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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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"General Comments This paper addresses novel and relevant scientific questions within the scope of CP. The authors use an impressive collection of data to assess the skill of the ECHAM5-wiso model. The main scope of the paper is to evaluate spatial, seasonal and interannual δ18O-temperature relationships, as well as deuterium excess and δ18O phasing. This information is important for correctly interpreting certain climate records in Antarctica, especially when using shallow ice core records of a few decades length." "Minor revisions are required for publication, as well as one major

revision and/or clarification." We thank the first referee for reviewing our manuscript. In the following lines, we answer to the reviewer comment by comment.

"Specific Comments * My biggest concern is how the authors addressed water isotope diffusion in shallow ice core records. The majority of diffusion occurs in the upper âĹij10- 20 meters of the ice sheet, thus this will have a significant effect on the results of this study (i.e. for ice core data from 1979-2013, or for any data extending beyond a few years in length). Can the authors clarify whether any consideration was given to the attenuation of the seasonal and multi-year variations due to diffusion? For example, at a typical inland West Antarctic site (mean annual temp = -30.3C, accumulation = 0.23 m/yr), the annual d18O and dD signal amplitudes will decrease by about âĹij50% in 30 years (calculated using a Johnsen firn model and a Herron-Langway densification model). For a colder site (temp = -40.3C, accum = 0.12 m/yr), the amplitudes decrease by 67% in 30 yrs. And for a warmer site with high accum (temp = -25.3C, accum = 0.38 m/yr), the amplitudes are decreased by 37% in 30 years. These are quick calculations, but show the importance of diffusion. Could firn diffusion be the cause of model-data mismatch? If so, and I think this is the case, the authors should either make these calculations and include the corrections in the paper, or state a few examples of signal attenuation for different temperatures and accumulation that are relevant to the ice core sites used in the paper. On the other hand, if I have misunderstood the results, please provide clarifications and explain why." 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 (Touzeau et al., 2017).

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 $\pm$ 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 can be interpreted as resulting from inter-annual 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 attenuation 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.”

“* Please explain “nudging”, and perhaps use different wording in the paper. While this may be common terminology, it is not immediately clear what it means, nor does it appear to be defined in the main text of the paper.”

“Nudging” is a common term used in atmospheric modelling studies, referring to a specific methodology related to data assimilation (e.g. Risi et al., 2013). Details of the nudging used for ECHAM5-wiso are given in Butzin et al. (2014): “the dynamic–

thermodynamic state of the ECHAM model is constrained to reanalysis data by an implicit nudging technique (Krishamurti et al., 1991; the implementation in ECHAM is described by Rast et al., 2013) – i.e. modelled fields of surface pressure, temperature, divergence and vorticity are relaxed to the corresponding ERA-40 and ERA-Interim reanalysis fields (Uppala et al., 2005; Berrisford et al., 2011; Dee et al., 2011). The nudging interval is 6 hours, ensuring that the simulated large-scale atmospheric flow is modelled in agreement with the ECMWF reanalysis data on all analysed timescales." As the manuscript is dedicated to non-modelers, we understand that this word is not understood prima facie from all, and thus referred to Butzin et al. (2014) in the introduction, p.6 l.12: "We explore a simulation performed for the period 1960-2013, where the atmospheric model is nudged to the European Reanalyses (ERA) ERA-40 and ERA-interim reanalyses (Uppala et al., 2005), ensuring that the day-to-day simulated variations are coherent with the observed day-to-day variations in synoptic weather and atmospheric circulation (see Butzin et al., 2014 for more explanation)."

"I would also suggest a short, 1- sentence explanation in the introduction that explains the relevance of slopes for ice core isotope-temperature relationships, etc." As suggested, we added one sentence in the introduction p.4 l.6, to show the relevance in the isotope-temperature slope to infer past temperatures: "Water stable isotope measured along ice cores were initially used to infer Antarctic past temperatures using the isotope-temperature slope (e.g. Lorius et al., 1969)."

"* Can you please confirm that for any averaged isotope data, that the same averaging was done in the model. If not, please state why, and how this could affect results. Also, please provide a clarification on how averaging could reduce the amplitude of the observed seasonal and multi-year signals." For comparison with precipitation data, as detailed in Section 2.3 "Methods for model-data comparison", daily precipitation outputs were extracted in ECHAM5-wiso to correspond to the same days than in the data. Thus, same averages (seasonal, annual, and time-averaged) were then processed in the data and in the model. The comparison between ECHAM5-wiso outputs and ice

core data is different, as monthly and annual model outputs are then calculated from precipitation weighted daily data to mimic ice core signals (without accounting for post-deposition processes, as described above). We have rewritten Section 2.3 "Methods for model-data comparison" clarify the fact that averaging was done exactly in the same way for model and precipitation data: "We have extracted daily 2-m temperature outputs (hereafter 2m-T) for comparison with surface air instrumental records, daily (precipitation minus evaporation) outputs (hereafter P-E) for comparison with SMB data, and daily precipitation isotopic composition outputs for comparison with measurements of isotopic composition data from precipitation samples. For the comparison of annual model outputs with ice core data, we averaged daily precipitation isotopic composition weighted by the daily amount of precipitation. For each specific site, we selected the model grid cell including the coordinates of the site. When comparing model outputs with the database of surface data (time-averaged SMB and isotopic composition), available data have been averaged within each model grid cell. Time selection was dependent on the variables. The 2-m T outputs have been compared with temperature records for the period 1960-2013, based on annual averages and selecting same years than in the data (see Section 3.1.1). The comparison with other datasets (SMB, snow and water stable isotopes from firn/ice cores) is restricted to the period 1979-2013, due to concerns about the skills of the reanalyses used for the nudging prior to 1979 in Antarctica (see next section). Daily (P-E) outputs were all extracted over the whole period 1979-2013 and averaged (see Section 3.1.2). For comparison with the surface isotopic database (Section 3.2.1), daily precipitation isotopic composition were averaged by weighting by the daily amount of precipitation over the whole period 1979-2013. For the inter-annual variability (same Section) or annual values (e.g. for d-excess outputs, see Section 4), daily precipitation isotopic composition were averaged by weighting by the daily amount of precipitation for each year of the period 1979-2013. For sub-annual isotopic composition, we used precipitation isotopic compositions (amplitude and mean seasonal cycle) and highly resolved ice cores (amplitude only). Precipitation isotopic composition data consist of a very small number of measurements, sometimes taken before 1979 (e.g. observations from DDU consist in 19 measurements during 1973), and thus model precipitation isotopic composition outputs were extracted at the very exact sampling date. Then, monthly averages were performed and mean seasonal cycles were calculated. The resulting mean seasonal cycles of precipitation isotopic composition were obtained the same way in both the precipitation data and the model outputs. For comparison with the mean season amplitude of the highly resolved ice cores, the mean seasonal amplitude was calculated from the mean seasonal cycle based on the monthly averages (weighted by the precipitation amount) over the period covered by the ice core record. Finally, for the spatial linear relationships, calculations reported for each grid cell are based on the relationship calculated by including the 24 grid cells ($\pm$ 2 latitude steps. $\pm$ 2 longitude points) surrounding the considered grid cell." Also, we detailed the time resolution of the outputs in the captions of Tables: - In Table 4: "δ18O mean seasonal amplitude (in ‰ calculated for precipitation and sub-annual ice core data, as well as simulated by ECHAM5-wiso for the same time period than the data. The time resolution used in the model corresponds to the time resolution of the precipitation data, and to the annual scale for the ice core data (i.e. yearly averages based on daily precipitation isotopic composition weighted by the amount of daily precipitation). The data type is identified as 1 for precipitation samples and 2 for ice core data." - In Table 6: "Slope (in ‰ ‰1), correlation coefficient (noted as "r") and p-value of the ïĄď18O-ïĄďD linear relationship from precipitation measurements (top of the table) and ice core data (bottom of the table) over the available period and at daily or monthly scale depending of the time resolution of the data, and from the ECHAM5-wiso model over the observed period at the time resolution of the data for the precipitation and at the annual scale for the ice core data (i.e. yearly averages based on daily precipitation isotopic composition weighted by the amount of daily precipitation). Numbers into brackets correspond to the standard errors." - In Table 7: "Mean value (noted as "μ" , in ‰) and standard deviation (noted as "σ", in ‰ of sub-annual d-excess in observational time series at daily or monthly scale (when the name of the station is associated with an asterisk) for the precipitation at the lowest time resolution

for the ice core data, and simulated d-excess by ECHAM5-wiso for the same time period as the observations for precipitation and at the annual scale for the ice core data (i.e. yearly averages based on daily precipitation isotopic composition weighted by the amount of daily precipitation). Mean values which are overestimated by ECHAM5-wiso are written in italic." - In Table 8: "Table 8: d-excess mean seasonal amplitude (in ‰ calculated for precipitation at daily or monthly scale (when the name of the station is associated with an asterisk) for the precipitation at the lowest time resolution for the ice core data and sub-annual ice core data at the lowest time resolution, as well as simulated by ECHAM5-wiso for the same time period as each record. The data type is identified as 1 for precipitation samples and 2 for ice core records. Amplitude values that are overestimated by ECHAM5-wiso are written in italic."

"* The authors state once that ". . . a stationary isotope-temperature slope cannot be applied for the climatic interpretation of Antarctic ice core." (pg 3, line 1-2). This is an important point. I think this point should be made in the Conclusion as well, specifically that the results of this study (or at least some of the results) may not hold in the deeper past (greater than a few decades). Please be clear in your assessment of the relevance for paleoclimate interpretations. This has the potential to be misunderstood."

We thank the reviewer for highlighting this conclusion, which was taken into account to propose temperature reconstructions spanning the last 2000 years (Stenni et al, 2017). We have added this finding in the conclusions, stressing that it only applies to inter-annual to decadal changes: p.26 l.21: "Expanding earlier site-specific studies, we show that the strength and slope of the δ18O-temperature linear relationship is not stationary in Antarctica over the last four decades. This finding has implications for past temperature reconstructions using ice core records."

"* In many instances, the citations are dated. There are many more recent studies that should be cited in this manuscript. I encourage the authors to provide citations of more recent studies." We thank Reviewer 1 for this suggestion. We have used the most recent references for our observation database. The peer-review literature for isotopic modeling, post-deposition processes and model-data comparisons has been screened to identify recent works which we had not cited. The following references have been added in the text We have thus cited: - In the introduction: o p.4 l.6 (Schoenemann et al., 2014) o p.4 l.10 (Jones et al., 2017;Münch et al., 2017;Sokratov and Golubev, 2009;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 (Steiger et al., 2017;Sturm et al., 2010) - Section 4.2 o p.24 l.8 (Pfahl and Sodemann, 2014;Jouzel et al., 2013;Kurita et al., 2016) o p.24 l. 9 (Schlosser et al., 2017)

Technical Corrections “pg 2 line 7 - nudged? please explain what this means somewhere in the introduction, and possibly change the wording.” The text has been modified to refer to Butzin et al. (2014), p.6 l.12.

“pg 2 line 15-17 - the description is unclear” The description has been clarified: “The comparison with accumulation and water stable isotope data is thus restricted to the period 1979-2013, for accumulation and water stable isotope data from snow and firn/ice core but not for the isotopic composition from precipitation data that would consist in a too few number of points.”

“pg 2 line 28 - slopes? “We show that local spatial or seasonal slopes” the relevance of slopes should be defined in the introduction so certain readers are not left wondering what this means” We did not detail in the abstract the relevance of the ïĄd’18O-temperature relationship and particularly its slope, due to space limitations. Nevertheless, we explained it in the introduction from p.4 l.22 to l.27: “Pioneer studies evidenced a close linear relationship between the spatial distribution of water stable isotopes and local temperature (e.g. Lorius and Merlivat, 1975), and explained this feature as the result of the distillation along air mass trajectories. Thereupon, local temperature (i.e. at a specific site) was reconstructed using δ18O measurements and based on the slope of the aforementioned empirical relationship (...)Evaporation conditions, trans-

port and boundary layer processes may vary through time, from seasonal (Fernandoy et al., 2018) to annual or multi-annual scale, thereby potentially distorting the quantitative relationship between snow isotopic composition and local surface air temperature estimated empirically for present day conditions (Jouzel et al., 1997).”

“pg 3 line 6 - “This work valuates” - evaluates?” We replaced it.

“pg 4 line 4 - consider saying “the hydrologic cycle” rather than “water cycle”” p.4 l.4: we replaced “water cycle” by “hydrological cycle”.

“pg 4 line 6-8: “Their climate interpretation is however limited, first by the alteration of the signal due to deposition and post-deposition processes, and second by the complexity of all parameters affecting the Antarctic snowfall isotopic composition” cite sources. For Antarctica, one of the more in-depth studies of “post-depositional processes” is Jones et al., 2017 “Water isotope diffusion in the WAIS Divide ice core during the Holocene and last glacial” doi:10.1002/2016JF003938. Also provide citations for depositional processes and “complexity of all parameters” - perhaps you mean isotopic recharge, etc?”

For post-deposition effects, we referred to Sokratov and Golubev (2009), Jones et al. (2017), Laepple et al. (2018) and Münch et al. (2017). By “complexity of all parameters”, we meant the interplay of all parameters driving the isotopic composition such as the origin of moisture or the intermittency of precipitation, as stressed by Krinner and Werner, (2003); Sime et al., (2009); Hoshina et al., (2014) and Touzeau et al. (2016). “The climate signal potentially recorded in precipitation isotopic composition is however difficult to disentangle. First the original signal from precipitation may be altered due to deposition and post-deposition processes (e.g. Jones et al., 2017;Münch et al., 2017;Sokratov and Golubev, 2009;Laepple et al., 2018), which cannot yet be quantified. Second, the Antarctic snowfall isotopic composition may be affected by the origin of moisture and the associated evaporation conditions, or by changes in the relationships between condensation and surface temperature, as well as by changes in the intermittency of precipitations (e.g. Sime et al., 2009;Krinner and Werner, 2003;Hoshina et al., 2014;Touzeau et al., 2016).” pg 4 line 6: “Their”? Who are they? “Their” stand for “Water stable isotope measured along ice cores” from the sentence before. We thus made more explicitly the link: “The climate interpretation of such records”.

“pg 4 line 6-8: “Their climate interpretation is however limited, first by the alteration of the signal due to deposition and post-deposition processes, and second by the complexity of all parameters affecting the Antarctic snowfall isotopic composition.” - please use another word other than limited. I think you mean to say that post depositional processes alter the original signal, which must be accounted for in climate interpretations?” We have reformulated the sentence for clarity (see above).

“pg 4 line 13-16, “However, recent studies cast doubt on this assumption, evidencing isotopic exchanges between the Antarctic snow surface and the atmosphere associated with snow metamorphism occurring at the diurnal and sub-annual scales (Ritter et al., 2016;Casado et al., 2016;Touzeau et al., 2016).” consider citing Steen- ËĞ Larsen et al.?” We thank the referee who pointed the work of Steen-Larsen et al., very complementary to our citations: “However, recent studies cast doubt on this assumption, evidencing isotopic exchanges between the Antarctic snow surface and the atmosphere associated with snow metamorphism occurring at the diurnal and sub-annual scales (Ritter et al., 2016;Casado et al., 2016;Touzeau et al., 2016;Jones et al., 2017;Steen-Larsen et al., 2014).”

“pg 4 line 16-18: Again, the most recent diffusion study I have seen is Jones et al. 2017, it provides important information with an Antarctic perspective, and it should be cited here. There are important points in Jones et al. 2017 that improve on Sigfus Johnsen’s 2000 paper.” We thank the referee for his suggestion to refer to the recent work of Jones et al., 2017. This contribution is indeed very important to improve the knowledge of post-deposition processes, especially the ice-deformational thinning along the ice core, and the crystal-type acting in diffusion. We have thus cited it: “Other processes such as melt and diffusion processes can also alter the preservation of isotopic signals in

firn and ice and cause smoothing of the initial snowfall signals (Johnsen, 1977;Whillans and Grootes, 1985;Johnsen et al., 2000;Jones et al., 2017).”

“pg 4 line 18-19: “So far, the overall importance of such post-deposition processes on the alteration of the initial precipitation signals cannot be quantified.“ This is not true. The alteration of the initial precip signal can be determined reasonably well by fitting a Gaussian to the data. Similarly, the Johnsen firn diffusion model, to the first order, is also a reasonable model for signal alteration. However, there are physical mechanisms that are still not understood.” We agree that post-deposition processes can be described using an empirical spectral analysis, but cannot yet by fully understood based on a mechanistic model (see Touzeau et al., 2017). Thus, we rewrote our sentence as follows: “So far, the mechanisms of such post-deposition processes on the alteration of the initial precipitation signals are not fully understood and quantified.”

“pg 5 line 7: “δ18O and deuterium”, should be “δ18O and δD (D refers to deuterium)” - something like this would be more consistent” We replaced “deuterium” by “δD”.

“pg 5 line 19: is this really the only exception??? “with one exception (Lee et al., 2008).”” Among the studies focusing on the stationary of the isotope-temperature relationship using simulations (Jouzel et al., 1997), Lee et al. (2008) is the only study at our knowledge, that shows, that the spatial isotope-temperature relationship is not a good approximation for glacial conditions.

“pg 6 line 2: what is motivating “interannual scale” research, I suggest mentioning why this matters in the introduction” As suggested, we deepened our motivation p.4 l.8 : “The focus on inter-annual variations is motivated by the goal to quantify temperature changes at the Earth’s surface, including Antarctica, during the last millennia, to place current changes in the perspective of recent natural climate variability (Jones et al., 2016), to understand the drivers of this variability, and to test the ability of climate models to correctly represent it (Stenni et al., 2017). This timescale is relevant for the response of the Antarctic climate to e.g. volcanic forcing, and for the Antarctic climate fingerprint of large-scale modes of variability such as ENSO and the Southern Annular Mode (Smith and Stearns, 1993;Turner, 2004;Stammerjohn et al., 2008;Schroeter et al., 2017). "

"pg 7 line 11: "cautious" - caution?" Thanks for having highlighted this mistake. We replaced "cautious" by "caution".

"pg 7 line 23: nudged to, what does this mean?" Please consider our response above.

"pg 8 line 10: just use dD rather than deuterium to avoid confusion, and make sure to define D, see above comment" As previously, we replaced "deuterium" by "δD".

"pg 8 line 18-19: unclear what this means, "the averaging period may be heterogeneous, including subintervals within 1960-2013, or longer time periods."" We changed the sentence for a better understanding: "(...) in this case, the averaging period is based on different periods, with potential not continuous records."

"pg 11 line 3-5: "While this bias is small (less than 2âŮęC)" - this is not small, please re-word" The 2°C bias for Dronning Maud Land is smaller compared to the 15°C bias for McMurdo. We have rewritten the sentence to: "While this bias is less than 2°C for Droning Maud Land (Mawson and Neumayer) and over the Peninsula (Palmer and Esperanza), it reaches 7°C for the Coastal Indian region (Casey and Dumont d'Urville) and is very strong over the Victoria Land region (McMurdo), reaching 15°C."

"pg 11 line 8: "above the ice sheet" - what does this mean?" We meant "inland", so we substitute "above the ice sheet" by this word. "In contrast, ECHAM5-wiso has a warm bias for all the stations located inland (Vostok, Dome C and Byrd)."

"pg 12 line 1-2: "despite the nudging technique (not shown)." - what exactly is not shown? As mentioned previously, please explain nudging." What is not shown is the mean values and the amplitude of inter-annual variations simulated by ERA-interim. We have rewritten this sentence to: "We note that mean values and the amplitude of inter-annual variations are different for ECHAM5-wiso and ERA (not shown), as expected from different model physics, despite the nudging technique." For the "nudging" term, we refer the referee to the above response.

"pg 14 line 21-24: "The largest deviations are encountered in coastal regions, where either the model resolution is too low to resolve advection and boundary layer processes (e.g. katabatic winds), or where post-deposition processes may have a larger influence." Why would post deposition processes have a larger influence? Larger compared to what?" Larger deviations are observed in coastal regions, affected by katabatic winds. Such processes are not resolved in the model, which thus do not account for the associated deposition effects (e.g. snow drift by the winds). Strong winds also enhance ventilation and thus the equilibration between surface snow and water vapor in the boundary layer, one of the component of post-deposition effects (See Waddington et al., 2002). We have thus rewritten the sentence to: "The largest deviations are encountered in coastal regions, where the model resolution is too low to resolve advection and boundary layer processes (e.g. small scale storms, katabatic winds). Katabatic winds also have the potential to enhance ventilation-driven post-deposition processes (Waddington et al., 2002;Neumann and Waddington, 2004)."

"pg 15 line 23: "We have calculated the mean amplitude of the δ18O sub-annual variations" - please clarify what amplitude you are calculating? Monthly?" Ice core data available at sub-annual resolution are dated by annual layer counting, at best at the seasonal scale (through the identification of summer peaks). For each year, an annual amplitude can be estimated through the difference between the corresponding minimum and maximum values. The mean amplitude of δ18O sub-annual variations correspond to the mean δ18O annual amplitude. We rephrased the sentence p.15 l.23: "We have calculated the mean of the δ18O annual amplitude (i.e. maximum – minimum values within each year) in ice core records (...)."

"pg 16 line 2-4: "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%)." âAËŸT could the seasonal amplitude over- estimation in the model be related to diffusion? These overestimations are similar to the annual signal attenuation examples I gave above." Please refer to the response to your first comment concerning diffusion/post-deposition effects, which is related to post-deposition effects damping the seasonal amplitude.

"pg 18 line 10-11: this needs more explaining and/or a citation - "Due to the temperature dependency of equilibrium fractionation coefficients, dexcess increases when temperature decreases."" As temperature decreases, the difference between equilibrium fractionation coefficients increases, leading to a gradual deviation from the meteoric water line (calculated at the global scale, where the coefficient of 8 results from the average equilibrium fractionation coefficients), and thus to a gradual increase in d-excess. We referred to Masson et al., 2008 and Touzeau et al., 2016, which deal with the temperature dependency of the deuterium excess: "Due to the temperature dependency of equilibrium fractionation coefficients leading to a gradual deviation from the meteoric water line (calculated at the global scale, where the coefficient of 8 results from the average equilibrium fractionation coefficients), d-excess increases when temperature decreases (Masson-Delmotte et al., 2008;Touzeau et al., 2016)."

"pg 19 lines 16-18: "ECHAM5-wiso systematically underestimates the d-excess mean seasonal amplitude when compared with precipitation data, while it systematically overestimates it when compared with ice core data." could the overestimation be due to diffusion, which would decrease the dxs amplitude? what is the range of overestimation (in percent)?" We have added a discussion of post-deposition effects (see above) and the potential associated loss of amplitude. "ECHAM5-wiso systematically underestimates the d-excess mean seasonal amplitude when compared with precipitation data, while it systematically overestimates it when compared with ice core data (from 9.4 to 15.5 ‰, with the exception of the GIP ice core. 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."

"pg 19 lines 26-27, pg 20 lines 1-2: "ECHAM5-wiso always underestimates seasonal

amplitude of δ 18O and d-excess in precipitation but always overestimates seasonal amplitude of δ 18O and d-excess in firn/ice cores (Table 4 and 8). Differences between the model and firn/core data might be due to diffusion processes, but no clear reason can be given for the other isotopic biases." - it is not accurate to say "might be due to diffusion", because diffusion must have a substantial effect" We agree that the potentiality of the effect of diffusion is inappropriate here. We thus turned the sentence to: "Differences between the model and firn/core data are at least partially due to diffusion processes, but no clear reason can be given for the other isotopic biases."

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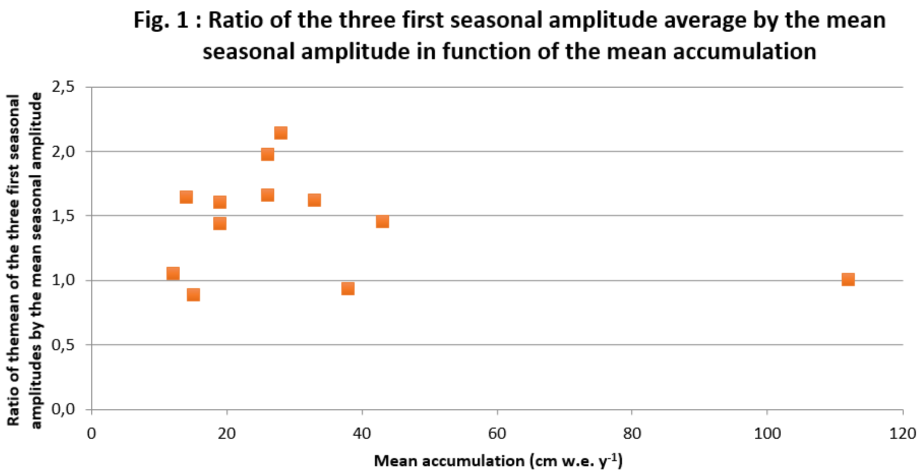
Fig. 1 : Ratio of the three first seasonal amplitude average by the mean seasonal amplitude in function of the mean accumulation
Ratio of themean of the three first seasonal amplitudes by the mean seasonal amplitude
2,5
2,0
1,5
1,0
0,5
0,0
0
20
40
60
80
100
120
Mean accumulation (cm w.e. y-1)

Fig. 1.