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Climate
of the Past
Discussions

Interactive comment on "Water stable isotopes spatio-temporal variability in Antarctica in 1960–2013: observations and simulations from the ECHAM5-wiso atmospheric general circulation model" *by* Sentia Goursaud et al.

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"This paper presents updated data and new model simulations for Antarctic isotope distributions. This is a worthy contribution, and appropriate for publication in Climate of the Past. I do have a several criticisms and technical points."

We thank the second referee for reviewing our manuscript. In the following lines, we answer to the reviewer comment by comment.

"**Much of the conclusions in the paper are not new, and this should be made clear."

Earlier studies focused on individual locations or specific time intervals have evidenced temporal changes in isotope-temperature relationships (e.g. different decadal to seasonal relationships, Masson-Delmotte et al., 2003), or different relationships in warmer than today climatic conditions (e.g. Sime et al., 2009). Our study is a step forward through a systematic quantitative analysis for all Antarctica, confronting seasonal, annual and time-averaged linear relationships. While our key findings are indeed not new, we confirm and expand the lines of evidence supporting these findings through a broader database and a systematic model-data comparison.

"For example, in the abstract, it is stated that "local spatial or seasonal slopes are not a correct surrogate for inter-annual temporal slopes". This is a very old result, and doesn't belong in the abstract."

Indeed, several earlier studies have challenged the use of spatial isotope-temperature relationships as a surrogate for temporal isotope-temperature relationships as it is crucial to assess the uncertainty associated with temperature reconstructions from ice core records. They evidenced spatial variations in this relationship (see for instance a review in Table 1 from Stenni et al. (2016) for the observed δ18O-temperature linear relationship at selected sites) as well as temporal variations. It suggests that different slopes have to be applied to reconstruct temperatures at different locations. Within the Antarctica2k effort, different statistical methods were thus tested to propose Antarctic temperature reconstructions from regional isotopic syntheses (Stenni et al., 2017a), expanding the pioneer work of Schneider et al. (2006). However, many of these earlier studies were based on site specific studies, or pure modeling work, without combining systematically available evidence, or without a systematic benchmarking of models against all available data. While our conclusions are not new, we provide a more systematic approach to such issues than in earlier studies. We have made clear in the revised manuscript that we are revisiting scientific questions using a more comprehensive database (combining precipitation and shallow ice core data) and with a systematic benchmarking of one isotope-enabled model which was run at higher spatial resolution then in earlier modeling studies, and in a nudged mode facilitating the comparison with short records. We stress that our work is the first to provide a quantitative synthesis of spatial and temporal (seasonal and annual) δ18O-temperature linear relationship (slopes and correlation coefficients) for all Antarctica.

“Similarly, the phasing between deuterium excess and d18O has been examined thoroughly in previous work. What is new here? Throughout the paper, I would like to see better delineation between new results and reiteration of old results.” - Most of model-data comparisons for Antarctica have been focused on model skills for spatial gradients in δ18O or δD. Our study is also the first one to benchmark ECHAM5-wiso outputs systematically using a synthesis of precipitation and ice core data, looking at spatio-temporal variations. In the abstract, we have clarified the novelty of our approach for the δ18O-temperature temperature and the d-excess - δ18O phasing: p.2 l.28 by writing: “Our study confirms key findings obtained from site specific focused studies, using a database of all existing records and a systematic model-data comparison.”

“**Too little reference is given to primary results, and it is difficult to determine what data are actually being used. Reference is given to the Stenni et al compilation of ice core data, but it is not clear which of the many records in that data set are actually used. For example, there are multiple cores from Dronning Maud Land and in the vicinity of Byrd Station and the West Antarctic ice sheet divide, but only a few locations are shown on the map? What are the primary data sources? Which of the cores (by latitutde/longitude) are included here? Which are excluded, and why?” The data extracted from the database compiled by the Antarctica2k group were restricted to the period 1979-present, resulting in the selection of 101 ice core data compared to the 122 original ice core data reported in Stenni et al (2017). The primary sources, latitude, longitude and covered periods of all data from our database are detailed in Supplementary Material. We have clarified this in our revised Section 2.1.3;

“(1) 101 high resolution ice core records, including 79 annually resolved records,

and 18 records with sub-annual resolution (including 5 records with both δ18O and δD data). These data have been extracted from the Antarctica2k data synthesis (Stenni et al., 2017b) with a filter for records spanning the interval 1979-2013, thus restricting the original 122 ice cores to a resulting 101 ice cores data. Primary data sources, geographical coordinates and covered periods are reported in Supplementary Material Table S1. (2) average surface snow isotopic composition data compiled by Masson-Delmotte et al. (2008) (available on http://www.lsce.ipsl.fr/Phocea/Pisp/index.php?nom=valerie.masson), expanded with datasets from Fernandoy et al. (2012); in this case, the averaging period is based on different periods, with potential not continuous record (see Supplementary Material Table S1). (3) precipitation records extracted from the International Atomic Energy Agency / Global Network of Isotopes in Precipitation (IAEA / GNIP) network (IAEA/WMO, 2016) with monthly records available for 4 Antarctic Stations, complemented by daily records for 4 Antarctic stations from individual studies. Precipitation records from Vostok are available but have excluded from our analysis, due to a too small number of measurements (29). (see Supplementary Material Table S1).

“**For the temperature data, it is stated that the READER data are used, and that "AWS" data are used for Byrd and Dome C. For Byrd, the best data are the updated record for Byrd, from Bromwich et al,. 2013. This should be used! It is not clear whether it is, nor not.” We thank the referee for suggesting to use of the temperature reconstruction of Bromwich et al. (2013). We have repeated our analysis replacing the AWS temperature data with the reconstructed Byrd station data. It made our conclusions more robust, as we found the same results with this longer time series, i.e. (i) a warm model bias (Table 1), (ii) no sharp increase from 1978 to 1979 in the data contrary to the model (Fig. 2c), (iii) stronger correlation coefficient and slopes between observed and simulated temperatures (Table 2, more coherent with the results obtained at other stations.

In revised Table 1, the observed standard deviation changed by 0.1°C (from 1.2 to 1.3

°C), and thus our conclusions about spatial model biases remain unchanged. In Table 2, we can have completed the line for Byrd station: Period 1960-2013 Period 1979-2013 slope (in °C °C-1) r p-value slope (in °C °C-1) r p-value . . . Byrd 1.1 (0.15) 0.7 <0.001 0.8 (0.12) 0.8 <0.001

Figure 2.c was also modified following this change.

In the text, we revised the description of the used temperature data in Section 2.1.1 p.7 l.17: "Due to the short duration of surface station records for the 90-180° W sector, we have added data from the automatic weather station (hereafter, AWS) of Dome C, but we have used it with caution as these records are associated with a warm bias in thermistor measurements due to solar radiation when the wind speed is low (Genthon et al., 2011). Finally, we extracted the reconstruction of temperature for Byrd station by Bromwich et al. (2013), based on AWS data and infilled with reanalysis data." In Section 3.1.1, we modified only one sentence of our results, p.13 l.15: "We observe that the model reproduces the amplitude of inter-annual variations, with a tendency to underestimate the variations as shown by model-data slopes from 0.7 to 1°C per °C."

"**There is reference to diffusion, but it's importance is not taken into account. "ECHAM5-wiso underestimates the seasonal amplitude (by 14 to 69%) when compared to precipitation data, but overestimates the seasonal amplitude when compared to ice core data (from 11 to 71%)." and "At Dome C, ECHAM5-wiso underestimates the standard deviation of temperature, but strongly overestimates the standard deviation of δ18O." Can diffusion explain these differences? It would be quite straightforward to evaluate whether this is likely. I suspect such difference can be explained entirely by diffusion, as has been pointed out in numerous previous papers."

We agree that post-deposition effects can explain the overestimation by ECHAM5-wiso of the seasonal amplitude recorded in ice cores, while it underestimates the seasonal amplitude recorded in precipitations. This comment was also made by the first referee. We repeat here the answer to the comment of Reviewer 1. This is an important issue

for the quantitative comparison of seasonal isotopic amplitudes in precipitation model outputs with firn data, potentially affected by diffusion (Johnsen et al, 2000).

The theory of Whillans and Grootes (1985) about isotopic diffusion in firn based on diffusional vapor flux through firn pore spaces, appears compatible with the estimated loss of seasonal amplitude through depth in diverse sites (e.g. Cuffey and Steig, 1998), but this validation is limited by the lack of comprehensive datasets (monitoring of precipitation isotopic composition over multiple years to be compared with the firn records), as well as uncertainties on key parameters. Accounting for firn ventilation effects on sublimation and condensation and disequilibrium between pore-space vapor and snow grains Neumann and Waddington (2004) shows more rapid isotopic changes in the upper few firn meters at low-accumulated site than explained by Whillans and Grootes (1985). Recent studies in Greenland have further evidenced changes in surface snow isotopic signal in between precipitation events, attributed to water vapour exchange associated with snow metamorphism (Steen-Larsen et al., 2014). While there has long been evidence for a loss of seasonal amplitude with depth, a reliable quantification of the effect of diffusion in firn for all available Antarctic records is currently out of reach, and thus cannot be applied to remove this bias in model-data comparisons of seasonal amplitudes.

Here, we just focus on all sub-annual records available from our database. For each record, we calculate the ratio of the seasonal amplitude estimated from the first three first seasonal cycles to the mean seasonal amplitude for all available seasonal cycles along this core. If the seasonal cycle of precipitation isotopic composition was constant through time, the interplay of diffusion and the averaging of seasonal amplitude over multiple seasonal cycles would make this ratio as an indication of the loss of seasonal amplitude, assuming that the amplitude of the first three seasonal cycles is representative of that of precipitation (Table 1 in Supplementary Material). We obtain a mean ratio of 1.40 ± 0.47. No significant relationship can be identified between this ratio and the corresponding estimated annual accumulation rates (see enclosed Figure 1). We note that a ratio lower than 1 is obtained in five ice cores, including one with a mean annual accumulation of 15 cm w.e. y-1; this situation is understood to result from interannual variations in precipitation isotopic composition and/or diffusion characteristics in the upper firn. Our simple empirical calculation shows that we cannot exclude a loss of seasonal amplitude in the firn data used to estimate the average seasonal isotopic amplitude, due to post-deposition processes; it also shows that the average seasonal amplitude obtained in our firn multi-year records may be affected by an average loss of about 70% (1/1.4) of the seasonal amplitude recorded during the first three years of each firn core. We cannot assess directly the potential distortion of the seasonal amplitude from the initial precipitation to the snow surface due to the lack of systematic precipitation, surface snow and firn multi-year monitoring datasets.

These elements are reported in our revised manuscript, in Section 3.2.2 “δ18O seasonal amplitude”, p.16 l.1 as follows: “In order to quantify post-deposition effects in ice cores, we calculated the ratio of the three first seasonal amplitudes by the mean seasonal amplitude in sub-annual ice cores (See Supplementary Information S2). We find a mean ratio of 1.40 $\pm$ 0.47. We explored whether this ratio was related to annual accumulation rates (See Supplementary Information S3), without any straightforward conclusion. We also observe that five ice cores depict a ratio lower than 1, including one with a mean yearly accumulation of 15 cm w.e. y-1, a feature which may arise from inter-annual variability in the precipitation seasonal amplitude or in post-deposition processes. This empirical analysis shows that a loss of seasonal amplitude due to post-deposition processes is likely in most cases, with an average loss of the seasonal amplitude of approximately 70% compared to the amplitude recorded in the upper part of the firn cores (first three years). ” Here, S2 and S3 correspond to the attached Figure 1 and Table 1 attached to this response.

We specified that the overestimation of the mean δ18O seasonal amplitude by ECHAM5-wiso compared to ice core data could be due to post-deposition effects: p.16 l.12 “The overestimation when comparing with ice core data could be due to the attenu-

ation of signal by post-deposition effects (as aforementioned) rather than a model bias.” p.20 l.23: “Again, we cannot rule out a loss of amplitude in ice core data compared to the initial precipitation signal, due to the temporal resolution and to post-deposition effects.the overestimation when comparing against ice core data, i.e. an attenuation in the data by post-deposition effects.”

“Also, it should be explained here whether EMCHAM-5 does a better or a worse job that ECHAM-4 or other models (GISS, for example). In other words, does ECHAM5 represent an improvement here, or not?” As explained in Werner et al. (2011) the ECHAM5 model includes a number of general model improvement as compared to ECHAM4. For the representation of the atmospheric water cycle, especially in polar regions like Antarctica, Martin Werner rated the separate prognostic equations were for cloud ice and cloud liquid water, a new flux-form semiâĂŘLagrangian transport scheme for all vapour, liquid water and ice in the atmosphere, and a different cloud micro-physical scheme as most important. Unfortunately, we have never published a present-day comparison study of the different isotope models (it was planned with the SWING2 project several years ago, but never realised). But for an LGM-PI comparison, please see Figure 5 of Jasechko et al. (2015) for the performance of the different models over Antarctica.

“**It is stated that there is an abrupt warming from 1978 to 1979, *possibly* caused by a discontinuity in the European Reanalyses (ERA) linked to the assimilation of remote sensing data starting in 1979..." This is not just "possible" – it’s certain. It is very well established that the ERA-interim data are essentially useless prior to 1979. I don’t think including the few data-model comparison prior to that time period is useful.” We agree that the he abrupt discontinuity from 1978-1979 in ERA reanalyses has been well established (Bromwich et al., 2007), so that most climate modelers have focused their analyses of simulations nudged to ERA reanalyses models to the period starting in 1979 (e.g. Lenaerts et al., 2012). We also note that some work on ice core data has explored historical reanalyses as a source of climate information. Finally, the nudged isotopic simulations give access to a comparison with ice core records independently of the data assimilated in reanalyses (e.g. accumulation and water stable isotopes), as an independent source of. While the finding that reanalyses are not reliable prior to remote sensing of sea ice (1979) is not new, we believe that this is still a valuable information, especially for the research community working on proxy records in natural archives.

“**References in general are inadequate. For example, it is noted that "recent studies cast doubt on this assumption [that isotope can be interpreted as precipitation weighted deposition signal" and a few recent papers are cited (Ritter et al., 2016;Casado et al., 2016;Touzeau et al., 2016). Those citations are good, but the original idea goes back at least to Waddington (2002: doi 10.3189/172756402781817004), and a number of papers by Steen-Larsen and others have also discussed this, some years prior to 2016. Such papers should be included. Another example is that reference is made to the impact of sea ice on isotopes, but only the very recent paper by Holloway et al 2016 is cited. This idea goes back to at least 1983 (e.g. Bromwich and Weaver, doi:10.1038/301145a0. Another key citation is Noone et al., 2004: doi: 10.1029/2003JD004228.” We thank Reviewer 1 and 2 for suggesting to add references to pioneer studies. Especially here, we thank reviewer 2 for directing us towards the studies of Bromwich and Weaver (1983), and Noone and Simmonds (2004) that we were not aware of. We thus expanded the citation of (Holloway et al., 2016) with those given, p.15 l.17: (Bromwich and Weaver, 1983;Noone and Simmonds, 2004;Holloway et al., 2016). Also, in response to Reviewer 1, we updated our citations : - In the introduction: o p.4 l.6 (Schoenemann et al., 2014) o p.4 l.10 (Sokratov and Golubev, 2009;Jones et al., 2017;Münch et al., 2017;Laepple et al., 2018) o p.4 l.14 (Smith and Stearns, 1993;Turner, 2004;Stammerjohn et al., 2008;Schroeter et al., 2017) o p.4 l.21 (Hoshina et al., 2014) o p.4 l.25 (Grazioli et al., 2017) o p.5 l.14 (Fernandoy et al., 2018) - Section 3.2.1 o p.16 l.8 (Waddington et al., 2002;Neumann and Waddington, 2004) - Section 4.1 o p.24 l.1 (Sturm et al., 2010;Steiger et al., 2017) - Section 4.2 o p.24 l.8 (Jouzel et al., 2013;Pfahl and Sodemann, 2014;Kurita et al., 2016) o p.24 l. 9

(Schlosser et al., 2017)

“**There is much discussion about the phase lag between deuterium excess and d18O, but no discussion of why this is important. As the authors will be aware, Pfahl and Sodemann [2014] have suggested a completely different idea (with respect to humidity) about this than the conventional one (about the delay between SST and air temperature). I realize that the present paper is not claiming to solve this puzzle, but some reference to the scientific context would greatly improve the paper.” Pfahl and Sodemann (2014) analysed global observational deuterium excess records and a diagnostic of moisture sources from atmospheric reanalyses, and found an empirical linear relationship between seasonal variations in deuterium excess in precipitation and relative humidity at the moisture sources. This finding was challenged by related studies of Antarctic precipitation data (Dittmann et al., 2016;Schlosser et al., 2017), calling for further investigations. Several earlier studies had also explored the seasonal relationship between d-excess and δ18O in Antarctic precipitation and snow samples, showing different results in central Antarctica (an antiphase, e.g. Stenni et al., 2016) and coastal Antarctica (e.g. Ciais et al., 1995;Delmotte et al., 2000). While an anti-phase is expected if d-excess would only respond to changes in condensation temperature (through the dependency on temperature of the equilibrium fractionation coefficients and the resulting local meteoric water line), a different phase relationship is understood to reflect a signal related to changes in moisture origin and/or evaporation conditions, which may theoretically include effects of relative humidity as well as effects of sea surface temperature (Jouzel et al., 1982). In this manuscript, we explore this relationship systematically in all available records (this was not done previously) and compare the ECHAM5-wiso outputs with these datasets to test if the model is able to produce realistic seasonal lags (to our knowledge, it was never be done previously either). We better introduced section 4.2 to show the importance of studying the deuterium excess - δ18O phase lag p.24 l.9: “The phase lag between d-excess and δ18O was initially explored to identify changes in evaporation conditions (Ciais et al., 1995). D-excess has been interpreted as a proxy for relative humidity at the moisture source (Pfahl and

Sodemann, 2014). However, recent studies of Antarctic precipitation data combined with back-trajectory analyses did not support this interpretation (e.g. Dittmann et al., 2016;Schlosser et al., 2017), calling for further work to understand the drivers of seasonal d-excess variations."

"** The figures could use improvement. Especially, there should be a variable name and units on the color bars of the various maps. For example, Figure 10 should read "lag, in months", on the color axis." For more clarity, we added the labels of Figures 4, 9 and 10.

"**The calculation of statistical significance, throughout the paper, is not clear. Is autocorrelation accounted for in stating that $p<0.05$?" We confirm that we consider a linear relationship as significant when the corresponding p-value is lower than 0.05. The criterion of a significant linear relationship are now explicitly indicated at the end of Section 2.3 (method section) p.11 l.22: "Our comparisons are mainly based on linear regressions. Note that through all the manuscript, we consider a linear relationship to be significant for p-value<0.05."

"**Several recent papers have demonstrated that the logarithmic form of deuterium excess is a much more reliable and robust measure than the traditional linear calculation. The paper really ought to look at this as well. See Markle and others (doi: 10.1038/ngeo2848) and Uemera et al., 2012 (doi: 10.5194/cp-8-1109-2012), Dutsch et al. 2017, 10.1002/2017JD027085"

We thank the referee for suggesting to test alternative definition of deuterium excess. We understand that the logarithmic definitions were introduced for large amplitude, glacial-interglacial changes (Uemura et al., 2012) or glacial abrupt events (Markle et al., 2017). However, Uemura et al. (2012) call for caution when interpreting this alternative parameter which does not highlight key second order features (e.g. deglacial lags; obliquity signals) as strongly as d-excess. Moreover, different logarithmic definitions have been introduced by different authors : a second-order polynomial (Uemura et al.,

2012;Markle et al., 2017) or a first-order polynomial approach (Dütsch et al., 2017), preventing comparisons between these studies. Such a logarithm definition removes the δ-scale effect (thus correcting for temperature-dependent d-excess signals, particularly strong at glacial-interglacial scales) but may be sensitive to the air-mixing effects (Risi et al., 2013). We also note that most studies exploring the potential of d-excess to identify changes in moisture origins also used the classical definition of deuterium excess (e.g. Schlosser et al., 2008;Dittmann et al., 2016). Finally, recent studies found similar signals using both definitions (Schoenemann and Steig, 2016). We nevertheless checked the implications of the logarithmic definition with our data (see Figure S1 from the Supplementary Material associated with this response). The first test is performed with the spatial distribution of water isotopes. Using the spatial distribution of data in Antarctica, we obtain a slightly better correlation coefficient using a δD-δ18O linear relationship compared to using a ln(RD)- ln(R18O) linear relationship (correlation coefficients of 0.9978 and 0.9963 respectively, and slopes of respectively 7.76 ‰ ‰1 and 10.49 ,see S1.a and S1.b from the Supplementary Material). We then performed the same test using daily precipitation data from two completely different sites, the plateauing site of Dome C (Stenni et al., 2016) (See S2 from the Supplementary Material) and the coastal site of Neumayer (Schlosser et al., 2008) (See S3 from the Supplementary Material). For each site, we processed δD-δ18O and ln(RD)- ln(R18O) linear relationships over all the data, and then over the mean seasonal cycle. As over all time-averaged data points from our database, we observe that the correlation coefficient does not vary much from one definition to another one. Also, the slope is different depending on the definition when focusing on a same site (e.g. 10.977 and 6.720 ‰ ‰1 for the logarithmic and the classical definition respectively using the precipitation data measured at Dome C). However, whatever the considered definition, it differs from one site to another one using the same time scale (e.g. 10.988 and 7.930 for Dome C and Neumayer respectively using the logarithmic definition over the daily data), as well as for different time scales at a same site (e.g. 10.988 and 11.385 for daily data and mean seasonal data respectively at Dome C). As a result, no criterion for this test allows us to choose one definition rather than another one. Finally, we compared the deuterium excess mean seasonal cycle using both definitions for the aforementioned sites (see S4 from the Supplementary Material). Although the variations are similar for precipitation data from Neumayer, they do not look like the same for precipitation data from Dome C. But the cause responsible for this difference is not understood. We conclude that none of the definition is stable in space and time using our data, opening the issue of the adequate slope to use for an alternative d-excess logarithm definition to be applied to our database and for the model-data comparison. Nevertheless, we prefer to use the classical definition for a better comparison with previous studies.

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