u>0.604</u>   | <u>0.623</u>   | <u>0.614</u>                            |
| <u>1816–1991</u>           | <u>0.459</u>   | <u>0.498</u>   | <u>0.479</u>                            |
| <u>1992–2011</u>           | <u>0.626</u>   | <u>0.651</u>   | <u>0.638</u>                            |

**SMBSMBSMB**

Table 2. Accumulation rates SMB of the last 10 years from IC12 ice core (oldest and youngest estimates, see text for details)

| <u>Year (A.D.)</u> | <u>Accumulation SMB (m w.e. a<sup>-1</sup>) (oldest estimate)</u> | <u>Accumulation SMB (m w.e. a<sup>-1</sup>) (youngest estimate)</u> |
|--------------------|---|---|
| <u>2011</u>        | <u>0.980</u>  | <u>0.980</u>  |
| <u>2010</u>        | <u>0.641</u>  | <u>0.641</u>  |
| <u>2009</u>        | <u>0.824</u>  | <u>0.824</u>  |
| <u>2008</u>        | <u>0.651</u>  | <u>0.651</u>  |
| <u>2007</u>        | <u>0.287</u>  | <u>0.699</u>  |
| <u>2006</u>        | <u>0.419</u>  | <u>0.661</u>  |
| <u>2005</u>        | <u>0.661</u>  | <u>0.681</u>  |
| <u>2004</u>        | <u>0.681</u>  | <u>0.666</u>  |
| <u>2003</u>        | <u>0.666</u>  | <u>0.621</u>  |
| <u>2002</u>        | <u>0.621</u>  | <u>0.891</u>  |

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Table 2. Average accumulation rates at IC12 for various time periods framed by volcanic horizons. The first year of each period is included, not the second (ex: 1768–2012: includes 1768, not 2012). Nye: correction for a linear decrease of annual layer thickness with depth. D–J: Corrected using a strain rate of 0.003 a<sup>-1</sup> which is the slope of the annual layer thickness (in m w.e.) vs. depth relationship before 1900.

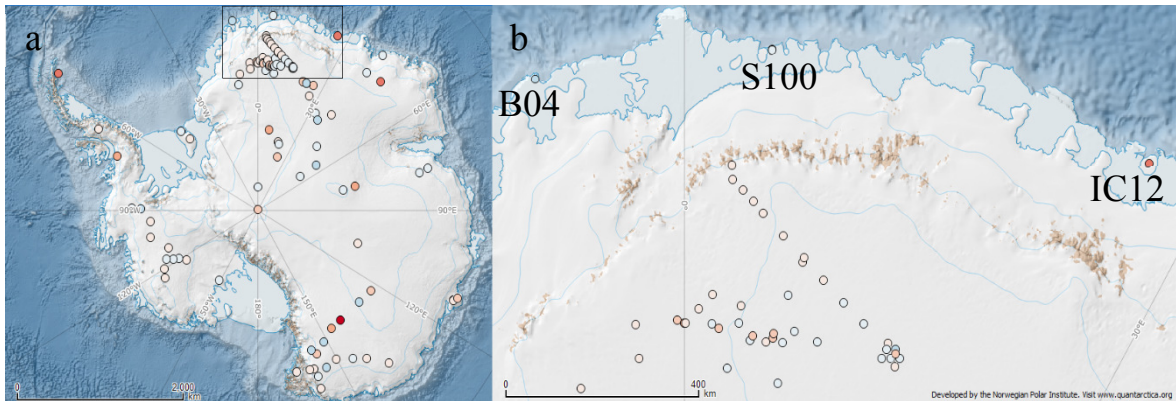
10

Table 3. Accumulation for the last 10 years from IC12 ice core. \*See Table 2 legend and text for explanation \*\*not a full year

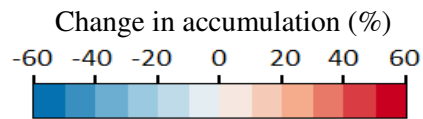
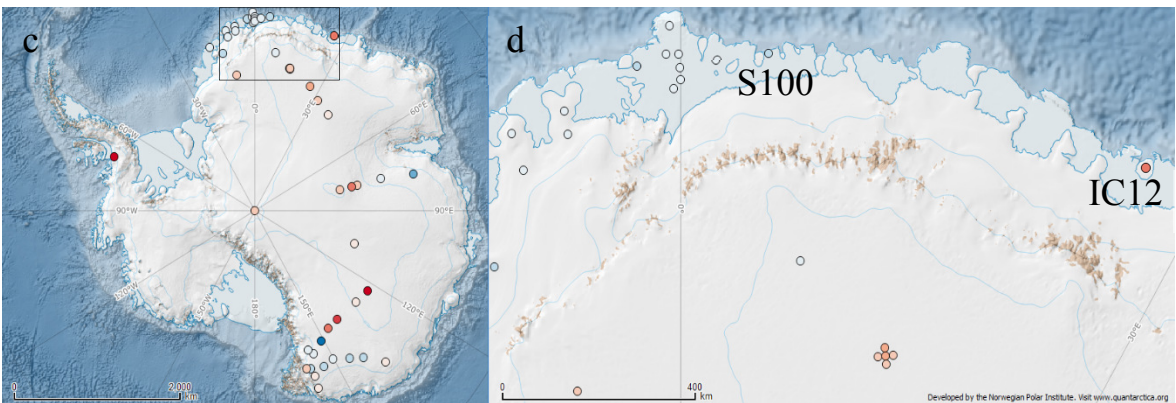
|

**Figure caption**

~1960-present vs ~1816-present



~1990-present vs ~1816-present



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Figure S1. Full vertical profile of water stable isotopes with a grey and black band on the left indicating sections of 10 cm and 5 cm resolution, respectively (a); major ion (b-f), normalized ECM conductivity expressed as multiple of standard deviation (c) (light grey: 1 mm resolution, dark grey: 0.05 m running mean). The 4σ threshold is shown as a dotted vertical line, and identified volcanic peaks as dashed grey horizontal lines (g);

~~annual layer boundaries in the youngest (Green) and the oldest (Blue) estimates. Each colour transition indicates a boundary (b).~~

~~Figure S2. Full vertical profile, as in Fig. S1 but split in 17 sections for more visibility.~~

5

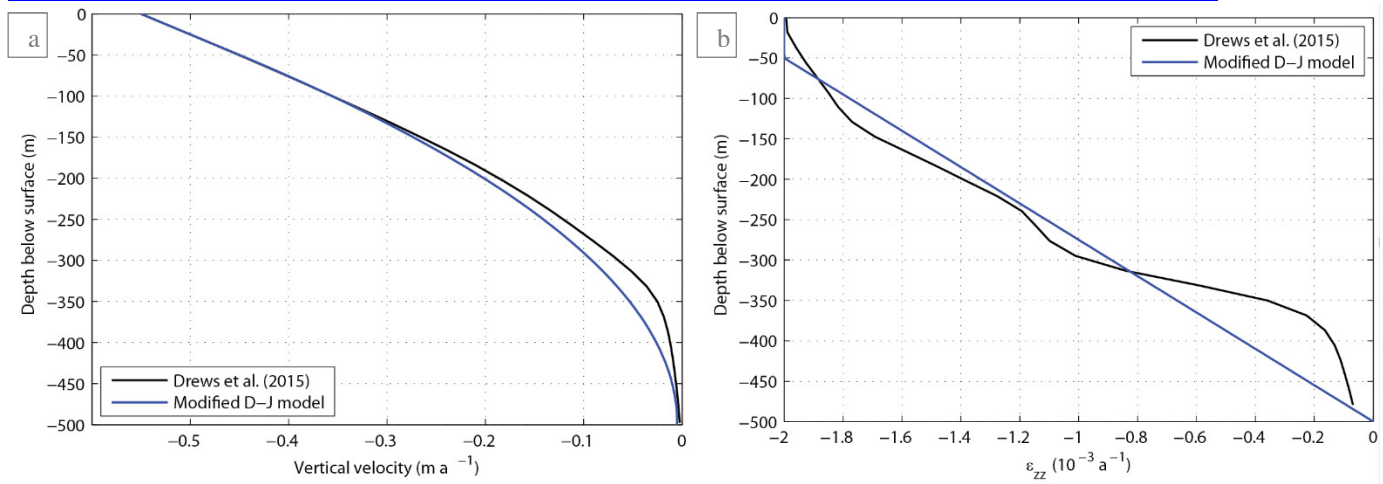
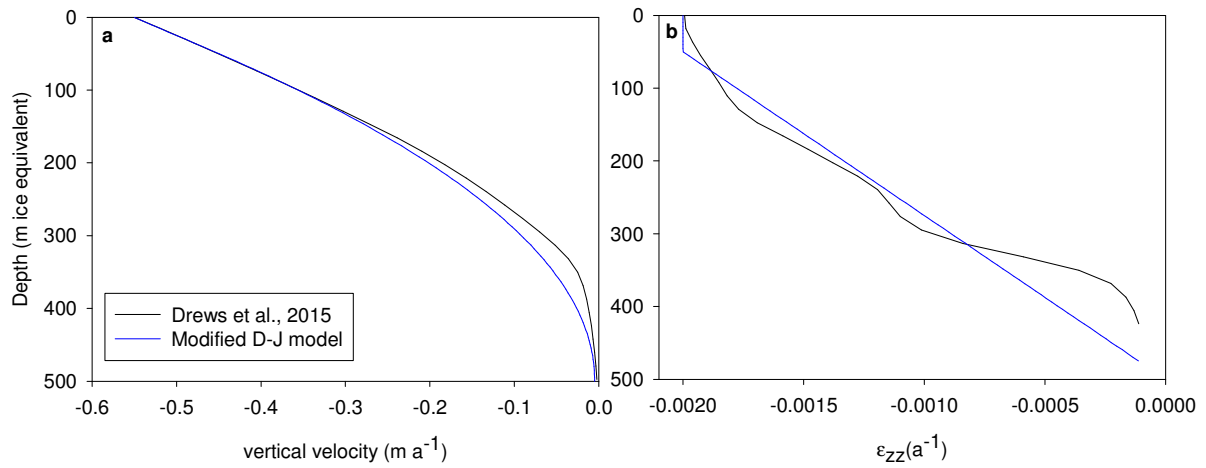
~~Figure 1: Location of IC12 and other ice cores referred to herein. (a-b) Difference in mean annual SMB between the period ~1960–present and the period ~1816–present (see Table A1 for exact periods); (a-b); (c-d) Same as (a-b) for the period ~1990–present compared to ~1816–present. (c-d). Panels (b) and (d) are expansions of the framed areas in panels (a) and (c).~~

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~~Figure 1: Location of IC12 and other ice cores referred to in the discussion. Difference in mean annual SMB for the periods ~1960–present (a b), and ~1990–present (c d), compared to the period ~1816–present (see Table A1 for exact periods). Panels (b) and (d) are zooms of the framed areas in panels (a) and (c).~~

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~~Figure 1: Location of IC12 and other ice cores referred to in the discussion. Change in Accumulation between ~1960–present average compared to ~1816–present average (a b) and ~1990–present compared to 1816–present (c d), see Table A1 for exact periods. Panels (b) and (d) are zoomed of the framed zone in panels (a) and (c).~~



**Fig. 2. (a) Vertical velocity profiles, according to the modified Dansgaard-Johnsen model (blue) and the full Stokes model (black, Drews et al., 2015). (b) Same as (a) for the vertical strain rate profiles.**

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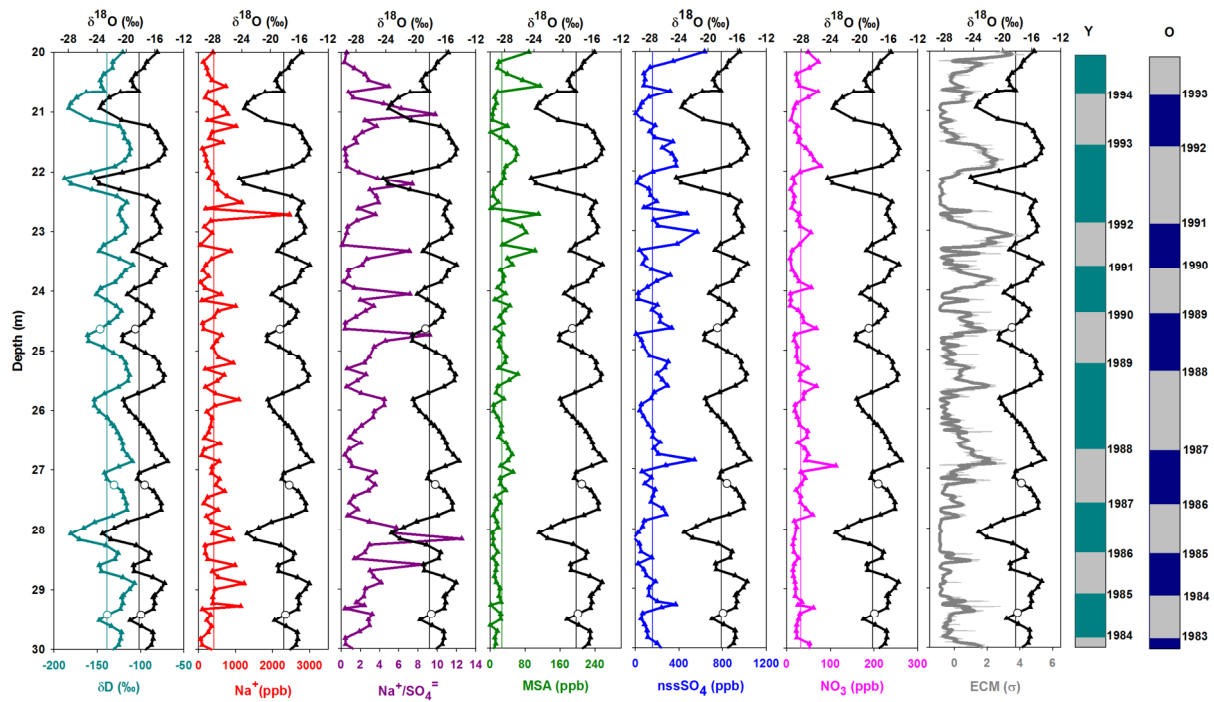


Fig. 3. A 10 m long illustrative example of how variations in stable isotopes ( $\delta^{18}\text{O}$ ,  $\delta\text{D}$ ), chemical species (and/or their ratios) and smoothed ECM (running mean, 0.1 m) are used to identify annual layers. Coloured bars on the right indicate the annual layer boundaries (middle depth of each period corresponding to above average  $\delta^{18}\text{O}$  values) for the youngest (Y) and oldest (O) estimates, with 1 year difference at 20 m depth. See Fig. S1 and S2 for the whole profile. White dots in the  $\delta^{18}\text{O}$  and  $\delta\text{D}$  profiles indicate thin ice layers identified visually in the core.

Figure 2. Variations in stable isotopes ( $\delta^{18}\text{O}$ ,  $\delta\text{D}$ ), smoothed ECM (running mean, 0.1 m), chemical species and their ratios used to constrain annual layer thickness in an example 10 m long section (20–30 m depth) of the IC12 ice core. Dashed horizontal lines indicate the annual layer limit (middle of the summer  $\delta^{18}\text{O}$  peak).

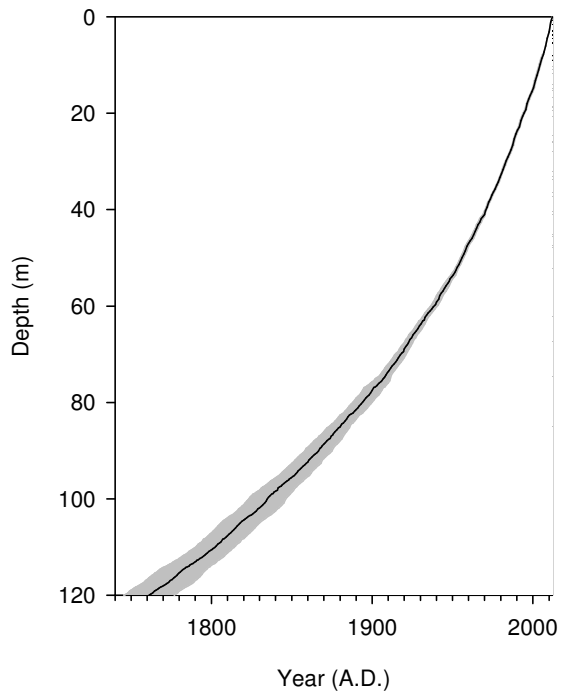


Fig. 4. Age–depth relationship for IC12 reconstructed from the relative dating process. Grey shading shows the uncertainty range between the oldest and the youngest estimates. At the bottom, the uncertainty is  $\pm 16$  years.

Figure 3. Age–depth relationships reconstructed from the relative dating process. Note that the approach results in no uncertainty above 62.38 m depth (year 1933). At 120 m depth, the uncertainty is  $\pm 10$  years.

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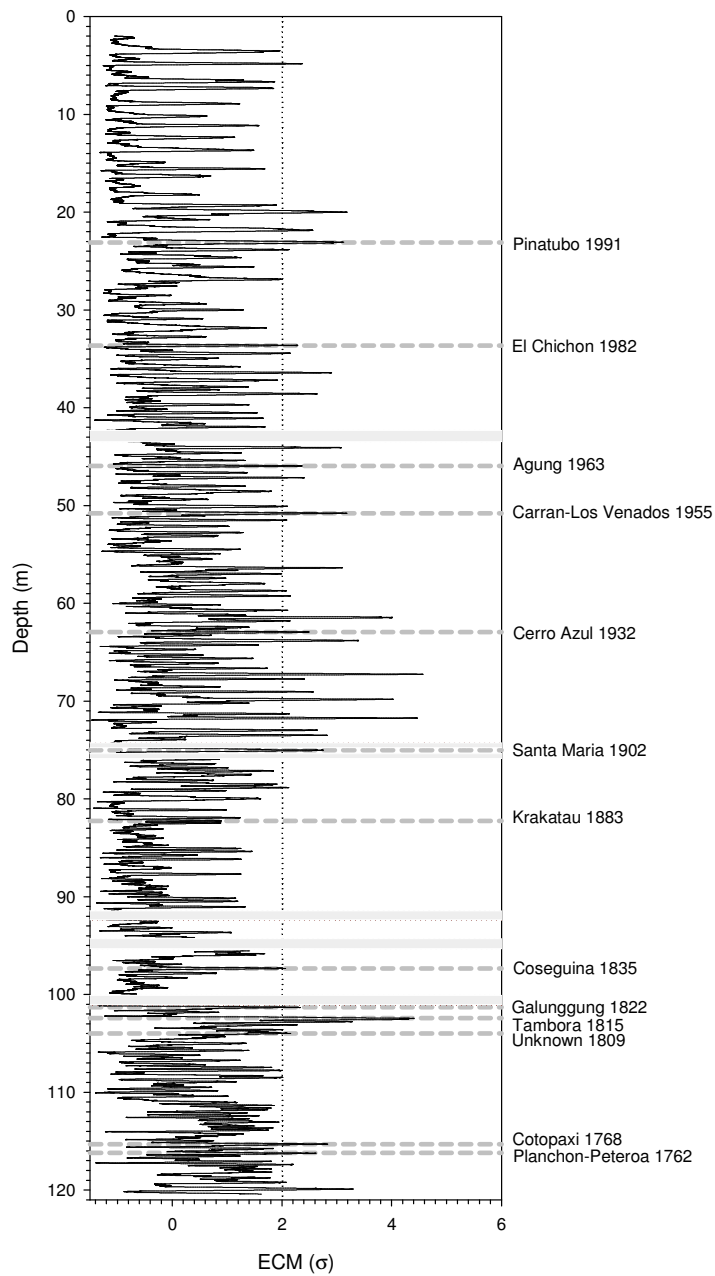
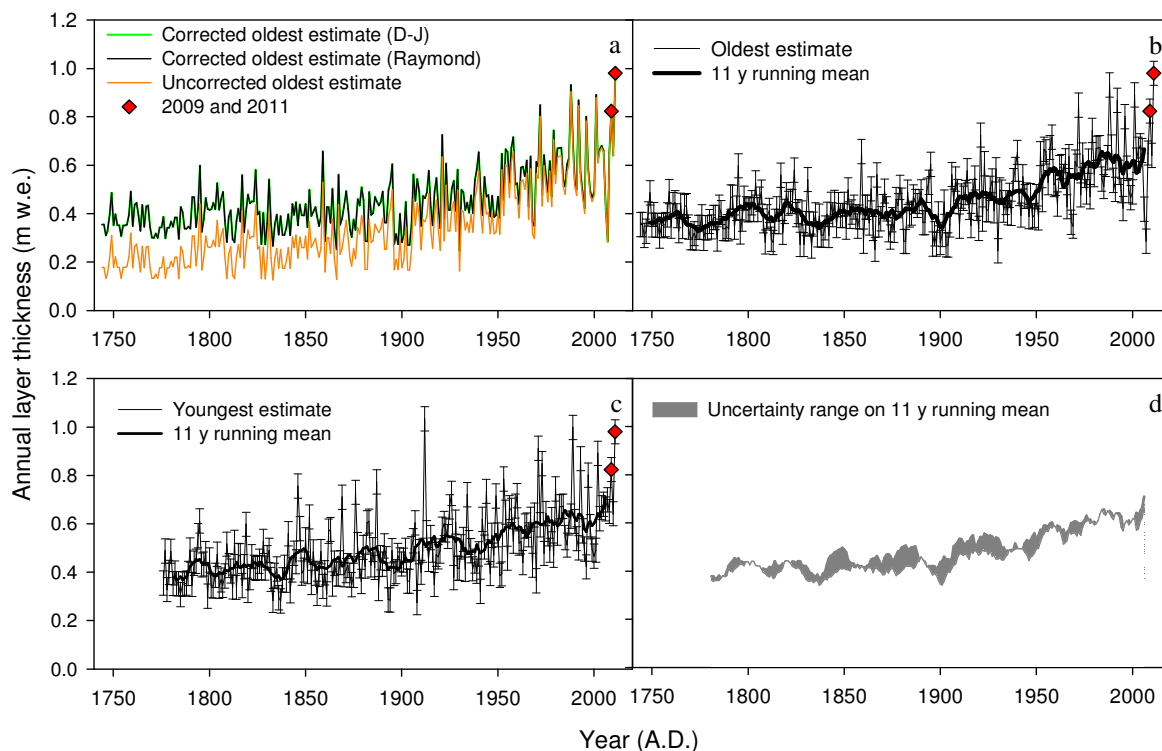


Fig. 5. Continuous record of ECM (except for 6 measurement gaps shown as grey bands). Normalized conductivity (black line) is expressed as multiple of standard deviation ( $\sigma$ ). The  $2\sigma$  threshold is shown as a dotted vertical line, and identified volcanic peaks as dashed grey horizontal lines.

Figure 4. Continuous record of ECM (except for 6 measurement gaps shown as grey bands). Normalized conductivity (black line) is expressed as multiple of standard deviation ( $\sigma$ ). The  $2\sigma$  threshold is shown as a dotted vertical line, and identified volcanic peaks as dashed grey horizontal lines.

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Figure 5. Annual layer thickness plotted against depth. The record is divided into two age/depth ranges, before and after 1900/49 m, for which best fit straight lines are presented. We use the hypothesis that no temporal drift in annual accumulation existed prior to 1900 (see text for details).



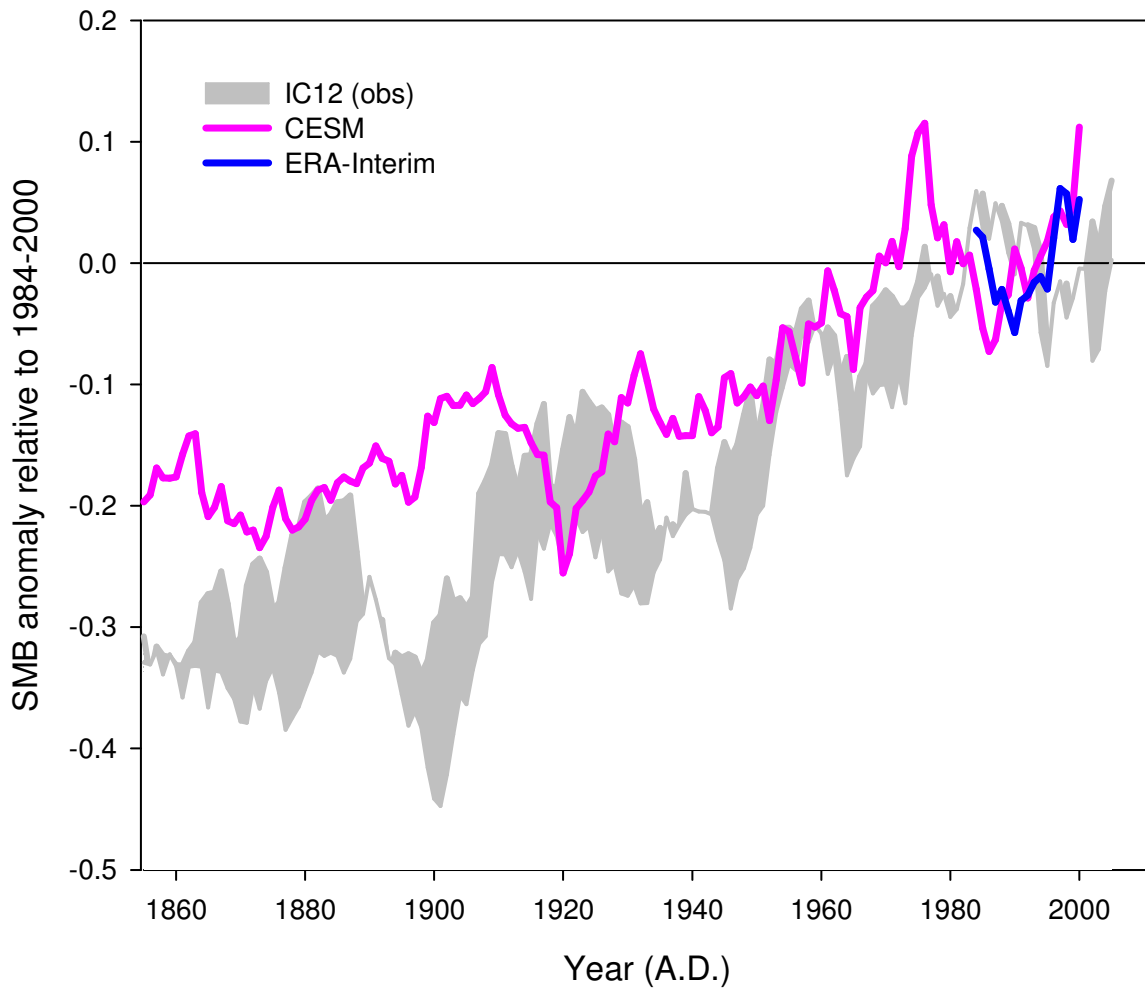
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Fig. 6. Annual layer thicknesses at IC12 in m w.e.: (a) for the oldest estimate: uncorrected annual layer thickness (orange line), corrected annual layer thickness using full stokes Drews et al. (2015) model (black line) and corrected annual layer thickness with the modified Dansgaard–Johnsen model (green line, undistinguishable from the black line at this scale); (b) corrected annual layer thickness using Drews et al. (2015) model with error

bars (thin black line) and 11 year running mean (thick black line) for the oldest estimate; (c) Same as (b) for the youngest estimate (c); (d) Range of uncertainty between youngest and oldest estimates (11 year running mean). Red diamonds highlight years 2009 and 2011, discussed in the text.

5 ~~Figure 6. Accumulation rates at IC12. (a) Annual (thin lines with error bars) and average (11 years running mean, thick lines) accumulation rates. The blue lines show uncorrected annual layer thickness in m.w.e. The red diamonds highlight years 2009 and 2011 discussed in the text (a-b) Corrected annual layer thicknesses are shown by green lines for the Nye approach and black lines for the Dansgaard and Johnsen approach (see text for details). (b) Dotted horizontal lines represent long term accumulation (mean plus standard deviation and mean minus standard deviation) for various time periods bounded by specific volcanic eruption events (indicated by vertical lines and bold years).~~

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5 Fig. 7. Comparison between trends in IC12 record (range between youngest (upper boundary) and oldest estimate (lower boundary), shown as grey band), CESM output (pink line) and ERA-Interim reanalysis (blue line) represented as relative anomaly compared to 1979–1989 (black line), for the overlapping period 1850–2011.

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Figure 7. Large scale atmospheric, ocean and sea ice anomalies in (a) high accumulation (10% highest) and (b) low accumulation (10% lowest) years in the CESM historical time series (1850-2005). The colours show the annual mean near surface temperature anomaly (in °C), the lines show the surface pressure anomaly (in hPa), and the stippled/hatched areas show the anomaly in sea ice coverage (stippled areas are areas with >20 days less sea ice cover than the mean, hatched areas show areas with >20 days more sea ice than the mean). The green star shows the location of the ice core.

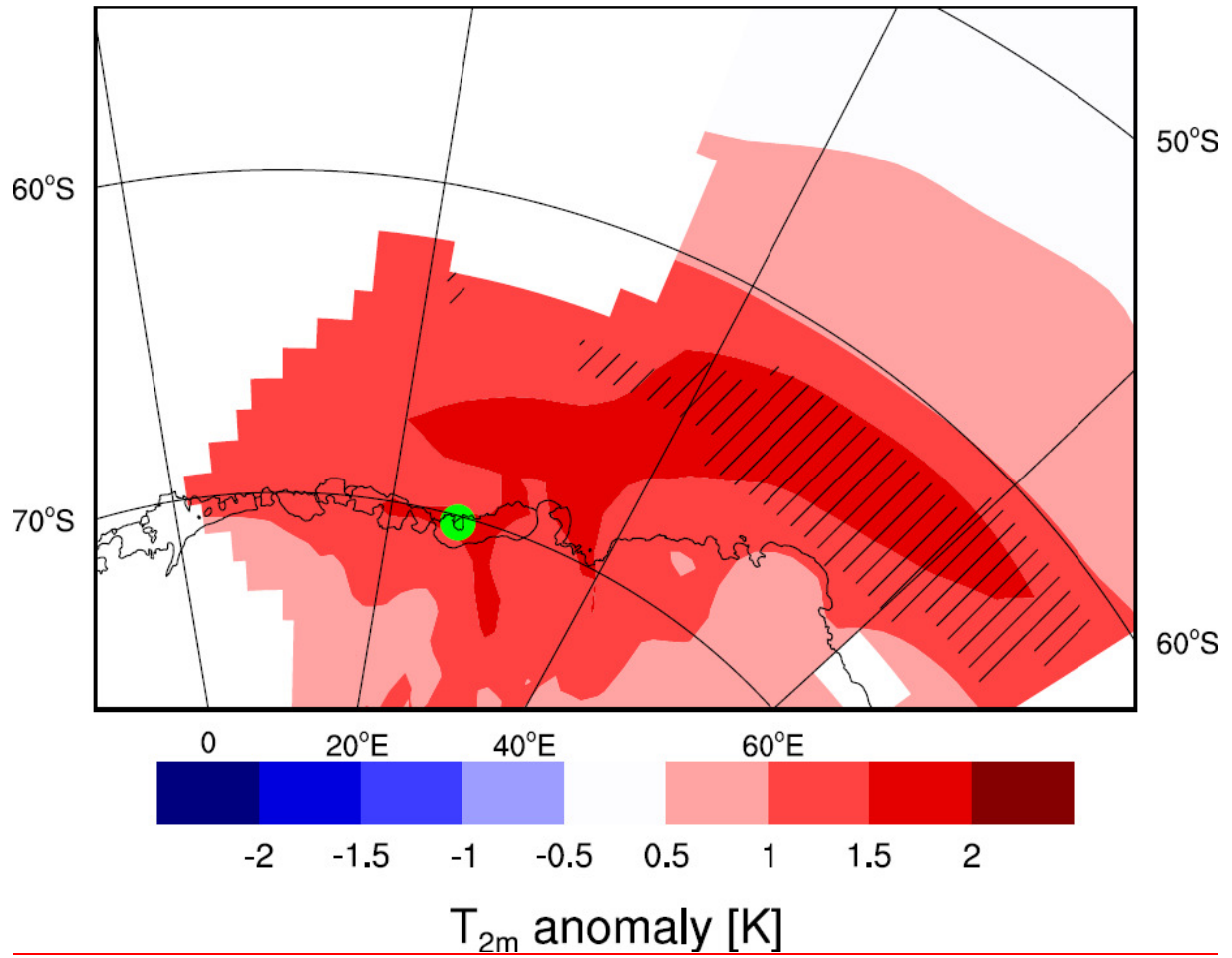


Fig. 8. Large-scale atmospheric, ocean and sea-ice anomalies in high-accumulation SMB (10 % highest) years in the CESM historical time series (1850–2005). The colours show the annual mean near-surface temperature anomaly (in °C), and the hatched areas show the anomaly in sea-ice coverage (>20 days less sea ice cover than the mean). The green dot shows the location of the ice core.

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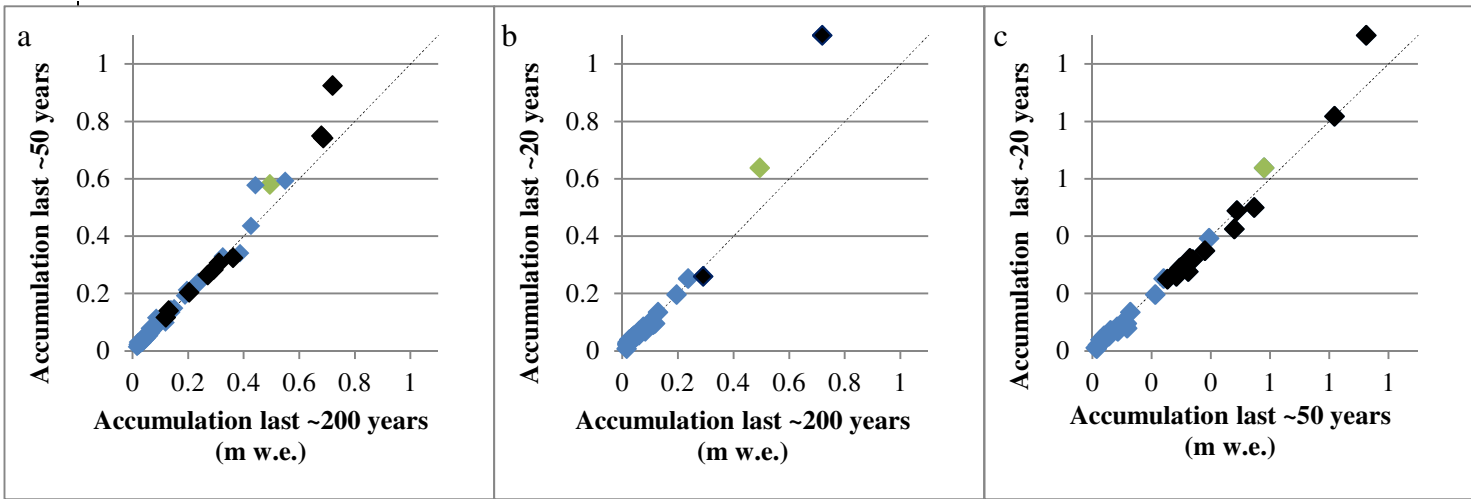
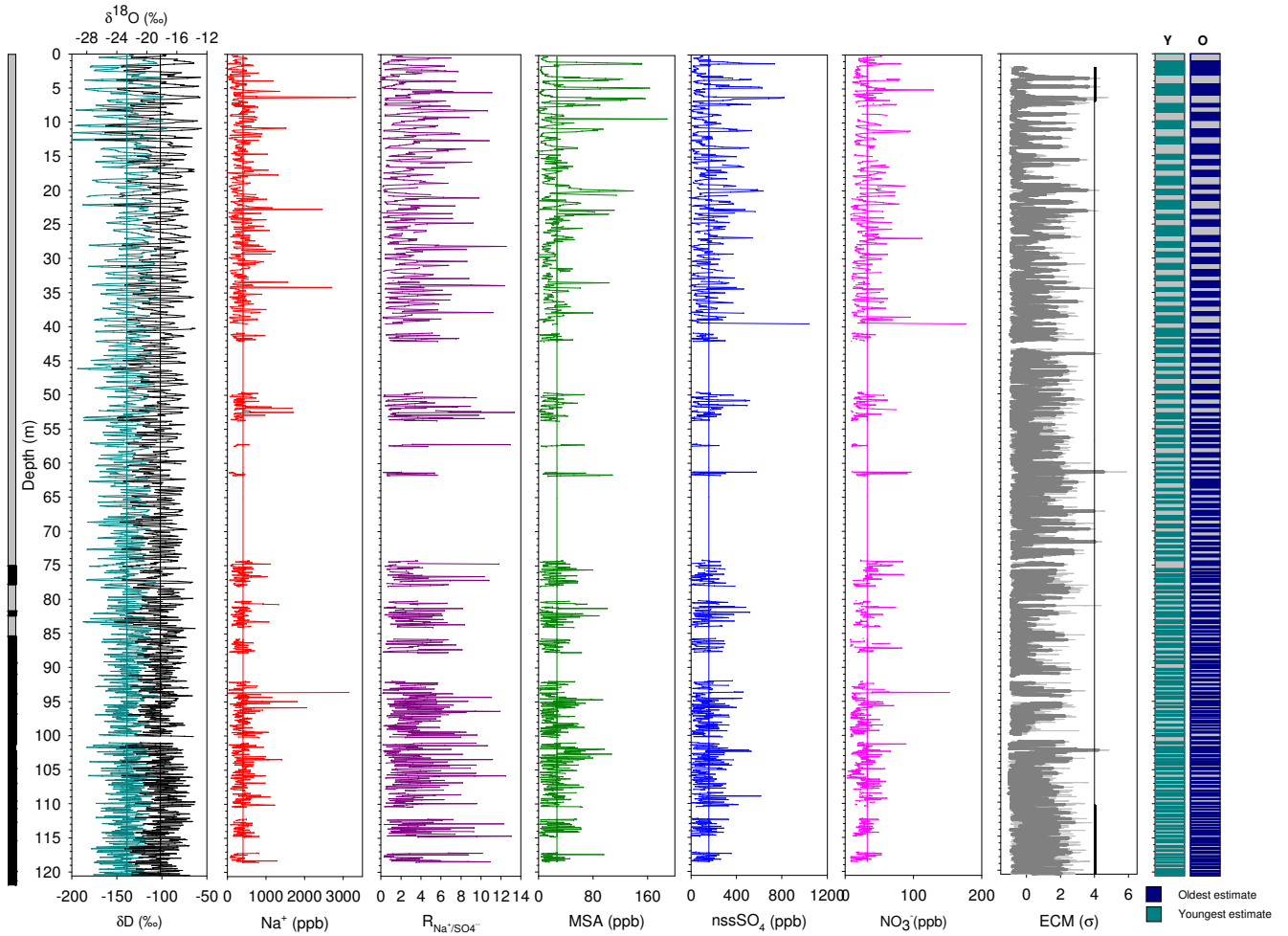


Fig. 9. Comparison of SMB between: (a) the last ~200 years and the last ~50 years; (b) the last ~200 years and the last ~20 years; (c) the last ~50 years and the last ~20 years. See Table A1 for exact periods. Coastal sites (< 1500 m a.s.l. and < 100 km away from the ice shelf) are shown in black, with the exception of our study site, IC12, which is shown in green. Inland sites are shown in blue. The 1:1 slope (0 % change) is shown as a dotted line.

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5 Figure 8. Comparison of SMB during (a) the last ~200 years and the last ~50 years (b) the last ~200 years and the last ~20 years, and (c) the last ~50 years and the last ~20 years. See Table A1 for exact periods. Sites above 0.3 m w.e. a<sup>+</sup> are shown in black, except our study site, IC12 shown in green. Sites below 0.3 m w.e. a<sup>+</sup> are shown in blue. The black lines show a linear regression through high accumulation sites. Increases in % between the periods compared are shown on the graph with R<sup>2</sup> value when relevant. The 1:1 slope (0% change) is shown as a dotted line.



10 Figure S1. Full vertical profile of water stable isotopes with, from left to right: a grey and black band indicating sections of 10 cm and 5 cm resolution, respectively; water stable isotopes, major ions and normalized ECM conductivity expressed as multiple of standard deviation ( $\sigma$ ) (light grey: 1 mm resolution, dark grey: 0.05 m



running mean). The  $4\sigma$  threshold is shown as a dotted vertical line, and identified volcanic peaks as dashed grey horizontal lines; annual layer boundaries in the youngest (Green) and the oldest (Blue) estimates. Each colour transition indicates a boundary.

Figure S1. Full vertical profile of water stable isotopes with a grey and black band on the left indicating sections of 10 cm and 5 cm resolution, respectively (a); major ion (b-f), normalized ECM conductivity expressed as multiple of standard deviation ( $\sigma$ ) (light grey: 1 mm resolution, dark grey: 0.05 m running mean). The  $4\sigma$  threshold is shown as a dotted vertical line, and identified volcanic peaks as dashed grey horizontal lines (g); annual layer boundaries in the youngest (Green) and the oldest (Blue) estimates. Each colour transition indicates a boundary (h).

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