In this article, Wang and co-authors use the atmospheric global climate model CAM5 to better understand the moisture origins and pathways toward Antarctica. This is a relevant scientific question for better interpreting ice cores and for better understanding the water cycle in the high Southern latitudes.

The novelty of this study is to use an explicit water source tagging capability in CAM5 to derive moisture sources of Antarctic precipitation. This cannot be done accurately with back-trajectories tools for long-ranged moisture transport.

I think this article is of interest, but conclusions must be deepened and I found substantial issues in the methods. Therefore, I recommend this article to be published in The Cryosphere after addressing the following issues.

Major issues

1. Objectives of the paper are not clearly stated

The introduction mixes issues related to the recent past (pre-industrial and historical=reanalyses periods, e.g. P3L10-13 and P3L24-P4L3) with issues related to future changes under RCP scenarios (e.g. P3 L13-17 and P4L3-7). However the article only deals with natural variability under pre-industrial conditions: the atmospheric global climat model CAM5 is ran with SIC and SST boundary condition taken from the pre-industrial control simulation of the CESM large ensemble (P5L21-30). And at the end, extreme « high » and « low » sea ice concentration (SIC) chosen from the CESM ensemble are very similar in winter (Fig. 1 JJA) and are divergent in the other seasons. This a major difference with future changes expected at the end of the 21st century, that will be driven by change in winter SIC (e.g. Agosta et al., 2015 as cited by the authors P4L5).

Consequently, the simulations performed by the authors can not address the impact of future change in SIC on the moisture pathway toward Antarctica, as driving mechanisms are expected to be different between pre-industrial and end-of-21C. For pre-industrial and historical periods, SMB changes and moisture pathways are dominated by strong natural variability, as stated P3 L13-17, whereas for large increase in temperature and decrease in winter SIC, as expected in future projections, SMB changes and moisture pathways are expected to be driven by the increase in moisture content, exponentially related to the increase in temperature (e.g. Krinner et al., 2014, Frieler et al, 2015).

I suggest to :

1.i) Explore the impact of future changes in SST/SIC on the moisture pathways, by performing new simulation using well chosen boundary condition among the CMIP5/6 datasets, and separate correctly issues related to internal variability vs. future changes in the introduction and the results.

1.ii) If these new simulations are not feasible, only focus on internal variability and remove all reference to future changes in the introduction. Better highlight the importance of better understanding water pathway toward Antarctica under natural variability, in particular for interpreting ice cores.

1.iii) Better exploit your current simulations to disentangle circulation changes vs. moisture input from SIC/SST changes (see Major issues 2 and 3 bellow).

Adapt the abstract consequently.

2. The baseline simulation might not be valid and is not evaluated

P5 L26-28 « A baseline simulation uses the mean SIC/SST distributions»

The baseline simulation is a simulation with CAM5 forced with mean SST and mean SIC from the CESM large ensemble. This is a major issue as SIC usually shows a sharp transition between SIC=1 and SIC=0. Averaging SIC across years/members lead to a SIC~0.5 over most of the Southern Ocean in all season except winter (Fig. 1). Combining mean SST and mean SIC might also lead to unrealistic boundary conditions, e.g. SST>-1.7 while SIC > 0.

As understanding water pathways toward Antarctic is one of the major goal of this study, that I think should be deepen, it is of importance that « baseline simulation » is proved to be relevant for analyzing current climate.

I suggest :

2.i) To use either observed SIC and SST, or to use a median simulation for keeping realistic SIC and consistency between SIC and SST.

2.ii) To show the differences in large scale circulation and SIC/SST between your 10-year simulations and reanalyses (1979-201X), to be able to analyze which of your conclusions may remain valid for the historical period, and which may not.

3. Conclusions need to be deepened

The goal of your study should be to disentangle the role of local moisture sources related to SIC/SST and the role of circulation on the moisture transport toward Antarctica. Currently this central point is not addressed by your study, as stated in the final sentences of the article.

3.i) All analyses related to circulation (sea level pressure), precipitation amounts, precipitable water and moisture fluxes can be analysed with regard to the CESM ensemble from which SIC/SST have been extracted (e.g. P6L30-P7L25). From the CESM ensemble you can derive the decadal variability for each of these variables (e.g. standard deviation of 10-year-mean of each of these variable, by season). This will help quantifying the significance of precipitation changes between your three simulations with regard to decadal variability.

P7 L5-7 « The sensible heat flux and evaporation over the northern latitudes of the SO also show large differences between the two cases, likely due to meteorological responses (e.g., changes in wind, temperature, and humidity) to the SIC/SST differences. »

You should remove « likely » and show here the difference in SLP and wind speed (your Fig. 10 should be Fig. 4). This should be the central point of your results and discussion.

P7 L9-12 « The coastal area that has less precipitation in the low SIC case, mostly occurring in austral winter (JJA) when SIC near coastal regions is almost the same in the two cases (Fig. 1), is characterized by anomalous meridional moisture divergence (figure not shown), echoing the finding of Fyke et al. (2017). »

You can show it in your current Fig 10 (future Fig 4?).

3.ii) You can exploit the fact that SIC changes between « low » and « high » SIC simulations are small in JJA and large in DJF to evaluate the impact of SIC change on circulation change. Indeed circulation changes between the 3 simulations might be due to changes in SIC but also due to internal(multidecadal) variability. This can be seen in Fig. 10 where circulation change in DJF is of appear significant but of a lower magnitude than in JJA. If you do new simulations with decreased winter sea ice, it should have an impact of circulation too.

3.iii) To disentangle the effect of moisture source due to changed SST vs. circulation change on Antarctic precipitation, you can focus on the contribution of tagged regions that see large change in SIC, such as Weddell Sea, Amundsen Sea, Ross Sea, etc., in DJF, vs. regions that see no SIC change. The amount of Antarctic precipitation that is changed because of changed moisture uptake might be quantified from the contribution of the region of changed SIC vs. contribution of regions with unchanged SIC. Maps as in Fig. 5 but showing the difference between « high » and « low » sic, in JJA and DJF, would be useful for this interpretation.

4. References

P3 L10-13 « However, the exact coupled-climate mechanisms driving this increase have not been well elucidated. In particular, the role of sea surface temperature (SST) changes, atmospheric moisture sources/transport/carrying capacity, sea ice loss, and atmospheric dynamical changes on Antarctic snowfall changes has not been clearly disaggregated. »

The increase in SMB expected at the end of the century is well understood: increase in moisture content is exponentially related to increase in temperature (~ Clausius Clapeyron). The relative contribution of thermodynamics (i.e. increase in temperature) vs. dynamics (i.e. circulation change) has already been addressed, e.g. in Krinner et al. (2014, doi: 10.1175/JCLI-D-13-00367.1), advocating for a major influence of thermodynamic changes in the future because of the expected large change in temperature.

P3 L22-23 « However, the origin of moisture (i.e., evaporation source) and the impact of sea ice anomalies in the Southern Ocean on moisture source availability remain unclear. »

Kittel et al. (2018, doi:10.5194/tc-12-3827-2018) analyzed the impact of sea ice anomalies on the Antarctic surface mass balance, with circulation nudged toward a reanalysis, and they showed that only large anomalies of sea ice directly affect the Antarctic SMB.

Minor comments

Abstract

a climate model ↦ the global ocean-atmosphere coupled model XXX

SST: not introduced

Southern Ocean (SO): remove this acronyme from the abstract for readability

S. ↦ replace by South or Southern in the abstract

/year ↦ year^{-1} (everywhere in the article)

“low” SIC case than in the “high” SIC case: rephrase with more explicit sentences

« so the contribution of nearby sources also depends on regional coastal topography »
I don’t understand, why does the contribution of nearby sources depends on topography?

« The impact of sea ice anomalies on regional Antarctic precipitation also depends on atmospheric circulation changes that result from the prescribed composite SIC/SST perturbations. In particular, regional wind anomalies along with surface evaporation changes determine regional shifts in the zonal and meridional moisture fluxes that can explain some of the resultant precipitation changes. » This last sentence is very general. Can you write a sentence more specific about the novel knowledge brought by your study?

Introduction

P3 L3 « by supplying the vast majority of the positive mass component »
Is there other positive mass component?

P3 L4 « Lenaerts et al., 2012 »: an observation-based article would be better

P3 L5 Remove « this » and « profound »

P3 L7-8 « Frieler et al., 2015; Grieger et al., 2016; Lenaerts et al., 2016; Zwally et al., 2015; Medley and Thomas, 2019 »
Sort the list

P3 L8-10 « This SMB increase has the potential to offset a significant portion of the overall AIS mass loss due to ocean-driven mass loss (e.g., Winkelmann et al., 2012). »
This paper does not say this at all. Change the reference.

P3 L24-25 « Oceanic areas close to the Antarctic coast are ice-covered most of the year » : it is not true in austral summer (e.g. https://nsidc.org/data/seaice_index)

P4 L1 « natural or internal »
What do you mean?

Methodology

P5 L4-7 « The atmospheric component, called the Community Atmosphere Model version 5 (CAM5), can also be run with prescribed sea surface temperature (SST) and sea ice concentrations (SICs) coupled with an interactive land component (CLM4, Oleson et al., 2010), which includes the evolution of ice and snow over land. »
In this sentence, it is not clear that it is indeed the model setting you used. Please rephrase: *« In this study, we ran the atmospheric component of CESM, called the Community Atmosphere Model version 5 (CAM5), with prescribed sea surface temperature (SST) and sea ice concentrations (SICs) coupled, and with an interactive land component … »*

P5 L24-26 « Three SIC (and corresponding SST) composites are constructed from the pre-industrial control simulation of the CESM large ensemble (Kay et al., 2015), which gives a continuous time series of over 1000 years to perform our composite analysis of SIC and SST. »
Give more details on the CESM large ensemble, and at least the number of members.

P5 L26-28 « A baseline simulation uses the mean SIC/SST distributions and two sensitivity simulations use the 10% lowest and highest annual average total Southern Hemisphere SIC, respectively, coupled to the corresponding anomalies in global SSTs. »

Does it mean accross all members and all years, i.e. N members x 1000 years?
For mean SIC/SST, do you average it day-by-day to preserve the seasonal cycle? (as I guess from Fig. 1)

P5 L28-30 « All other forcing conditions (e.g., solar, greenhouse gases, anthropogenic aerosols) are identical across simulations. »

Set to which values ? pre-industrial ?

P6 L9 « Antarctic/SO »

SO defined latter in the text.

P6 L10 « CESM LENS »

Not defined, what is LENS?

P6 L15 « CESM »

CAM5? To clarify that you use CAM5 only and not the ocean-atmosphere coupled version CESM?

P6 L15 « Southern Ocean (SO) »

To be defined sooner. And be consistent all over the article, you often use « S. Ocean »

Results and Discussions

P7 L19 « 150 Gt/year »

Specify the mean precipitation in Gt year-1, and the area of your ice sheet mask (~14 M km2 ?)

P7 L26 « contributed »

contribution?

P9 L6-9 « As shown in previous studies (e.g., Wang et al., 2014; Singh et al., 2017), as well as indicated in the previous section (Fig. 5), the horizontal transport pathways of atmospheric constituents such as vapor and aerosol particles from individual source regions to a receptor are largely determined by large-scale atmospheric circulations. »

This is widely known indeed. Simplify the sentence, without citations.

P9 L12-15 « In general, vapor originating from remote source regions at lower latitudes and northern hemisphere takes elevated pathways to Antarctica while vapor from the nearby tags in the SO moves southward within the lower troposphere, as noted in previous studies (e.g., Noone and Simmonds, 2002; Sodemann and Stohl, 2009). »

See also Kittel et al. 2018

P9 L16 « mean moist isentropes moist »

Typo

P10 L19-20 « The pattern of variations in meridional moisture flux is also correlated with precipitation differences (Fig. 3f). »

Correlated? Precipitation is a result of large scale circulation... SLP represents the large scale circulation

P10 L20-22 « As a result, decreases in precipitation in the “low” SIC case over the King Haakon VII Sea and Wilkes Land sector can be traced to a SIC-caused reduction in meridional flow and related moisture fluxes from the north (Fig.10a). »

SIC-caused because SIC is the imposed boundary condition in CAM5, but how can you be sure it is not internal variability? In JJA it is arguable, as changes in SIC is the largest in this season and result in larger changes in SLP. But this should be discussed. How do you disentangled rigorously internal variability of the model vs. impact of changed SIC?

P10 L22-24 « Although the experimental design in this study doesn’t allow us to pinpoint a causal relationship among the three effects (i.e., lower SIC, reduced meridional moisture flux, and precipitation decrease) »

Precipitation decrease is a result of circulation change.

P10 L29-31 « Therefore, the impact of sea ice anomalies and corresponding SST changes on Antarctic precipitation stem both from their direct impact on moisture sources and from the circulation changes that accompany the different SIC and SST patterns »

Your aim is to disentangle SIC change from circulation change. Here SIC does not change much in DJF, so changes in circulation cannot be attributed to changes in SIC.

P11 L11-13 « Conversely, the strength and location of the ABSL can also be affected by the sea ice and temperature changes, as depicted in Fig. 10e. »

For JJA only, and significance must be quantified vs. internal variability.

P11 L18-20 « In this study, we use a coupled atmosphere-land version of the Community Earth System Model (CESM1-CAM5) with explicit water tagging capability to quantify the impact of sea surface temperature (SST) and sea ice concentration (SIC) changes on the moisture sources of Antarctic precipitation. »

You use CAM5 with water tagging, not the coupled model. This sentence is confusing.

P11 L23 « 1800 »

Typo? 1000?

P11 L25-26 « are used as prescribed boundary conditions for atmosphere- only simulations. »

Add the length of simulations: 10 years

P11 L28-30 « Because of the prescribed changes in the SIC and SST, surface sensible heat fluxes and evaporation over the lower SIC areas in the Southern Ocean (SO) have a large increase in the “low” SIC case, compared to 30 the “high” SIC case. »

The relation with circulation change must be clarified here, significance of change must be quantified, depending of the season.

P12 L3-5 « The three remote source regions have a reduced absolute contribution to water vapor further inland in the “low” SIC case, which leads to a discernable reduction in their fractional contribution, especially, in the lower and mid troposphere. »

Because of change in circulation

P12 L7-8 « This is qualitatively consistent with the source attribution change in response to warming from CO2 doubling (Singh et al., 2017). »

Explain more.

P12 L9-12 « This difference is larger than the interannual variability of Antarctic precipitation (characterized by one standard deviation of annual mean precipitation) within the 10 years of the “mean” SIC case as well as over 1000 years of the CESM LENS experiment. »

And compared to decadal variability?

P12L32-P13L « The resultant changes in meridional moisture fluxes from the Southern Ocean to the Antarctic continent can intuitively explain some of the precipitation differences between the “low” and “high” SIC cases. »

Not quantified, very approximative

Figures

Figure 1

Don't use a divergent colorbar for sea ice concentration. Use a sequential colorbar instead.

Figure 2

Don't use a divergent colorbar for evaporation/sublimation, or around 0.

Display evaporation in kg m^{-2} $year^{-1}$ (= mm $year^{-1}$)

Figure 3

Use symmetric colorscales around 0 (for Fsh, E, and P)

Change unit for E and P: kg m^{-2} $year^{-1}$

Figure 4

Add a) and b) and change the main text accordingly

For precipitation, give the value in Gt year-1 or in Gt month-1, as in the text.

Figure 5, 6 and 7

Don't use divergent colorbars.

Figure 10

Use symmetric colorscales around 0.

> Same remarks for supplement