Review of "Evaporative controls on Antarctic precipitation: An ECHAM6 model study using novel water tracer diagnostics" by Gao et al., 2023 submitted to The Cryosphere

This study quantifies the evaporative sources of Antarctic precipitation for a preindustrial simulation with the ECHAM6 model. The spatial and seasonal variability of the evaporative moisture source contributions to Antarctic precipitation at different elevations and for precipitation events of different intensities are discussed along with the typical moisture transport pathways to the ice sheet. Different moisture source conditions relevant for setting the evaporation flux and impacting water isotope records as well as the anomalies of these source conditions during uptakes contributing to Antarctic precipitation compared to climatology are investigated. Finally, shifts in moisture source regions associated with variations in the Southern Annular mode are analysed. The chosen methodological approach is based on an innovative scaled-flux water tracer approach implemented in ECHAM6 similarly as initially proposed by Fiorella et al. 2021 using the iCAM6 global circulation model. I much enjoyed reading this interesting and innovative paper, which is well-written and has nice and captivating figures. For me personally the scientific highlights of this paper are i) the anomalously strong storminess at the moisture source of humidity feeding Antarctic precipitation and ii) the shifts in source locations and conditions observed with the SAM. On a methodological side, I find the scaled flux water tracer implementation very attractive and the documentation of their implementation in ECHAM6 in Appendix A useful. I particularly like the comparison done with the traditional numerical tracer setup using pre-specified evaporative regions (Appendix A).

I have only one "easy" general comment, which is related to the fact that this study is based on preindustrial simulations. This is all fine per se, but the authors should make this much clearer in their introduction, in which anticipated future changes with global warming are mainly discussed. Currently, for me as a reader there is a mismatch between the use of a preindustrial simulation and the knowledge gap uncovered in the introduction with sentences like "It is not yet clear how SAM variations and associated changes in moisture flux tracks will impact precipitation across Antarctica". One cannot address this question with a pre-industrial simulation, but of course the mechanisms linking variations in SAM with changes in moisture sources and transport pathways can be studied very well with a preindustrial simulation and the authors do it elegantly. Even more importantly, the fact that the authors use a simulation with preindustrial climate conditions matters, when they compare their moisture source decomposition with other studies such as the Lagrangian study by Sodemann and Stohl, 2009. I would therefore suggest to smooth out this mismatch by pointing more at the need for a better process understanding in the introduction, and remind the reader of the different time period covered in their simulations when comparing their results to previous studies.

Minor comments:

1) "novel" in the title is a bit unspecific, could be more precise
2) L. 1: "for gaining insights into **past and future** polar, and global changes"
3) L. 1: "changes" in what exactly? Environmental changes?
4) L. 7-10 and results section about Fig. 4: "The tendency of poleward vapour transport to follow moist isentropes means that central Antarctic precipitation is sourced from more equatorward (distant) sources via elevated transport pathways than coastal Antarctic precipitation. We find however this tendency breaks down in the lower

troposphere, likely due to diabatic cooling." I find this analysis based on Fig. 4 interesting but also very puzzling. Fig. 4 shows a zonally averaged mass-weighted vertical cross section of the source latitude of water vapour. This Fig. is discussed in the result section in a moist isentropic framework, from which we would expect moisture from a given latitude to follow the moist isentrope corresponding to the surface equivalent potential temperature from that latitude. I am a not so sure about what Fig. 4 tells us exactly:

To me it seems like the moist isentropic framework is a very crude approximation to the typical transport pathways and doesn't provide more than a justification for the fact that precipitation falling on the plateau tends to come from further equatorward than coastal precipitation. Similarly, it most likely explains why precipitation in the warm season comes from further equatorward than in the cold season. But other than that, when looking at Fig. 4, I see mainly deviations from the moist isentropic framework. On the Antarctic plateau the highest elevations don't pool their moisture from the most equatorward/warmest sources. And even more generally, in the upper troposphere, I see substantial deviations of the steepness of the source latitude contours from the moist isentropes. Of course, we expect that because in these dry upper tropospheric regions water vapour can be substantially older and make the distribution of source latitudes much wider. Could the authors maybe provide a weighted mean standard deviation or interquartile range of the source latitude in addition to the mean? This would provide a way of characterising the widths of the source distributions. I would assume that it is widest in the center of the storm track but maybe I am wrong.

→ Thus, in short, from this analysis, I see mainly deviations from the moist isentropic poleward moisture transport framework, rather than agreement with it. I think this aspect ought to be discussed more in depth along with Fig. 4 (both panels). And, in particular, if diabatic processes are invoked for explaining these deviations, then why not name, which one the authors think could play a role?

5) L. 14: "wind10": this variable is not yet defined in the abstract, please be specific at this stage. I also think that it is not such an elegant variable name for the main text.
6) L. 63: "issues with the **Lagrangian** identification of precipitation events solely using thresholds in specific humidity changes". Yes, true, but reproducing precipitation events at the right place and at the right time is tricky as well for ECHAM6. Actually, as long as the precipitation statistics are faithfully reproduced over the ice sheet over the time period considered, this aspect of precipitation event representation is irrelevant in the context of a free running simulation. So, I am not sure this is a fair point to make at this stage. I would simply say that the Eulerian method presented in this study is complementary to the Lagrangian one and offers an elegant online diagnostic of the moisture sources of Antarctic precipitation.
7) L. 81: "revised definitions of Heavy Precipitation": revised compared to what? I would remove "revised". Maybe also think about not using any abbreviation (and not necessarily capital letters) for heavy and light precipitation because there are already many abbreviations used in this paper.
8) L. 92: "the EAIS may be slightly too low in elevations" Why may? Some "valleys" may be missing too in the topography at this coarse resolution. Do you mean that the EAIS is on average too low?
9) L. 102: is $q^{\text{near\_sfc}}$ the q at the lowest model level?

10) L. 120: to characterise the near-surface humidity gradient $q_{near\_surface}$-q_{SST} or RH_{SST} would be more effective, see Aemisegger and Papritz et al. 2018
Aemisegger, F., and L. Papritz, 2018: A Climatology of Strong Large-Scale Ocean Evaporation Events. Part I: Identification, Global Distribution, and Associated Climate Conditions. J. Climate, 31, 7287–7312, https://doi.org/10.1175/JCLI-D-17-0591.1.
11) L. 125: "moisture parcels" -> moisture in air parcels?
12) L. 141: "The difference…" in what? In the chosen definition of LP and HP?
13) Section 2.3: Do I understand it correctly that the LP and HP definitions are chosen such that these categories contribute to a significant share of the mass balance? Just to be symmetric in the information given about the two categories: how much does the HP category contribute to total precipitation? (i.e. what is the top-10%-precipitation-days' share of total precipitation?).
14) L. 154: "on the low side" -> lower than the reconstruction, "high across some coastal areas" -> larger than in the reconstruction
15) L. 157: I would say that ECHAM6 clearly shows a larger interannual variability (2x larger than the reconstruction): is this expected given the temporal resolution of the ice core data?
16) L. 160: mention the ERA5 period with which you compared your preindustrial simulation. The warm season precipitation (NDJFMA) is quite substantially higher in ERA5, is this an effect of the slightly warmer Southern Hemisphere atmosphere in the period 1979-2021?
17) L. 169-170: make clear that this is in the annual mean.
18) L. 170: The share of moisture sourced from sublimation over Antarctica probably depends on the parametrisation of the surface sublimation flux (e.g. Gerber et al. 2023). Could it be that the regions affected by very high sublimation fluxes with e.g. strong katabatic winds and blowing snow sublimation tend to feed cold air outbreaks and contribute more to precipitation over the ocean? Or are the sublimation fluxes over Antarctica just so small compared to the available moisture in the atmosphere?
Gerber, F., Sharma, V., & Lehning, M. (2023). CRYOWRF—Model evaluation and the effect of blowing snow on the Antarctic surface mass balance. Journal of Geophysical Research: Atmospheres, 128, e2022JD037744, https://doi.org/10.1029/2022JD037744.
19) L. 179: does this finding about the precipitation coming from the open ocean south of 50°S also relate to the fact that the ocean surface of this oceanic region is larger around the AP and WAIS than for the EAIS? Does it have to do with the sea ice extent in the different basins? Does the steeper topography of the EAIS play a role (forcing the rain out of the humidity sourced from the South Atlantic south of 50°S along the EAIS slopes). Also, in terms of dynamical drivers of this share of precipitation from south of 50°S: it is really interesting to note that the Dronning Maud land receives the most equatorward moisture of whole Antarctica (even though the highest elevation of the Plateau lies much further to the southeast). This might be linked to the spiral shaped form of the Southern Ocean storm track. In the South Atlantic many extratropical cyclone genesis points are climatologically located relatively far North compared to the South Pacific (see Wernli and Schwierz, 2006). Cyclones likely play a key role in poleward moisture transport in this region.

Wernli, H., and C. Schwierz, 2006: Surface Cyclones in the ERA-40 Dataset (1958–2001). Part I: Novel Identification Method and Global Climatology. J. Atmos. Sci., 63, 2486–2507, https://doi.org/10.1175/JAS3766.1.

20) L. 186 & L. 194: “tends to take an elevated path” -> “has to rise to higher altitudes”? An elevated pathway nearly sounds as if it would travel in the upper troposphere for a very long time before raining out over the Antarctic ice sheet.
21) L. 189: “so” -> “therefore”
22) L. 191: “approximating a moist adiabatic poleward ascent”, this tendency is discussed already in Stohl and Sodemann, 2009, albeit with isentropes (not moist isentropes) Stohl, A., and Sodemann, H. (2010), Characteristics of atmospheric transport into the Antarctic troposphere, J. Geophys. Res., 115, D02305, doi:10.1029/2009JD012536.
23) L. 191: “this tendency to follow contours of equivalent potential temperature breaks down in the lower troposphere” -> tendency to follow moist isentropes?
24) L. 191: about the “break-down” of the moist isentropic approximation of poleward transport: Which diabatic cooling mechanism do the authors think plays a role? Could diabatic heating especially in the upper troposphere also explain part of the observed deviations from the moist isentropic framework?
25) L. 197: as mentioned in my general comment: just make sure that it stays in the mind of the reader that this study covers another time period.
26) L. 201: most equatorward sources for DJF: that is surprising because of the minimal sea ice extent and the slightly weaker jet and storm track in summer. Is this simply due to the warmer atmosphere on average, leading to higher humidity contents and longer transport distances? And as you write flatter isentropes “giving access” to more equatorward sources?
27) L. 203: milder->flatter
28) L. 209: The fact that source longitude shows the largest interannual variability is interesting and shows that the strength of the westerlies and the storm track dynamics is likely important for modulating the moisture source properties.
29) L. 211: “source latitude and longitude”
30) L. 214: “lies within the range of estimates from the literature”
31) L. 220-227: Interesting! This corresponds to the range of wind speeds associated with events of strong ocean evaporation in the Southern Ocean as discussed by Aemisegger and Papritz, 2018. Extratropical cyclones and trailing fronts were identified as key weather systems with which enhanced ocean evaporation is associated.
32) L. 226: “other forms of storms” what is meant here: tropical cyclones or polar lows? I think if you write “extratropical cyclones propagating along the Southern Ocean storm track” you also include subgroups such as mesocyclones or polar lows.
33) L. 230: what does “evaporation processes will cause some decoupling of moisture source properties” mean? Do you mean that synoptic-scale variability at the source causes variability in the evaporative conditions?
34) L. 234: what do you mean by “wind10 at source” -> climatological wind 10 at the source?
35) L. 239: in the previous two paragraphs you just discussed **dynamic** not thermodynamic controls on moisture availability for Antarctic precipitation.
36) L. 256: A case study discussing this suppression of ocean evaporation during polarward moisture transport in warm sectors of extratropical cyclones is Thurnherr and Aemisegger, 2022.

Thurnherr, I. and Aemisegger, F.: Disentangling the impact of air–sea interaction and boundary layer cloud formation on stable water isotope signals in the warm sector of a Southern Ocean cyclone, Atmos. Chem. Phys., 22, 10353–10373, https://doi.org/10.5194/acp-22-10353-2022, 2022.

37) L. 282-285: The impact of the SAM on the storm track dynamics and shifts in strong ocean evaporation patterns as well as near surface conditions is discussed in Aemisegger and Papritz, 2018.
38) L. 291: "These results quantify the degree to which poleward moisture fluxes are associated with the SAM" -> are modulated by the SAM? And maybe instead of fluxes rather use poleward moisture transport?
39) Fig. 10: the stippling is very difficult to see
40) L. 300: "SAM states exert controls" -> "the SAM impacts"
41) L. 310: "limits on" -> "of"
42) L. 328: "yields a more precise value compared to previous method" -> explain why explicitly
43) L. 330-332: this is a bit obscure to me. True in close approximation for SST but not necessarily for rh2m and the wind speed.
44) L. 355: "other types of tracers in numerical systems" -> what do you mean by this?
45) L. 356: "the full potential of our water tracing diagnostics is yet to be identified" -> This last sentence is a bit unspecific for the end of such a nice paper.
46) Appendix A: very nice and interesting documentation. I just get lost at line 385. What does the index *i* represent and what do you mean when you write "by summing up all vapour contributions in a grid box, we obtain:"? Do you sum up over a number of grid points in a given region? In equation A4 some variables have an index *i* and others not. I didn't get why. And in A1 t, λ, ϕ have an index *i*, but in the next lines not. Sorry to be picky, but I really would like to understand this Appendix.
47) Appendix A: I like your comparison with the predefined-region water tracing method described at lines 410ff a lot. To me this is a highly effective way to show the advantages of the scaled-flux approach and I would find it very helpful to have a short version of the results from this comparison in the main text.