

Authors' response:

We thank the reviewers for their constructive comments.

Below, the reviewers' comments are in black, our responses to the individual comments are displayed in red and the modified text is in blue.

Anonymous Referee #1

General comments: This MS presented a new Antarctic climate data over the past 2k. Many ice core data compiled under PAGES 2k were evaluated quantitatively as changes in air temperatures. The updated results showed over all cooling trend from 0 to 1900CE and the absence of continental-scale warming over the past 100 yr. Although these results are essentially very similar to those published in previous report (PAGES 2k 2013), this MS is suitable to be published in CP because of its robustness supported by the increased numbers of data and various temperature reconstruction methods.

We thank the referee for her/his positive comments.

Specific comments: In this MS, a trend is defined as significant when $p < 0.05$ (e.g., Table 2). Of course, this is widespread practice. However, it should be carefully considered for the choice of this arbitrary-chosen threshold value because significance of the slope is a central issue of this MS. Is there no rule about statistical terms for PAGES 2k consortium? For example, in IPCC AR5, "very likely" indicates 90-100% probability and "likely" indicates 66-100% probability. In this paper, the statistical significance can be ranked such as: ** ($p < 0.05$) and * ($p < 0.10$).

There is no rule for statistical terms within the PAGES 2k consortium (the community guidelines are more around data stewardship). But the reviewers' suggestion can easily be added to our tables to highlight significance at the $p < 0.10$ level as well as at the more stringent $p < 0.05$ level. This revision does not alter any of the interpretations made in the manuscript.

We provide in table 2, 3 and 4 the p-value of the trends, so that the reader can use the significance level of his choice.

Technical corrections: Conclusions and implications; I feel the conclusions would be too long.

We have shortened them. The paragraph between lines 22 and 34 of page 18 (original manuscript) has been reduced. At page 19 the lines between 2 and 7 have been deleted and the lines between 27 and 33 have been moved to section 4.1.4.

Page 2, l. 29-30; Please add appropriate citations for each phenomenon that may produce non-climate signals.

We have added the following citations: intermittency of precipitation (Masson-Delmotte et al., 2011: Clim. Past, 7, 397–423, doi:10.5194/cp-7-397-2011; Sime et al., 2009: GRL, doi:10.1029/2009GL038982); precipitation source region variability (Sodemann and Stohl, 2009: GRL, 36, L22803, doi:10.1029/2009GL040242); post depositional effects of snow layers including wind drift and scouring, sublimation, and snow metamorphism (Frezzotti et al., 2007: JGR, 112,

F02032, doi:10.1029/2006JF000638; Ekaykin et al., 2014: Ann. Glaciol., 55, 259-266, doi:10.3189/201AoG66A189; Touzeau et al., 2016: The Cryosphere, 10, 837–852, doi:10.5194/tc-10-837-2016; Hoshina et al., 2014: J. Geophys. Res., 119, 274–283; Steen-Larsen et al., 2014: Clim. Past, 10, 377–392, doi:10.5194/cp-10-377-2014).

Page 2, l. 35, “deuterium” > hydrogen?

Done.

Page 4, l. 15, “RACMO2.4 model results”; Please add citation for this model results.

These model results are shown in the companion paper on snow accumulation rate by Thomas et al. (under review for this CP special issue): their figures 2 and 3. We refer to this paper in the text, as well as to the reference Van Wessem et al., 2014 (J. Glaciol., 60, 761-770), for the model.

Section 3.4.2 and 3.4.3, The final sentences of these sections (We refer to. . .) may be removed or be moved to the last sentence of the previous paragraph.

We have moved these sentences, as well as the one for ECHAM, at the end of 3.4 Paragraph (Page 9).

Figure 2; NB2014 records (bold black lines) in Wilkes Land and Weddell Sea appears to be horizontal zero lines from 1990-2000. Are these correct? They lines should be shown in gray, if these are reference lines.

There are no data in correspondence to these features. We have modified this figure.

Figure 3; Same as Figure 2. NB2014 records (bold black lines) in Wilkes Land, Weddell Sea, and DML appears to be zero for older part of the records. These should be shown in gray.

Same as above.

Figure 9a; In the x-axis, year (1830?) was labelled wrongly (183).

We have modified the figure.

Anonymous Referee #2

General Comments:

This is an important piece of work on temperature variability and change over the Antarctic from large regional areas to continental scales for up to 2000 years. It is based on assembling 112 water stable isotope time series from ice cores and converting these concentrations into temperature

using three approaches. And it is a very important data set for testing the performance of coupled climate models, as stated.

We thank the referee for her/his positive comments.

I have two main issues that should be addressed in the revised manuscript.

First, there is the conversion of isotope variations into temperature. The introduction lays out the many complicating factors contributing to controls on the proxy temperature derived from isotopes. I expected to see in Section 5 an evaluation of the impact of these factors on the results.

Our introduction summarizes the different processes other than surface temperature which may affect isotope variations, as described at page 2 lines 28–31 and page 2 line 40, page 3 line 13, e.g. changes of the origin of moisture sources, intermittency in precipitation, snow drift, snow-air exchanges, snow metamorphism, diffusion in ice cores, as well as boundary layer processes which can modify the relationship between condensation temperature and surface air temperature.

Our analysis is not focused on the understanding of these processes but on the assessment of relationships between ice core isotopic composition and surface air temperature, as a focus of PAGES2k reconstructions in various regions. For this purpose, we work both on statistical analyses of regional temperature reconstructions and ice core records, as well as the coherent framework provided by the ECHAM5-wiso model, where we also investigate the relationships between surface air temperature and precipitation isotopic composition.

The conclusions that isotope-temperature relationships differ from region to region indeed call for further investigations to understand which of the processes identified above differ from region to region and explain differences in the relationships.

This further analysis is beyond feasibility at this stage. Indeed, recent studies showed a relationship between the range values of isotopic composition in precipitation or shallow cores and air mass pathways, but most studies were restricted to specific arrival points (e.g. Markle et al., *J. Geophys. Res.*, 2012; Sinclair et al. *Geoph. Res. Lett.*, 2014; Kurita et al., *Geoph. Res. Lett.*, 2016; Ramahan et al., *The Holocene*, 2016; Schlosser et al., *The Cryosphere*, 2017). Systematic analyses of moisture transport pathways and evaporation conditions through time and space have yet to be performed and combined with isotopic records; such analysis is beyond the scope of our manuscript.

Post-deposition effects cannot be evaluated neither from ice core data, nor in the ECHAM5-wiso model (as they are not resolved and we rely on precipitation outputs); obtaining new monitoring data in multiple Antarctic regions is crucial for an improved understanding, when the implementation of post-deposition processes such as snow-air exchanges is in progress in snow models (Touzeau et al., in prep.).

We discuss the limits of making a linear isotope/temperature relationship in section 3.4. We are clear in the manuscript about the fact that the temperature scaling is approximate, and we make an attempt at evaluating the uncertainty associated with it by using different approaches, and independent datasets for the calibration. To our knowledge, we have been exhaustive in the range of approaches possible. The detailed study of the impact of each fractionation process is impossible, simply because we do not have independent observations to constrain them individually. This is a whole field of research that cannot be addressed in a single community paper. Here, our approach

was to do our best at reconstructing temperature based on water isotopes. Surface temperature is our objective, and we use isotopes to infer surface temperature. We look at all processes in “bulk”, acknowledging that several mechanisms responsible for isotope fractionation may be correlated, and reinforce each other in a simple regression.

Finally, most of our results are based on looking at the $\delta^{18}\text{O}$ anomalies, independently of the temperature scaling, and our conclusions about the significance of the trends hold independently of the temperature scaling.

We added a description of the method at the beginning of section 3.4:

The relationship between $\delta^{18}\text{O}$ and local surface temperature is complicated by the influence of a large range of processes (origin of moisture sources, intermittency in precipitation, snow drift, snow-air exchanges, snow metamorphism, diffusion in ice cores). It is not possible to consider each process independently, because in many cases, there are simply no observations to constrain them well enough. However, the atmospheric circulation often leads to several processes to be correlated (reduced sea ice, increased precipitation and warmer temperature, for instance). We follow here the classical approach, which is to perform a linear regression of ice core $\delta^{18}\text{O}$ with local surface temperature, on the regional average products. This method has the advantage of looking at all the climatic processes influencing $\delta^{18}\text{O}$ in “bulk”, and the use of regional average allows us to limit the influence of small scale processes.

Two aspects come particularly to mind. Isn't it true that low altitude ice cores are particularly susceptible to local influences like sea ice variations? (Masson-Delmotte et al. (2008) mention different moisture sources and transportation paths below and above 2000 m elevation). You have many near coastal ice cores shown in Figure 1. How do such effects contaminate/modulate your results?

In our paper, we indeed selected seven distinct climatic regions: the Antarctic Peninsula, the West Antarctic Ice Sheet, the East Antarctic Plateau, and four coastal domains of East Antarctica, using the 2,000 m elevation contour. The reason for choosing this 2,000 m elevation as a boundary between coastal/low altitude regions and the East Antarctic Plateau is based on the reasons mentioned by the reviewer and the work presented in Masson-Delmotte et al., 2008. Our regional selections are also supported by spatial correlation of temperature using the NB2014 reanalysis data and by regional atmospheric RACMO2.4 model results (surface mass balance and temperature spatial correlation plots). In the region selection paragraph 3.1 we have better explained the possible different moisture sources and transportation paths below and above 2000 m elevation referring to Masson-Delmotte et al. (2008) paper. Considerable differences between cores from the plateau and the coast have been reported in the Altnau et al. 2015 (The Cryosphere) for the DML area covering the most recent period and where several records are present. We will refer to this paper too.

Addition to section 3.1:

In particular, we separated coastal regions (below 2000m altitude) from the East Antarctic Plateau: coastal sites receive moisture from the high-latitude Southern Ocean, and are affected by the nearby sea ice cover (Masson-Delmotte et al., 2008). In contrast, high altitude sites receive moisture

that has travelled at higher altitude, originating from further afield, and from clear sky precipitation (Ekaykin et al., 2004).

The other issue is that the stable isotope concentration is a precipitation signal (you use precipitation weighting with the ECHAM5-wiso simulated isotope results – good) and a better temperature is the condensation temperature where the precipitation forms, not the surface temperature. I didn't see any mention of this, so what do your derived temperatures actually represent?

The focus of this PAGES2K effort is a reconstruction of regional surface air temperature, and therefore this is our target.

Historically, a linear relationship was found between local surface temperature and the isotopic composition of surface snow along spatial traverse data (e.g. Dansgaard et al., *Nature*, 1975; Jouzel et al., *J. Geophys. Res.*, 1983; Morgan et al., *Clim. Change*, 1985, Aristarain et al., *Geoph. Res. Lett.*, 1986 and Rozanski et al., *Science*, 1992). These results lead to the common reconstruction of surface temperature from the isotopic composition recorded in ice cores using a single spatial relationship. Our study goes beyond this classical approach in assessing different options for the isotope-temperature scaling.

Moreover, Stenni et al. (2016) recently reported a better correlation between Dome C precipitation $\delta^{18}\text{O}$ and 2 m air temperature than for inversion temperature, whatever the considered timescale (daily, monthly or inter-annual scale). This calls for more assessment of the driver of final isotopic depletion in central Antarctica. Finally, the ECHAM5-wiso framework offers in principle the possibility to analyse such relationships; however, condensation temperature was not archived as a standard diagnostic from daily model outputs, precluding further analyses.

We added a few sentences clarifying the target of our reconstruction at the start of section 3.4:

We follow here the classical approach, which is to perform a linear regression of ice core $\delta^{18}\text{O}$ with local surface temperature, on the regional average products. This method has the advantage of looking at all the climatic processes influencing $\delta^{18}\text{O}$ in "bulk", and the use of regional average allows us to limit the influence of small-scale processes.

Changes to advection conditions (and thus the moisture source) can and do happen and influence the condensation temperature, and the advection conditions may not stay fixed across decades to millennia. Consider the following paper: Gorodetskaya, I. V., M. Tsukernik, K. Claes, M.F. Ralph, W.D. Neff, and N. P. M. Van Lipzig (2014), The role of atmospheric rivers in anomalous snow accumulation in East Antarctica, *Geophys. Res. Lett.*, 41, 6199-6206, doi:10.1002/2014GL060881. Such atmospheric river events contribute up to 80% of the annual accumulation at Princess Elizabeth Station in East Antarctica, with significant interannual variability; in some cases the precipitation origin resides in the subtropics. This perspective surely adds to the envelope of uncertainty for the temperature reconstructions and it seems unlikely that ECHAM5 even at 100 km resolution would adequately capture such narrow moisture transport events.

This study is of course limited by the spatial resolution of the model (here run at T106 resolution). At such a resolution, the simplified mapping of coastal topographies affects the atmospheric

circulation on these areas, and processes such as uplift of air masses onto the continent or katabatic winds.

We have not performed systematic assessments of the skills of ECHAM5-wiso for overall moisture transport towards Antarctica, but ECHAM5-wiso is used here nudged to ERA-interim outputs. A recent study using radiosounding data has shown the good skills of ERA-interim for overall moisture transport towards Antarctica, including the representation of extra-tropical storms (PhD thesis, Ambroise Dufour).

In Antarctica, recent atmospheric river events have been diagnosed in the Atlantic sector, in the last years. A large atmospheric river event was also identified in July 2012 towards and above the Greenland ice sheet, where isotopic measurements were available. Bonne et al. (2014) has demonstrated the ECHAM5-wiso skills to capture both this atmospheric river and the associated water vapour isotopic composition. While not in an Antarctic context, this finding suggests that our model framework is able to correctly simulate such processes. Further analyses would be needed to identify such events systematically around Antarctica since 1979 and understand how they may affect the isotopic signal and the resulting isotope-temperature relationships at inter-annual scale.

Moreover, in our reconstructions using 5 and 10 year average values we should in part overcome this interannual variability of precipitation and surface mass balance.

We added a sentence to section 2.3 to highlight the skill of ECHAM5-wiso to capture atmospheric rivers:

A study of the 2012 atmospheric river event in Greenland has demonstrated the skill of ECHAM5-wiso to reproduce these events, with a good representation of the water isotope signature (Bonne et al., 2014).

The second major issue is that section 4.3 on “Response to volcanic forcing” comes across as so premature that it should be dropped from the manuscript. There is no consistent signal in Figure 9. Why should one believe the results for some regions and not others without some compelling reason other than this is the expected result. Page 18, line 18 calls this “only a preliminary attempt to assess the possible climatic response of Antarctic climate to short-term volcanic eruptions”. Page 19, line 4 says “showed possible negative temperature effects in some regions”. The big story here is the temperature reconstructions that need substantially more consideration as outlined above. The inconclusive volcanic aspect is an unnecessary distraction. Better to leave this topic for detailed exploration elsewhere.

We thank the reviewer for this comment and can partly agree that the analysis may not be a 100% match to a general content of the manuscript. This section indeed shows in brief what the compiled dataset can further be used for beyond the presented analysis for the trends, touching on a much more extensive issue of climatic drivers throughout the late Holocene. Regardless of what actually drives the late Holocene cooling (so called Neoglaciation) - volcanic, orbital forcing, circulation changes triggered by volcanic/solar forcing or a combination of these factors, the study of the climate response at a short, sub-decadal timescale, contributes to answering the issue of a direct regional climate sensitivity. The major motivation for us to retain this section as is, is that it clearly demonstrates the limitations of the newly compiled dataset. In our opinion this should be considered as important as reporting the “positive” results in the rest of the manuscript.

We further demonstrate that at the present quality level of the database, unambiguous research on this topic should use the chronology control/reassessment to promote a better synchronization of the records at least on the regional level as a starting point. Emphasizing this in the present manuscript in our opinion gives a future prospective research on the topic a good starting point.

Lesser aspects:

1. Page 2, lines 17 and 19: please discriminate between the two Jones et al. (2016) references.

It is the same reference. We have deleted one citation.

2. “Weddel” is incorrectly used in Tables 3-4 and Figures 1 and 4-6.

We have corrected this error in labelling of the Tables and Figures.

3. Consider redoing the time series in Figures 4 and 5 that are too faint.

We have modified the figures to fix this issue.

4. What is the source of the NB2014 data used extensively in this analysis?

We added in section 2.2 and in Data Availability section the link to the NB2014 data archive, which is: http://polarmet.osu.edu/datasets/Antarctic_recon/

5. Page 9, line 31 onward to Page 10, line 10 discusses the very variable delta 18Otemperature slopes. To me this says that the conversion from isotope concentrations to temperature is not robust except perhaps in the Antarctic interior.

We have added Root Mean Square Error associated to each region linear regression, as reported in the table below.

Geographic region	slope (°C/‰)	slope (‰/°C)	r	p-value
1. East Antarctic Plateau	0.95 ± 0.05	1.05 ± 0.06	0.6249	0.0001
2. Wilkes Land Coast	1.91 ± 0.11	0.52 ± 0.03	0.4385	0.0084
3. Weddell Sea Coast	1.01 ± 0.06	0.99 ± 0.06	0.3411	0.0449
4. Antarctic Peninsula	2.50 ± 0.15	0.40 ± 0.02	0.3145	0.0658
5. West Antarctic Ice Sheet	1.04 ± 0.06	0.96 ± 0.05	0.5894	0.0002
6. Victoria Land Coast	0.83 ± 0.05	1.21 ± 0.07	0.4916	0.0027
7. Dronning Maud Land Coast	1.08 ± 0.06	0.93 ± 0.05	0.3868	0.0217
West Antarctica	1.03 ± 0.06	0.97 ± 0.05	0.6195	0.0001
East Antarctica	1.00 ± 0.05	1.00 ± 0.05	0.5842	0.0002

All Antarctica	1.02 ± 0.06	0.98 ± 0.05	0.5649	0.0004
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There are indeed substantial variations in the isotope-temperature slopes produced by different approaches (model or observational-based) in some parts of Antarctica. Each of the different approaches has advantages and limitations, and it is not possible with the data sources currently available to say which approach is the most robust. We note though that the differences in isotope-temperature conversions only alter the magnitude and significance of the temperature trends produced, but do not alter the sign of the trends. In this regard, we would argue that the ice core isotope data provide a robust representation of changes in Antarctic temperature, but that there is uncertainty in the scaling of isotopic changes to temperature in some regions. We propose to clarify the text to more clearly specify the implication of the differences in isotope-temperature conversions have in specific regions where there are differences in the conversions produced by different methods.

This is another reason for having an extended evaluation of isotope-temperature conversion at the end of your manuscript and how the associated uncertainties impact your results. This information (basically the error bars) is needed to ensure that a robust evaluation of climate model results can be conducted.

In our paper, we provide 4 different temperature reconstruction data sets (see figure 8 and Fig S15 in supplementary materials):

- 1) "ECHAM" method: ECHAM5-wiso to determine the regional $\delta^{18}\text{O}$ temperature relationship;
- 2) "NB2014" method: scales the normalized record to the instrumental period temperature variance;
- 3) "borehole" method: temperature scaling using the borehole measurements at WAIS divide core site (Orsi et al., 2012). This method is used for WAIS region, the West Antarctic Ice Sheet and Whole Antarctica only.
- 4) "CPS" method: used in the previous PAGES 2013 consortium paper and here using NB2014 data as a target.

The quite good agreement among these 4 method supports the robustness of our reconstructions and could provide information on T reconstruction uncertainties at regional and continental scale.

We discussed the uncertainty in the temperature reconstruction at the start of Section 4.1.2:

We estimate the uncertainty of the slope based on the $\pm 2\sigma$ uncertainty in the regression parameters. The robustness of the slope estimation to individual data points was further checked by taking out 10% of data points randomly and calculating the slope again, but the uncertainty estimates this yields is much smaller than the uncertainty based on regression parameters. The slopes obtained by each of the temperature scaling methods are presented in Table 3. The uncertainty in the amplitude of the 0-1900 CE trend is dominated by the uncertainty in the temperature scaling of the composite.

We also added in the conclusions:

Similar conclusions are reached using different approaches (ECHAM, NB2014 and borehole methods) giving support to our temperature reconstructions.

Interactive comment on data stewardship

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 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).

As soon as we know that the paper will be accepted for publication we will assemble our temperature reconstruction data to submit to NOAA and assemble metadata and data citations for all records.

Essential additions for this paper:

(1) Add a "data availability" section that describes where the data can be accessed, including a Data Citation for the temperature reconstructions generated in this study (#4 below), and the target datasets.

The data will be uploaded to NOAA and we will generate a data citation for the temperature reconstructions generated in this study.

We have added a “Data availability” section to the revised manuscript:

Data availability

The target dataset of NB2014 is archived at: http://polarmet.osu.edu/datasets/Antarctic_recon/.

The table S1 (Supplementary Information) contains the data citations, as well as the primary bibliographic reference, for each record used in this study. We used the URL links for existing published data from public repositories.

The regional and continental scale isotopic composites and temperature reconstructions generated during the current study are available in the NOAA World Data Center for Paleoclimatology (WDC Paleo) at the following link: <https://www.ncdc.noaa.gov/paleo/study/22589>.

(2) Add Data Citations (in addition to publication citations) for all 112 datasets listed in Table S1. For those data not already in a public repository, submit essential metadata along with the time series and include the Data Citation in Table S1.

We have added data citations in Table S1 (see above) for all the records used in generating the composites.

(3) For those records with previous PAGES 2k IDs, please include cross references to those IDs. These can be found in Table 1 of PAGES2k Consortium (in press). If the data are included in the Iso2k dataset, then please include a cross reference to that data product.

We have provided in Table S1 full cross referencing for all records used in the previous 2k temperature paper (PAGES 2k Consortium, 2013) and the recently published 2k Scientific Data paper (PAGES 2k Consortium, 2017).

(4) Submit the primary outcome of the data analyses to a public repository and include the Data Citation in "data availability". This includes the (a) composite isotope time series by region (Figs 2 and 3), (b) climate-region temperature reconstructions with the different scaling and binning (Figs 4 and 5), (c) Antarctica-wide (Fig 7) and broadregions reconstructions (Fig 8) with the different scaling and including the uncertainty statistics.

As soon as we know that the paper will be accepted for publication we will archive the different temperature reconstructions to NOAA (see above).

Recommended elements are:

(5) Archive the weightings used for each of the records in the weighted composite.

The matlab codes could be available from the authors upon request.

(6) Archive the target datasets, including the modeled data.

The target dataset of NB2014 is already archived at: http://polarmet.osu.edu/datasets/Antarctic_recon/. We have provided this link in the data availability section.

(7) Archive the results of the trend analyses (Fig. 6).

All the trend analysis statistics is reported in Table 3 and 4.

Antarctic climate variability at regional and continental scales over the last 2,000 years

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Abstract. Climate trends in the Antarctic region remain poorly characterised, owing to the brevity and scarcity of direct climate observations and the large magnitude of interannual to decadal-scale climate variability. Here, within the framework of the
40 PAGES Antarctica 2k working group, we build an enlarged database of ice core water stable isotope records from Antarctica, consisting of 112 records. We produce both unweighted and weighted isotopic ($\delta^{18}\text{O}$) composites and temperature reconstructions since 0 CE, binned at 5 and 10-year resolution, for 7 climatically-distinct regions covering the Antarctic continent. Following earlier work of the Antarctica 2k working group, we also produce composites and reconstructions for the broader regions of East Antarctica, West Antarctica, and the whole continent. We use three methods for our temperature
45 reconstructions: i) a temperature scaling based on the $\delta^{18}\text{O}$ -temperature relationship output from an ECHAM5-wiso model simulation nudged to ERA-interim atmospheric reanalyses from 1979 to 2013, and adjusted for the West Antarctic Ice Sheet region to borehole temperature data; ii) a temperature scaling of the isotopic normalized anomalies to the variance of the regional reanalysis temperature and iii) a composite-plus-scaling approach used in a previous continental scale reconstruction of Antarctic temperature since 1 CE but applied to the new Antarctic ice core database. Our new reconstructions confirm a

significant cooling trend from 0 to 1900 CE across all Antarctic regions where records extend back into the 1st millennium, with the exception of the Wilkes Land coast and Weddell Sea coast regions. Within this long-term cooling trend from 0-1900 CE we find that the warmest period occurs between 300 and 1000 CE, and the coldest interval from 1200 to 1900 CE. Since 1900 CE, significant warming trends are identified for the West Antarctic Ice Sheet, the Dronning Maud Land coast and the Antarctic Peninsula regions, and these trends are robust across the distribution of records that contribute to the unweighted isotopic composites and also significant in the weighted temperature reconstructions. Only for the Antarctic Peninsula is this most recent century-scale trend unusual in the context of natural variability over the last 2000-years. However, projected warming of the Antarctic continent during the 21st Century may soon see significant and unusual warming develop across other parts of the Antarctic continent. The extended Antarctica 2k ice core isotope database developed by this working group opens up many avenues for developing a deeper understanding of the response of Antarctic climate to natural and anthropogenic climate forcings. The first long-term quantification of regional climate in Antarctica presented herein is a basis for data-model comparison and assessments of past, present and future driving factors of Antarctic climate.

1 Introduction

Antarctica is the region of the world where instrumental climate records are shortest and sparsest. Estimates of temperature change with reasonable coverage across the full Antarctic continent are only available since 1958 CE (Nicolas and Bromwich, 2014), and the large magnitude of year-to-year climate variability that characterises Antarctica makes the interpretation of trends in this data sparse region problematic (Jones et al., 2016). As a result, the knowledge of past Antarctic temperature and climate variability is predominantly dependent on proxy records from natural archives. While coastal proxy records are being developed from terrestrial and marine archives (~~Jones et al., 2016~~), information on Antarctic climate above the ice sheet exclusively relies on the climatic interpretation of ice core records.

Within the variety of measurements performed in boreholes and ice cores, only water stable isotopes can provide subdecadal resolution records of past temperature changes (Küttel et al., 2012). In high accumulation areas of coastal zones and West Antarctica, annual layer counting is feasible during the last centuries to millennia (Plummer et al., 2012; Abram et al., 2013; Thomas et al., 2013; Sigl et al., 2016; Winstrup et al., ~~2017 under-in preprint~~), and annual water stable isotope signals can be delivered. However, in the dry regions of the central Antarctic plateau, where the longest ice core records are available, chronologies are less accurate and rely on the identification of volcanic deposits that can be used to tie ice cores from different sites to a common Antarctic ice core age scale (Sigl et al., 2014 and 2015).

The chemical and physical signals measured in an individual ice core reflect a local climatic signal archived through the deposition and reworking of snow layers. The intermittency of Antarctic precipitation (Masson-Delmotte et al., 2011; Sime et al., 2009), variability in precipitation source regions (Sodemann and Stohl, 2009), and post-depositional effects of snow layers including wind drift and scouring, sublimation, and snow metamorphism (Frezzotti et al., 2007; Ekaykin et al., 2014; Touzeau et al., 2016; Casado et al., 2016; Hoshina et al., 2014; Steen-Larsen et al., 2014) can distort the climate signal preserved within ice cores and produces non-climatic noise. As a result, obtaining a robust climate signal can only be achieved through the combination of multiple ice core records from a given site and/or region, and through the site-specific calibration of the relationships between water stable isotopes and temperature.

Water can be characterised by the stable isotope ratios of oxygen ($\delta^{18}\text{O}$: the deviation of the ratio of $^{18}\text{O}/^{16}\text{O}$ in a sample, relative to that of the standard, Vienna Standard Mean Ocean Water) and of ~~deuterium-hydrogen~~ (δD : the deviation of the ratio of $^2\text{H}/^1\text{H}$). Both of these parameters within ice cores provide information on past temperatures. There is solid theoretical understanding of distillation processes relating moisture transport towards the polar regions with air mass cooling and the progressive loss of heavy water molecules along the condensation pathway (Jouzel and Merlivat, 1984). This theoretical understanding is further supported by numerical modelling performed using atmospheric general circulation models equipped with water stable isotopes (Jouzel, 2014). The effects of these processes are observed in the spatial relationships between the

isotopic composition of Antarctic precipitation/surface snow and surface air temperature across the continent. However, relationships between water stable isotopes in snow and surface temperature may vary through time as a result of changes between condensation and surface temperature (in relationship to changes in boundary layer stability), changes in moisture origin and initial evaporation conditions, changes in atmospheric transport pathways and changes in precipitation seasonality or intermittency (Masson-Delmotte et al., 2008). Investigations based on the sampling of Antarctic precipitation have demonstrated that seasonal and inter-annual isotope versus temperature slopes are generally smaller than spatially-derived relationships (van Ommen and Morgan, 1997; Schneider et al., 2005; Stenni et al., 2016; Schlosser et al., 2004; Ekaykin et al., 2004; Fernandoy et al., 2010). Moreover, emerging studies combining the monitoring of surface water vapour isotopic composition with the isotopic composition retained in surface snow and precipitation have revealed that snow-air isotopic exchanges during snow metamorphism affect surface snow isotopic composition (Ritter et al., 2016; Casado et al., 2016a; ~~Casado et al., 2016b~~; Touzeau et al., 2016). It is not yet possible to assess the importance of such post-deposition processes for the interpretation of ice core water stable isotope records, but they may enhance the relationship between snow isotopic composition and surface temperature more than expected from the intermittency of snowfall (Touzeau et al., 2016). Changes in ice sheet height due to ice dynamics may also affect the surface climate trends inferred from water stable isotope records; however, this influence should be of second order over the last 2000-year interval that is the focus of this study (Fegyveresi et al., 2011).

As a result, the two key challenges to reconstruct past changes in Antarctic temperature from ice core isotope records are (1) to develop methodologies to combine different individual or stacked ice core records in order to deliver regional-scale climate signals, and (2) to quantify the temperature changes represented by water stable isotope variations.

Goosse et al. (2012) first calculated a composite of Antarctic temperature simply by averaging seven standardized temperature records inferred from water stable isotopes using a spatial isotope-temperature relationship for the last millennium. The first coordinated effort to reconstruct Antarctic temperature during the last 2000 years (PAGES 2k Consortium, 2013) screened published ice core records for annual layer counting or alignment of volcanic sulphate records and overlap with instrumental temperature data (Steig et al., 2009), leading to the selection of 11 records. The reconstruction procedure used a composite-plus-scaling approach similar to the methodology of Schneider et al. (2006), and produced reconstructions of the continent-wide temperature history as well as specific West Antarctica and East Antarctica reconstructions. The skill of the reconstructions was limited by the number of available records through time (for instance, only one predictor in each region prior to 166CE). This analysis identified significant ($p < 0.01$) cooling trends from 166 to 1900 CE, 2.5 times larger in West Antarctica than in East Antarctica. A robust cooling trend over this time period has also been identified from terrestrial and marine reconstructions from other regions (PAGES 2k Consortium, 2013; McGregor et al., 2015).

The comparison of these first Antarctic 2k time series with those from other regions obtained within the PAGES 2k working groups identified three specificities: (i) Antarctic reconstructed centennial variations did not correlate with those from other regions; (ii) the Antarctic region was the only one where a protracted cold period was not starting around 1580 CE; (iii) the Antarctic region was the only one where the 20th century was not the warmest century of the last 2000 years. A recent effort to characterize Antarctic and sub-Antarctic climate variability during the last 200 years also concluded that most of the trends observed since satellite climate monitoring began in 1979 CE cannot yet be distinguished from natural (unforced) climate variability (Jones et al., 2016), and [observed instrumental climate trends](#) are of the opposite sign to those produced by most forced climate model simulations over the same post-1979 CE interval. The only exception to this conclusion was for changes in the Southern Annular Mode (SAM), the leading mode of atmospheric circulation variability in the high latitudes of the SH, which has showed a significant and unusual positive trend since 1979 CE.

While changes in the SAM have been related to the human influence on stratospheric ozone and greenhouse gases (Thompson et al., 2011), major gaps remain in identifying the drivers of multi-centennial Antarctic climate variability. For instance, the influence of solar and volcanic forcing on Antarctic climate variability remains unclear. This is due to both the lack of

observations and to the lack of confidence in climate model skill for the Antarctic region (Flato et al., 2013). Goosse et al. (2012) have used simulations from an intermediate complexity model to attribute the Antarctic annual mean cooling trend from 850 to 1850 CE to volcanic forcing. Recent comparisons of climate model simulations with the PAGES2k regional reconstructions have highlighted greater model-data disagreement in the Southern Hemisphere (SH) than in the Northern Hemisphere (PAGES 2k–PMIP3 group, 2015; Abram et al 2016); such disagreement could be due either to model deficiencies or to large uncertainties in the reconstructions which were built on relatively small number of records. Changes in ocean heat content and ocean heat transport have likely contributed to the different temperature evolution at high southern latitudes compared to other regions of the Earth (Goosse 2017), and model based studies have suggested that circulation in the Southern Ocean may act to delay by centuries the development of sustained warming trends in high southern latitudes (Armour et al., 2016). Antarctic temperature reconstructions spanning the last 2000 years may help to better constrain the processes and timescales by which natural and anthropogenic forcing act to affect climate changes in the Antarctic region.

This motivates our efforts to produce updated Antarctic temperature reconstructions. The previous continent-scale reconstruction (PAGES 2k Consortium, 2013), where only a limited number of records have been used, may mask important regional-scale features of Antarctica’s climate evolution. Here we use an expanded paleoclimate database of Antarctic ice core isotope records and new reconstruction methodologies to reconstruct the climate of the past 2000 years, at decadal scale and on a regional basis. Seven distinct climatic regions have been selected: the Antarctic Peninsula, the West Antarctic Ice Sheet, the East Antarctic Plateau, and four coastal domains of East Antarctica. This regional selection, which is supported by regional atmospheric RACMO2.4-3p2 model results (Thomas et al., 2017; Van Wesseem et al., 2014), is applied to both Antarctic ice core-derived isotopic (temperature-proxy) and snow accumulation rate reconstructions (see companion paper in the same issue by Thomas et al.). Section 2 describes the ice core and the temperature data sets used in this study, as well as the modelling framework used to support the analysis. The climate region definition, the pre-processing of the data and the different reconstruction methods are presented in Section 3. Section 4 discusses our new regional isotopic and temperature reconstructions for Antarctica, including the application of the previous methodology to the new database. Finally, section 5 presents the summary of our results and their implications.

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2 Datasets

2.1 Ice core records

Here we present and use a new expanded database which has been compiled in the framework of the PAGES Antarctica 2k working group. The initial selection criteria are those requested by the PAGES 2k network (<http://www.pages-igbp.org/ini/wg/2k-network/data>) for the building of the community-sourced database of temperature-sensitive proxy records (PAGES2k Consortium, ~~2017~~*revised for Scientific Data*). Briefly, i) the records must be publically available and published, ii) a relation between the climate proxies and variables should be stated, iii) the record duration should be between 300 and 2000 years, iv) the chronology, certified by the data owner, should contain at least one chronological control point near the end (most recent) part of the record and another near the oldest part of the record, v) the resolution should be at least one analysis every 50 years.

In building the Antarctica2k database we also allow shorter records to be included, although request a stratigraphic control using volcanic markers (Sigl et al., 2014) and whenever possible, a dating by annual layer counted chronology. This last requirement is only possible in the high-accumulation regions of West Antarctica, the Antarctic Peninsula and coastal areas of East Antarctica. The inclusion of shorter records is designed to improve data coverage for assessments of climatic trends in Antarctica during the past century. The 11 records included in the previous continental-scale reconstruction (PAGES 2k Consortium, 2013) relied on a highly precise chronological framework consisting of a common chronology, which used 42 volcanic events to synchronize the records. Here, we use both high and low-resolution records. Most of the records have a data

resolution ranging from 0.025 to 5 years (only three records have a resolution of >10 years). Previous studies (Frezzotti et al., 2007; Ekaykin et al., 2014) have shown that post-depositional and wind scouring effects, acting more effectively when the accumulation rate is very low, limit our ability to obtain temperature reconstructions at annual resolution in most of the interior of Antarctica. Because of this, in our regional reconstructions we use 5-year averaged data for reconstructing the last 200 years, and 10-year averages for reconstructing the last 2000 years. Using 5, or 10-year averages also decreases our dependence on an annually precise chronological constraint between the ice core records, allowing us to more confidently use the expanded database. The data have been also screened for glaciological problems, with those records that are very likely to be affected by ice flow dynamics excluded.

This enlarged database consists of 112 isotopic records. A list of the records used are reported in Table S1 (Supplementary Information) and their spatial distribution is shown in Figure 1. Figure S1 shows the location of the ice core sites along with a visualization of the record lengths. Most of the records of this new database cover the last 200 years and this is particularly true for the more coastal areas. Within the database, 36 records cover just the last 50 years or less, while 50 records cover the whole length of the past 200 years. There are 15 records that cover the last 1000 years, while only 9 records reach as far back as 0 CE.

2.2 Temperature product

The instrumental record is very short in Antarctica, and most ice core sites do not have weather station measurements associated with the cores. In addition, the retrieval of the first meter of firn can be difficult, due to poor cohesion of the snow. As a result, for many sites, there is no overlap between instrumental and proxy data, which complicates the proxy calibration exercise. To enlarge the calibration dataset, we use the climate field reconstruction from Nicolas and Bromwich (2014) (hereafter NB2014; http://polarmet.osu.edu/datasets/Antarctic_recon/). This surface temperature dataset provides homogeneous data at 60 km resolution, extends from 1957 to 2013, and includes the revised Byrd temperature record (Bromwich et al., 2013) that improves the skill of the temperature product over West Antarctica. It covers a longer timespan than reliable atmospheric reanalysis products for Antarctica (which begin only 1979 CE), and has a higher spatial resolution than available isotope enabled GCM outputs. This dataset is used to estimate the spatial representativeness of individual core sites (Section 3.3.2), to scale the normalized isotopic anomaly data to temperature (Section 3.4.2), and to calculate the surface temperature reconstructions with the Composite-Plus-Scale (CPS) method (Section 3.4.4).

2.3 Modelling framework

In order to use model information on isotope-temperature relationships in Antarctic precipitation, we use a reference simulation performed using the Atmospheric General Circulation Model ECHAM5-wiso. The initial ECHAM5 model (Roeckner et al., 2003) has been equipped with water stable isotopes (Werner et al., 2011), following earlier work on ECHAM3 (Hoffmann et al., 1998) and ECHAM4 (Werner et al., 2001), and accounting for fractionation processes during phase changes. This model is used here because recent studies, based on model-data comparisons using observations of precipitation and surface vapour isotopic composition at a global scale and in the Arctic (e.g. Werner et al, 2011; Steen-Larsen et al., 2017), have shown strong model skill of ECHAM5-wiso when it is run in high resolution as in this study (T106, with a mean horizontal grid resolution of approximately $1.1^\circ \times 1.1^\circ$). [A study of the 2012 atmospheric river event in Greenland has demonstrated the skill of ECHAM5-wiso to reproduce these events, with a good representation of the water isotope signature \(Bonne et al., 2014\).](#) In Antarctica, model performance was assessed against a compilation of surface data (Masson-Delmotte et al., 2008) and recent measurements of vapour and precipitation (~~Goursaud et al., in preparation;~~ Ritter et al., 2016; Dittmann et al., 2016).

Here, we use a 1958-2014 CE simulation where ECHAM5-wiso was nudged to atmospheric reanalyses from ERA40 (Uppala et al., 2005) and ERA interim (Dee et al., 2011), and run using the same ocean surface boundary conditions (SST and sea-ice) as in ERA40 and ERA interim. Ocean surface water isotopic values were set to constant values using a compilation of

observational data (Schmidt et al., 2007). Inter-comparisons of reanalysis products showed good skills of ERA-interim for Antarctic precipitation (Wang et al., 2016), surface temperature, as well as vertical profiles of winds and temperatures. However, comparisons with in-situ observations reveal an underestimate of precipitation and slight cold bias in the surface temperatures in some regions (Thomas and Bracegirdle, 2015).

- 5 The ECHAM5-wiso simulations produce a large increase in the temperature and the $\delta^{18}\text{O}$ outputs prior to 1979, which is not observed in instrumental or ice core data (Goursaud et al., 2017; ~~Goursaud et al., in prep.~~). This arises from a discontinuity in the ERA-40 reanalyses due to the lack of observations available for assimilation and boundary conditions prior to the satellite era (e.g. Antarctic sea ice) (Nicholas and Bromwich, 2014). We therefore use the ECHAM5-wiso simulations only for 1979-2013 CE.
- 10 For the analysis of the isotope-temperature relationships at each individual ice core site, we extracted the grid point data closest to each site. For the analysis of isotope-relationships at regional scale, we calculated the area-weighted average of model outputs at grid points within the region. The $\delta^{18}\text{O}$ -temperature relationship was calculated using the annual or seasonal average 2-meter temperature and annual precipitation-weighted $\delta^{18}\text{O}$, to mimic deposition processes. The simulation does not account for post-deposition processes (i.e., diffusion, which is not important on the 5 and 10-year timescales considered here; e.g. Küttel et al., 2012).

3 Methodology

3.1 Defining climatic regions

Earlier work of the PAGES Antarctica 2k working group produced a continent-scale temperature reconstruction for the whole of Antarctica, as well as reconstructions for East and West Antarctica based on a separation approximated by the Transantarctic mountain chain (PAGES 2k Consortium 2013). These broad-scale groupings mask important regional climatic trends noted in individual studies. In particular, the absence of recent significant warming in the Antarctica 2k continent-scale temperature reconstruction is known to not be representative of all Antarctic locations (e.g. Steig et al., 2009; Mulvaney et al., 2012; Abram et al., 2013; Steig et al 2013).

In this ~~study~~ study, we choose seven climatic reconstruction regions (Figure 1). These regions are defined based on our knowledge of regional climate and snow deposition processes in the Antarctic region, as well as the availability of ice core isotope records. In particular, we separated coastal regions (below 2000m altitude) from the East Antarctic Plateau-: coastal sites receive moisture from the high-latitude ~~southern ocean~~ Southern Ocean, and are affected by the nearby sea ice cover (Masson--Delmotte et al., 2008). In contrast, high altitude sites receive moisture that has travelled at higher altitude, originating from further afield, and from clear sky precipitation (Ekaykin et al., 2004). ~~The~~ The regional selections were further validated and refined by spatial correlation of temperature using the NB2014 data product. The seven climatic regions are defined as follows (see Table S1):

1. EAST ANTARCTIC PLATEAU: All East Antarctic contiguous regions at an elevation higher than 2000m, including everything south of 85°S. We exclude high peaks of the Transantarctic Mountains if they belong to the Victoria Land - Ross Sea coast (e.g. Taylor Dome or Hercules Nève).
2. WILKES LAND COAST: A region that sits at an altitude <2000m, and extends from Lambert Glacier (67°E) east to the start of Victoria Land and the Transantarctic Mountains (160°E).
3. WEDDELL SEA COAST: Extending eastward from longitude 60°W to 30°W, and south of 75°S, and lying at an altitude <2000m. Eastward of the 30°W longitude, the 75°S latitude defines the boundary with the Dronning Maud Land coast region, with the northeastern corner of the Weddell Sea coast region occurring where the 75°S latitude meets the 2000m elevation contour. This region includes the Filchner Ice Shelf and most of the Ronne Ice Shelf.

4. ANTARCTIC PENINSULA: This region encompasses the mountainous Antarctic Peninsula. Between 74°S and 70°S the longitudinal boundaries lie between 60-80°W, while north of 70°S the longitudinal boundaries increase to 50-80°W so as to capture the northern end of the peninsula.

5. WEST ANTARCTIC ICE SHEET: A region bounded by longitudes 60°W to 170°W, and north of 85°S. In the Peninsula region (60-80°W) a northern bound of 74°S is also applied.

6. VICTORIA LAND COAST - ROSS SEA: This region is north of 85°S, and at an altitude <2000m, with the exception of some localised peaks within the Trans-Antarctic mountain range. It extends from 160°E to 190°E (i.e. 170°W) and incorporates most of the Ross Ice Shelf.

7. DRONNING MAUD LAND COAST: Extending eastward from 30°W to 67°E (Lambert glacier). The southern-most boundary lies at 75°S (where this region borders with the Weddell Sea region), or at the 2000-meter elevation contour elsewhere.

In addition to these seven climatic regions, we also produce reconstructions for a continent-wide Antarctic region. Broad-scale East Antarctic (incorporating the climatic regions of the East Antarctic Plateau, as well as the Weddell Sea, Dronning Maud Land, Wilkes Land and Victoria Land coasts) and West Antarctic (incorporating the climatic regions of the West Antarctic Ice Sheet and Antarctic Peninsula) reconstructions are also presented. These additional reconstructions facilitate comparisons of our new results, using additional methods and an expanded database, with earlier findings of the Antarctica 2k working group and subsequent research using the 2013 continent-scale reconstruction for Antarctic temperature.

3.2 Data pre-processing

All ice core records in the Antarctica 2k database were assigned to one of the climatic regions described in section 3.1 (as well as to East vs. West Antarctica, and to the Antarctic-wide classifications). The majority (94 out of 112) of ice core water isotope records in the database are based on oxygen isotope ratios ($\delta^{18}\text{O}$). In cases where only deuterium isotope (δD) data is available, the ice core time series were converted to $\delta^{18}\text{O}$ -equivalent by dividing by 8, a value that represents the slope of the global mean meteoric relationship of oxygen and deuterium isotopes in precipitation, and is close to the ratio of 7.75 observed in surface Antarctic snow (Masson-Delmotte et al., 2008).

The ice core $\delta^{18}\text{O}$ (and $\delta^{18}\text{O}$ -equivalent) records were compiled on a common annual average age scale. For records with sub-annual resolution this involved averaging all data from within a calendar year to generate an annual average dataset. Pseudo-annual records were generated for the ice core $\delta^{18}\text{O}$ records with lower than annual resolution. These pseudo annuals assume that each low-resolution isotopic value represents an average of the full-timefull-time interval that the sample covers. As such, a nearest-neighbour interpolation method was used to generate stepped (piecewise constant) pseudo-annual records that continue the measured isotopic value across all of the calendar years that it represents.

Records were next binned to 5y and 10y average resolution and converted to $\delta^{18}\text{O}$ anomalies. This reduction in resolution is designed to reduce the influence of small age uncertainties between the records, as well as the non-climatic noise induced by post-deposition (e.g. wind erosion, diffusion) processes (Frezzotti et al. 2007; Ekaykin et al., 2014). The 5y resolution records were converted to anomalies relative to their mean over the 1960-1990 CE interval, and records that don't include a minimum of 6 bins (30y) coverage since 1800 CE are excluded based on length. Overall, 79 records in the new Antarctica 2k water isotope database meet the minimum requirement of having at least 30y data coverage since 1800 CE. In some cases, records meet this minimum length requirement but do not include data for the full 1960-1990 CE reference interval. We adjust the mean value of each of these records by matching the mean $\delta^{18}\text{O}$ of their most recent 6 bins (30y) of data to the mean of all anomaly records from the same climatic region and over the same 6-bin interval. We also produce normalised records by adjusting the variance of the records using the same reference period and method as for the anomaly records.

The 10y resolution anomaly and normalised records were generated using the same method but using a reference period of 1900-1990 CE and a minimum data coverage of 9 bins (90y) since 0 CE. Similarly, records that don't include the full 1900-

1990 CE reference period have the mean of their most recent 9-bin (90y) interval adjusted to match the mean of all other anomaly records from the same region and over the same 9-bin interval. Overall, 67 records in the new Antarctica 2k water isotope database meet the minimum requirement of having at least 90y data coverage since 0 CE

Some regions of Antarctica include dense networks of ice core data, such as coastal and plateau sites in Dronning Maud Land (Fig. S1). To reduce possible bias towards these data-rich regions an additional data reduction method was used, based on a 2° latitude by 10° longitude grid. Where multiple ice core records from the same climatic-region fall within the same grid cell, their isotopic anomalies (or normalised data) are averaged to produce a single composite time series for the grid. This replicates the simple unweighted compositing method described in section 3.3.1, but at the grid-scale to reduce the representation of data-rich areas prior to the regional compositing. Supplementary figures 2 and 3 show the distribution of records by region that meet the 6-bin (30y) and 9-bin (90y) minimum requirements for the 5y and 10y composites, respectively, after the gridded data reduction step.

3.3 Compositing Methods

We use a suite of reconstruction methods of varying complexity in order to assess robust trends and variability in Antarctic ice core $\delta^{18}\text{O}$ records and temperature.

3.3.1 Unweighted Composites

Our first reconstruction method involves calculating simple composites of $\delta^{18}\text{O}$ anomalies. For each 5 or 10y bin we calculate the mean $\delta^{18}\text{O}$ anomaly across all records in the climatic region, as well as the distribution of $\delta^{18}\text{O}$ anomalies within each bin (Figures 2 and 3). This basic reconstruction method is analogous to that used for the Ocean 2k low-resolution reconstruction (McGregor et al. 2015). The benefit of this simple method is that it requires no weighting or calibration assumptions, which is advantageous for data sparse regions such as Antarctica (and the global oceans). The disadvantage is that it applies equal weighting to all records within a climatic region, which may introduce biases related to record length, location and climatic skill.

3.3.2 Weighted composites based on site-level temperature regressions

In order to avoid biases from uneven data sampling, we performed, for each region, a multiple regression between each site temperature and the relevant regional average temperature (Figures 2 and 3). Most of the ice core records do not cover the full instrumental period, so it is problematic to use the $\delta^{18}\text{O}$ anomalies directly to determine the regression vectors required for a weighted temperature reconstruction. Instead, we use the climate field reconstruction of NB2014 to estimate the weights: the annual mean temperature time series at the grid cell corresponding to each ice core site is extracted from the NB2014 product, and the regional average is also calculated for each reconstruction region. Regression-based weightings are calculated based on the relationship between site temperature and regional average temperature, and the regression is performed for each combination of ice core records through time. The weights are then applied to the ice core $\delta^{18}\text{O}$ anomalies to produce regional averaged standardized anomalies.

We further reproduced this regression method using both the $\delta^{18}\text{O}$ and temperature field outputs from the ECHAM5-wiso experiments. The regression of site- $\delta^{18}\text{O}$ against regional average- $\delta^{18}\text{O}$, or site-temperature onto regional-temperature gave nearly identical weighting factors, supporting the use of the temperature field to calculate regressions. The effects of the different weighting methods on each regional isotopic composite, as well as the initial 10y isotopic anomaly records, are reported in the Supplementary Information (Figures from S4 to S10). The small differences between ECHAM and NB2014-based regressions were due to the lower resolution of ECHAM-5wiso, which does not include islands and topographic features such as Roosevelt Island and Law Dome. For this reason, we preferentially use the NB2014 dataset for the temperature regression reconstruction method.

3.4 Temperature Reconstructions

The relationship between $\delta^{18}\text{O}$ and local surface temperature is complicated by the influence of a large range of processes (origin of moisture sources, intermittency in precipitation, snow drift, snow-air exchanges, snow metamorphism, diffusion in ice cores). It is not possible to ~~take into account~~ consider each process independently, because in many cases, there are simply no observations to constrain them well enough. However, the atmospheric circulation often leads to several processes to be correlated (reduced sea ice, increased precipitation and warmer temperature, for instance). We follow here the classical approach, which is to perform a linear regression of ice core $\delta^{18}\text{O}$ with local surface temperature, on the regional average products. This method has the advantage of looking at all the climatic processes influencing $\delta^{18}\text{O}$ in “bulk”, and the use of regional average allows us to limit the influence of small-scale processes.

The lack of an overlap period between our site $\delta^{18}\text{O}$ records and direct temperature observations makes the proxy calibration difficult. The CPS method (Section 3.4.4), which replicates the 2013 PAGES 2k reconstruction method, is limited to sites where this calibration is possible. ~~In order to~~To overcome this limitation and include the largest number of records, we also use models to scale the regional isotope composites. A first method uses ECHAM5-wiso to determine the regional $\delta^{18}\text{O}$ -temperature relationship in a mechanistic way (Section 3.4.1). A second method uses a more statistical approach, and simply scales the normalized record to the instrumental period temperature variance (Section 3.4.2). ~~Both of these~~Both approaches are equally valid and share the same hypothesis: that the instrumental period (1979-2013) is representative of the longer-term climate variability. Finally, for the West Antarctic Ice Sheet region, an independent longer-term temperature record is available from borehole temperature measurements (Orsi et al., 2012). We use this independent temperature record to scale the long term 1000-1600 temperature trend for the West Antarctic Ice Sheet region, to provide our best estimate of temperature change in line with current knowledge (Section 3.4.3).

~~In the figure captions, we refer to the different methods as “ECHAM”, “NB2014” and “borehole”, respectively. We refer to this scaling as the “ECHAM” method in the figure captions. We refer to this scaling as the “NB2014” method in the figure captions.~~

3.4.1 Scaling using model-based regional $\delta^{18}\text{O}$ -Temperature relationships

We use the coherent physical framework of the 1979-2013 CE simulation performed at T106 resolution with ECHAM5-wiso to infer constrains on regional $\delta^{18}\text{O}$ -temperature slopes through linear regression analysis between regional averages of simulated annual mean temperature and precipitation-weighted $\delta^{18}\text{O}$ (Table 1). These regional $\delta^{18}\text{O}$ -temperature regressions were applied to the regional ice core composites ($\delta^{18}\text{O}_{\text{region}}$ anomalies) to scale them from $\delta^{18}\text{O}$ to temperature units (Figures 4 and 5), and produce temperature anomalies (T_{region}). ~~The correlation coefficient α_{region} is calculated using the York et al. (2004) method, taking into account uncertainties both in T_{region} and in $\delta^{18}\text{O}_{\text{region}}$, with each prior uncertainty equals to 20% of the variance.~~

$$T_{\text{region}} = \alpha_{\text{region}} \delta^{18}\text{O}_{\text{region}} = \alpha_{\text{region}} \sum_{\text{sites } i} w_i \delta^{18}\text{O}_i$$

In this equation, w_i represents the weights assigned to each site i , and $\delta^{18}\text{O}_i$ the site $\delta^{18}\text{O}$ anomalies in 5 or 10 year averaged records. The limited length of the observational period (1979-2013 CE), does not allow us to precisely estimate the slope α on 10-year averages, and we preferred to use 1-year anomalies, where the slopes are significant (Table 1), and apply these slopes on the 10-year binned composites. It implies that the interannual $\delta^{18}\text{O}$ -temperature relationship comes from mechanisms that are also applicable to decadal scale variability. It is impossible to further test this hypothesis without longer independent temperature records. The use of the ECHAM-wiso isotope enabled climate model is the most up-to-date tool we have to

quantify the $\delta^{18}\text{O}$ -temperature on broad spatial-temporal scales, and is our best tool to infer the $\delta^{18}\text{O}$ -temperature relationship in the absence of data. Its main limitation is the model resolution: it is missing some coastal topographical features, notably James Ross Island, Roosevelt Island, and Law Dome, and cannot faithfully represent regions where these sites are important.

~~We refer to this scaling as the “ECHAM” method in the figure captions.~~

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Table 1: Linear regression analysis (slope with $\pm 1\sigma$ uncertainty, correlation coefficient r , and p -value) of the simulated $\delta^{18}\text{O}$ -temperature relationships extracted from the ECHAM5-wiso model for each climatic region, as well as the broad East Antarctic, West Antarctic and whole Antarctic regions.

Geographic region	<u>slope</u> ($^{\circ}\text{C}/\text{‰}$) slope	<u>slope</u> ($\text{‰}/^{\circ}\text{C}$)	<u>r</u>	<u>p-value</u>
1. East Antarctic Plateau	<u>0.95 ± 0.05</u> 0.66	<u>1.05 ± 0.06</u>	<u>0.62</u>	<u>0.0001</u> <0.001
2. Wilkes Land Coast	<u>1.91 ± 0.11</u> 0.23	<u>0.52 ± 0.03</u>	<u>0.44</u>	<u>0.0084</u> 0.0084
3. Weddell Sea Coast	<u>1.01 ± 0.06</u> 0.34	<u>0.99 ± 0.06</u>	<u>0.34</u>	<u>0.0449</u> 0.0449
4. Antarctic Peninsula	<u>2.50 ± 0.15</u> 0.13	<u>0.40 ± 0.02</u>	<u>0.31</u>	<u>0.0658</u> 0.0658
5. West Antarctic Ice Sheet	<u>1.04 ± 0.06</u> 0.57	<u>0.96 ± 0.05</u>	<u>0.59</u>	<u>0.0002</u> <0.001
6. Victoria Land Coast	<u>0.83 ± 0.05</u> 0.59	<u>1.21 ± 0.07</u>	<u>0.49</u>	<u>0.0027</u> 0.00271
7. Dronning Maud Land Coast	<u>1.08 ± 0.06</u> 0.36	<u>0.93 ± 0.05</u>	<u>0.39</u>	<u>0.0217</u> 0.0271
<u>East-West</u> Antarctica	<u>1.03 ± 0.06</u> 0.58	<u>0.97 ± 0.05</u>	<u>0.62</u>	<u>0.0001</u> <0.001
<u>West-East</u> Antarctica	<u>1.00 ± 0.05</u> 0.55	<u>1.00 ± 0.05</u>	<u>0.58</u>	<u>0.0002</u> <0.001
All Antarctica	<u>1.02 ± 0.06</u> 0.60	<u>0.98 ± 0.05</u>	<u>0.56</u>	<u>0.0004</u> <0.001

10

All regional $\delta^{18}\text{O}$ temperature relationships produced by the ECHAM-wiso output are statistically significant (at 95% confidence) with the exception of the Antarctic Peninsula. Weak correlations are also found for the Weddell Sea coast ($r = 0.34$). Stronger correlation coefficients are obtained inland, for the larger-scale East and West Antarctic sectors, and maximum values ($r=0.62$) are identified ~~at~~ for the whole East Antarctic Plateau-scale.

15

Similarly, the simulated regional $\delta^{18}\text{O}$ -temperature slopes are highest for ~~the inland plateau~~ Victoria Land (0.66 ~~1.2146~~ $\text{‰ } ^{\circ}\text{C}^{-1}$) and lowest for the Peninsula (0.13 ~~0.4015~~ $\text{‰ } ^{\circ}\text{C}^{-1}$). ~~These~~ low slopes for the Antarctic Peninsula ~~does~~ not agree with the temporal $\delta^{18}\text{O}$ -temperature relationships that have ~~has~~ been reported for the highly-resolved James Ross Island ice core (0.86 $\text{‰ } ^{\circ}\text{C}^{-1}$; Abram et al., 2011), while it is similar to one reported for the Gomez ice core (0.5 $\text{‰ } ^{\circ}\text{C}^{-1}$; Thomas et al., 2009) ~~ice~~ cores and ~~for~~ precipitation samples collected at the O’Higgins Station (0.41 $\text{‰ } ^{\circ}\text{C}^{-1}$, Fernandoy et al., 2012). ECHAM finds that the only site on the peninsula with a significant correlation between $\delta^{18}\text{O}$ and temperature is Bruce Plateau (66°S , 64°W) (slope= 0.63 ± 0.58 $\text{‰ } ^{\circ}\text{C}^{-1}$, $r=0.13$, $p=0.03$), and the overall low $\delta^{18}\text{O}$ -temperature slope is largely attributable to model resolution. We expect that the ECHAM scaling will produce a temperature reconstruction with a low~~high~~-amplitude bias in the Antarctic Peninsula.

20

High slopes similar to the ~~inland East Antarctic plateau~~ Victoria Land are identified in the inland East Antarctic plateau, Weddell Sea Coast ~~Victoria Land~~ and West Antarctic Ice Sheet regions (~~0.59~~1.058, 0.998 and ~~0.57~~0.964~~0.96~~ $\text{‰ } ^{\circ}\text{C}^{-1}$, respectively), together with intermediate values in coastal ~~regions (i.e. coastal Indian, Weddell Sea and Dronning Maud Land regions)~~ with a 0.93~~1.182~~ $\text{‰ } ^{\circ}\text{C}^{-1}$ mean slope. At the whole Antarctic ice sheet scale, the overall temporal slope is dominated by inland regions and simulated at 0.60~~0.986~~ $\text{‰ } ^{\circ}\text{C}^{-1}$. This analysis is more thoroughly examined in a study comparing an isotopic dataset from surface snow, snowfalls and ice cores (Goursaud et al., in prep).

30

3.4.2. Scaling based on NB2014 variance

In addition, we used an independent method of scaling the normalized $\delta^{18}\text{O}$ anomalies to the standard deviation ($\sigma(T)$) of the regional temperature from NB2014, over the 1960-1990 CE interval for the 5-year binned averages, and the period 1960-2010 CE for the 10-year binned averages. This scaling is similar to the one used for the CPS method (see next section).

$$T_{region} = \sigma(T)_{region} \delta^{18}O_{region} (normalized)$$

This scaling method implies that the $\delta^{18}O$ -temperature relationship can be inferred from the ratio of temperature to $\delta^{18}O$ standard deviation, which would be true if the relationship between the two was purely linear. If some of the $\delta^{18}O$ variance is due to something else than temperature, this scaling will under-estimate temperature variations. This method also assumes that the last 30 to 50 years provide a good estimate of the 5 or 10-year temperature variance. In the absence of longer temperature reconstructions, this is the best estimate of $\sigma(T)_{region}$ that we can provide.

~~We refer to this scaling as the “NB2014” method in the figure captions.~~

3.4.3. Scaling based on borehole temperature for the WAIS region.

In the West Antarctic Ice Sheet region, the approaches described above give different results (Figs 4 and 5), with the first method (temperature scaling from the $\delta^{18}O$ -T relationship in ECHAM-wiso) giving a smaller amplitude. At WAIS-Divide, there is an independent temperature record, which can be used to scale the long-term temperature evolution. We used the borehole temperature reconstruction at WAIS Divide (Orsi et al, 2012) to adjust the amplitude of temperature variations, matching the cooling trend over the period 1000-1600 CE ($-1.1^{\circ}C.1000y^{-1}$). with a correction factor relating the WAIS-Divide site to the West Antarctic region ($C=\sigma_{WAIS}/\sigma_{WDC} = 0.65$), with σ_{WAIS} the standard deviation of the annual NB2014 WAIS regional mean dataset, and σ_{WDC} the standard deviation of the annual NB2014 time series at the WAIS-Divide site, which gives a 1000-1600 cooling trend of $-0.76^{\circ}C$.

This scaling is actually in line with the ~~scaling inferred from the NB2014 variance over 1960-2010 CE~~ other two scalings: (1000-1600 slope of $-0.65^{\circ}C$ for ECHAM and $-1.01^{\circ}C$ for NB2014 scaling). The temperature calibration presented here is the best estimate we can provide with current knowledge, but we expect it to be revised in the future, with more precise $\delta^{18}O$ modeling, and more independent quantitative temperature reconstructions.

~~We refer to this scaling as the “borehole” method in the figure captions.~~

3.4.4 Replication of the 2013 Antarctica2k reconstruction method

To facilitate comparison with the preceding Antarctica2k temperature reconstruction published by the PAGES 2k Consortium (2013), we apply their reconstruction method to the updated ice-core isotope data collection. The method is a simple Composite-Plus-Scale (CPS) approach (Jones et al., 2009), updated from Schneider et al. (2006) and implemented similarly to Neukom et al. (2014). We apply this method to all sub-regions defined above, the broad East and West Antarctic divisions and to the Antarctic-wide database, replicating the Antarctic reconstructions presented in the PAGES 2k Consortium (2013) study.

First, the annual-average records are allocated to the climatic regions as defined above. The following steps are then repeated for each region separately. Second, only the records with no missing values in the 1961-1991 CE calibration period are selected. These records are then scaled to mean zero and unit standard deviation over their common interval of data availability. Next, the normalised records are correlated against the NB2014 regional mean temperatures over 1961-1991 CE. Between 0% and 33% of the ice core records within each region have negative correlations (physically implausible) with the target and are removed from the proxy matrix. A composite of the remaining records is then calculated by creating a weighted average, where the weighting of each ice core record is based on its temperature correlation from the previous step. The composite is then scaled to the mean and standard deviation of the NB2014 regional temperatures over the 1961-1991 CE period. The compositing and scaling steps are done in a nested approach, i.e. repeated for all periods with different proxy data availability. In the reconstruction of the PAGES 2k Consortium (2013), three records were infilled with neighbouring sites to have no missing data in the calibration window: WDC06A was infilled with data from WDC05A, Siple Station and Plateau Remote were infilled by least median of squares multiple linear regression using nearby records (PAGES 2k Consortium, 2013). To allow comparison, we also used the infilled data for these records. Thus, the only difference to the reconstruction of PAGES

2k Consortium (2013) is that we use an extended proxy database with more records and an updated temperature target (NB2014 instead of Steig et al. 2009).

While this CPS approach allows a quantitative calibration to the NB2014 temperature data, it has some limitations compared to the above methods. First, in this implementation it allows only the inclusion of data covering the calibration period, thereby removing more than half of the available records (62 out of 112). Second, the calibration period is extremely short and therefore individual years (for example with outliers) can significantly bias the reconstruction and reasonable validation of the reconstruction is hardly possible. The main difference from the other compositing methods described above is the weight of each record and the interval, over which the data are standardized.

4 Results and Discussion

10 We use the varying reconstruction methods to identify robust trends in the Antarctic ice core database. We present results based on isotopic trends, as well as temperature reconstructions, and examine these for the seven climatic regions and for the larger-scale Antarctic regions (Section 4.1); compare our results to the previous Antarctic temperature reconstruction (Section 4.2), and investigate the link between temperature and volcanic activity (Section 4.3).

4.1 Regional-scale $\delta^{18}\text{O}$ and temperature reconstructions

15 Five year-binned $\delta^{18}\text{O}$ composite records since 1800 CE years are reported for each of the seven climatic regions in Supplementary Figure 2 (unweighted isotope anomalies) and Figure 2 (weighted and unweighted data). The unweighted composites are shown with respect to the distributions of data within each bin, and expressed relative to the 1960-1990 CE interval. Figure 2 also shows the reconstructions that are obtained by weighting the records within each region based on the NB2014 temperature field and by the ECHAM5-wiso $\delta^{18}\text{O}$ field. Figure 3 (and Supplementary Figure 3) shows equivalent data, but for 10y averages since 0 CE relative to the 1900-1990 CE interval.

The highest density of ice core records is present in the last century, but these are not evenly distributed over Antarctica (Supplementary Figure 1) with most of the records in the plateau and coastal areas of Dronning Maud Land and across the West Antarctic Ice Sheet. On the other hand, only 1 and 3 records are present in the Weddell Sea and Wilkes Land coastal areas, respectively.

25 In order to separate the uncertainties due to the stacking procedure from uncertainties in the temperature scaling, we first discuss the main features of the un-weighted regional $\delta^{18}\text{O}$ anomalies (Section 4.1.1), and then proceed to discuss the weighted regional $\delta^{18}\text{O}$ anomalies, and finally the temperature reconstructions. The weighted and unweighted composites produce similar results for the seven climatic regions (see figures in Supplementary Information from S4 to S10), suggesting that our reconstructions are robust, and don't depend on the exact methodology used (Figures 2 and 3). There are two exceptions to this: the Antarctic Plateau (Fig. S4), where the many sites in Dronning Maud Land perhaps still bias the simple average towards this area even with the gridded data-reduction process, and the West Antarctic ice Sheet (Fig. S8) where the two long records from WAIS-Divide and Roosevelt Island (RICE) have diverging trends for much of the last 2000 years. The weighted reconstruction gives a higher weight to WAIS-Divide, which maintains a long-term negative isotopic trend over the last 2ka in this region (see section 4.1.2). We further checked that WAIS-Divide is indeed more representative of temperatures averaged across the West Antarctic Ice Sheet region than RICE looking at temperature correlation maps which use the NB2014 temperature field (Fig. S8). The temperature reconstructions obtained with the different methods are further shown in Fig. S15. We assess trends for the seven climatic regions (and in the larger-scale Antarctic groupings) for the reconstructions prior to 1900 CE (up to 1,900 years length) (Section 4.1.2), and since 1900 CE (up to 110 years length) (Section 4.1.3), and estimate the significance of the most recent 100-year trend relative to natural variability (Section 4.1.4).

40

4.1.1 Trend significance in unweighted composites

We first use a Monte Carlo approach to assess the significance of trends in the unweighted composites. This test is designed to test the significance of trends in relation to the distribution of data within each bin of the isotopic composites. For each bin where 2 or more ice cores contribute data we scale random Gaussian data about the median value and $\pm 2\sigma$ distribution of isotopic data within that bin. We then sample from this scaled Gaussian data to produce 10,000 simulations of each regional composite. We then assess the proportion of ensemble members which produce trends of the same sign as the mean composite, and the proportion of ensemble members where the trend is of the same sign as the mean composite and also significant at greater than 95% confidence. These trend analyses are based on 10-year binned isotopic anomalies for trends prior to 1900 CE, and 5-year binned data for trends over the last 100 years of the composites (although equivalent results are found if 10-year binned data are used to assess trends in the last 100 years).

Results of unweighted composite trend analysis are summarised in Table 2. This analysis shows that for the unweighted composites the long-term cooling trend from 0-1900 CE is only significant for the East Antarctic plateau. Visual examination of the unweighted composites (Figure 3) suggest that many of the other climate regions appear to also have a negative unweighted isotopic trend over part of the last 2000 years (e.g. Wilkes Land and West Antarctic Ice Sheet regions), but these trends are not significant in the unweighted composites when calculated across the full interval from 0-1900 CE. The Victoria Land coast trend prior to 1900 CE is not significant in the mean or median unweighted composites, but over the interval where two or more ice cores contribute to the composites the Monte Carlo assessments indicate that negative isotopic trends are produced in all 10,000 ensemble members and are significant ($p < 0.05$) more often than can be explained by chance alone.

The significant trend that is produced in the unweighted composite for the East Antarctic Plateau climate region is also evident in the broader East Antarctic compilation and for the Antarctic continent-scale composite. The continent-scale cooling trend produced in unweighted composites using the expanded Antarctica 2k database is in agreement with the PAGES 2k Consortium (2013) results where a long-term cooling trend over the Antarctic continent was identified. It is also consistent with robust pre-industrial cooling trends that have been identified in other continental reconstructions (PAGES 2k Consortium, 2013) and in the global oceans (McGregor et al 2015).

Isotopic trends in the last 100 years of the unweighted composites show significant positive trends across a number of regions. In particular, significant isotopic trends, indicative of climate warming, are evident in the unweighted composites for the Antarctic Peninsula, and the Wilkes Land and Dronning Maud Land coasts. The West Antarctic Ice Sheet region does not display a significant ($p < 0.05$) positive trend in the mean or median of the unweighted composites, but the Monte Carlo analysis across the distribution of isotopic data within each 10-year bin suggests that positive trends are produced in 99.5% of the 10,000 simulations and are significant ($p < 0.05$) more often than can be explained by chance alone (20.5% of simulations). Similarly, the Victoria Land-Ross Sea region shows a negative but insignificant trend in the mean and median composites, but in the Monte Carlo simulations this negative (cooling) trend is produced in 99.9% of ensemble members and is significant in 13.6% of ensemble members. The apparent inverse isotopic trends during the last century between the Victoria Land-Ross Sea region and the West Antarctic Ice Sheet and Antarctic Peninsula regions may be indicative of dynamical processes in the Amundsen Sea sector, which on interannual time scales are known to cause opposing climate anomalies between these regions. The PAGES 2k Consortium (2013) study concluded that Antarctica was the only continent-scale region to not see of the long-term cooling trend of the past 2000 years reverse to recent significant warming. However, at the regional scale examined in this study recent significant warming is suggested by many of the unweighted isotopic composites, particularly for coastal regions of Antarctica and the West Antarctic ice sheet. It should be stressed that these results are based only upon the simple unweighted compositing of the regional isotopic data, and the significance of trends is further assessed in the following section after weighting of the individual ice core records based on how representative they are of isotopic and temperature variability within each climatic region.

Table 2: Summary of trend statistics for isotopic anomalies using unweighted composites. Trends are expressed as isotopic anomalies, in per mil $\delta^{18}\text{O}$ per decade units. Trends and their significance (p; based on the Student's t-statistic) are calculated using a linear additive model, and reported for the mean and median composites. Monte Carlo testing is applied to 10,000 ensemble members based on the unweighted composite distributions, which are assessed to determine the percentage of trends with the same sign as the mean trend, and the percentage with the same sign and a significance of $p < 0.05$. Bold values indicate mean and median trends with a significance of $p < 0.05$, and Monte Carlo simulations where significant, same-signed trends exceed 5% of the ensemble.

Region	Pre-1900 CE trends			Last 100y trends		
	Mean trend ‰ 10y ⁻¹ (p)	Median trend ‰ 10y ⁻¹ (p)	Monte Carlo % (% p<0.05)	Mean trend ‰ 10y ⁻¹ (p)	Median trend ‰ 10y ⁻¹ (p)	Monte Carlo % (% p<0.05)
1. East Antarctic Plateau	-0.003 (0.000)	-0.002 (0.000)	100 (99.2)	0.011 (0.675)	0.040 (0.096)	96.2 (14.1)
2. Wilkes Land coast	0.017 (0.444)	0.017 (0.444)	80.6 (2.3)	0.098 (0.001)	0.098 (0.001)	100 (90.5)
3. Weddell Sea coast	-0.002 (0.376)	-0.002 (0.376)	-	-0.060 (0.318)	-0.060 (0.318)	-
4. Antarctic Peninsula	0.006 (0.188)	0.004 (0.361)	84.3 (2.9)	0.112 (0.000)	0.111 (0.000)	100 (98.2)
5. West Antarctic ice sheet	0.000 (0.435)	0.000 (0.428)	85.4 (1.4)	0.033 (0.226)	0.042 (0.091)	97.0 (14.4)
6. Victoria Land Coast- Ross Sea	-0.006 (0.118)	-0.006 (0.101)	100 (12.76)	-0.054 (0.220)	-0.074 (0.102)	99.9 (13.6)
7. Dronning Maud Land Coast	-0.032 (0.366)	-0.027 (0.448)	95.3 (0.1)	0.147 (0.000)	0.158 (0.001)	100 (99.8)
East-West Antarctica	0.000 (0.437) 0.003 (0.000)	-0.001 (0.118) 0.002 (0.000)	95.57 (11.2) 100 (100)	0.054 (0.021) 0.037 (0.035)	0.082 (0.001) 0.064 (0.003)	100 (79.8) 99.8 (55.1)
West-East Antarctica	-0.003 (0.000) 0.000 (0.437)	-0.002 (0.000) 0.001 (0.118)	100 (100) 95.57 (11.2)	0.037 (0.035) 0.054 (0.021)	0.064 (0.003) 0.082 (0.001)	99.8 (55.1) 100 (79.8)
All Antarctica	-0.002 (0.000)	-0.002 (0.000)	100 (99.5)	0.044 (0.005)	0.073 (0.000)	99.9 (76.2)

4.1.2 Long term trends in weighted reconstructions

To extend this trend analysis further we next assess the pre-1900 CE (Figure 5) trends in the temperature reconstructions produced by scaling the ice core data based on our different approaches (see section 3.3.3). We estimate the uncertainty of the slope based on the $\pm 2\sigma$ uncertainty in the regression parameters. The robustness of the slope estimation to individual data points was further checked by taking out 10% of data points randomly and calculating the slope again, but the uncertainty estimates this yields is much smaller than the uncertainty based on regression parameters. The slopes obtained by each of the temperature scaling methods are presented in Table 3. The uncertainty in the amplitude of the 0-1900 CE trend is dominated by the uncertainty in the temperature scaling of the composite. To make the discussion clear, we first focus on the trend in terms of normalised $\delta^{18}\text{O}$ anomalies, with respect to the 1900-1990 CE periods, which circumvents the temperature scaling issues.

The period 0-1900 CE exhibits significant negative trends in most regions, from -0.4 to -1.32σ 1000y⁻¹. The trend is largest in West Antarctic Ice Sheet ($-1.32 \pm 0.23\sigma$ 1000y⁻¹), Victoria Land ($-0.899 \pm 0.394\sigma$ 1000y⁻¹), and the Antarctic Plateau ($-0.768 \pm 0.283\sigma$ 1000y⁻¹) regions. It is smaller but still significant for the Wilkes Land coast ($-0.596 \pm 0.485\sigma$ 1000y⁻¹, $p=0.007$) and Antarctic Peninsula ($-0.50 \pm 0.223\sigma$ 1000y⁻¹). It is insignificant on the Weddell Sea coast ($p=0.3$), and the dataset is not long enough to estimate millennial-scale trends on the DML coast. These observations indicate a broad scale cooling trend over the continent, that is comparable in amplitude to the variance over the past 100 years. As previously mentioned, the 0-1900 CE negative trend is largest in the normalized datasets for the West Antarctic Ice Sheet region, but this feature masks

sub-regional scale differences, with the RICE record indicating increasing rather than decreasing anomalies. This result is puzzling because both WAIS Divide (to the west) and Victoria Land cores (e.g. VLG, to the east of RICE) show a clear cooling trend prior to 1900 CE, and together this points to a more complex picture of the evolution of the atmospheric circulation around the Ross Sea than can be captured with the current network of cores. The RICE $\delta^{18}\text{O}$ record, situated on Roosevelt Island on the Ross Ice Shelf, is more influenced by air masses from the eastern Ross Sea sector than the rest of the West Antarctic Ice Sheet region which is influenced predominantly by air masses from the Amundsen Sea (Neff et al., 2015; Emanuelsson et al. ~~in~~under review). Moreover, borehole temperature and $\delta^{15}\text{N}$ thermal fractionation records at RICE highlight some notable differences to the isotope temperature reconstruction, which suggest that sea ice extent exerts an important control, perhaps masking aspects of the longer-term temperature trends in the region (Bertler et al., ~~in preparation~~RICE Community, 2017 under review).

Over the period from 0-1900 CE the ECHAM temperature scaling suggests that the mean cooling trends are $-0.2^{\circ}\text{C}-38^{\circ}\text{C}$ 1000y^{-1} for the east Antarctic Plateau ~~and Antarctic Peninsula~~, $-0.3^{\circ}\text{C}-47^{\circ}\text{C}$ 1000y^{-1} for the West Antarctic ice sheet, $-0.52^{\circ}\text{C}-1000\text{y}^{-1}$ for the Antarctic Peninsula, and -0.234°C 1000y^{-1} for Victoria Land. Coastal East Antarctic regions do not show significant trends (Weddell Sea, Dronning Maud Land coast and Wilkes Land coast). The NB2014 temperature scaling produces ~~50% larger trends overall~~lower trends overall (Table 3), ~~and triples the values except~~ for the West Antarctic Ice Sheet where the trend doubles (-0.92°C 1000y^{-1}). The trend in the West Antarctic Ice Sheet region can be assessed independently by comparing the WAIS composite to the borehole temperature record of Orsi et al. (2012) at WAIS-Divide for the period 1000-1600 CE. The borehole-derived trend at WAIS divide is $-1.1^{\circ}\text{C}0.55^{\circ}\text{C}$ 1000y^{-1} for the 0-1900CE period, ~~close to the in between the~~ $-1.00.92^{\circ}\text{C}$ 1000y^{-1} value found with the NB2014 method ~~over 1000-1600 CE, but much larger than and the~~ -0.3847°C 1000y^{-1} found with the ECHAM scaling. The CPS method finds a slope of -0.59°C 1000y^{-1} for the period ~~1000-1600-1900~~ CE, ~~slightly lower than what is inferred from the borehole temperature reconstruction~~ very close to the borehole method. Over all of Antarctica, we find a cooling trend of -0.26 to -0.4°C 1000y^{-1} between 0-1900 CE across the various scaling approaches (Table 3). This trend is comparable in magnitude ~~to of~~ the $-0.22\pm 0.06^{\circ}\text{C}$ 1000y^{-1} found for the Arctic region (Kaufman et al, 2009). This trend was attributed to a decrease in JJA solar insolation due to precession of the equinoxes.

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Table 3: Trend analysis of the period 0-1900 CE (or shorter depending on maximum record length), for the various temperature scaling approaches detailed in Section 3.4.

<u>Geographic region</u>	<u>start</u>	<u>end</u>	<u>ECHAM</u>		<u>NB2014</u>		<u>borehole</u>	<u>Borehole</u>
	<u>date</u>	<u>date</u>	<u>Slope</u> ($^{\circ}\text{C}/1000\text{y}$)	<u>p-value</u>	<u>Slope</u> ($^{\circ}\text{C}/1000\text{y}$)	<u>p-value</u>	<u>Slope</u> ($^{\circ}\text{C}/1000\text{y}$)	<u>p-value</u>
<u>1. East Antarctic Plateau</u>	<u>0</u>	<u>1900</u>	<u>-0.38 ± 0.14</u>	<u><0.0001</u>	<u>-0.32 ± 0.12</u>	<u><0.0001</u>	<u>NaN</u>	<u>NaN</u>
<u>2. Wilkes Land Coast</u>	<u>170</u>	<u>1900</u>	<u>-0.24 ± 0.17</u>	<u>0.0072</u>	<u>-0.16 ± 0.13</u>	<u>0.0161</u>	<u>NaN</u>	<u>NaN</u>
<u>3. Weddell Sea Coast</u>	<u>1000</u>	<u>1900</u>	<u>-0.24 ± 0.54</u>	<u>0.3763</u>	<u>-0.12 ± 0.27</u>	<u>0.3763</u>	<u>NaN</u>	<u>NaN</u>
<u>4. Antarctic Peninsula</u>	<u>0</u>	<u>1900</u>	<u>-0.52 ± 0.23</u>	<u><0.0001</u>	<u>-0.20 ± 0.09</u>	<u><0.0001</u>	<u>NaN</u>	<u>NaN</u>
<u>5. West Antarctic Ice Sheet</u>	<u>0</u>	<u>1900</u>	<u>-0.47 ± 0.10</u>	<u><0.0001</u>	<u>-0.92 ± 0.16</u>	<u><0.0001</u>	<u>-0.55 ± 0.11</u>	<u><0.0001</u>
<u>6. Victoria Land Coast</u>	<u>0</u>	<u>1900</u>	<u>-0.34</u> <u>± 0.18</u>	<u>0.0003</u>	<u>-0.29 ± 0.12</u>	<u><0.0001</u>	<u>NaN</u>	<u>0.0003N</u> <u>aN</u>
<u>7. Dronning Maud Land Coast</u>	<u>1530</u>	<u>1900</u>	<u>5.96 ± 3.27</u>	<u>0.0007</u>	<u>0.97 ± 0.62</u>	<u>0.0032</u>	<u>NaN</u>	<u>0.0007N</u> <u>aN</u>
<u>West Antarctica</u>	<u>0</u>	<u>1900</u>	<u>-0.24 ± 0.07</u>	<u><0.0001</u>	<u>-0.44 ± 0.10</u>	<u><0.0001</u>	<u>-0.30 ± 0.10</u>	<u><0.0001</u> <u><0.0001</u>
<u>East Antarctica</u>	<u>0</u>	<u>1900</u>	<u>-0.30 ± 0.10</u>	<u><0.0001</u>	<u>-0.32 ± 0.10</u>	<u><0.0001</u>	<u>NaN-</u> <u>0.30 ± 0.10</u>	<u>NaN</u> <u><0.0001</u>

All Antarctica	0	1900	-0.36±0.08	<0.0001	-0.40±0.08	<0.0001	-0.26±0.06	<0.0001
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Geographic region/Region	normalized normalised		CPS/CPS			
	Slope (σ/1000y) slope (σ/1000y ⁻¹)	p-value p-value	Slope (°C/1000y) slope	p-value p-value	start date/Start year	end date/End year
1. East Antarctic Plateau/4- Plateau	-0.76±0.28-0.76±0.28	00.000	-0.15±0.06-0.15±0.06	00.000	1010	19001900
2. Wilkes Land Coast/2- Wilkes Coast	-0.59±0.48-0.59±0.48	0.01610.016	-0.10±0.07-0.10±0.07	0.00800.008	180180	19001900
3. Weddell Sea Coast/3- Weddell coast	-0.41±0.92-0.41±0.91	0.37630.376	-0.09±0.27-0.09±0.27	0.49350.494	10001000	19001900
4. Antarctic Peninsula/4- Peninsula	-0.50±0.23-0.50±0.23	00.000	-0.09±0.09-0.09±0.09	0.04790.048	00	19001900
5. West Antarctic Ice Sheet/5- WAIS	-1.32±0.23-1.32±0.23	00.000	-0.59±0.08-0.59±0.08	00.000	00	19001900
6. Victoria Land Coast/6- Victoria Ross	-0.89±0.39-0.89±0.39	00.000	-0.54±0.58-0.54±0.58	0.06610.066	11401140	19001900
7. Dronning Maud Land Coast/7- DML coast	4.98±3.204.98±3.2	0.00320.003	NaNNaN	NaNNaN	1890NaN	1900NaN
West Antarctica/West Antaretica	-0.76±0.16-0.76±0.16	00.000	-0.55±0.07-0.55±0.55	00.000	00	19001900
East Antarctica/East Antaretica	-0.59±0.19-0.59±0.19	00.000	-0.18±0.06-0.18±0.06	00.000	1010	19001900
All Antarctica/All Antaretica	-0.76±0.15-0.76±0.15	00.000	-0.38±0.05-0.38±0.05	00.000	00	19001900

4.1.3 Trends of the last 100 years in weighted reconstructions

5 Studies based on individual ice cores have identified significant positive trends in the last century (Mulvaney et al., 2012; Steig et al., 2013). Similar to the findings for unweighted composites, significant warming trends in the last 100 years (Table 4) of the weighted anomalies are evident for the Antarctic Peninsula (+2.65σ 100y⁻¹ with respect to the 1960-1990 CE normalisation period), Dronning Maud Land coast (+2.51σ 100y⁻¹) and the West Antarctic Ice Sheet (+1.17σ 100y⁻¹) regions. The trends in other regions are not significant (Table 4). In temperature units, the NB2014 method gives a scaling about twice as within 30%
10 of ECHAM, while CPS is in-between generally 50% lower (Table 4). Since 1900_CE, the reconstructions indicate that the Antarctic Peninsula has been warming by 0.91.14-1.992.87°C 100y⁻¹, West Antarctic Ice Sheet by 0.6646-2.01.32°C 100y⁻¹, and the Dronning Maud Land coast by 0.51.59 to 0.981.33°C 100y⁻¹. The borehole temperature adjustment needed to match the long-term trend leads to an over-estimation of the 100-year trend in the WAIS region. Indeed, the same borehole
15 temperature record finds a warming trend of 0.70°C 100y⁻¹ for the past 100 years, and 1.22°C 50y⁻¹ for the past 50 years. This example shows that a simple linear scaling cannot be valid for all timescales, and that another approach will be needed to improve quantitative temperature reconstructions for Antarctica.

Despite these uncertainties on absolute scaling, our analyses underline that the sustained warming of the Antarctic Peninsula over the last century stands out as being a robust feature across all methods. Moreover, while the West Antarctic Ice Sheet and the Peninsula regions have now seen reversal of the long-term cooling trend of the past 2000 years, this is not the case for the
20 rest of the continent, where temperatures changes over the last century have not been significant (Figure 4, Table 4).

Table 4: Regression of the last 100-year slope based on the 5-year averages

normalized	ECHAM	NB2014	Borehole	CPS
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Region	Slope (σ 100y ⁻¹)	p- value	Slope (°C 100y ⁻¹)	p-value	Slope (°C 100y ⁻¹)	Slope (°C 100y ⁻¹)	slope	p-value
1. Plateau	-0.85	0.133	-0.31	0.174	-1.28	NaN	0.66	0.024
2. Wilkes Coast	1.08	0.115	0.75	0.034	0.47	NaN	0.15	0.586
3. Weddell coast	-1.10	0.351	-0.27	0.351	-0.50	NaN	-0.27	0.608
4. Peninsula	2.65	0.000	0.90	0.000	1.99	NaN	1.42	0.001
5. WAIS	1.17	0.014	0.66	0.020	0.97	2.03	0.44	0.239
6. Victoria Ross	-0.79	0.195	-0.27	0.247	-0.64	NaN	0.05	0.845
7. DML coast	2.51	0.012	0.51	0.006	0.98	NaN	0.74	0.050
West Antarctica	1.50	0.001	0.78	0.007	1.12	1.85	0.63	0.091
East Antarctica	0.04	0.924	0.05	0.743	0.06	NaN	0.32	0.082
All Antarctica	0.72	0.040	0.45	0.060	0.99	0.21	0.40	0.049
-			ECHAM		NB2014		Borehole	
Geographic region	start date	end date	Slope (°C/100y)	p-value	Slope (°C/100y)	p-value	Slope (°C/100y)	p-value
1. East Antarctic Plateau	1915	2010	-0.49±0.73	0.174	-1.28±1.71	0.133	NaN	NaN
2. Wilkes Land Coast	1915	1995	1.70±0.55	0.034	0.47±0.60	0.115	NaN	NaN
3. Weddell Sea Coast	1915	1995	-0.79±1.75	0.351	-0.50±1.12	0.351	NaN	NaN
4. Antarctic Peninsula	1915	2010	2.87±1.12	<0.001	1.99±0.75	<0.001	NaN	NaN
5. West Antarctic Ice Sheet	1915	2015	1.12±0.92	0.020	0.97±0.75	0.014	1.32±1.08	0.020
6. Victoria Land Coast	1915	2005	-0.55±0.97	0.247	-0.64±1.00	0.195	NaN	NaN
7. Dronning Maud Land Coast	1915	2010	1.33±0.90	0.006	0.98±0.73	0.012	NaN	NaN
West Antarctica	1915	2015	1.25±0.86	0.007	1.12±0.62	0.001	0.09±0.58 NaN	NaN 0.743 43
East Antarctica	1915	2010	0.09±0.58	0.743	0.06±1.23	0.924	0.09±0.58 NaN	0.743 NaN
All Antarctica	1915	2015	0.79±0.82	0.060	0.99±0.94	0.040	0.21±0.38	0.262

- Geographic region	normalized		CPS			
	Slope (σ /100y)	p-value	Slope (°C/100y)	p-value	start date	end date
1. East Antarctic Plateau	-0.85±1.14	0.133	0.77±0.46	0.004	1900	2000
2. Wilkes Land Coast	1.08±1.37	0.115	0.05±0.49	0.820	1900	1980
3. Weddell Sea Coast	-1.10±2.45	0.351	-0.25±0.93	0.544	1900	1980
4. Antarctic Peninsula	2.65±0.99	<0.001	1.14±0.60	0.002	1900	2000
5. West Antarctic Ice Sheet	1.17±0.90	0.014	0.46±0.63	0.132	1900	2000
6. Victoria Land Coast	-0.79±1.23	0.195	0.22±0.52	0.364	1900	1990
7. Dronning Maud Land Coast	2.51±1.88	0.012	0.59±0.61	0.057	1900	1990
West Antarctica	1.50±0.83	0.001	0.60±0.61	0.052	1900	2000
East Antarctica	0.04±0.85	0.924	0.43±0.33	0.017	1900	2000
All Antarctica	0.72±0.68	0.040	0.43±0.32	0.013	1900	2000

4.1.4 Significance of most recent 100y trends relative to natural variability

Finally, we assess how significant the trends in the most recent 100-years of the regional temperature reconstructions are relative to the range of all other 100-year trends in the reconstructions since 0 CE (Figure 6). The most recent 100y trend and its ($\pm 1\sigma$) uncertainty range are compared to the distribution of all other 100y trends for that region. [This assessment method uses overlapping trend analysis intervals that are not fully independent, but captures the full range of possible trends in all 100y intervals of the regional reconstructions.](#) In this analysis, the significant recent positive trends for the Dronning Maud Land coast and West Antarctic ice sheet do not emerge as unusual in the context of similar length trends of the last two millennia, consistent with the findings of Steig et al. (2013) based on the WAIS Divide ice core. However, the most recent 100-year warming of the Antarctic Peninsula is unusual compared to the range of natural century-scale warming trends of the last two millennia (Mulvaney et al., 2012). Thus, across all of our trend tests, the warming of the Antarctic Peninsula over the last century stands out as being robust to the binning of multiple isotopic anomaly records for the region, significant after weighting and scaling of the regional isotopic records to represent regional temperature, and unusual compared with the range of natural century-scale temperature variability of this region over the last two thousand years. The companion Antarctica 2k paper (Thomas et al., [in review 2017](#)) that examines snow accumulation across Antarctica over the last 1000 years also concludes that the most robust recent changes in snowfall are evident for the Antarctic Peninsula. [Temperature and precipitation increases over the Antarctic Peninsula in recent decades have previously been linked to the Southern Annular Mode \(Abram et al., 2014\) and the effects of the coupling between SAM and ENSO on the strength and position of the Amundsen Sea Low pressure and sea ice conditions offshore of West Antarctic and the Antarctic Peninsula \(Thompson and Solomon, 2002; Ding et al., 2011; Thomas and Abram, 2016\). The variability of these driving forcings over the past 2000 years could also explain part of the opposite regional climate variability that appears to be present at decadal-centennial scales between our reconstructions for the Antarctic Peninsula and the Victoria Land-Ross Sea regions.](#)

Prior to this recent warming, which has been most significant for the Antarctic Peninsula region of Antarctica, long-term cooling is evident for many regions of Antarctica. In particular, it is the long-term cooling of the East Antarctic Plateau which emerges as significant in the weighted reconstructions and also robust across the distribution of contributing records in the unweighted composites. This is also in agreement with what was recently found by Hakim et al. (2016) using a data assimilation approach to identify a very strong SH cooling trend through the last 2000 years, up to about 1850 CE.

4.2 Continent-scale temperature reconstructions

Figure 7 shows the results obtained by applying the Composite-Plus-Scale (CPS) method published in 2013 (PAGES2k Consortium, 2013) to the expanded Antarctica2k database to reconstruct temperature across the whole Antarctic continent. A good agreement is observed between the new reconstruction and the previously published one (Figure 7), both at annual and decadal scale ($r=0.897$ and 0.9189 , respectively). There is a slightly stronger negative temperature trend in the new Antarctic continent-scale reconstruction, which is related mainly to a slightly cooler temperature estimate for the 1600-1900 CE interval using the expanded database. Figures in supplementary material, similarly repeat this CPS comparison for the West Antarctica and East Antarctica regions and find similar agreement between the 2013 results and those using the expanded ice core database (Figs S11, S12, and S13 respectively).

Figure 8 shows the continental scale (All Antarctica), East Antarctica and the West Antarctic temperature reconstructions that have been obtained from the different temperature scaling approaches in comparison with the CPS method. The period between 1200 and 1900 CE appears as the coldest interval in the East Antarctic reconstruction, and this is also reflected in the reconstruction at the whole continental scale. The warmest interval is identified between 300 and 1000 CE, especially for West Antarctica. The comparison between the CPS method and our new reconstruction methods shows a better agreement in East Antarctica than in West Antarctica when considering the ECHAM temperature scaling (Figure 8). However, a better agreement between the CPS method and the temperature reconstruction obtained with the borehole scaling method is observed for West

Antarctica. Note that ECHAM and NB2014 use two independent datasets for scaling the $\delta^{18}\text{O}$ signal to temperature, and that the difference between them is a measure of the uncertainty in the temperature reconstruction.

Over the period from 165-1900 CE (the reconstruction interval of the 2013 PAGES 2k reconstruction for Antarctica), a cooling trend is common to all three broad-scale reconstruction regions and across all reconstruction methods (see Table S2). Cooling trends range between $-0.13\text{--}0.21$ and $-0.26\text{--}0.45^\circ\text{C } 1000\text{y}^{-1}$ for the ECHAM method, and between $-0.18\text{--}0.34$ and $-0.74\text{--}0.53^\circ\text{C } 1000\text{y}^{-1}$ for the borehole method. These values are in the range of those previously reported by the 2013 reconstruction (PAGES2k Consortium, 2013) where cooling trends of -0.18 and $-0.46^\circ\text{C } 1000\text{y}^{-1}$ were calculated, for the same interval, for East and West Antarctica, respectively. By comparison, cooling trends of -0.25 and $-0.56^\circ\text{C } 1000\text{y}^{-1}$ are calculated from the 10y binned data obtained with the same CPS methods but applied to this new database.

East Antarctica is one of the last places on the globe where the long-term cooling trend of the last millennium has not been inverted (PAGES2k Consortium, 2013; Abram et al., 2016). This feature of delayed onset of industrial warming is clear in our reconstruction, but is not captured by climate models (PAGES 2k-PMIP3 group, 2015). Climate models are known to overestimate inter-hemispheric synchronicity (Neukom et al., 2014). The model-data mismatch may come from an over-estimation of the response to external forcing in climate models, an under-estimation of the role of internal ocean-atmosphere dynamics in models, or incorrect inference from proxy data. This quantitative reconstruction will provide an important constraint on the forced vs unforced nature of trends observed for the last century.

4.3 Response to volcanic forcing

The radiative forcing caused by major volcanic eruptions is known to drive hemispheric-scale cooling at subdecadal to decadal timescale (e.g. Sigl et al., 2015; Stoffel et al., 2015). Previous model-based assessments have suggested that the long-term cooling trend over Antarctica during the 850-1850 CE interval may be attributed to volcanic forcing of the climate (Goosse et al., 2012). Volcanic forcing may also affect atmospheric and oceanic dynamics, including modes of variability, causing substantial seasonal and regional variations in the climate footprint of volcanic forcing (e.g. Otterå et al., 2010; Schleussner et al., 2015; Ortega et al, 2015; Swingedouw et al, 2015). For example, the long-term cooling trend of the global oceans during the last two millennia has been attributed to the effects of short-term cooling from episodic eruptions being cycled into subsurface layers of the oceans (McGregor et al., 2015).

We use the composite reconstructions of Antarctic temperature anomalies to explore whether a signatures/imprints of past major eruptions can be identified. Since different normalizations applied during the reconstruction procedure are not expected to affect a qualitative interpretation of the results, we present the analysis based on the reconstruction that fits 5-year annual $\delta^{18}\text{O}$ to regional temperature anomaly from ECHAM-wiso forced by ERA-Interim.

A robust identification of the climate impacts of volcanism from Antarctic ice cores faces a number of challenges. ~~Low accumulation and wind driven post depositional processes are limitations to seasonal layer counting of stable water isotopes and/or chemical profiles, and to climatic signals retrieved from single cores.~~ In addition to ~~the poor~~ chronological ~~constraints~~ uncertainties due to low accumulation and post-depositional alterations, processes other than local temperature may affect water stable isotopes in Antarctic precipitation, therefore making the detection of a temperature response to volcanic

forcing more challenging. Finally, stacking the individual core records acts as a low-pass filter, suppressing the variability in the shorter, interannual timescales, thereby eliminating potentially short-lived cooling signals triggered by volcanic forcing.

Despite these limitations, it should be possible to record a volcanic cooling signal from well-dated cores from high accumulation areas and/or around the time periods with clear markers of volcanic origin, widely used as precise age control points for constructing ice core chronologies. For example, the chemical fingerprints of two consecutive tropical eruptions of 1808/09 (VEI 6-7) and Tambora 1815 (VEI 7) are detected in many Antarctic ice cores as a pronounced double peak in a number of measured ice parameters such as electrical conductivity or non-sea salt- SO_4^{2-} profiles (Sigl et al., 2015).

Due to the aforementioned difficulties in the identification of a potential Antarctic temperature response to volcanic forcing, we restrict our analysis to the eruptions associated with the estimated strongest volcanic forcing, which are more likely to leave a clear footprint in ice core records. The highest resolution reconstruction (5 year averages) is available for a period which experienced only three eruptions with a Volcanic Explosivity Index (VEI) of 6-7, namely the tropical eruptions of 1808/09, 1815 Tambora and 1883 Krakatoa. The signatures of the first two eruptions are commonly used as reference horizons when constructing the core chronologies. Due to a low number of replicates, we cannot use a Superposed Epoch Analysis, commonly applied for detecting the signature of the climate response to volcanic forcing (e.g. Fischer et al., 2007; Stoffel et al, 2015). Figure 9 simply displays the regional surface atmospheric temperature anomalies for the two periods centred at 1815 CE and 1883 CE.

Following the Tambora eruption, cooling is recorded in 5 out of our 7 regional reconstructions, namely in the Dronning Maud Land coast, Wilkes Land coast, Victoria Land coast, East Antarctic Plateau and possibly West Antarctic Ice Sheet regions. Following the 1808/09 eruption, cooling appears in 3 out of our 7 regional reconstructions (West Antarctic Ice Sheet, Wilkes Land coast regions and to a lesser extent the Antarctic Peninsula). Following the Krakatoa eruption, regional cooling emerges for 4 out of 7 regions (East Antarctic Plateau, Antarctic Peninsula, Wilkes Land coast and West Antarctic Ice Sheet regions). Potential response time lags should be interpreted with caution due to effects of the data binning procedure as well as age scale uncertainties.

Within the limitations associated with our reconstructions and with the small number of large eruptions in the studied time period, we can only report a lack of consistent pan-Antarctic cooling, and a variable regional response. Such features have also been identified for the largest volcanic eruptions in the Northern Hemisphere (e.g. Guillet et al., in press). Local negative anomalies following major eruptions may arise from non-temperature drivers of water stable isotope records and be an artefact of inconsistencies in chronologies; they may also reflect an actual regional cooling. Further studies will require to focus on ice core records with a solid chronological control, and sufficient regional records to assess the common climatic signal from the deposition noise. Second order isotopic parameters such as deuterium excess which preserve a signal associated with moisture source characteristics may also provide insights on the response of the Southern Ocean surface state to volcanic forcing.

This analysis represents only a preliminary attempt to assess the possible short-term climatic response of Antarctic climate to short-term volcanic eruptions forcing, and we suggest that this is a good avenue for further detailed study using the expanded Antarctica 2k isotope database assembled here.

5 Conclusions and Implications

We have presented a new enlarged database of high and low resolution ice core water stable isotope records from Antarctica, which has been compiled in the framework of the PAGES Antarctica2k working group. To further develop our scientific understanding based on continental scale reconstructions of Antarctic temperature, we define seven climatic regions based on our knowledge of the regional Antarctic climate and further supported by spatial correlation of temperature using the NB2014 reanalysis data. In our reconstructions of both regional and continental scale climate, we use 5y and 10y averaged data in order to limit our dependence on annually precise dating which faces real problems, especially in interior Antarctica, due to the very low snow accumulation there. ~~Of the initial 112 records, 79 and 67 records meet our minimum requirement of having at least 30y or 90y data coverage since 1800 or 0 CE, respectively. We produce simple unweighted and weighted composites of ice core $\delta^{18}\text{O}$ anomalies, as well as weighted temperature reconstructions which take into account the regression between each ice core site and the regional temperature. Similar conclusions are reached using different approaches (ECHAM, NB2014 and borehole methods) giving support to our temperature reconstructions. Different weighting methods and temperature scaling performed using the NB2014 temperature product as well as the ECHAM temperature and isotopic fields support the robustness of our reconstructions. Furthermore, a replication of a the CPS approach used in a previous continental scale~~

reconstruction but adapted to the new database also produces consistent results. ~~The range of the values obtained by these four methods provide information on the uncertainties related to the temperature reconstructions at regional and continental scale.~~

Our new continental scale reconstructions, based on the extended database, corroborates previously published findings for Antarctica from the PAGES2k Consortium (2013): (1) ~~Temperatures over the Antarctic continent show an overall cooling trend during the period from 0 to 1900CE, which appears strongest in West Antarctica, and~~ (2) no continent-scale warming of Antarctic temperature is evident in the last century.

The robust and significant long-term cooling trend of Antarctic-wide temperatures from 0-1900 CE is also reflected in the broader East Antarctic and West Antarctic regions. In East ~~Antaretica~~Antarctica, the coldest interval occurs from 1200 and 1900 CE. During the same time period five intervals of volcanic-solar downturns have been previously linked to cooling in temperature reconstructions for other continental regions (PAGES2k Consortium, 2013). These intervals of negative radiative forcings are in agreement with our lower temperature estimates during this time (Fig. 8). ~~A test of volcanic impact performed on our 200y regional temperature reconstructions, although not conclusive due to the limit imposed by our 5y binned data set, has nevertheless showed possible negative temperature effects in some regions, in particular the East Antaretic Plateau and some coastal regions. More research on this topic with a special focus on individual records with limited age uncertainties and high resolution data sets would be needed for reaching a more conclusive answer and could be facilitated using the expanded Antaretic 2k database.~~

The absence of significant continent-scale warming of Antarctica over the last 100 years is in clear contrast with the significant industrial era warming trends that are evident in reconstructions for all other continents (except Africa) and the tropical oceans (Abram et al., 2016). As noted in other studies (e.g. Abram et al., 2016; Jones et al., 2016) the absence of continent-scale warming over Antarctica is not in agreement with climate model simulations, which consistently produce a 20th ~~c~~Century warming trend over Antarctica in response to greenhouse gas forcing. The high interannual climate variability with respect to the magnitude of climate trends over Antarctica, and the small number of ice core records that have contributed to previous continent-scale reconstructions of Antarctic temperature, have been suggested as possible sources for the lack of detection of continent-scale warming trends in palaeoclimate records from Antarctica. However, we replicate this finding of a continent-scale absence of 20th Century warming using our greatly expanded ice core database and with composites and reconstructions based on a range of methods. This suggests that the absence of continent scale warming over Antarctica during the last century is a robust result and alternate reasons for data-model divergences need to be investigated.

Despite the lack significant warming over the last 100 years at the continent scale, there are three regions which show positive and significant isotopic and temperature trends: the Antarctic Peninsula, the West Antarctic Ice Sheet and the coastal Dronning Maud Land. However, currently only for the Antarctic Peninsula is the last 100 y trend unusual in the context of natural century-scale trends over the last 2000 years, although if sustained and significant warming of Dronning Maud Land coast and the West Antarctic ice sheet continues during the coming decades (as would be expected based on climate model simulations), then these areas may soon also see the recent warming emerge as unusual in the context of natural variability. A companion paper (Thomas et al., ~~in review~~2017), which examines the snow accumulation rate variability over Antarctica during the last millennium, reaches the same conclusion showing that in the Antarctic Peninsula region the late 20th century snowfall increase is unusual in the context of the past 300 years. ~~Temperature and precipitation increases over the Antaretic Peninsula in recent decades have previously been linked to the Southern Annular Mode (Abram et al., 2014) and the effects of the coupling between SAM and ENSO on the strength and position of the Amundsen Sea Low pressure and sea ice conditions offshore of West Antarctic and the Antaretic Peninsula (Thompson and Solomon, 2002; Ding et al., 2011; Thomas and Abram, 2016). The variability of these driving forcings over the past 2000 years could also explain part of the opposite regional climate variability that appears to be present at decadal-centennial scales between our reconstructions for the Antaretic Peninsula and the Victoria Land-Ross Sea regions.~~ These regional to local scale patterns of climate changes, and the processes that these illustrate, are another target for future research that could be explored using the new Antarctica2k database. Future work will also consider

the comparison of the results obtained in this study with those by Thomas et al. (~~in review, same issue~~2017) assessing the snow accumulation rate variability in the same regions, with the aim of exploring a long-standing question about the relationship between temperature and precipitation in Antarctica.

Our new regional and continental scale reconstructions of Antarctic temperatures highlight again the urgent need to increase the spatial coverage of this sparse data continent with new temperature records, particularly focusing in the coastal areas. These regions are typically seen to be data-poor areas in our extended database. However, the coastal areas are also the places where high-resolution ice cores can be retrieved, where strong climatic differences can occur over relatively short distances, where there is some evidence for non-significant but emerging development of warming trends, where even small amounts of warming can rapidly move the local climate beyond the threshold and where surface melting of snow occurs potentially leading to widespread impacts of any future Antarctic warming.

Data availability

The target dataset of NB2014 is archived at: http://polarmet.osu.edu/datasets/Antarctic_recon/.

The table S1 (Supplementary Information) contains the data citations, as well as the primary bibliographic reference, for each record used in this study. We used the URL links for existing published data from public repositories.

The regional and continental scale isotopic composites and temperature reconstructions generated during the current study are available in the NOAA World Data Center for Paleoclimatology (WDC Paleo) at the following link: <https://www.ncdc.noaa.gov/paleo/study/22589>.

Supplementary Information

Supplementary figures (from Fig. S1 to S15) and tables (from table S1 to S4) are available as Supplementary Information.

Author contribution

BS led Phase 2 of the Antarctica 2k project, and MAJC was data manager. The data analysis presented in this paper was carried out by NJA, AO, SG, RN and DD. BS, NJA and AO led the writing of the manuscript, with contributions by MAJC, SG, RN, VM-D, HG, DD and EJS. All authors contributed to discussions on the analysis design and manuscript.

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