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Climate of the Past Discussions

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

Elizabeth R. Thomas et al.

lith@bas.ac.uk

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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.

Anonymous Referee #2

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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. We can also include the individual correlations with RACMO at each site, as an additional column in table 1.

- 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.

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 δ18O) 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.

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