Authors' Response:

We thank the Reviewer for the comments and suggestions. In the text below, we outline our response in blue.

Anonymous Referee #2

In this study, the authors are presenting high-resolution isotopic (dD) and snow accumulation rate records of a new ice core (RICE) drilled on the Roosevelt Island in the eastern Ross Sea and covering in its upper part the last 2700 years. The authors are comparing these new records to other ice core records present in the near-by areas interpreting these records in terms of the climate variability which in these areas (Eastern and Western Ross Sea) is characterized by a climate pattern referred to as the Ross Sea dipole. The paper is noteworthy and the authors are doing a good job in calibrating the new records against the Era-interim re-analysis data (temperature and precipitation) as well as to other climate indexes as SAM, SOI, Nino3.4, IPO, as well as Sea Ice extent. However, some methodological questions are arising in this part (see C1 below). The manuscript is quite well structured and the topic is appropriate for Climate of the Past. Nevertheless, the authors should consider the comments reported below before resubmitting a revised version.

One general comments refers to the fact that the manuscript (Winstrup et al., CPD) presenting the ice core dating, on which most of the interpreted data are relying on, is not published yet.

This publication is now in review and can be accessed here: https://www.clim-past-discuss.net/cp-2017-101/ including comments from two reviewers. We will update the reference to that publication accordingly.

There are also other papers (one is Emanuelsson et al.), to which the authors are referring that are still at the submission7review stage, please check and update.

Three additional references used in our manuscript are still in review: Emanuelsson et al. (in review), Keller et al. (in review), and Pyne et al. (in review). We will update these references as they become available. In the meantime, we offer to provide copies of the manuscripts to the Reviewer.

General as well as detailed comments are reported below.

Page 3, line 3: may you check this sentence? Over the observational period (satellite era) the sea ice should be increasing in the Ross Sea sector and decreasing in the Amundsen–Bellingshausen sector.

We have corrected the sentence to state "…changes in sea ice (wind driven, regional decreases and increases in the Amundsen and Ross Seas, respectively."

Page 3, line 11: here the authors are saying that they will compare these new records to other ones existing in the region but it is not clear why they do not consider the Taylor Dome ice core record.

The Taylor Dome age scale is constrained for the past 3,000 years with a flow model, which assumes a constant snow accumulation rate and lacks independent age benchmarks. The record prior to 3,000 years ago has an improved age scale due to ties with Greenland records through the correlation of their respective methane data. The lack of age control points in the past 3,000 year record make the Taylor Dome data unsuitable to investigate the timing and phasing of climatic shifts on decadal or centennial time scales. However, we agree with Reviewer 2 that it is useful to show the Taylor Dome isotope data to support longer term temperature trends in the region and for this reason we now include the record in Figure 6. Like the Talos Dome data, the Taylor Dome isotope record shows no trend over the past 2,700 years. We have revised the manuscript to include the description of the Taylor Dome isotope record.

Page 6, lines 27-32. Here the authors are optimizing the dD/T relation to the age scale. I am wondering why the authors did not consider optimizing the snow accumulation rate to the ERA-I precipitation rather than the dD/T relation. In fact, it is known and also the authors are clearly showing this, that the isotopic composition rely not only on the temperature but also on other circulation-related factors. How, this choice is affecting the climate interpretation? The authors should answer to this comment.

The brevity of the overlap between the RICE data and reanalysis products (1979-2012) provides some challenges for the assessment of correlations between the proxy records and climate parameters. Using an optimisation approach, we investigated whether the shift of up to ±1.3 years (within the age scale uncertainty of ±2 years) can significantly impact the results. The optimisation increased the correlation from r=0.42 to r=0.66) between temperature and isotope data. In a second step, we assessed how this optimised age model solution affects other parameters. The correlation between the snow accumulation data and the ERAi precipitation data on the RICE17 age scale is already high with r=0.60. Using the same approach marginally improves the correlation value between snow accumulation and ERAi precipitation (r=0.62). However, here we wanted to test whether the age scale optimised for the isotope data would positively or negatively influence the correlations for other parameters. Using the isotope optimised age model, ERAi precipitation and RICE Acc_o remains statistically significant but is reduced to r=0.42. We conclude from this that the optimised age solution is not superior to the original RICE17 age scale. We also conclude that the RICE data are useful parameters to reconstruct both temperature and snow accumulation within the given uncertainties and that the obtained correlations values are likely limited by the brevity of the records.

Page 6, line 31: Figure 2b should be 2c.

Done.

Page 6, line 35: in the Masson-Delmotte paper only spatial d/T slope are considered.

We have broadened the cited δ/T slopes to include the range reported by Schneider et al. 2005 (interannual δ/T slopes) which includes the range from 2.9 to 3.4 ‰ per degC.

Page 7, line 5: Is the lack of correlation valid also considering only the 1979-2012?

We agree with Reviewer 2 that the brevity of the records limits the usefulness of the correlations. If the longer time frame from 1958-2012 is considered, the correlation between RICE δD and NB2014 becomes weakly statistically significant (r=0.23, p=0.09). However, it is curious that the ERAi and NB2014, which both use similar inputs of observational and satellite data, do not correlate at the RICE site. The Roosevelt Island topography currently cannot be adequately represented in the data products because of their grid resolution. Yet, the topography might have sufficient vertical profile to influence the inversion layer thickness and precipitation pattern that alter the local conditions from the precipitation pattern of the surrounding Ross Ice Shelf. However, the comparison between ERAi and NB2014 is beyond the scope of this paper. For this reason, we do not offer a hypothesis for the cause of the observed difference. Furthermore, we note that statistically significant relationships between RICE δD and ENSO indices (SOI, Niño 3.4 and 4) are observed when a shorter time frame 1979-2009 period is considered. In 2009, the IPO changes sign which influences the teleconnection between the ENSO signal and the South Pacific climatic response, perhaps masking this important ENSO-RICE relationship. We have added a sentence describing this observation. However, the observational time series are too short to quantify the impact of the changing IPO with RICE δD data and is beyond the scope of this manuscript.

Page 7, line 6: RICE dD should be RICE dDo.

We changed it to “RICE dD and dDo” (as neither correlates)

Page 7, lines 11-14: Is this strong accumulation rate gradient suggesting possible movements of the dome in the past. May you explain this?

It is possible that the divide has migrated in the past as a result of an imbalance in the ice flux on either side of the divide, but this is not necessarily caused by changes in the accumulation gradient; it could equally well arise from changes in the efflux across the grounding-line, caused by changes in buttressing. The small migration in divide position suggests that neither accumulation gradient nor grounding line efflux have changed very much; this implies that the buttressing has not changed significantly either.

Page 7, line 37-38: the region which exhibits a negative correlation seems to be at lower latitudes than the ASL, at least looking at the figure . . ..

Agreed. We changed the description to: “A negative correlation is found in the regions of the South Pacific, Antarctic Peninsula and the eastern West Antarctica”.

Page 8, lines 10-12: the strong impact of blocking events at this site would support my comment above (Page 6, lines 27-32).

As described above, ERAi precipitation and RICE snow accumulation correlate at r=0.60. Using the same optimisation methodology as tested for the RICE δD record only marginally improves the correlation (r=0.62). For this reason, no optimisation was carried out.

Page 8, line 13: the negative correlation seems to interest more the Amundsen Sea. Page 8, line 17: are polynyas resolved by the model data?

We have clarified the paragraph: “Snow accumulation at RICE is negatively correlated with SIE in the Ross Sea and northern Amundsen Sea region (Figure 5a), which predominantly represents sea ice exported from the Ross Sea. We observe that years of increased (decreased) SIE leading to reduced (increased) accumulation at RICE, confirming the sensitivity of moisture-bearing marine air mass intrusions to local ocean moisture sources and hence regional SIE. The correlation between ERAi SIE and the optimised RICE δD_o record (Figure 5b) similarly shows a negative correlation of SIE in the Ross and northern Amundsen Sea (perhaps with the exception of the Ross and Terra Nova polynyas) suggesting more depleted (enriched) values during years of increased (reduced) SIE.” We do not use a model in our analysis but the large and generally persistent Ross Sea and Terra Nova polynyas are well observed in satellite data.

Page 8, line 21: I would move this sentence: "We focus . . .." at the beginning of the paragraph.

Agreed. We have revised the sentence to: "We focus on the SIE in the Ross and Amundsen Seas to investigate the relationship between the SIE and the temperature and precipitation at Roosevelt Island. In Figure 5 c and d, the Ross-Amundsen Sea SIE index (SIE_J), developed by Jones et al. (2016), is correlated with ERAi SAT and precipitation data."

Page 8, line 20: please add C2 a URL link to these data (SIEj).

We will add the sources of all data and indices used in this manuscript under the section "Data Availability" once the paper has been accepted for publication.

Page 9, lines 1-7: please add data citation or URL in Data Availability section for all the climate indexes used.

Please see comment above.

Page 9, line 9: why using the SAMa index instead of SAM for this period? Are these two indexes the same over this period?

We focus here on the Abram et al. (2014) SAM index (SAM_A) as it provides a reconstruction of the SAM to 1000 CE. We use the SAM_A index for the 1979-2012 correlations to assess the fidelity of the relationship between this index and our records to support a comparison over past centuries. The Marshall SAM record, which is based on meteorological observations, starts in 1957 and thus cannot support comparisons beyond the modern frame. During the common time period, the Marshall and Abram SAM indices are similar but also revealed some interesting differences as shown in the graph below. However, a detailed discussion of those difference is beyond the scope of this paper.

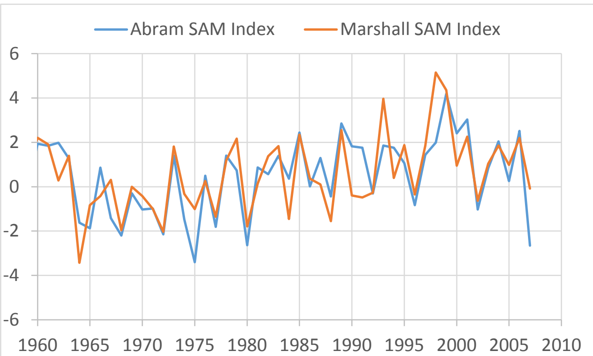


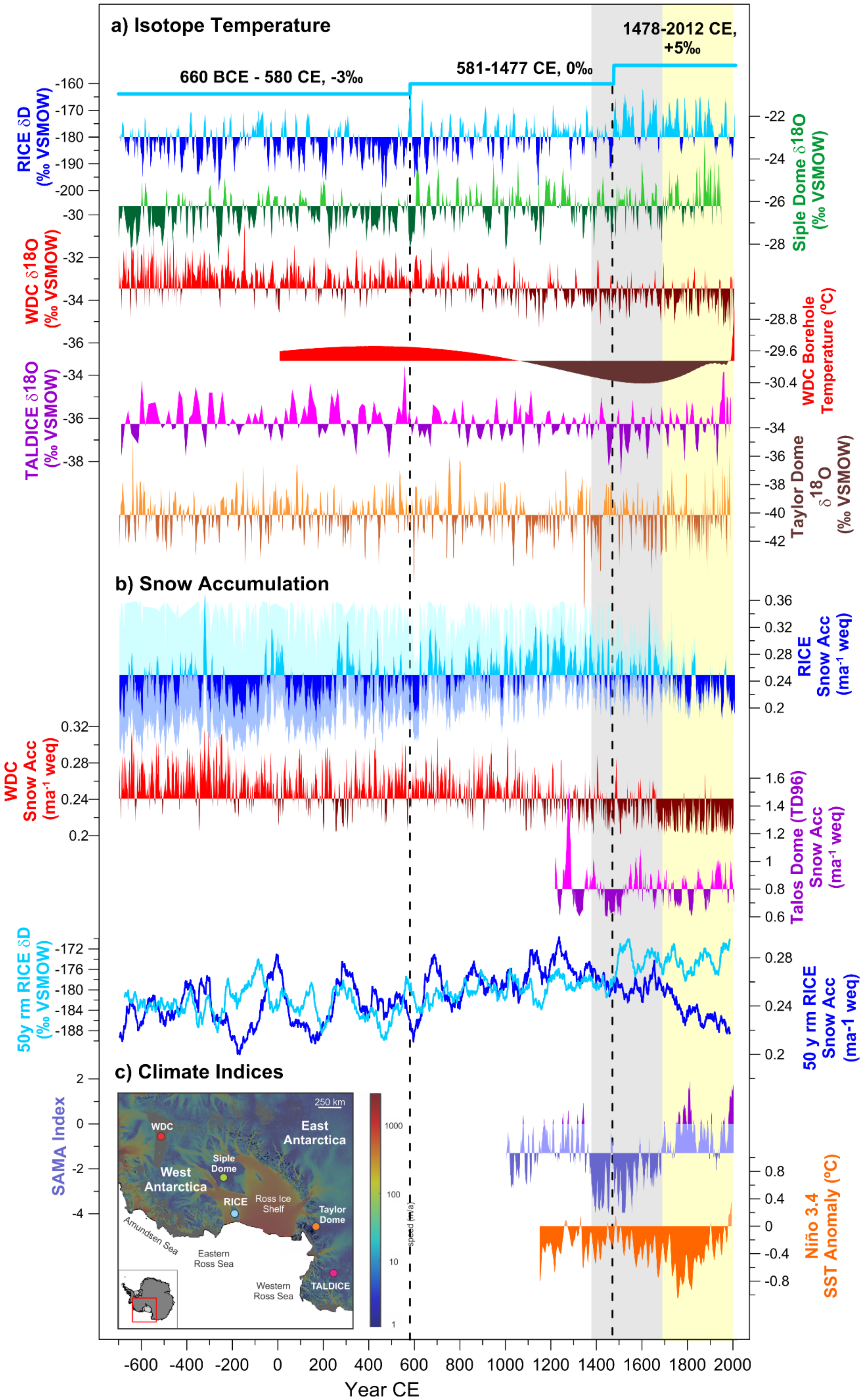
Figure R2-1: Comparison between the Marshall and Abram SAM indices (r=0.75).

Page 9, line 13: . . ... (but not with Rice snow accumulation). . . See again my comment above (Page 6, lines 27-32).

We do not use a snow accumulation record optimised to correlate with ERAi snow precipitation because the optimisation only led to a marginal improvement of the already high correlation value of r=0.60). Furthermore, the optimisation only improved either the correlation with temperature or the correlation with snow accumulation but not both with the same optimisation.

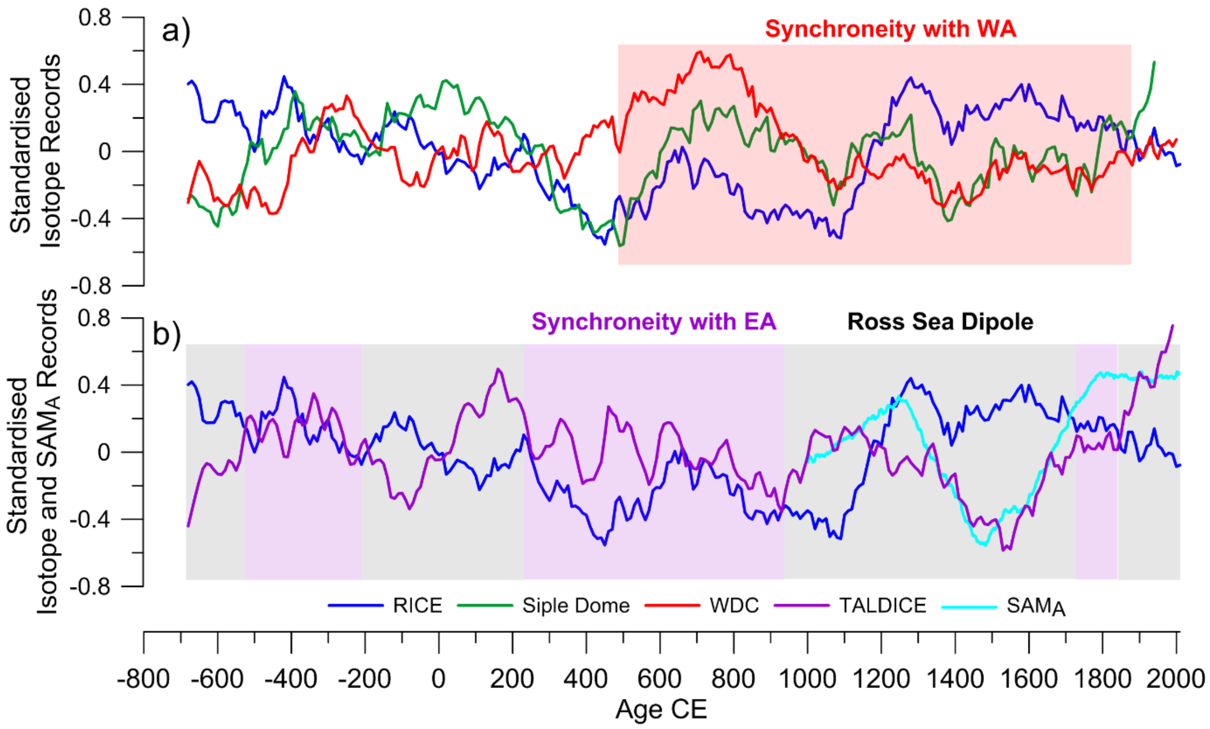
Page 9, lines 22-24: again why not using Taylor Dome? On the other side, regarding the use of TALDICE data: I would suggest to use Talos Dome (89 m core) isotopic and snow accumulation rate data (Stenni et al., 2002) rather than TALDICE for this recent period. The TALDICE data are low resolution data and the snow accumulation rate, here considered, comes from the dating model and as such implicitly connected to the isotopic record from which it is derived. On the contrary, the isotopic and snow accumulation rate records from the Talos Dome core, although limited to the past 800 years, are high-resolution data and the dating has been performed by nssSO4 annual data constrained by the volcanic chronology. Moreover, the TALDICE data, here reported are on the Buiron et al. (2011) age scale which has been replaced by the AICC-2012 chronology. Between the two there are in some cases differences up to 150 years than for the purposes of this paper could be important. So, the authors could consider using both isotopic data sets (Talos Dome and TALDICE but the latter on the AICC-2012 age scale) and the snow accumulation rate from only Talos Dome. An alternative to the AICC2012 age scale for TALDICE is the Severi et al. (2012, CP) chronology, which uses the volcanic synchronisation between the TALDICE and the EPICA Dome C ice cores and in practice identical to AICC2012 age scale.

We have replaced the TALDICE (a) snow accumulation and (b) $\delta^{18}O$ records on the Buiron et al. 2011 age scale with (a) the Talos Dome (TD96) record for snow accumulation on the Severi et al. 2012 age scale and (b) TALDICE $\delta^{18}O$ on the Severi et al. 2012 age scale for the temperature reconstruction. We have updated the relevant figures (Figure 6, 8, and 9). The use of the updated age scale did not change the conclusions of our interpretation but led to a clearer dipole pattern shown in revised Figure 8. The Talos Dome (TD96) snow accumulation record spans a shorter time period that the TALDICE data. We have revised the text to reflect this. Please see our comment below.

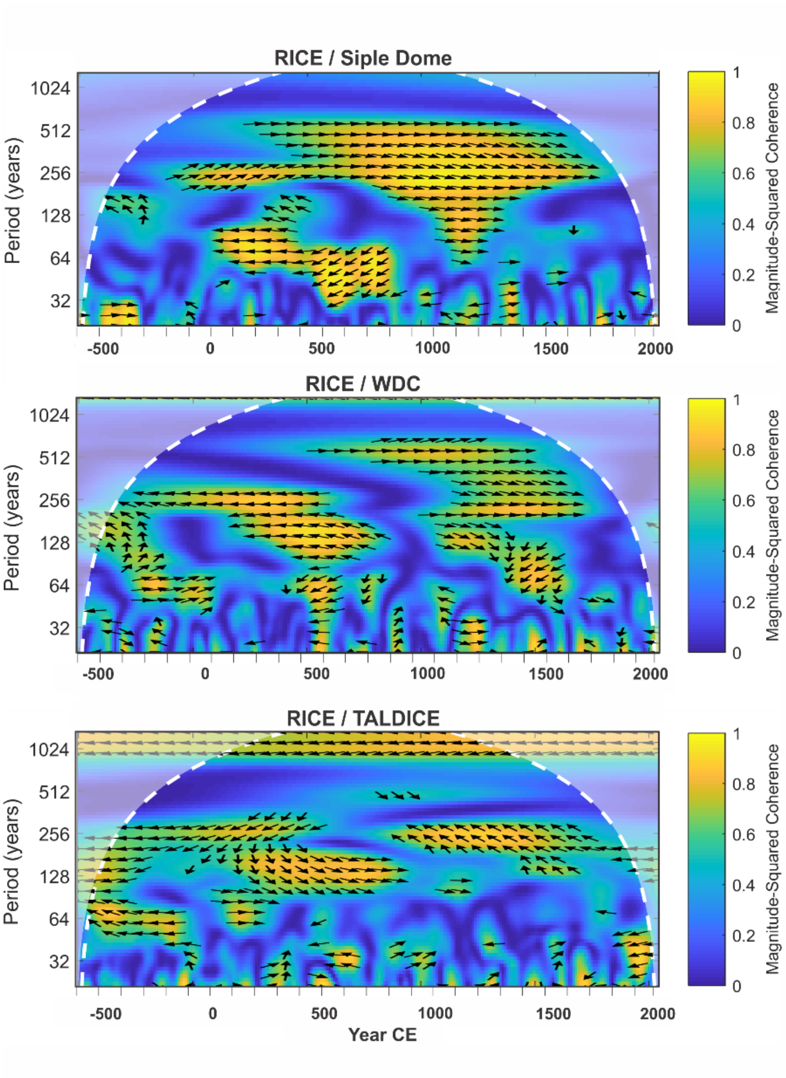


a) Isotope Temperature
660 BCE - 580 CE, -3‰
581-1477 CE, 0‰
1478-2012 CE, +5‰
RICE δD (‰ VSMOW)
Siple Dome δ18O (‰ VSMOW)
WDC δ18O (‰ VSMOW)
WDC Borehole Temperature (ºC)
TALDICE δ18O (‰ VSMOW)
Taylor Dome δ18O (‰ VSMOW)
b) Snow Accumulation
RICE Snow Acc (ma-1 weq)
WDC Snow Acc (ma-1 weq)
Talos Dome (TD96) Snow Acc (ma-1 weq)
50y rm RICE δD (‰ VSMOW)
50 y rm RICE Snow Acc (ma-1 weq)
c) Climate Indices
SAMA Index
Niño 3.4 SST Anomaly (ºC)
250 km
WDC
East Antarctica
West Antarctica
Siple Dome
RICE
Ross Ice Shelf
Taylor Dome
Amundsen Sea
Eastern Ross Sea
Western Ross Sea
TALDICE
speed (m/a)
Year CE

Revised Figure 1: a) Isotope records for the past 2,700 years for RICE, Siple Dome (Brook et al., 2005; WAIS Divide Project Members, 2013), WDC (WAIS Divide Project Members, 2013) and TALDICE (Stenni et al., 2011); b) snow accumulation data for RICE (Winstrup et al., in preparation), WDC (Fudge et al., 2016), and TALDICE (Buiron et al., 2011). No snow accumulation data are available for Siple Dome; c) Reconstructions of Climate Indices for SAM_A (Abram et al., 2014) and Niño 3.4 based on HadSST2 (Emile-Geay et al., 2013). Colour coding identifies above and below average values. Grey shaded area emphasises period of negative SAM_A, yellow shaded area emphasises period of synchronous warming at RICE, Siple Dome, WDC and TALDICE.



Revised Figure 2: Phasing of multi-decadal and centennial climate variability at RICE, Siple Dome, WDC and TALDICE using detrended, normalised isotope records smoothed with a 200-year moving average. RICE and Siple Dome are compared with a) WDC and b) TALDICE to investigate phase relationships of climate variability in the eastern Ross Sea with West (WDC) and East Antarctica (TALDICE). WA= West Antarctica, EA= East Antarctica. The detrended, normalised SAM_A record (Abram et al. 2014, light blue) has been smoothed with a 200-year moving average and is shown in panel (b). Shaded periods indicate synchroneity of RICE (and Siple Dome) data with WA (red box) or EA (purple box). Grey shading indicate time periods where RICE (eastern Ross Sea) shows an antiphase relationship (a Ross Sea Dipole) with TALDICE (western Ross Sea).



Revised Figure 3: Wavelet coherence and cross spectrum analysis of a) RICE δD and Siple Dome $\delta^{18}O$, b) RICE δD and WDC $\delta^{18}O$, c) RICE δD and TALDICE $\delta^{18}O$. The Analysis was conducted on decadally averaged, detrended data, smoothed with a 200 year moving average. The coherence is computed using the Morlet wavelet and is expressed as magnitude-squared coherence (msc). The phase of the wavelet cross-spectrum is provide for values over 0.6 msc using a Welch's overlapped averaged periodogram method (Kay, 1988;Rabiner et al., 1978). Arrows to the right indicate RICE is leading, arrows the left indicate RICE is lagging. An upright or downward arrow represents ¼ cycle difference.

Page 10, line 14: the onset of a decline in WDC isotopes at 579 CE is not clear from the figure . . .

We agree that this sentence is an imprecise statement of the reported observation. We changed the sentence to: "We note that within ~200 years of the onset of the warming at RICE (at 581±27 year, dotted line in Figure 6), the WDC borehole temperature and isotope data start to record a temperature decline, in line with the observed anti-phased relationship between WDC and RICE and Siple Dome."

Page 10, lines 25-26: the sentence "From the 17th century . . .. . . " it is not very clear, at least looking at the figure, and the word in phase seems to be not the correct word to use. . ..

We have revised this sentence to: "While WDC water stable isotope temperatures continue to cool, from the 17th Century onwards, the WDC borehole temperature record a warming. At the same time RICE and Siple Dome experience warmer temperatures while TALDICE recovers from its coldest recorded temperatures during the study period."

Page 10, line 30: TALDICE data: see the comments above.

Done.

Page 10, lines 37: from here ("until the 15th century . . ..") to the end of the paragraph it is not easy to follow the reasoning. . .

We are now using the Talos Dome (TD96) snow accumulation record which covers the time period from 1213-2012 CE. We revised this section to reflect the use of the shorter, higher resolution record: „Investigating long-term trends in snow accumulation records (Figure 6b), the decadally-smoothed RICE data (Winstrup et al., in review) show a discernible positive trend from about 600 CE for the eastern Ross Sea, while WDC (Fudge et al., 2016) displays a decreasing trend for central West Antarctica. The RICE snow accumulation data reach a maximum in the 13th Century, with a trend towards lower values from 1686 CE onward. Based on the negative correlation between RICE snow accumulation and SIE in recent decades, we interpret the long-term increase in snow accumulation to represent a long term reduction in SIE the Ross Sea, consistent with a long term increase in RICE isotope temperature. The modern decadal average (2002-2012) of 20 cm weq a^{-1} lies within the 2 σ variability of decadal RICE ice core snow accumulation rates (Figure 7). Talos Dome records its maximum snow accumulation rates at the end of the 13th Century and reduced snow accumulation during the Little Ice Age period (Stenni et al. 2002). Until the 15th Century, RICE and WDC snow accumulation and isotope data show an expected positive correlation between their respective isotope and snow accumulation records. Regionally, RICE and WDC isotope and snow accumulation data are antiphased. From the 16th Century, this relationship reverses and RICE and WDC snow accumulation are now in phase, suggesting below average snow accumulation in the eastern Ross Sea and West Antarctica. We note that from the 16th Century snow accumulation at RICE and WDC display a negative correlation with water stable isotope (RICE) and borehole (WDC) temperature reconstructions, respectively. At RICE this relationship is again positive for 1979-2012. During the 20th Century, Talos Dome records an increase in snow accumulation of approximately 11% in the western Ross Sea (Stenni et al.2002). However, the values are not unique within the variability of 800 years captured in the record."

Page 11, line 19: how this date (1367 +/-12 CE) is chosen? Not clear. Please, explain . . ..I suppose from the SAMA record. . .

That is correct. The age uncertainty is derived from the RICE17 age scale. For clarity, we add to the sentence on page 11, line 16: '… we identify three major time periods of change: 660 BCE to 1367 CE (long-term baseline), 1367-1683 CE (negative SAM_A), and 1684-2012 CE (onset of the positive SAM_A)."

Page 12, line 24: increased marine air mass intrusions: from borehole C3 or isotopic record?

This conclusion is drawn from the WDC isotope record as described on page 10, line 14. We have added the reference (Steig et al. 2013) here and changed the sentence to: "…and increased marine air mass intrusions into West Antarctica as inferred from WDC isotope data (Steig et al. 2013) but is …"

Page 13, line 30: . . ... are anti-correlated . . ... before the authors were claiming that they are correlated (see fig 8) at least from 400 to 1900 CE.

Here we refer to the long-term trends with RICE and Siple Dome warming, while WDC records a cooling. In Figure 8 these trends have been removed and only centennial scale variability, superimposed on the longer-term trends, are investigated.

Page 17, line 1: the author list of this reference (Jones et al) seems to be not complete.

We corrected the reference: Jones, J. M., Gille, S. T., Goosse, H., Abram, N. J., Canziani, P. O., Charman, D. J., Clem, K. R., Crosta, X., de Lavergne, C., Eisenman, I., England, M. H., Fogt, R. L., Frankcombe, L. M., Marshall, G. J., Masson-Delmotte, V., Morrison, A. K., Orsi, A. J., Raphael, M. N., Renwick, J. A., Schneider, D. P., Simpkins, G. R., Steig, E. J., Stenni, B., Swingedouw, D., and Vance, T. R.: Assessing recent trends in high-latitude Southern Hemisphere surface climate, Nature Climate Change, 6, 917-926, 2016.

Page 22 Table 1: I would suggest adding the resolution of the different records. Again, for TALDICE I would suggest using the AICC2012 or the Severi et al. (2012) age scales. Always in the Table 1: the reference WAIS Divide Members, 2013 refers to WDC and not Siple Dome.

We have removed the WAIS Divide Members, 2013 reference. Now Brook et al.2005 is listed as sole reference for the Siple Dome data set.

Page 26, Figure 4 caption: add the explanation for panels c and d.

Done. We have added the following: "Comparison of the ERAi precipitation time series with d) RICE snow accumulation data and e) RICE snow accumulation with optimised RICE δD data alignment. Coloured dots indicate locations of WDC (red), Siple Dome (green), RICE (blue), and TALDICE (purple), and Taylor Dome (orange)."

Page 28, figure 6 caption: for RICE, are these decadal averages or what?

RICE isotope and snow accumulation data are shown as decadal averages as noted on page 9, line 22 and page 10, line 29. In addition, we revised the Figure 6 caption to note the resolution.

Page 30, figure 8 caption: please add that these are isotopic data.

Done.