Author's response

We thank two anonymous reviewers and the PAGES data team for their helpful and constructive comments and suggestions. Thank you for the helpful and constructive suggestions. We have addressed all the concerns raised and made all the minor corrections to the revised text. We have done the additional analysis suggested and feel the paper is much improved as a result.

Below we address each comment individually.

In addition to the specific reviewer comments we have also updated the histograms of 50-year and 100-year trends (Fig. 8). In the previous version the full length of the record was used for each region but now we have selected only the time period 1800-2010, where we have greatest coverage. The histograms are now all representing the same time period and highlight some interesting trends and relationships that were missed in the previous interpretation.

Anonymous Referee #1 Received and published: 3 May 2017

Overall comments

The authors compile some 80 Antarctic ice core records that meet their requirements for temporal coverage, time resolution, and corrections for layer thinning. The records are grouped into regions, composited, and then the regional trends and variability over the past 200-1000 years are discussed. Finally, estimate an overall increase in SMB of ~44 GT since 1800 AD, with much of it occurring within the past couple decades. In general, the paper is very well written and logically organized. It is hard to find a major fault with this paper. It is an accomplishment just to compile the records, requiring the cooperation of scientists from many nations and reflecting many years of field work. If anything, the paper is a bit too guarded and tentative at times: "However, this is just a qualitative explanation, more research using model and field data would be needed to prove this." or "The reduced period of overlap...makes this interpretation less C1 reliable." and many other examples. Caveats are of course a natural part of science, but the inclusion of so many in this paper prevents it from being the final word on snow accumulation or even a paper that would get cited a lot (perhaps they are planning a Nature paper that will pack more punch.).

In response to the general comments (and following discussions with others) we have decided to shorten the title. Removing the word "review" from the title will hopefully increase the papers impact as this is an independent study into Antarctica mass balance, not just a review.

Specific comments

Affiliations, page 1: I think some of the affiliations are incorrect, please check. For instance, I believe B. Medley is at #9 (NASA), not #10 (U Victoria).

Updated

Abstract, line 14: increase in SMB across grounded AIS of ~44 GT since 1800: Some context for this number would be helpful. Is that a lot in terms of mitigating SLR? What is the SLR equivalent? Does this number make sense in terms of published global sea level budgets over the past 100-200 years (is it in the noise or a significant number?)?

During the revision process we updated the RACMO data (version 2.3p2) and noticed a minor error in the mask we had selected for certain regions (which included ocean as well as land). The data has all be updated and the new values of total SMB change included.

The total AIS SMB has been presented in a new figure, with a histogram of the running 50-year and 100-year trends.

The increased SMB has been related to SLR equivalents. To add context we relate the net reduction in sea level as a result of the increase in snowfall in Antarctica since 1800 AD to the estimated sea level contribution from the mass loss in the southern Patagonian ice fields.

Page 4, first paragraph: Given the projected increase in SMB, is it expected to offset overall ice sheet mass loss; is Antarctica expected to be a net contributor to SLR given the overall mass budget?

The snowfall is expected to mitigate some of the sea level, but not completely offset the ice loss. In the introduction I am reviewing the current literature but make no claims that snowfall will offset mass loss.

Page 4, line 30: PAGES Antarctica 2K community: Only a select few readers may know what PAGES is, let alone the 2K community. Define?

Defined PAGES and future earth

Page 6, lines 11-14: Was their any requirement for proven dating precision and accuracy? Are we assuming that all of the records are perfectly dated?

A full assessment of all the published age-scales for each ice core was beyond the scope of this study. All data submitted to the Antarctica 2k database was required to submit evidence of independent reference horizons (eg volcanic tie-points) or have evidence in the published literature. For data extracted from other databases, or direct from authors, we checked that independent reference horizons had been used when calculating the age-scale. We cannot be 100% confident that dating errors do not exist, but we have confidence that the published snow accumulation records were dated as accurately as possible.

The published dating errors range from 1-3 years for the period 1800-2010, increasing to ~5 years for some sites prior to ~1500 AD. This has been added to section 2.3.

Page 8, lines 19-20: "predominantly positive phase of the IPO/PDO." There was a major shift in the PDO/IPO in 1998-1990, from positive to negative, affecting more than a third of the 1979-2010 period. This has been shown to impact a number of Antarctic climate trends and it may even be reflected in the recent increase in accumulation in the AP and the decrease in VL. So, I don't think it is accurate to say the the IPO/PDO was predominantly in its positive phase.

I acknowledge that the IPO has changed sign during the instrumental period (1979-2010), so I have made reference to the changing sign of the IPO during this period.

Pages 13-14: “The principal teleconnection associated with the Rossby wave propagation from the western tropical Pacific...which originates from the central, tropical C2 Pacific.” This sentence is repetitive, as well as contradictory (western Pacific vs central Pacific). A rewrite is needed.

Sentence re-written (pages 13-14).

Also, in the discussion of the VL and AP composites (sections 3.24 and 3.26), I can’t help but notice that the teleconnection patterns of these two regions are roughly opposite in sign. See Figure 4d and 4f. I’m surprised this isn’t mentioned somewhere in the paper. 4d resembles the trend pattern associated with the negative PDO, which could have played a role in the recent increase in AP accumulation and decrease in VL precipitation. I also wonder why tropical teleconnections aren’t mentioned with respect to AP accumulation.

The discussion on SAM, ENSO and PDO has been expanded in the section relating to AP.

Reference to the similarities in VL and AP has been expanded in the VL section.

Page 15, line 14: change “unit less” to “unitless.” Page 15, bottom two paragraphs: As mentioned above, it would be interesting to discuss the opposing accumulation trends in terms of the PDO phase and/or the ASL deepening trend.

Word changed

Page 17, line 27: Change “were, quality” to “were quality”

Corrected

Figures 4 and 5: In contrast to figures 2 and 3, no significance levels are indicated on Figures 4 and 5. Could stippling for significance be added to Figures 4 and 5?

Figures 4 & 5 stippling added for 95% significance

Figure 5 caption, page 23: should be “correlations...cover” or “correlation...covers.”

Changed

Interactive comment on “Review of regional Antarctic snow accumulation over the past 1000 years” by Elizabeth R. Thomas et al.

D.s Kaufman darrell.kaufman@nau.edu

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The PAGES Data Stewardship Integrative Activity seeks to advance best practices for sharing data generated and assembled as part of all PAGES-related activities. As part of this activity, a team of reviewers has been constituted for the “Climate of the Past 2000 years” Special Issue. The data team is reviewing the data handling within each of the CP-Discussion papers in relation to the CP data policy and current best practices. The team has identified essential and recommended additions for each paper, with the goal of achieving a high and consistent level of data stewardship across the 2k Special Issue. We recognize that an additional effort will likely be required to meet the high level of data stewardship envisaged, and we appreciate the dedication and contribution of the authors. This includes the use of Data Citations (see example in supplement). We ask authors to respond to our comments as part of the regular C1 open interactive discussion. If you have any questions about PAGES Data Stewardship principles, please contact any of us directly.

Best wishes for the success of your paper, 2k Special Issue Data Review Team (Darrell Kaufman, Nerilie Abram, Belen Martrat, Raphael Neukom, Scott St. George) and ex-officio team members (Marie-France Loutre, Lucien von Gunten)

Essential additions for this paper:

(1) Update the "Data Availability" section to include an explicit URL address to locate the input datasets and the reconstructions generated in this study. For the input datasets, we suggest creating a landing page for this study that lists the 80 individual datasets.

The data used in this study is stored at the UK Polar Data centre. I've updated the data section with the DOI for the composite data produced by this study.

(2) Add Data Citations (in addition to publication citations) for each of the 80 datasets used in this study. For those data not already in a persistent public repository, submit essential metadata (including the name of the Antarctica region to which it was assigned in this study) along with the accumulation time series itself and add the Data Citation/URL in Table 1.

I've added a supplementary table to the paper. This expands upon table 1, to include the data citation for each record used. I have cited the paper it was first published in, made reference to the region of Antarctica, provided the contact of the data provider and the link to the data centre. This information is also stored alongside the composite data stored at the UK Polar Data centre.

3) If any of the cores used in this study were also used in previous PAGES 2k databases (temperature or isotopes), please include cross references to those IDs.

None of the records were used in the previous 2k database as they only include isotopes and temperature proxies.

(4) Submit the primary outcome of this study, the composite accumulation time series by region (Fig 7), to a public repository and include the Data Citation/URL in "

Data Availability". Data submitted to UK PDC and a DOI has been issued.

Recommended elements are:

(5) Archive the gridded spatial correlations of snow accumulation data shown in Figs 2 though 5.

I have not been able to archive the gridded data. The composite records are freely available, as are the ECMWF and RACMO data, ensuring that any other researcher can replicate the spatial plots should they wish. I've included a reference to the ECMWF and RACMO data.

(6) Archive the 50- and 100-year trends for each record as shown in Fig 8.

Again, the original data is available to ensure the trends can be reproduced. I am not sure that uploading a separate document, with just the trends, would be of value. It has taken several weeks to get the DOIs for the UK PDC so I have taken the decision to focus on the essential elements.

In response to the editor's request we have encouraged all data owners to upload their original data sets to a recognised data centre. As this wasn't always possible we have decided to store all original snow accumulation data used in this study at the UK Polar Data Centre, alongside the data citations and the regional composites produced in this study.

Thomas, E. (2017) "Antarctic regional snow accumulation composites over the past 1000 years" Polar Data Centre, Natural Environment Research Council, UK. https://doi.org/10.5285/c4ecfe25-12f2-453b-ad19-49a19e90ee32

Anonymous Referee #2

Received and published: 14 July 2017

Thomas et al. have compiled available high-resolution ice core accumulation records from Antarctica, and review those within the PAGES 2k framework. They divide the cores into 7 regions to provide a regional perspective on ice accumulation and surface mass balance in Antarctica. The surface mass balance of Antarctica is an important topic of study, with implications for the Antarctic contribution to sea-level rise. Overall the study is relevant, interesting, well-written and clear. I propose some minor corrections and additions for readability, procedural clarity and a more thorough analysis.

General comments:

1) My first concern is procedural clarity and treatment of uncertainties.

1a) Combining individual records must be done carefully to avoid jumps in the composite at the locations where the number of cores changes. There is some discussion in section 2.6, but it could be expanded. How did you normalize the records? Did you scale the variance, or just the mean? Did all records include the full 1960-1990 reference period?

I appreciate the concern about combining records and that was why it was important to show the number of records in the plots. The largest number of records occurs between 1800 – 2000, and therefore this period was chosen as a focus, rather than attempting to draw too much from the longer time period.

The text has been clarified to confirm that all records were normalized, based on the mean and standard deviation during the reference period.

Yes, all records cover the reference period.

1b) How are age uncertainties incorporated? Are all chronologies based on annual layer counts? Section 2.3 merely states they need to have annual resolution, so I assume this is the case. The age uncertainties are of course critical when comparing to RACMO and ERA-interim. What is the typical uncertainty in the age scales, and can this influence the conclusions? Also, dating uncertainties will introduce accumulation uncertainties, because accumulation is essentially the derivative of the depth-age relationship. So a 5% age uncertainty results in a 5% accumulation uncertainty.

Yes, there are undoubtedly age uncertainties involved. It is beyond the scope of this study to do independent dating on all the records and therefore we have to assume that since all records have been published and peer-reviewed the records are dated as accurately as possible. As a quality control we ensured that all records were referenced against dating horizons, such as volcanic tie points. I have included a line about dating errors in section 2.3

"Published dating errors range from 1-3 years for the period 1800-2010, increasing to ~5 years for some sites prior to ~1500 AD."

1c) I assume that all RACMO and ERA data are annual means? Were these taken as calendar years? The annual proxies used in the layer count could of course represent another time period (e.g. spring to spring).

Yes, annual means taken as Jan – December. The accumulation data is also assumed to be summer-summer, approximately Jan – December. However, we acknowledge that with ice core annual layer counting the exact timing of a year is not precise.

1d) How was the layer thinning correction done? Was the treatment identical for all records? Section 2.2 reviews several methods (Nye, Dansgaard-Johnsen and Roberts), but it's not stated which one is used. Was this done on a case-by-case basis? This does not matter for the inter-annual variability, but this is critical for investigating the long-term trends. Details are needed for the reader to evaluate how reliable the trends are. Please elaborate on this.

Each record used a different thinning model, depending on which was most appropriate. In order to make it clearer I have added a sentence to section 2.3 to confirm that the published thinning function was used.

1e) What is the typical uncertainty in the thinning correction, and how does it influence the reconstructed centennial-scale trends?

The influence of vertical strain rate increases with depth. Therefore, uncertainties in the accumulation rate associated with assumptions about the vertical distribution of the vertical strain rate also increase with the relative depth compared to the local ice thickness. Most of the ice cores in this study are relatively shallow, and therefore uncertainty in the vertical strain rate is unlikely to be a major source of error. For the deeper ice cores, it is difficult, in general, to quantify the influence of the uncertainty in the vertical strain rate. The authors are aware of only one study that compares the accumulation rate *calculated using difference vertical strain rate models: Roberts et al (2015) found the influence of the vertical strain rate model to be concentrated at lower frequency, and to be small (less than 4% of the accumulation rate).*

The following has been added to section 2.2:

"Uncertainties in the accumulation rate associated with the vertical strain increase with depth. Most of the ice cores in this study are relatively shallow, and therefore uncertainty in the vertical strain rate is expected to be low. Roberts et al (2015) found the influence of the vertical strain rate model to be concentrated at lower frequency, and to be small (less than 4% of the accumulation rate)."

2) My second suggestions focus on the analysis of the records

2a) The authors test how representative the records are by comparing them to RACMO and ERA-interim using spatial correlation plots, which is very qualitative and includes some hand-waving. Since RACMO and ERA-interim are gridded products, it should be trivial to extract the SMB time series directly at the core locations – these model time series could then be composited for the exact same time periods and in the same way as the ice core records were composited. This will allow for easy quantitative analysis. For example, how well are the model and data composites correlated? How well does the model capture variability within each region? Etc. This could complement the figures provided.

In order to expand upon the relationship between modelled SMB and ice core derived snow accumulation we have included a plot of the annual average snow accumulation (1979-2010) at each site, overlain on the SMB from RACMO (Fig 1b). We have also added stars to Fig 1a to highlight ice cores where the correlation between snow accumulation and RACMO SMB is significant at $p > 0.05$.

Following the reviewers suggestion we have extracted the RACMO time series at each ice core location and followed the same method to produce a regional composite. The results were helpful in demonstrating that even if the snow accumulation at each site is 100% certain (for example if we assume RACMO SMB to be the true value), in regions such as East Antarctica the resulting composite would still not represent regional SMB. We simply do not have enough data points (ice cores) to provide the spatial coverage needed.

However, in regions where we have a greater number of sites (or better spaced sites), such as West Antarctica and the Antarctic Peninsula, we have more confidence that the regional composite is representative of regional SMB. This is demonstrated by high correlations between the ice core derived regional composite and the RACMO derived regional composite.

The findings are presented in a supplementary figure (Fig. S1).

2b) How well do individual cores in a region represent the regional composite? It would be very easy to figure out in a principal component analysis. The variance explained by the first component will tell you how much of the signal variance is shared between the records.

We have demonstrated how well individual cores represent the regional snow accumulation, based on the correlations with RACMO.

Snow accumulation is highly variable spatially and individual ice core sites represent not only the regional climate signal but also local variability and "noise". The intention of this study was to combine records in a given region with the intention of reducing the signal to noise ratio. The results demonstrate that in high accumulation sites, such as WAIS, the signal to noise is low and thus the composite is representative of regional precipitation variability. However, for low accumulation sites where noise is high (sastrugi etc), the individual sites are poorly represents local SMB and therefore the composite poorly represents regional SMB.

Regarding PCA, this approach was taken for a previous study of this kind (Frezzotti et al., 2013), but the results were not useful and therefore it was decided not to run this analysis for this paper. I don't feel this analysis would be possible in the time available and based on the expertise from within the group we don't feel it would improve the paper.

2c) In Figs 4 and 5 the authors attempt to link the accumulation records to atmospheric drivers. However, in some regions the simulated accumulation does not match the observed accumulation. Would it be worth repeating these analyses using the modeled accumulation rates for each of the regions? That way you're evaluating something that has consistent internal physics, which would presumably make the correlations stronger and the conceptual picture more clear.

I have repeated the spatial correlations from Fig 4 & 5 using the modelled SMB from RACMO. The plots are presented as supplementary figures. I have added some text in the section relating to WS, to describe the expected relationship with 850 hPa and sea ice and also included a sentence to demonstrate that the pattern between SMB and 850 hPa is similar when using both modelled (RACMO) and ice core derived SMB.

2d) There is much interest in the relationship between temperature and accumulation in Antarctica. Is there a paper planned on this topic within the Antarctic 2k consortium? If not, it would be interesting to include it here. I understand this would go beyond the scope of the present work, and it is of course not a prerequisite for publication.

Comparing the snow accumulation records with temperature (or $\delta^{18}O$) is planned as a future activity for the PAGES team.

Minor comments:

P2L11: “composites capture the regional precipitation and SMB variability”: I don’t understand what this sentence means. Do the composites capture the SMB variability in the models? Or do you see coherence between the records, suggesting a regional signal?

As defined by the models

P2L15-16: Do you mean there are only 4 records that cover the last 1000 years, and all 4 show a decrease? Or are there more 1000 year records, but they don’t show a decrease?

Just four records and they show a decrease. I’ve added “they” to sentence for clarity.

Please clarify P4L2: I couldn’t find Frieler et al in the reference list. I didn’t check all references, but there may be more like this. Please check all references.

References checked and updated

P5L26-27: I don’t get what “equally spaced” means here. The distance between all layers will decrease, whether or not they were equally spaced at the surface.

Removed “that were equally spaced”.

Please rephrase. P8L9: to clarify: the regional, annual mean from the data are correlated with the annual-mean RACMO values at each grid point?

Added

Fig 2 and 3: is there a way to outline the area of interest? I found myself going back and forth between Figs 1 and 2 to figure out what the acronyms meant again. Alternatively, you could just write out the acronyms in full, in which case we’d know what part of the map is relevant. The figure is not incorrect, it would just be a kind thing to do for the readers.

I’ve added an outline to the plots to highlight the region of interest.

P8L27: WS appears reasonably well correlated to RACMO over Berkner Island – which is where the only core is from? This could be quantified by extracting the RACMO SMB at the core location, rather than looking at the entire WS area.

We have used the RACMO regional composite for the spatial correlations (Fig 4 & 5), rather than the Berkner ice core data. This demonstrates the "expected" relationships with atmospheric circulation and sea ice.

P10L6: "high interannual variability": in the data, the model, or both? I suppose sastrugi etc. matter more at low-accumulation sites, as a wind feature of a given size influences more annual layers there?

Both, but the reference in this paragraph is to the data.

P12L1: "positive phase of the SAM and the ASL". What is a positive phase of the ASL? Does this mean the ASL has a negative pressure anomaly? Please just write it out in pressure terms.

Clarified

P12L7: is it possible that the AP snow accumulation anomaly and Bellingshausen sea ice are both just driven by the same SAM trend? Or do you suggest that the Bellingshausen sea-ice anomaly drives the AP accumulation?

I think both are being driven by the same (or similar) atmospheric drivers, eg SAM. However, there is evidence that changing sea ice will influence the availability of surface level moisture and therefore the effect on snow accumulation is amplified.

P15L13 What does this "conversion" entail? Is it basically just a linear scaling, or is there more going on? Why not just compare accumulation, rather than SMB? I guess I don't see the added value of this step.

Updated text description

15L14 unitless (no space)

Corrected

P15L21: Out of the 650 mm/year, the trend of 0.15 mm is just a 0.02% increase. Given the variability and uncertainties (such as in the thinning correction), I would just call this trend zero – i.e. I cannot believe it is statistically robust

I have changed the text to only include the trends that are statistically significant ($p<0.01$).

P15L31: Is the AP increase the only one that is statistically robust? That would be an important conclusion.

The trend in four regions (EAP, WS, DML and AP) is statistically significant at the 99% level. However the AP trend is by far the highest.

P16L34: Can you express how unusual the current AP trend is in terms of nr. of standard deviations? Is the current trend 2sigma above mean, or 4sigma, for example.

In the original version we already concluded that "the early 2000s exceeds two standard deviations above the record average for the entire 200-year period."

P17L14 Is the SMB increase 44 GT w.e. *per year*? Please check units.

The units have now been updated as Gt yr^{-1}.
During the revision process we updated the RACMO data (version 2.3p2) and noticed a minor error in the mask we had selected for certain regions (which included ocean as well as land). The data has all be updated and the new values of total SMB change included.

P17L20: I guess for all four regions with a single 1000-year record it is questionable how well a single core represents the entire region – not just WS.

Yes, which is why we didn't want to draw too much from these sites and expand to the full ~2k available.

P18L10: Your analysis says nothing about how exceptional the current SMB trend is on the long term perspective. Perhaps you could add an Antarctic-wide histogram to Fig. 8?
The total AIS SMB has been presented in a new figure, with a histogram of the running 50-year and 100-year trends. Both the most recent 50-year and 100-year trends are significant and appear unusual in the context of the past 300 years.
The total SMB increase has been related to relative change in sea level and % of annual average SMB to add context and perspective.

~~Review of r~~Regional Antarctic snow accumulation over the past 1000 years

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Abstract. Here we review Antarctic snow accumulation variability, at the regional scale, over the past 1000 years. A total of 80 ice core snow accumulation records were gathered~~, as part of a community led project coordinated by the PAGES Antarctica 2k working group. The ice cores were~~ and assigned to seven geographical regions, separating the high accumulation coastal zones below 2000m elevation from the dry central Antarctic Plateau. The regional composites of annual snow accumulation were evaluated against modelled surface mass balance (SMB) from RACMO2.~~4~~ 3p2 and precipitation from ERA-interim reanalysis. With the exception of the Weddell Sea coast, the low-elevation composites capture the regional precipitation and SMB variability as defined by the models. The central Antarctic sites lack coherency and are either not representing regional precipitation or indicate the models inability to capture relevant precipitation processes in the cold, dry central plateau. ~~The drivers of precipitation are reviewed for each region and the temporal variability and trends evaluated over the past 100, 200 and 1000 years. Our study suggests an overall increase in SMB across the grounded Antarctic ice sheet of ~44 GT since 1800 AD, with the largest (area-weighted) contribution (72%) is from the Antarctic Peninsula (AP)~~Our results show that SMB for the total Antarctic ice sheet (including ice shelves) has increased at a rate of 7 +/- 0.13 Gt dec^{-1} since 1800 AD, representing a net reduction in sea level of ~ 0.02 mm dec^{-1} since 1800 and ~0.04 mm dec^{-1} since 1900 AD. ~~representing a net reduction in sea level of ~ 0.039 mm dec^{-1}.~~ The largest contribution is from the Antarctic Peninsula (~75%) where the annual average SMB during the most recent decade (2001-2010) is 123 +/- 44 Gt yr^{-1} higher than the annual average during the first decade of the 19th century. Only four ice core records cover the full 1000 years and they suggest a decrease in snow accumulation during this period. However, our study emphasizes the importance of low elevation coastal zones~~ (especially AP and DML)~~, which have been underrepresented in previous investigations of temporal snow accumulation.

1. Introduction

The Antarctic Ice Sheet (AIS) is the largest reservoir of fresh water on the planet and has the potential to raise global sea level by about 58.3 m if melted completely (IPCC, 2013). Even small changes in its volume could have significant impacts, not just on global mean sea level, but also on the wider hydrological cycle, atmospheric circulation, sea surface temperature, ocean salinity, and thermohaline circulation. The mass balance of the AIS constitutes the difference between mass gains, mainly by snow accumulation, and mass losses, mainly by ice flow over the grounding line. Ice sheet mass balance is currently estimated in three ways: 1) Ice sheet volume change is calculated using repeated surface elevation measurements from radar/laser altimeters on airborne/spaceborne platforms, followed by a conversion from volume change to mass change using a model for firn density. 2) Ice sheet mass changes can be directly measured using the Gravity Recovery And Climate Experiment (GRACE) satellite system. 3) Surface mass balance (SMB) and solid ice discharge can be individually estimated and subtracted (Rignot et al., 2011). These three techniques have significantly advanced our understanding of contemporary AIS mass balance, with growing evidence of increased mass loss over recent decades (Velicogna and Wahr, 2006; Allison et al., 2009; Chen et al., 2009; Rignot et al., 2011; Shepherd et al., 2012). However, the uncertainties in these assessments may be as high as 75% (Shepherd et al., 2012), and another study even suggested a positive trend over the same period (Zwally et al., 2015).

The discrepancies and uncertainties may in part reflect the large interannual (Wouters et al., 2013) and spatial (Anschuetz et al., 2006) variability in snowfall and hence SMB, but also the difficulty with which SMB is measured and the complexities of the data interpretation. AIS SMB is the net result of multiple processes such as surface mass gains from snowfall and deposition, and losses from snow sublimation and wind erosion. Mass losses from meltwater runoff are small in Antarctica, except for some parts of the Antarctic Peninsula. Multiple in situ SMB observations can be combined to produce an SMB map for selected ice sheet regions (Rotschky et al., 2007) or for the entire AIS (Favier et al., 2013). Alternatively, SMB can be simulated by (regional) atmospheric climate models, such as the Regional Atmospheric Climate Model (RACMO) version 2.3 (Van Wessem et al., 2014) and various reanalysis products (such as ERA-Interim, Dee et al., 2001) or JRA55

(Kobayashi et al., 2015). Estimates of SMB can be improved by combining methods following e.g. the approach of Arthern et al. (2006), interpolating field measurements with remotely sensed data as a background field, or Van de Berg et al. (2006), who fitted output from a regional model to in situ observations. The resulting values of SMB averaged over the grounded AIS range from 143 kg m^{-2} yr^{-1} (Arthern et al., 2006) to 168 kg m^{-2} yr^{-1} (van de Berg et al., 2006). Several studies have evaluated modelled SMB with in situ observations across Antarctica (Thomas and Bracegirdle, 2009; 2015; Agosta et al., 2012; Sinisalo et al., 2013; Medley et al., 2013 and Wang et al., 2015). Finally, the resulting maps of SMB can be combined with estimates of dynamical mass loss to estimate regional or continental ice sheet mass balance.

An increase in Antarctic SMB is expected in a warmer climate, as a result of increased precipitation when atmospheric moisture content increases (Krinner et al., 2007; Agosta et al., 2013; Ligtenberg et al., 2013; Frieler et al., 2015), with climate models on average predicting a 7.4 %/°C precipitation increase per degree of atmospheric warming (Palerme et al., 2017). This potentially results in a mitigation of sea level rise in the future (Krinner et al. 2007; Agosta et al., 2013) ranging from 25 to 85 mm during the 21st century, depending on the climate scenario (Palerme et al., 2017). However, almost all of the models in the Fifth Climate Model Intercomparison Project (CMIP5) overestimate Antarctic precipitation (Palerme et al., 2017).

In order to better constrain predictions of future contributions to global sea level, it is therefore of vital importance to gain a thorough understanding of past and present changes in SMB, and its relationship with the climate system. Whereas the methods discussed above are invaluable in determining contemporary SMB and its spatial variability, only ice core records have the ability to investigate past SMB beyond the instrumental and satellite period. Previous studies have evaluated ice core records to reveal an insignificant change in Antarctic accumulation rates since the 1950s (Monaghan et al., 2006a; 2006b) and Frezzotti et al. (2013) extended this analysis to conclude that the current SMB is not exceptionally high in the context of the past 800 years.

However, in recent years the number of ice core accumulation records have increased, revealing large differences in the spatial pattern of snow accumulation and trends. Ice core records from the Antarctic Peninsula (AP) show dramatic increases in snowfall during the 20th century (Thomas et al., 2008, Goodwin et al., 2015), which appear unusual in the context of the past ~300 years (Thomas et al., 2015). In Dronning Maud Land (DML), similarly large increases in precipitation have been observed in an ice core from a coastal ice rise (Philippe et al., 2016), consistent with remotely sensed estimates of recent mass gain (Shepherd et al., 2012). However, other coastal cores in DML exhibit a decrease in SMB in recent decades (Altnau et al., 2015; Schlosser et al., 2014; Sinisalo et al., 2013), despite evidence of several high-accumulation years since 2009 related to a persistent atmospheric blocking flow pattern (Boening et al., 2012; Lenaerts et al., 2013; Schlosser et al., 2016). In Wilkes Land, the Law Dome ice core record reveals similarly elevated accumulation during the most recent 30 years, but also periods of elevated snowfall ~1600 and ~1200 years ago (Roberts et al., 2015). The growing evidence for large regional differences in snow accumulation trends demonstrates the need for a regionally focused study of snow accumulation beyond the instrumental period.

Here we ~~review~~ compile all the available Antarctic ice core snow accumulation records as part of the PAGES (Past Global Changes) Antarctica 2k ~~community effort~~working group, an initiative of the Future Earth research platform. The aim is to improve regional estimates of SMB variability using well constrained and quality checked snow accumulation records from ice cores. We will assess the regional representativeness of ice core snow accumulation composites, and the spatial pattern of variability, by utilising precipitation data derived from reanalysis products and SMB from the RACMO2.~~4~~ 3p2 regional climate model. We review the dominant atmospheric drivers of regional SMB and evaluate the changes over centennial timescales, and ~~where possible~~ place these changes in the context of the past 1000 years.

2. Data and Methods

2.1. Snow accumulation from ice cores

Ice cores have the potential to record the amount of snow accumulation at a specific location over a range of timescales. Barring post-depositional processes, the recorded snow accumulation is the net result of solid precipitation, sublimation, wind erosion/deposition and meltwater runoff. Integrated over the AIS the contributions made by sublimation/deposition, wind redistribution, rainfall and meltwater runoff are relatively small (van Wessem et al., 2014) and therefore the dominant component of Antarctic SMB is solid precipitation. Locally, however, drifting snow erosion/deposition and sublimation may play an important role, especially in regions of strong katabatic flow (Lenaerts and Van den Broeke, 2012).

2.2. Calculating snow accumulation and correcting for thinning and flow

Estimates of snow accumulation are based on the physical distance between suitable age markers within the ice core, corrected for firn density and the integrated influence of the vertical strain rate profile (so-called "layer thinning"). Depending on the time-scale of interest, age markers may include bulk changes in isotopic composition reflecting glacial cycles, volcanic eruptions for decadal-to-millennial time-scales to seasonal variations in stable water isotopes and chemical species including sea-salts, hydrogen peroxide, radio-isotopes and biological controlled compounds (Dansgaard and Johnsen 1969). Once suitable age markers have been identified, the effects of firn density can be corrected for by convolving the physical depth in the ice core (z') by the density as a function of depth ($\rho(z')$) as a fraction of a reference density (ρ_{ref}), to give an equivalent depth (z),

$$z = \frac{1}{\rho_{ref}} \int_{surface}^{z'} \rho(y)dy$$

Typically the reference density is either the density of glacial ice (resulting in "ice equivalent" measurements) or taken as 1000 kg m^{-3} to give "water equivalent" (w.e) results.

Finally, due to the differential vertical velocity with depth (the vertical strain rate), the distance between layers ~~that were equally spaced~~ at the surface will decrease with depth. If the profile of vertical strain rate with depth is known, and is assumed to be invariant over time, then it can be corrected for. However, typically the vertical stain rate is unknown. In the absence of any other data, the vertical strain rate profile can be approximated as a constant (Nye, 1963), which in general is applicable in the upper portion of the ice sheet. Further refinement to this approximation was suggested by Dansgaard and Johnsen (1969) who proposed a piecewise linear vertical strain rate profile, constant in the upper portion of the ice sheet and below that decreasing linearly to zero at the base of the ice-sheet, or a non-zero value in the presence of basal melt.

Roberts et al., (2015) show that a more realistic vertical strain rate profile, based on the power law distribution of horizontal velocity of Lliboutry (1979), may provide a better estimate of strain rate even in the upper portion of the ice sheet. Additionally, recently deployed ground based phase sensitive ice penetrating radar systems have demonstrated the ability to measure the vertical strain rate profile (Nicholls et al., 2015).

Uncertainties in the accumulation rate associated with the vertical strain increase with depth. Most of the ice cores in this study are relatively shallow, and therefore uncertainty in the vertical strain rate is expected to be low. Roberts et al (2015) found the influence of the vertical strain rate model to be concentrated at lower frequency, and to be small (less than 4% of the accumulation rate).

2.3. Antarctica 2k snow accumulation database

The criteria for th~~e Antarctica 2k database~~is study was that all ice core derived snow accumulation records must be published ~~and~~, peer reviewed~~,~~ and have an annual resolution. ~~and cover at least the reference time period of 1960-1990.~~Each record must cover at least the reference period (1960-1990) and have demonstrated that reference horizons (such as volcanic markers) were used to constrain the dating. Published dating errors range from 1-3 years for the period 1800-2010, increasing to ~5 years for some sites prior to ~1500 AD. ~~All records are corrected for thinning (following a suitable method as described above) and presented in m w.e.~~ The published thinning function was applied to each record (from one of those described above), as this is assumed to be the most suitable for the individual site.

From a total of 144 records submitted to the Antarctica 2k database, 80 records were eligible for this study (Table 1), building upon previous SMB compilation studies by Favier et al., (2013) and Frezzotti et al., (2013). Of the 80 records selected, 41 records extend over the past 200 years, and therefore this period has been selected as a focus for our reconstruction. All spatial correlations, plots and trends presented during this period (with the exception of the Weddell Sea Coast (WS)) are based on multiple records in each region, to avoid introduced errors associated with the switch to single sites. Prior to 1800 the number of records drops dramatically, with only eight records covering the past 500 years, four records covering the past 1000 years and only the Law Dome, RICE and WAIS ice cores covering the full 2000-year period. Therefore it was decided to limit our analysis to the past 1000 years.

2.4. Modelled surface mass balance

In this study we utilize the precipitation fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA) (1979-onwards) (Simmons et al., 2007; Dee et al, 2011). It replaces the previous ERA-40 reanalysis, with improved model physics and observational data supplemented by ECMWF's operational archives, providing a better representation of the hydrological cycle in the high Southern Hemisphere latitudes than earlier reanalyses (Bromwich et al., 2011; Bracegirdle and Marshall, 2012). A recent evaluation of 3265 multiyear averaged in situ observations concluded that ERA-interim exhibits the highest performance of capturing interannual variability on observed Antarctic precipitation out of the available reanalysis products (Wang et al., 2016).

In addition, we use the latest version of RACMO version 2.~~4~~ 3p2 (RACMO2.~~4~~3p2), which succeeds RACMO2.3 (Van Wessem et al., 2014) and combines the hydrostatic dynamics of the High Resolution Limited Area Model (HIRLAM) with the physics package of the ECMWF Integrated Forecast System. RACMO2.~~4~~ 3p2 has been specifically adapted for use over glaciated regions, as it is coupled to a multilayer snow model (Ettema et al., 2010) that calculates processes in the firn, such as grain size growth, firn compaction, meltwater percolation/retention and meltwater runoff. As it also includes a drifting snow routine that calculates sublimation and divergence/convergence of blowing snow (Lenaerts et al 2012), RACMO2.~~4~~ 3p2 explicitly calculates all SMB components over the AIS.

ERA-Interim reanalysis data (Dee et al., 2011) force the model at its lateral boundaries and prescribe sea surface temperature and sea-ice cover for the period 1979-2015. The relaxation zone, where the forcing is applied to RACMO2.~~4~~3p2, is located over the oceans, such that the model is able to evolve freely over the continent. An important update in RACMO2.~~4~~3p2, with respect to RACMO2.3, is the addition of upper-air relaxation at the two top model layers as described in (Van de Berg and Medley, 2016.), which improves the interannual variability of the modelled SMB, which now better matches annually resolved ice core records.

2.5. Defining the regions

One of the goals of this paper is to investigate the regional differences in snow accumulation, reducing the bias introduced in previous continental reconstructions, where regions of high data density overpower the signal in the data sparse, low elevation and coastal zones. Therefore, the Antarctic continent is divided into seven geographical regions (Fig. 1) each with distinct climates. The East Antarctic Plateau (EAP) corresponds to locations in East Antarctica above 2000 m elevation, allowing separation of ice cores with a continental signal from those with a marine signature. The coastal regions of East Antarctica were separated into DML, defined as the areas between 15° W and 70° E, Wilkes Land Coast (WL) (70° E -150° E), and Victoria Land (VL) (150° E -170° E). The Weddell Sea Coast (WS) covers the Ronne-Filchner ice shelf and into Coats Land (60-15° W). Note the difference from the common usage of the geographical names, DML and WL in our definition that refer only to the coastal regions, whereas the higher altitude regions belong to EAP. In this study the AP is treated separately from the West Antarctic Ice sheet (WAIS), with a division at 88° W.

2.6. Methods for composite time series

The ice cores ~~in the Antarctica 2k database~~ were first separated into geographical regions (Fig. 1a) and normalized based on the mean and standard deviation during ~~standardised relative to~~ the reference period 1960-1990. Based on the defined boundaries, the largest density of data is the EAP (accounting for 45 % of the records), nevertheless the spatial distribution of data is often poor. There are inadequate records in high accumulation coastal and slope areas and in the vast polar plateau, where snow accumulation is lower than 70 mm w.e. yr^{-1} and seasonally deposited chemical or physical signals are frequently erased or changed by the action of the near- surface wind (Eisen et al., 2008). To avoid biases introduced because of high data density, especially relevant in areas such as EAP and WAIS, records from the same grid box (chosen with a size of 2° latitude vs 10° longitude) were averaged together. The standardized records were then averaged together to form the standardized regional composites.

3. Results and discussion

3.1. Representative of regional SMB?

Due to small-scale variations in surface slope and roughness, the snow accumulation at an ice core site may vary somewhat from the local spatial mean. The comparison between the annual average snow accumulation at each site and the annual average SMB from RACMO 2.3p2 since 1979 is shown in ~~figure~~Fig. 1b, individual sites where the correlation is significant at $p>0.05$ are highlighted in Fig 1a. Before we investigate the temporal changes in the records we first establish how representative each composite is of regional SMB, by testing annual average snow accumulation against ~~modelled~~ annual average (January to December) SMB from RACMO2.~~4~~ 3p2 (Fig. 2) and precipitation from ERA-interim (Fig. 3) (direct SMB is not available from the reanalysis product). Areas of high correlation (red) indicate that a large fraction of snow accumulation variability in the composite time series is explained by the modelled SMB or precipitation variability during the period 1979-2010. The cut-off of 2010 was chosen as very few records extend beyond this.

Comparison with both RACMO2.~~4~~ 3p2 SMB and ERA-interim precipitation suggests that the composite snow accumulation records from AP, WAIS, WL, DML, and VL (Fig. 2 and 3) are indeed representative of regional accumulation. These records capture ~25-40 % of the variance in their respective regions and may be used to investigate changes in SMB beyond the instrumental period. It is important to note that this comparison covers a relatively short time period (1979-2010) and a period of known climate forcing. In the Pacific sector the calibration period ~~falls within a predominantly positive~~coincides with a shift in the ~~-~~phase of the Interdecadal Pacific Oscillation (IPO), ~~which is~~ known to influence the atmospheric circulation transporting moisture to Law Dome (Vance et al., 2015), from positive at the start of the period (1977-1997) to negative from the late-1990s. The Southern Annular Mode (SAM), the dominant mode of atmospheric variability in the southern hemisphere, is ~~also~~ predominantly in its positive phase during this period, which has been demonstrated to influence precipitation especially in AP (Thomas et al., 2008; Abram et al., 2014) and WAIS (Fogt et al., 2012; Raphael et al., 2016). Therefore, some care must be taken when extrapolating results beyond the instrumental period, when the same climate forcings may be different.

Despite the good agreement in most regions, the opposite is true for the records from EAP and WS. WS represents a single ice core and therefore we have been unable to reduce the signal to noise ratio achieved in the regions with multiple records spread over a large area. The poor relationship between snow accumulation and precipitation at this site may be a result of post depositional changes at the coastal dome or reflect the models inability to capture precipitation and SMB variability at this site. In addition, there is a relatively small period of overlap with the modelled and reanalysis datasets (1979-1992).

The EAP has many records that cover the full calibration period (1979-2010), but they are restricted in the area of DML plateau around Kohnen station, South Pole and Talos Dome, while the inner part is represented only by the Vostok site. As such, the EAP composite is poorly related to SMB (Fig. 2a and 3a), but reducing the EAP area and producing smaller "sub-regions" is no improvement. One possible ~~explination~~explanation is that the models do not take into account precipitation processes such as diamond dust, likely having a relatively large influence on precipitation variability in these extremely cold areas (van de Berg et al., 2005; Mahesh at al., 2001). Additionally, large glaze/dune fields cover a large percentage (more than 500,000 km^2) of the EAP (Fahnestock et al., 2000) and these have been shown to significantly confound accumulation measurements in ice cores (Dixon et al., 2013). A combination of large topographical gradients and strong katabatic winds provides challenges for models in the grounding line area and this is where the largest differences appear between field data and the modeled SMB (e.g. Sinisalo et al., 2014). Large areas along the margins of the EAP are characterized by steep slopes and are thus often suffering from challenges in describing the physical processes related to SMB in the lower resolution model domains.

Modelled regional composites were produced by extracting annual RACMO 2.3p2 SMB at each ice core site. The data was standardized and averaged following the same method as the ice core records (however, the reference period is 1979-2010, compared to 1969-1990 for the ice cores) and the resulting spatial correlations for each region presented in Fig S1. The results demonstrate that even if the ice core records were accurately capturing SMB at each site (i.e. not subject to post depositional changes), the resulting regional composite would still not represent regional changes because the spatial coverage is not good enough. For completeness we are including EAP and WS composites in this study, however, caution should be used when interpreting the climatological drivers and temporal changes in these regions.

The standardized regional composites have been averaged together to form a West Antarctic ("WEST" combines AP, WAIS and VL), East Antarctic ("EAST" combines WS, DML, WL and EAP) and continental ("ALL" combines all records) composite, adopting a similar approach to previous SMB studies focusing on continental reconstructions (eg Monaghan et al., 2006a; Frezzotti et al., 2013). Evaluation with RACMO2.~~4~~ 3p2 (Fig. 2) and ERA-interim (Fig. 3), confirm that continental style reconstructions reduce the representativeness of SMB, and are susceptible to bias from high sampled and high accumulation areas. Such that WEST resembles AP, EAST resembles WL and ALL is a combination of these two regions, but with the area of significance across the whole continent significantly reduced. For this reason, our study will focus on regional SMB and not attempt to produce a continental reconstruction.

Spatial correlation plots with SMB from RACMO2.~~4~~ 3p2 (Fig. 2) and precipitation from ERA-interim (Fig. 3) highlight some interesting relationships. Significant positive correlations with precipitation in AP are mirrored by negative correlations in WAIS, especially the region around Marie Byrd Land (Fig. 2d and 3d). The relationship is reversed for the WAIS composite, which reveals positive correlations with precipitation in continental WAIS but negative correlations in the northern AP (Fig. 2e and 3e). This pattern likely reflects the influence of the Amundsen Sea Low (ASL) and its association with the Antarctic Dipole and El Niño-Southern Oscillation (ENSO) ~~ENSO~~ (Yuan & Martinson, 2001). This persistent area of low pressure, the result of the frequency and intensity of individual cyclones (Baines and Fraedrich, 1989; Turner et al., 2013), is known to affect the climatic conditions on the AP and WAIS (Hoskings et al., 2013; Thomas et al., 2015; Raphael et al., 2016).

In East Antarctica, positive correlations exist between WL and DML due to similar synoptic regimes and the influence of changes in the general atmospheric circulation, such as the Southern Annular Mode (SAM, e.g. Marshall, 2003) or zonal wave number 3 (ZW3) index (Raphael, 2007). We explore the drivers of regional SMB further, using the available meteorological data from ERA-interim together with satellite observations of sea ice conditions.

3.2. Drivers of regional precipitation

3.2.1. East Antarctic Plateau (EAP)

Accumulation in EAP is generally extremely low (<50mm/a on the high plateau) and exhibits high interannual variability. The temporally prevailing type of precipitation is diamond dust, consisting of very fine needles or platelets formed when air in an almost saturated atmosphere is further cooled radiatively or mixed with colder air of the inversion layer (Fujita and Abe, 2006; Stenni et al., 2016; Walden et al., 2003). Much less frequently, synoptically caused snowfall occurs, which typically has daily amounts an order of magnitude higher than diamond dust precipitation. Thus a few snowfall events per year can yield up to 50% of the annual accumulation. The occurrence of such event-type precipitation is closely related to amplification of Rossby waves, sometimes with corresponding blocking anticyclones (e.g. Massom et al., 2004), and is thus more frequent in the negative state of the SAM or positive ZW3 index (Raphael, 2003; Schlosser et al., 2016), when meridional exchange of heat and moisture is increased. This agrees well with the pattern in Fig. 4a, which shows three distinct maxima in the correlation of SMB and the 850 hPa geopotential height above the Southern Ocean between ca. 60°S and 45°S, south of South Africa, Australia and west of South America, respectively. A similar pattern is observed when comparing the SMB from RACMO2.3p2 with 850 hPa geopotential height (Fig. S2), adding confidence that the ice core composite and the modelled SMB are influenced by similar atmospheric drivers. This spatial pattern is most likely due to the above mentioned positive ZW3 index related to distinct troughs and ridges in the westerlies, which cause advection of relatively warm and moist air to the interior of the continent (Noone et al., 1999; Schlosser et al., 2008; 2010a; 2010b; Massom et al., 2004). There is no straightforward correlation with sea ice extent (Fig. 5a).

Ice and firn cores from EAP do not exhibit a uniform temporal trend. At Kohnen station (EPICA DML drilling site), which is situated at 2892m elevation at the slope, an increase in SMB was found in the past two centuries (Oerter et al., 2000; Altnau et al., 2015), which is parallel to an increase in temperature (derived from stable isotopes), thus most likely caused thermodynamically (Altnau et al., 2015). Anschuetz et al. (2009; 2011) found no clear overall trend in SMB based on data from a traverse from coastal DML to South Pole, with an increase at some sites, and a decrease at others. However, above 3200m, all sites exhibited a decrease in SMB since 1963. Fujita et al. (2011) report that SMB data from a traverse between Dome Fuji and EPICA DML is strongly influenced by topography and is found to be approximately 15% higher in the second half of the 20th century than averages over centennial or millennial averages. No significant trend was found in accumulation rates in up to 100yr old cores before 1996 on Amundsenisen in DML (Oerter et al., 1999). The Dome C area (Frezzotti et al., 2005; Urbini et al., 2008) has exhibited high accumulations since the 1960s, as observed along the traverse between Dome Fuji and EPICA DML, whereas no significant changes have been apparent at Dome A since 1260 (Ding et al., 2011a; Hou et al., 2009). In Talos Dome area, at the border between EAP and VL, century-scale variability shows a slight increase (of a few percent) in accumulation rates over the last 200 years, in particular, since the 1960s, as compared with the period 1816 – 1965 (Frezzotti et al., 2007).

3.2.2. Wilkes Land Coast (WL)

The snow accumulation regime of Law Dome is determined by the intensity of onshore transport of maritime air masses by cyclonic activity (Bromwich 1988). While the magnitude of snow accumulation varies along the Wilkes Land Coast, the accumulation is temporally coherent at least as far away as the Shackleton Ice Shelf (Roberts et al, 2015). In general, this region shows accumulation variability associated with both~~ the El Niño-Southern Oscillation (~~ENSO~~)~~ and IPO (Roberts et al., 2015, Vance et al, 2015) which influence the meridional component of the large scale circulation (van Ommen and Morgan, 2010; Roberts et al 2015, Vance et al., 2015).

Law Dome sea ice proxies (Curran et al., 2003; Vallelonga et al., 2017) are correlated with observations of sea ice extent. The weak negative correlation between WL accumulation and sea ice concentration (Fig. 5b) may be indicative of a common forcing from cyclonic systems depositing snow over Law Dome while also contributing to local sea ice break-up and/or dispersion.

3.2.3. Weddell Sea Coast (WS)

The WS sector appears to exhibit a positive relationship with sea level pressure (SLP) in the South Pacific, and over the Antarctic continent, while a negative relationship exists over the south Indian Ocean (Fig. 4c). However, this is based on just one ice core which is poorly related to modelled SMB or precipitation. Figure 5c suggests snow accumulation is associated with sea ice concentration in the Weddell Sea, possibly resulting in enhanced moisture availability or reflecting an anticyclone that could draw more northerly air masses to the site. Unfortunately the reduced period of overlap for this site (1980-1992) makes the interpretation less reliable.

In order to establish the expected atmospheric drivers and relationship with sea ice, we repeat the spatial correlation plots in Fig 4 and Fig 5 using RACMO 2.3p2 SMB. The relationship with 850 hPa geopotential height is reversed when using the modelled SMB, with negative correlations over the Antarctic continent, especially over the Bellingshausen Sea (Fig. S2c), reminiscent of the pattern for AP (Fig 4d and Fig S1d). The strong correlations with sea ice concentration also disappear when using the modelled SMB, suggesting a positive correlation with sea ice in the Bellingshausen and north western Weddell Sea (Fig S3c).

3.2.4. Antarctic Peninsula (AP)

SMB on the AP exhibits a large west-to-east gradient, exceeding 3000mm w.e. yr^{-1} on the western coast and less than 500 mm w.e. yr^{-1} on the eastern coast [Van Wessem et al., 2016], largely controlled by orography. The AP has been underrepresented in previous SMB studies. However, recent drilling efforts have greatly increased the spatial coverage, but the high annual snowfall still limits the temporal coverage in this region. SMB in AP is dominated by the pattern of SLP in the Amundsen Sea (Fig. 4d), a region of high synoptic activity and the largest contributor of the total Antarctic meridional moisture flux (Tsukernik and Lynch, 2013), with the highest interannual and seasonal variability. High snow accumulation is associated with reduced regional SLP, leading to strengthened circumpolar westerlies and enhanced northerly flow. The mechanism of lower SLP in the Amundsen Sea sector creates a dipole pattern of enhanced precipitation in Ellsworth Land and reduced precipitation over western West Antarctica (Thomas et al., 2015), reflecting the clockwise rotation of air masses and moisture advection paths, explaining the dipole of correlations observed in Fig. 2 and 3.

~~Ice cores in this region~~AP ice cores reveal a significant increase in snowfall during the 20^{th} century (Thomas et al., 2008; 2015, Goodwin et al., 2015), that has been linked to the positive phase of the ~~SAM~~ SAM, marked by high pressure anomalies in the mid-latitudes and stronger circumpolar westerly winds since the 1970s.~~and the ASL~~. ~~High snow accumulation is associated with reduced regional SLP, leading to strengthened circumpolar westerlies and enhanced northerly flow.~~ ~~The mechanism of lower SLP in the Amundsen Sea sector creates a dipole pattern of enhanced precipitation in Ellsworth Land and reduced precipitation over western West Antarctica (Thomas et al., 2015), reflecting the clockwise rotation of air masses and moisture advection paths, explaining the dipole of correlations observed in Fig. 2 and 3.~~ ENSO also plays a role, through the modulation of the South Pacific Convergence Zone (IPCZ), however the relationship between snow accumulation and both SAM and ENSO is not temporally stable (Thomas et al., 2008; 2015, Goodwin et al., 2016), It has been suggested that the coupling between these two modes of variability modulates snow accumulation in the AP (Clem and Fogt, 2013) and may explain the acceleration since the 1990s when both modes are in-phase. The increased snowfall has also been linked to warming sea surface temperatures in the western Pacific (Thomas et al., 2015), an area not associated with ENSO, and with the phase changes of the Pacific Decadal Oscillation (PDO), which exhibits major phase shifts in the late 1940s and mid-1970s (Goodwin et al., 2016).

Snow accumulation in the Antarctic Peninsula is also closely related to sea ice conditions in the Bellingshausen Sea (Fig. 5d) (Thomas et al., 2015; Porter et al., 2016). Sea ice plays an important role in the climate system, acting as a barrier for the transport of moisture and heat between the ocean and the atmosphere. Sea ice reconstructions have revealed a 20^{th} century decline in sea ice in the Bellingshausen Sea (Abram et al., 2010) and evidence that the current rate of sea ice loss is unique for the post-1900 period (Porter et al., 2016). The result is enhanced availability of surface level moisture and increased poleward atmospheric moisture transport (Tsukernik and Lynch, 2013). This was used to explain the longitudinal differences between AP ice core sites (Thomas et al., 2015), with the least significant changes in accumulation in Ellsworth Land and the greatest changes observed in the southwestern AP, where adjacent sea ice exhibits the largest decreasing trend (Turner et al., 2009).

3.2.5. West Antarctic Ice Sheet (WAIS)

The WAIS region has been comparatively well-sampled (Fig. 1) with records covering a large portion of the area and spanning many centuries. Although accumulation rates ~~here~~ are relatively high, firn cores recovered as part of the WAIS Divide ice core project have provided records covering the past 2000 years. Because of its complex topography and divide geometries, the WAIS region is commonly differentiated into two smaller regions: the Amundsen Sea sector, home to Pine Island and Thwaites Glaciers, and the Ross Sea sector, where the Siple Coast ice streams flow into the Ross Ice Shelf.

The low elevation terrain of the Amundsen Sea sector penetrates far into the interior; thus, the region is subject to frequent warm, marine air intrusions that bring cloud cover, higher amounts of snowfall, and higher temperatures (Nicolas and Bromwich, 2011). In general, the accumulation gradient is dependent on elevation, however, terrain geometry plays an important role~~ as well~~. The steep coastal region of Marie Byrd Land receives relatively high accumulation because of orographic lifting, while the region directly south, in the precipitation shadow of the Executive Committee Range, is precipitation starved. Thus, the highest accumulation rates are found on the low elevation coastal domes and much of the interior of the Amundsen Sea sector, where marine air intrusions bring moisture and heat (Nicolas and Bromwich, 2011).

Because of the ice sheet geometry, the accumulation records from the Amundsen Sea sector are poorly correlated with those from the Ross Sea sector. Correlation of the WAIS record with RACMO2.~~4~~ 3p2 SMB and ERA-Interim precipitation shows a very strong resemblance to the Amundsen Sea sector and very weak relationship with the Ross Sea sector (Fig. 2e & 3e). Even though there are records from the Ross Sea sector (Fig. 1), they are largely out of date, covering up to the mid-to-late 1990s. Records from the Amundsen Sea sector provide data up to 2010; thus, the most recent decade of the WAIS record is composed of records only from the Amundsen Sea sector, which has a stronger correlation with modelled SMB. This limitation must be considered when evaluating the drivers of WAIS accumulation.

Higher atmospheric pressure over the Drake Passage brings enhanced northerly flow over the central Amundsen Sea and directs warm, moist air to the low elevation central WAIS (Fig. 4e & 6e). The additional accumulation brought to the Amundsen Sea sector extends deep into the Antarctic interior reaching the South Pole sector (Fig. 2e). This scenario is more representative of the Amundsen Sea rather than the Ross Sea sector, the latter being largely driven by the strength and position of the Amundsen Sea Low (Kaspari et al., 2004; Nicolas and Bromwich, 2011; Thomas et al., 2015).

3.2.6. Victoria Land (VL)

For the purpose of this paper, we cluster records derived from the Ross Ice Shelf and from the coastal regions (below 2,000m elevation) of the Trans-Antarctic Mountains (TAM) into VL (Fig. 1). Despite its geographical diversity, ranging from a low lying, flat ice shelf to the east (towards West Antarctica) and a steep relief in the west (towards East Antarctica), this region is dominated by cyclonically driven snow accumulation, sensitive to tropical and local climate drivers that significantly impact the wider region (Bertler et al., ~~submitted~~2017, Emanuelsson et al., in review).

Accumulation in northern Victoria Land, where the coast faces north, comes primarily from storms in the Indian Ocean (Scarchilli et al., 2011), the origin of air masses similar to that of adjacent Wilkes Land ~~(Scarchilli et al., 2011)~~. However, the TAM block flow to southern Victoria Land, such that this region is influenced by storms that cross the Ross Sea (Sodeman and Stohl, 2009). As a consequence, the snow accumulation rates are higher in Northern and Southern Victoria Land, while the middle region (including the McMurdo Dry Valleys) lies in precipitation shadows of cyclones from the north and the south, experiencing overall lower snow accumulation rates (Sinclair et al., 2010).

Accumulation across the Ross Ice Shelf and southern VL is linked to that of the AP and WAIS, through the position and intensity of the ASL, which affects the frequency and trajectory of storms in the Ross Sea (Raphael et al., 2016; Turner et al., 2013, Fogt et al., 2012, Bertler et al., 2004). Markle et al., (2012) also found that the phase of ENSO, but not SAM, affected the frequency of Ross Sea storms reaching southern VL. In particular blocking (ridging) events, whose position and frequency are determined by the intensity and position of the ASL (Renwick et al. 2005), have been identified as a major driver of snow precipitation in the eastern Ross Sea region, enhancing meridional flow across the eastern Ross Sea (Emanuelsson et al., in review). The principal tropical teleconnection associated with the Rossby wave propagation from the western tropical Pacific exerts its influence on the entire Ross Sea region, ~~the Pacific-Southern-American 2 (PSA2) pattern, which originates from the central, tropical Pacific, shows a~~with ~~distinct,~~ opposing influence between the ~~eastern and western Ross Sea~~ east and west (Raphael et al., 2016, Bertler et al., ~~submitted~~2017) ~~leading to a secondary climate signal~~ which explains some of the differences observed in these two regions.

The availability of local moisture from open water in the Ross Sea is also associated with high accumulation events (Sinclair et al., 2013). Furthermore, riming (deposition) might contribute as much as 28 % of all precipitation events, in particular during winter at sites in the vicinity to polynyas, such as RICE (Tuohy et al., 2015). As rime is poorly captured in reanalysis data, the potentially significant contribution of rime at particular sites, might be an important consideration of understanding regional precipitation differences.

The VL composite has the greatest correlation with precipitation in the northward-facing section of VL and the western portion of the Ross Sea (Fig. 3f). The correlation in the Transantarctic Mountains is low, likely due to topographic complexity. The VL composite is positively correlated with geopotential heights in the eastern Ross Sea (Fig. 4f), illustrating the connection to the ASL, which is more pronounced for Roosevelt Island than for Talos Dome and Hercules Neve. The pattern resembles that of AP, although weaker and opposite in sign When the ASL is shifted to the west, weaker storms more frequently penetrate into VL, rather than being focused in central WAIS and AP.

3.2.7. Dronning Maud Land (DML)

Precipitation in coastal DML is closely connected to synoptic activity in the circumpolar trough and related frontal systems. Interannual variability of both temperature and precipitation is influenced by SAM, which partly determines the amount of meridional exchange of heat and moisture. Generally, precipitation decreases from the coast towards the interior, local maxima can occur at the windward side of topographic features, such as ice rises on ice shelves or steep slopes of the escarpment (Rotschky et al., 2007; Schlosser et al., 2008; Vega et al., 2016). Katabatic winds also influence SMB, especially at the grounding line, at the transition of ice shelf and grounded ice, leading to negative SMB values due to wind erosion and increased evaporation (Sinisalo et al., 2013; Schlosser et al., 2014).

The correlation plot of SMB and 850 hPa geopotential height (Fig. 4g), exhibits three distinct maxima above the Southern Ocean, however, compared to EAP they are situated closer to the coast and shifted in longitude by approximately 30°. This also hints at a ZW3 pattern. There is also a fairly strong positive correlation with sea ice extent in the northwestern Weddell Sea and a rather weak negative correlation with the area between 0° and 30° E (Fig. 5g). A plausible explanation for this could be that positive sea ice anomalies in the northern part of the Weddell Sea is often related to a comparably strong southwesterly flow that, taking into account Ekman transport, pushes the ice away from the coast, at the same time new ice is formed close to the coast due to cold air advection and re-opened polynyas (e.g. Schlosser et al., 2011). The compensating northwesterly flow further east could enhance precipitation in DML. ~~However, this is just a qualitative explanation, more research using model and field data would be necessary to prove this.~~

Ice and firn cores from coastal DML do not show a uniform trend over the past century. However, in recent decades, all but the core from Derwael Ice rise (Philippe et al., 2016) agree in having a negative trend in SMB, whereas temperatures/stable isotope ratios are increasing or constant (Isaksson and Melvold, 2002; Schlosser et al., 2012; Sinisalo et al., 2013; Schlosser et al., 2014; Altnau et al., 2015; Vega et al., 2016). For some cores this negative trend is found for the last 100 years (e.g. Kaczmarska et al., 2004). This suggests that the SMB/precipitation in DML is influenced by the atmospheric flow conditions, i.e. dynamically rather than thermodynamically as at EAP (Altnau et al., 2015).

3.3. Regional precipitation variability over the past 200 years

The standardized regional composites have been converted into records of SMB, based on SMB extracted from RACMO2.~~4~~3p2.~~.~~ We use a geometric mean regression ~~technique~~ technique, which allows for error in both the modelled SMB and the ice core snow accumulation (Smith, 2009), to convert the unit~~-~~less standardized regional composites into regional SMB (~~mm w.e~~Gt yr^{-1}). This method allows for error in both the regional composites and the RACMO2.~~4~~ 3p2 data and has been widely used for other ice core proxies, for example regressing sea ice proxies onto satellite derived records of winter sea ice extent (Abram et al., 2010; Thomas and Abram et al., 2016).

The regional SMB records reveal significant variability ~~during the past 200 years~~ since 1800 AD (Fig. 6). With the exception of WL (Fig. 6b), all regions exhibit an increasing trend in SMB ~~since 1800 AD~~, with statistically significant trends in the EAP, WS and DML (+0.83, +0.83 and +0.96 Gt dec^{-1}). The largest increase is observed in the AP, where SMB has increased at a rate of 4.3 Gt dec^{-1} representing a total increase in SMB of 123 +/- 44 Gt yr $^{-1}$ between the average in the first decade (1801-1810) and the average in the last decade (2001-2010). ~~ranging from +1.8 mm w.e. per decade in AP (Fig. 6d) to just +0.15 mm w.e. per decade in EAP and WAIS (Fig. 6a & 6c). In contrast, WL exhibits a decrease in SMB of 0.7 mm w.e per decade since 1800 AD.~~

~~WAIS, DML and VL reveal positive trends in SMB since 1800 AD (0.16, 0.69 and 0.84 mm w.e. per decade respectively), but negative trends during the 20th century (-0.57, -0.33 and -0.59 mm w.e. per decade respectively).~~ . ~~These changes have low statistical significance ($p>0.1$), suggesting fluctuations of this magnitude are not unusual. For WAIS there is an increase in SMB during the most recent decade (2000-2010), with SMB 13 mm (2 %) higher than the reference period, while in VL, the most recent decade represents a 4 % reduction (-26 mm) from the reference period. However, the paucity of records and their limited spatial coverage since the 2000s limits our ability to assess how regionally representative this trend is.~~

The 20th century increase~~s~~ observed in AP (Fig. 6d) ~~do appear~~is unusual in the context of the past 200 years. In this region, the annual average SMB during the most recent period is 88 +/- 49 Gt yr^{-1} higher than the reference period (1961-1990) and the running decadal mean during the early 2000s exceeds two standard deviations above the record average for the entire ~~200~~300-year period. SMB in the AP has been increasing at a rate of ~~6.6~~12 ~~mm w.e~~Gt ~~per decade~~ dec^{-1} since 1900 ($p<0.01$), equivalent to a ~~76~~ 138 ~~mm~~ +/-58 Gt yr^{-1} (~~~19~~ 20 %) increase between the decadal average at the start of the 20th century (1901-1910) and the decadal average at the start of the 21st century (2001-2010). As observed in previous studies the increase in SMB in the AP began in the ~1930 and accelerated during the 1990s (Thomas et al., 2008; 2015; Goodwin et al., 2015).

Histograms of running 50-year and 100-year trends are shown in Figure 8. For AP, the positive trends observed in the most recent 50-year and 100-year period (1960-2010 and 1910-2010) are the highest since 1800 AD and both significant at $p < 0.01$. Conversely in VL, the negative trends observed during the same period are the lowest since 1800 AD, significant for the 50-year trend ($p < 0.01$) but not the 100-year trend. The rate of increase in snowfall in AP and the opposing decrease in VL during the late 20th and early 21st century is exceptional in the context of the past 200 years and reflects the influence of the ASL, especially since the 1990s, when SAM and ENSO are in-phase and the tropical teleconnection was strongest.

~~The second highest increase is observed in the WS region (Fig. 6c), where SMB has increased at a rate of 1 mm w.e. per decade (p<0.05) since 1800 AD and 2.6 mm w.e. per decade (p<0.05) since 1900 AD (1900-1992). The spatial correlation between the AP composite, with both RACMO2.4 and ERA-interim (Fig 2d & 3d), revealed that the region of significant correlations extends into the WS, suggesting the increases observed in AP may extend over the WS. However, there is some doubt about the WS record capturing regional precipitation and more records are needed to confirm this connection.~~

In DML, two of the three records which cover the entire 20^{th} century reveal a decreasing trend. ~~,~~ ~~while~~ However, the Derwael Ice Rise record reveals a statistically significant increase in snow accumulation during the 20^{th} century, resulting in the most recent 50-year trend in DML ($p < 0.05$) sitting outside of the expected range for the previous 200 years (Fig. 8g)~~.~~ Snow accumulation at this low elevation coastal site has been related to sea ice and atmospheric circulation patterns (Philippe et al., 2016), with SMB during the most recent decade (2000-2010) 5 % higher than the reference period.

The most recent 50-year and 100-year trends for the other regions (EAP, WS, and WAIS), fall within the range of expected variability. In WL, the most recent 100-year trend is outside of the expected range but it is not significant at $p < 0.10$.

3.4. Regional precipitation variability over the past 1000 years

To assess the significance of the recent trends we extend the records back 1000 years (Fig. 7). Only the Law Dome, RICE, WAIS and Berkner ice cores cover the full period and the increased variability in these regions beyond ~1400 AD is an artefact of the shift from multiple to single sites.

There is considerable interannual and multi-decadal variability in all records, however, there is little consistency or commonality between regions. Previous studies have related Antarctic SMB changes to solar irradiance (Frezzotti et al., 2013), with three periods of low accumulation variability identified at 1250-1300, 1420-1550 and 1660-1790 AD that correspond to periods of low solar activity. A decrease in snow accumulation for the entire Little Ice Age Period (defined as ~1300-1800 AD) was also observed in the western Ross Sea by a lower resolution record (Bertler et al., 2011). Examination of our regional composites over the past 1000 years indicates that this may be restricted to the EAP and perhaps small regions not captured in this array, with little evidence for a large scale reduction in variability related to solar variability in other regions. The relatively low accumulation over EAP, combined with the major (>50 %) contribution of non-synoptic precipitation, may explain the stronger influence of solar variability over EAP while local wind regimes in the TAM have been shown to be sensitive to solar radiation (Bertler et al., 2005). However, the updated network presented here suggests that the strong synoptic influence on coastal regions is likely to outweigh any direct solar influence.

~~Histograms of running 50-year and 100-year trends are shown in Figure 8, with the last 50 and 100-year trends of the 20th century highlighted. With the exception of AP (Fig. 8d), the trends during the late 20th century are within the expected range of variability in the context of the past 1000 years (300 yrs for AP and DML, 770 yrs for EAP). However, in AP the 50 and 100-year trends at the end of the 20th century appear unusual. Both the highest 50 and 100-year trends occur during the most recent period (1960-2010 and 1910-2010), suggesting the rate of increase in snowfall during the late 20th and early 21st century in this region is exceptional in the context of the past 300 years. However, the shorter records in AP (and DML) reduce the significance of the recent trends here relative to the other regions.~~

4. Total Antarctic SMB change

An estimate of the SMB change for the ~~grounded~~ total AIS (including ice shelves) is calculated by ~~weighting the regional SMB composites relative to their total area (as defined in Fig. 1)~~combining the area integrated regional composites. ~~The area weighted SMB change is calculated as the sum of the “area weighted” regional SMB composites, divided by the area of Antarctica (~12 million km^2)~~. The direct SMB data from RACMO 2.3p2 has been used to extend the reconstructions in EAP and WS to 2010 in line with the other regions.

The total Antarctic SMB ~~has~~ increased ~~by ~ 44 GT w.e.~~ at a rate of 7 +/- 1.3 Gt dec^{-1} between 1800 AD and ~~2000~~ 2010 AD and 14 +/- 1.8 Gt dec^{-1} since 1900 AD. The annual average SMB for the AIS was 272 +/-29 Gt yr^{-1} higher during the first decade of the 21st century compared to the first decade of the 19th century. This equates to a relative reduction in sea level of 0.02 mm dec^{-1} since 1800 AD and 0.04 mm dec^{-1} since 1900 AD, with the increased SMB acting to mitigate sea level rise as predicted under future warming scenarios (Palerme et al., 2017). The estimated sea level reduction, resulting from the increased snowfall since 1800 AD, is comparable with the estimated mass loss and subsequent sea level contribution from the southern Patagonian ice fields (Glasser et al., 2011).

The largest (area weighted) increase in SMB is observed in the AP, accounting for ~~~72~~ 75 % of the total Antarctic SMB increase since 1900. Despite the relatively low annual snowfall, the EAP is the second highest contributor (~~22~~ 10 %), due to its extremely large area ~~(accounting for 45 % of the total area)~~.

Only four records cover the full 1000 years (Fig. 7). The combined SMB in these regions (WAIS, WL, WS and VL) ~~decreased by~~ suggests a decline of ~1.4 Gt dec^{-1} ~~39 GT w.e~~. since 1000 AD. However, it is important to note that these four regions represent just ~30 % of the total area of Antarctica and in the case of WS, doubt exists as to how regionally representative the record is. Evidence from the 20th century suggests that even small changes in SMB, in either the low accumulation/ high area EAP region or the high accumulation AP region, can have significant impacts on the total Antarctic SMB budget.

5. Conclusions

As part of the Antarctica 2k community effort we present regional snow accumulation composites to investigate snow accumulation variability over the past 1000 years. Eighty ice core snow accumulation records were~~,~~ quality checked and separated into seven geographical regions, to reduce the bias towards over-represented regions and separate the high accumulation coastal zones from the low accumulation high elevation sites.

The snow accumulation records from each region were evaluated against SMB from RACMO2.~~4~~ 3 p2 and precipitation from ERA-interim. With the exception of the EAP and WS region, the regional composites capture a large proportion of the regional SMB and precipitation variability. The lack of correlation in the EAP is likely due to the greater influence of wind (erosion or deposition), sublimation, and post-depositional processes (surface glazing and dune formation) in the interior than in coastal regions. Another explanation is that the models cannot capture processes such as deposition of diamond dust, likely having a relatively large influence on precipitation variability in these extremely cold areas (van de Berg et al. 2005, Mahesh at al. 2001). Either way, the lack of coherency in trends from ice core records across the central Antarctic Plateau suggests that ice core snow accumulation records from this region are less well suited to studies investigating temporal changes in Antarctic SMB.

Our study ~~suggests an overall increase in SMB across the grounded Antarctic ice sheet since 1800 AD, of approximately 44 GT~~reveals that SMB for the total AIS has increased at a rate of 7 +/- 1.3 Gt dec^{-1} since 1800 AD, equivalent to a net reduction in sea level of 0.02 mm dec^{-1}.~~, with the largest (area-weighted)~~ The largest contribution is from the AP, where the annual average SMB during the most recent decade (2001-2010) is 123 +/- 44 Gt yr^{-1} higher than the annual average at the start of the 19th century. The AP is the only region where both the most recent 50-year and 100-year trends are outside of the observed range for the past 300 years. This contradicts some previous studies which suggest a negligible change in Antarctic SMB since 1957 (Monaghan et al., 2006) and that the current SMB is not exceptionally high compared to the past 800 years (Frezzotti et al., 2013). The later study did acknowledge high SMB in coastal regions since the 1960s, however, these studies were hindered by a lack of recent records (especially from the coastal zones) and were heavily weighted by the EAP region. Recent drilling campaigns, and the collation of records as part of the Antarctica 2k program, have allowed us to better represent several important regions and derive a more accurate representation of SMB changes over the past 200 years.

The inclusion of new snow accumulation records that cover the past 1000 years have provided valuable information about SMB changes in certain regions, however estimating Antarctic SMB using these sites alone would be misleading. For example, based on the four available records which cover the past 1000 years there is evidence for a decreasing trend in SMB since 1000 AD. However, the combined regional representation of these records is less than 30 % of the total Antarctic continent and includes single ice core sites with only limited regional representation in SMB. Our findings suggest that small changes in the high accumulation AP, or the low accumulation but geographically much larger EAP region, could change the sign and significance of the total Antarctic SMB trend dramatically.

Greater spatial representation (especially WS and EAP) and the inclusion of sufficiently deep ice cores from high-accumulation coastal zones (especially AP and DML) are vital to our understanding the true nature of Antarctic SMB in the past and providing an accurate benchmark for how SMB may change in the future.

Figure 1: (a) Location of all ice cores and the regional boundaries used in this study. EAP (blue), WL (cyan), WS (green), AP (yellow), WAIS (orange), VL (red) and DML (brown). Stars denote sites where correlation between ice core snow accumulation and RACMO 2.3p2 SMB is significant at p <0.05 (b) RACMO 2.3p2 SMB (1979-2016) overlain with ice core SMB since 1979 at each location.

Figure 2: Spatial correlation plots of standardized regional and continental composites of snow accumulation with SMB from RACMO2.~~4~~ 3p2 (1979-2010). Grid points with >95 % significance are dotted. Note, correlation with WS only covers the period 1979-1992.

Figure 3: Spatial correlation plots of standardized regional and continental composites of snow accumulation with precipitation from ERA-interim (1979-2010). Grid points with >95 % significance are dotted. Note, correlation with WS only covers the period 1979-1992.

Figure 4: Spatial correlation plots of standardized regional snow accumulation composites with annual 850 hPa geopotential heights from ERA-interim (1979-2010). Grid points with >95 % significance are dotted. Note, correlation with WS only covers the period 1979-1992.

Figure 5: Spatial correlation plots of standardized regional snow accumulation composites with annual sea ice concentration from bootstrap analysis (1981-2010). Grid points with >95 % significance are dotted. Note, correlation with WS only covers the period 1979-1992.

Figure 6: Regional SMB composites (1800-2010 AD) shown as annual averages (thin lines) and 5 year means (thick lines). Plots 1-7 East Antarctic Plateau (EAP dark blue), Wilkes Land Coast (WL cyan), Weddell Sea Coast (WS green), Antarctic Peninsula (AP yellow), West Antarctic Ice Sheet (WAIS orange), Victoria Land (VL red) and Dronning Maud Land (DML brown). Bottom plot represents the total number of records (solid grey) and the number of records by region.

Figure 7: Regional SMB composites (1000-2010 AD) shown as annual averages (thin lines) and 10 year running means (thick lines). Plots 1-7 East Antarctic Plateau (EAP dark blue), Wilkes Land Coast (WL cyan), Weddell Sea Coast (WS green), Antarctic Peninsula (AP yellow), West Antarctic Ice Sheet (WAIS orange), Victoria Land (VL red) and Dronning Maud Land (DML brown). Bottom plot represents the total number of records (solid grey) and the number of records by region.

Figure 8: Histogram of running 50-year (lighter shading) and 100-year (darker shading) trends for each region (mm w.e. yr^{-1}). Solid vertical line represents the most recent 50-year trend and dashed vertical line the most recent 100-year trend (respectively, 2010-1961 and 2010-1911).

Figure 9: (a) Total AIS SMB derived from 80 ice core records (blue) and RACMO 2.3 p2 (red) as annual averages (dashed lines) and 10-year averages (solid line). Solid horizontal line represents the record average and the dashed horizontal lines are 1 and 2 standard deviations above and below this. (b) Histogram of 50-year (light shading) and 100-year (darker shading) trends in AIS SMB. Solid vertical line represents the most recent 50-year trend and dashed vertical line the most recent 100-year trend (respectively, 2010-1961 and 2010-1911).

6. Data availability~~:~~

The composite records produced in this study are available from the UK Polar Data Centre (Thomas (2017) "Antarctic regional snow accumulation composites over the past 1000 years" Polar Data Centre, Natural Environment Research Council, UK. https://doi.org/10.5285/c4ecfe25-12f2-453b-ad19-49a19e90ee32 or by contacting Elizabeth Thomas (lith@bas.ac.uk). ~~All data presented in this study is available at the~~The complete data citation from all data used in this study is presented in Table S1 and stored alongside the composite data at the UK Polar Data Centre.~~Antarctica 2k database (http://www.pages-igbp.org/ini/wg/antarctica2k/data).~~ ~~The composite records are also available from the UK Polar Data Centre (www.bas.ac.uk/data/uk-pdc) or by contacting Elizabeth Thomas (lith@bas.ac.uk).~~The ECMWF ERA-interim data and the RACMO data used in the spatial correlations is available at http://apps.ecmwf.int/datasets/ and https://www.projects.science.uu.nl/iceclimate/models/antarctica.php.

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~~**Site Name**~~	~~**Latitude**~~	~~**Longitude**~~	~~**Elevation (m)**~~	~~**Years AD**~~	~~**Reference**~~
~~Vostok composite VRS13~~	~~-78.47~~	~~106.83~~	~~3488~~	~~1654-2010~~	~~Ekaykin et al., 2014~~
~~B31Site DML07~~	~~-75.58~~	~~-3.43~~	~~2680~~	~~1000-1994~~	~~Graf et al., 2000~~
~~B32Site DML05~~	~~-75~~	~~-0.01~~	~~2892~~	~~1248-1996~~	~~Graf et al., 2000~~
~~B33Site DML17~~	~~-75.17~~	~~6.5~~	~~3160~~	~~1250-1997~~	~~Graf et al., 2000~~
~~FB96DML01~~	~~-74.86~~	~~-2.55~~	~~2817~~	~~1895-1995~~	~~Oerter et al., 1999~~
~~FB96DML02~~	~~-74.97~~	~~-3.92~~	~~3014~~	~~1919-1995~~	~~Oerter et al., 1999~~
~~FB96DML03~~	~~-74.49~~	~~1.96~~	~~2843~~	~~1941-1996~~	~~Oerter et al., 1999~~
~~FB96DML04~~	~~-74.40~~	~~7.21~~	~~3161~~	~~1905-1996~~	~~Oerter et al., 1999~~
~~FB96DML05~~	~~-75.00~~	~~0.012~~	~~2882~~	~~1930-1996~~	~~Oerter et al., 1999~~
~~FB96DML06~~	~~-75.01~~	~~8.01~~	~~3246~~	~~1899-1996~~	~~Oerter et al., 1999~~
~~FB96DML07~~	~~-74.59~~	~~-3.439~~	~~2669~~	~~1908-1996~~	~~Oerter et al., 1999~~
~~FB96DML08~~	~~-75.75~~	~~3.2936~~	~~2962~~	~~1919-1996~~	~~Oerter et al., 1999~~
~~FB96DML09~~	~~-75.93~~	~~7.2217~~	~~3145~~	~~1897-1996~~	~~Oerter et al., 1999~~
~~FB96DML10~~	~~-75.22~~	~~11.35~~	~~3349~~	~~1900-1996~~	~~Oerter et al., 1999~~
~~FB9803~~	~~-74.85~~	~~-8.497~~	~~2600~~	~~1921-1997~~	~~Oerter et al., 1999~~
~~FB9804~~	~~-75.25~~	~~-6.0~~	~~2630~~	~~1801-1996~~	~~Oerter et al., 1999~~
~~FB9805~~	~~-75.16~~	~~-0.99~~	~~2840~~	~~1800-1997~~	~~Oerter et al., 1999~~
~~FB9807~~	~~-74.99~~	~~0.036~~	~~2880~~	~~1758-1997~~	~~Oerter et al., 1999~~
~~FB9808~~	~~-74.75~~	~~0.999~~	~~2860~~	~~1801-1997~~	~~Oerter et al., 1999~~
~~FB9809~~	~~-74.49~~	~~1.960~~	~~2843~~	~~1801-1997~~	~~Oerter et al., 1999~~

~~FB9810~~	~~-74.66~~	~~4.001~~	~~2980~~	~~1801-1997~~	~~Oerter et al., 1999~~
~~FB9811~~	~~-75.08~~	~~6.5~~	~~3160~~	~~1801-1997~~	~~Oerter et al., 1999~~
~~FB9812~~	~~-75.25~~	~~6.502~~	~~3160~~	~~1810-1997~~	~~Oerter et al., 1999~~
~~FB9813~~	~~-75.17~~	~~5.00~~	~~3100~~	~~1800-1997~~	~~Oerter et al., 1999~~
~~FB9814~~	~~-75.08~~	~~2.50~~	~~2970~~	~~1801-1997~~	~~Oerter et al., 1999~~
~~FB9815~~	~~-74.96~~	~~-1.50~~	~~2840~~	~~1801-1997~~	~~Oerter et al., 1999~~
~~FB9816~~	~~-75~~	~~-4.51~~	~~2740~~	~~1800-1997~~	~~Oerter et al., 1999~~
~~FB9817~~	~~-75.00~~	~~-6.49~~	~~2680~~	~~1800-1997~~	~~Oerter et al., 1999~~
~~South Pole 1995~~	~~-90~~	~~0~~	~~2850~~	~~1801-1991~~	~~Mosely-Thomposn et al., 1999~~
~~GV2~~	~~-71.71~~	~~145.26~~	~~2143~~	~~1670-2003~~	~~Frezzotti et al., 2004; 2013~~
~~D66~~	~~-68.94~~	~~136.94~~	~~2333~~	~~1864-2003~~	~~Frezzotti et al., 2004; 2013~~
~~LGB65~~	~~-71.85~~	~~77.92~~	~~1850~~	~~1745-1996~~	~~Xiao et al., 2004~~
~~US-ITASE-2002-7~~	~~-88.99~~	~~59.97~~	~~3000~~	~~1900-2002~~	~~Mayewski and Dixon, 2013~~
~~US-ITASE-2002-4~~	~~-86.5~~	~~-107.99~~	~~2586~~	~~1594-2003~~	~~Mayewski and Dixon, 2013~~
~~DSS Law Dome~~	~~-66.77~~	~~112.81~~	~~1370~~	~~0-1995~~	~~Roberts et al., 2015~~
~~105th km~~	~~-67.43~~	~~93.38~~	~~1407~~	~~1757-1987~~	~~Vladimirova et al., 2014~~
~~200th km~~	~~-68.25~~	~~94.08~~	~~1990~~	~~1640-1988~~	~~Ekaykin et al., 2016~~
~~Berkner Island (South)~~	~~-79.57~~	~~-45.72~~	~~890~~	~~1000-1992~~	~~Mulvaney et al., 2002~~
~~Gomez~~	~~-73.59~~	~~-70.36~~	~~1400~~	~~1858-2006~~	~~Thomas et al., 2008~~
~~James Ross Island~~	~~-64.22~~	~~−57.68~~	~~1640~~	~~1832-1997~~	~~Aristarain et al., 2004~~
~~Dyer Plateau~~	~~-70.68~~	~~-64.87~~	~~2002~~	~~1505-1988~~	~~Thompson et al., 2004~~
~~Bruce Plateau~~	~~-66.04~~	~~-64.08~~	~~1976~~	~~1900-2009~~	~~Goodwin et al., 2016~~
~~Beethoven~~	~~-71.9~~	~~74.6~~	~~580~~	~~1949-1991~~	~~Pasteur and Mulvaney, 2000~~
~~Ferrigno~~	~~-74.57~~	~~-86.9~~	~~1354~~	~~1703-2010~~	~~Thomas et al., 2015~~
~~Bryan Coast~~	~~-74.50~~	~~-81.68~~	~~1177~~	~~1712-2010~~	~~Thomas et al., 2015~~
~~DIV2010~~	~~-76.77~~	~~-101.74~~	~~1330~~	~~1786-2010~~	~~Medley et al., 2013~~
~~THW2010~~	~~-76.95~~	~~-121.22~~	~~2020~~	~~1867-2010~~	~~Medley et al., 2013~~
~~PIG2010~~	~~-77.96~~	~~-95.96~~	~~1590~~	~~1918-2010~~	~~Medley et al., 2013~~
~~WDC05A~~	~~-79.46~~	~~-112.09~~	~~1806~~	~~1775-2005~~	~~Banta et al., 2008~~
~~WD05Q~~	~~-79.46~~	~~-112.09~~	~~1759~~	~~1522-2005~~	~~Banta et al., 2008~~
~~WAIS 2014~~	~~-79.46~~	~~-112.09~~	~~1759~~	~~0-2006~~	~~Fudge et al., 2016~~
~~CWA-A~~	~~-82.36~~	~~-119.286~~	~~950~~	~~1939-1993~~	~~Reusch et al., 1999~~
~~CWA-D~~	~~-81.37~~	~~-107.275~~	~~1930~~	~~1952-1993~~	~~Reusch et al., 1999~~

~~Siple dome-94~~	~~-81.65~~	~~-148.79~~	~~620~~	~~1891-1994~~	~~Kaspari et al., 2004~~
~~Upstream-C (UP-C)~~	~~-82.44~~	~~-135.97~~	~~525~~	~~1870-1996~~	~~Kaspari et al., 2004~~
~~Ross ice drainage system A~~	~~-78.73~~	~~-116.33~~	~~1740~~	~~1831-1995~~	~~Kaspari et al., 2004~~
~~Ross ice drainage system B~~	~~-79.46~~	~~-118.05~~	~~1603~~	~~1922-1995~~	~~Kaspari et al., 2004~~
~~Ross ice drainage system C~~	~~-80.01~~	~~-119.43~~	~~1530~~	~~1903-1995~~	~~Kaspari et al., 2004~~
~~US-ITASE-1999-1~~	~~-80.62~~	~~-122.63~~	~~1350~~	~~1724-2000~~	~~Kaspari et al., 2004~~
~~US-ITASE-2000-1~~	~~-79.38~~	~~-111.24~~	~~1791~~	~~1673-2001~~	~~Kaspari et al., 2004~~
~~US-ITASE-2000-3~~	~~-78.43~~	~~-111.92~~	~~1742~~	~~1971-2001~~	~~Mayewski and Dixon, 2013~~
~~US-ITASE-2000-4~~	~~-78.08~~	~~-120.08~~	~~1697~~	~~1798-2000~~	~~Kaspari et al., 2004~~
~~US-ITASE-2000-5~~	~~-77.68~~	~~-123.99~~	~~1828~~	~~1718-1999~~	~~Kaspari et al., 2004~~
~~US-ITASE-2001-1~~	~~-79.16~~	~~-104.97~~	~~1842~~	~~1986-2002~~	~~Mayewski and Dixon, 2013~~
~~US-ITASE-2001-2~~	~~-82.00~~	~~-110.01~~	~~1746~~	~~1892-2002~~	~~Kaspari et al., 2004~~
~~US-ITASE-2001-3~~	~~-78.12~~	~~-95.65~~	~~1620~~	~~1858-2002~~	~~Kaspari et al., 2004~~
~~US-ITASE-2001-4~~	~~-77.61~~	~~-92.24~~	~~1483~~	~~1986-2001~~	~~Mayewski and Dixon, 2013~~
~~US-ITASE-2001-5~~	~~-77.06~~	~~-89.14~~	~~1239~~	~~1780-2002~~	~~Kaspari et al., 2004~~
~~Hercules Névé~~	~~-73.1~~	~~165.4~~	~~2960~~	~~1770-1992~~	~~Stenni et al., 2000~~
~~TD96 Talos Dome~~	~~-72.8~~	~~159.06~~	~~2316~~	~~1232-1995~~	~~Graf et al., 2002~~
~~GV7~~	~~-70.68~~	~~158.86~~	~~1947~~	~~1854-2004~~	~~Frezzotti et al., 2004; 2014~~
~~GV5~~	~~-71.89~~	~~158.54~~	~~2184~~	~~1777-2004~~	~~Frezzotti et al., 2004; 2007~~
~~RICE~~	~~-79.36~~	~~161.64~~	~~560~~	~~0-2012~~	~~Bertler et al., submitted~~
~~Fimbulisen S20~~	~~-70.25~~	~~4.82~~	~~63~~	~~1956-1996~~	~~Isaksson et al., 1999~~
~~Fimbulisen S100~~	~~-70.24~~	~~4.8~~	~~48~~	~~1737-1999~~	~~Kaczmarska et al., 2004~~
~~Georg-von-Neumayer (B04)~~	~~-70.62~~	~~-8.37~~	~~28~~	~~1892-1981~~	~~Schlosser et al., 1999~~
~~Kottas Camp FB9802~~	~~-74.21~~	~~-9.75~~	~~1439~~	~~1881-1997~~	~~Oerter et al., 2000~~
~~H72~~	~~-69.2~~	~~41.08~~	~~1214~~	~~1832-1999~~	~~Nishio et al., 2002~~
~~Derwael Ice Rise IC12~~	~~-70.25~~	~~26.34~~	~~450~~	~~1744-2011~~	~~Philippe et al., 2016~~

Site Name	**Latitude**	**Longitude**	**Elevation (m)**	**Years AD**	**Reference**
1. East Antarctic Plateau					
Vostok composite VRS13	-78.47	106.83	3488	1654-2010	Ekaykin et al., 2014
B31Site DML07	-75.58	-3.43	2680	1025-	Sommer et al., 2000; Oerter et

				1990	al., 2000
B32Site DML05	-75	-0.01	2882	1025-1990	Sommer et al., 2000; Oerter et al., 2000
B33Site DML17	-75.17	6.5	3160	1025-1990	Sommer et al., 2000; Oerter et al., 2000
FB96DML01	-74.86	-2.55	2817	1895-1995	Oerter et al., 1999
FB96DML02	-74.97	-3.92	3014	1919-1995	Oerter et al., 1999
FB96DML03	-74.49	1.96	2843	1941-1996	Oerter et al., 1999
FB96DML04	-74.40	7.21	3161	1905-1996	Oerter et al., 1999
FB96DML05	-75.00	0.012	2882	1930-1996	Oerter et al., 1999
FB96DML06	-75.01	8.01	3246	1899-1996	Oerter et al., 1999
FB96DML07	-74.59	-3.439	2669	1908-1996	Oerter et al., 1999
FB96DML08	-75.75	3.2936	2962	1919-1996	Oerter et al., 1999
FB96DML09	-75.93	7.2217	3145	1897-1996	Oerter et al., 1999
FB96DML10	-75.22	11.35	3349	1900-1996	Oerter et al., 1999
FB9803	-74.85	-8.497	2600	1921-1997	Oerter et al., 2000
FB9804	-75.25	-6.0	2630	1801-1996	Oerter et al., 2000
FB9805	-75.16	-0.99	2840	1800-1996	Oerter et al., 2000
FB9807	-74.99	0.036	2880	1758-1996	Oerter et al., 2000

FB9808	-74.75	0.999	2860	1801-1996	Oerter et al., 2000
FB9809	-74.49	1.960	2843	1801-1996	Oerter et al., 2000
FB9810	-74.67	4.001	2980	1801-1996	Oerter et al.,2000
FB9811	-75.08	6.5	3160	1801-1996	Oerter et al., 2000
FB9812	-75.25	6.502	3160	1810-1996	Oerter et al., 2000
FB9813	-75.17	5.00	3100	1800-1996	Oerter et al., 2000
FB9814	-75.08	2.50	2970	1801-1996	Oerter et al., 2000
FB9815	-74.95	-1.50	2840	1801-1996	Oerter et al., 2000
FB9816	-75	-4.50	2740	1800-1996	Oerter et al., 2000
FB9817	-75.00	-6.50	2680	1800-1996	Oerter et al., 2000
South Pole 1995	-90	0	2850	1801-1991	Mosely-Thomposn et al., 1999
GV2	-71.71	145.26	2143	1670-2003	Frezzotti et al., 2013
D66	-68.94	136.94	2333	1864-2003	Frezzotti et al., 2013
LGB65	-71.85	77.92	1850	1745-1996	Xiao et al., 2004
US-ITASE-2002-7	-88.99	59.97	3000	1900-2002	Mayewski and Dixon, 2013
US-ITASE-2002-4	-86.5	-107.99	2586	1594-2003	Mayewski and Dixon, 2013
2. Wilkes Land Coast					

DSS Law Dome	-66.77	112.81	1370	0-1995	Roberts et al., 2015
105th km	-67.43	93.38	1407	1757-1987	Vladimirova et al., 2014
200th km	-68.25	94.08	1990	1640-1988	Ekaykin et al., 2017
3. Weddell Sea Coast					
Berkner Island (South)	-79.57	-45.72	890	1000-1992	Mulvaney et al., 2002
4. Antarctic Peninsula					
Gomez	-73.59	-70.36	1400	1858-2006	Thomas et al., 2008
James Ross Island	-64.22	−57.68	1640	1832-1997	Aristarain et al., 2004
Dyer Plateau	-70.68	-64.87	2002	1505-1988	Thompson et al., 2004
Bruce Plateau	-66.04	-64.08	1976	1900-2009	Goodwin et al., 2016
Beethoven	-71.9	74.6	580	1949-1991	Pasteur and Mulvaney, 2000
Ferrigno	-74.57	-86.9	1354	1703-2010	Thomas et al., 2015
Bryan Coast	-74.50	-81.68	1177	1712-2010	Thomas et al., 2015
5.West Antarctic Ice sheet					
DIV2010	-76.77	-101.74	1330	1786-2010	Medley et al., 2013
THW2010	-76.95	-121.22	2020	1867-2010	Medley et al., 2013
PIG2010	-77.96	-95.96	1590	1918-2010	Medley et al., 2013
WDC05A	-79.46	-112.09	1806	1775-2005	Banta et al., 2008
WD05Q	-79.46	-112.09	1759	1522-	Banta et al., 2008

				2005	
WAIS 2014	-79.46	-112.09	1759	0-2006	Fudge et al., 2016
CWA-A	-82.36	-119.286	950	1939-1993	Reusch et al., 1999
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Ross ice drainage system A	-78.73	-116.33	1740	1831-1995	Kaspari et al., 2004
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Ross ice drainage system C	-80.01	-119.43	1530	1903-1995	Kaspari et al., 2004
US-ITASE-1999-1	-80.62	-122.63	1350	1724-2000	Kaspari et al., 2004
US-ITASE-2000-1	-79.38	-111.24	1791	1673-2001	Kaspari et al., 2004
US-ITASE-2000-3	-78.43	-111.92	1742	1971-2001	Mayewski and Dixon, 2013
US-ITASE-2000-4	-78.08	-120.08	1697	1798-2000	Kaspari et al., 2004
US-ITASE-2000-5	-77.68	-123.99	1828	1718-1999	Kaspari et al., 2004
US-ITASE-2001-1	-79.16	-104.97	1842	1986-2002	Mayewski and Dixon, 2013
US-ITASE-2001-2	-82.00	-110.01	1746	1892-2002	Kaspari et al., 2004
US-ITASE-2001-3	-78.12	-95.65	1620	1858-2002	Kaspari et al., 2004
US-ITASE-2001-4	-77.61	-92.24	1483	1986-	Mayewski and Dixon, 2013

				2001	
US-ITASE-2001-5	-77.06	-89.14	1239	1780-2002	Kaspari et al., 2004
6. Victoria Land					
Hercules Névé	-73.1	165.4	2960	1770-1992	Stenni et al., 1999
TD96 Talos Dome	-72.77	159.08	2316	1232-1995	Stenni et al., 2002
GV7	-70.68	158.86	1947	1854-2004	Frezzotti et al., 2007; 2013
GV5	-71.89	158.54	2184	1777-2004	Frezzotti et al., 2007; 2013
RICE	-79.36	161.64	560	0-2012	Bertler et al., submitted
7. Dronnning Maud Land					
Fimbulisen S20	-70.25	4.82	63	1956-1996	Isaksson et al., 1999
Fimbulisen S100	-70.24	4.8	48	1737-1999	Kaczmarska et al., 2004
Georg-von-Neumayer (B04)	-70.62	-8.37	28	1892-1981	Schlosser et al., 1999
Kottas Camp FB9802	-74.21	-9.75	1439	1881-1997	Oerter et al., 2000
H72	-69.2	41.08	1214	1832-1999	Nishio et al., 2002
Derwael Ice Rise IC12	-70.25	26.34	450	1744-2011	Philippe et al., 2016

Table 1: Ice core data used in this study. Data citations can be found in supplementary table 1 and in Thomas (2017) ~~"Antarctic regional snow accumulation composites over the past 1000 years" Polar Data Centre, Natural Environment Research Council, UK. https://doi.org/10.5285/c4ecfe25-12f2-453b-ad19-49a19e90ee32~~