We appreciate the insightful review and constructive comments from all three referees. The paper has been improved after addressing all the comments and concerns. Below we outline the point-by-point responses and changes made to the manuscript. Direct changes to the paper quoted here are italicized and all figures referenced are either within this document, in the original manuscript, or for the updated version of the manuscript. The responses to Referee #2 begin on page 15 and the responses to Referee #3 begin on page 24.

Anonymous Referee #1

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.

Please see our responses to the specific comments below.

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.

This is a great point. By design our current simulations were conducted to separate the impact of Southern Ocean SIC/SST anomalies from the effect of anthropogenic warming (e.g., associated with GHGs) on source–receptor relationships for moisture and precipitation over Antarctica. Thus we took the SIC and SST anomalies from the pre-industrial control simulation of CESM Large Ensemble simulations. In a previous study, Singh et al. (2017) examined the response of Antarctic hydrological cycle to warming from CO_2 doubling. As we discussed in the manuscript (P12L7), some of the qualitative results in terms of the water source attribution are consistent with their findings (under the GHGs warming scenario). Similarly, we referred to some previous studies (mostly in the introduction) that can provide a broader context for the motivation of the present study to focus on the isolated impact of SIC/SST anomalies associated with internal climate variability. Nonetheless, we have followed the referee's suggestions (ii, iii) to clarify the objective of the present study and revise the manuscript accordingly. In particular, we have made a note in Section 2.2 (Experimental Design) as follows.

"*Although the magnitude and location of prescribed SIC anomalies are comparable to the observed SIC changes during the recent decades (Hobbs et al., 2016), the prescribed seasonal SIC anomalies associated with internal variabilities under the CESM LENS pre-industrial conditions are likely to be different from future changes. Here the widespread anomalies occur in austral summer (DJF), while sea ice reductions by the end of 21st century or in response to CO_2-doubling and the resulted global warming are expected to be dominated by winter (JJA) changes (Singh et al., 2017). Therefore, the simulations designed here are to examine Antarctic precipitation changes and moisture transport pathways dominated by natural variabilities, as opposed to the projected future changes driven by the increase in atmospheric moisture content related to temperature increase (e.g. Krinner et al., 2014, Frieler et al, 2015).*"

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.

We would respectfully argue that climatological SST and SIC for individual months being used in atmospheric GCMs are normally averages over many years as well. We can imagine that the sharp transition between SIC=1 and SIC=0 can happen in the real world, but in coarse-grid models we don't see such a sharp transition near sea ice edges, where sea ice concentrations, if being prescribed, are often interpreted from two monthly mean datasets at each model time step.

Nonetheless, we have taken the referee's suggestion to compare our baseline simulation to the fifth generation ECMWF reanalysis (ERA5, 1979-2018). All the spatial distribution fields showed in the original Figs. 3 and 10 are analyzed and included in the Supplement (new Figs. S1-S4). Annual mean SIC, surface temperature and sea level pressure are shown here (see Fig. R1 below). SIC in the baseline simulation is apparently higher than the ERA5 reanalysis, especially in the Weddell, Amundsen and Ross seas where the SIC internal variability (difference between the "low" and "high" SIC cases) is also large. Certainly, SIC in the ERA5 reanalysis reflects anthropogenic forcing already. Surface temperature differences are consistent with SIC differences. We don't see any unrealistic boundary conditions that the referee concerned about. The SLP pattern in the baseline simulation resembles the one in ERA5, although the magnitude of SLP gradient between Antarctic and the Southern Ocean is weaker in the baseline simulation. The comparison suggests that our pre-industrial simulations of the model sensitivity to SIC anomalies are still relevant for the recent historical conditions. We have now included some discussions on this in the manuscript (Section 2.2).

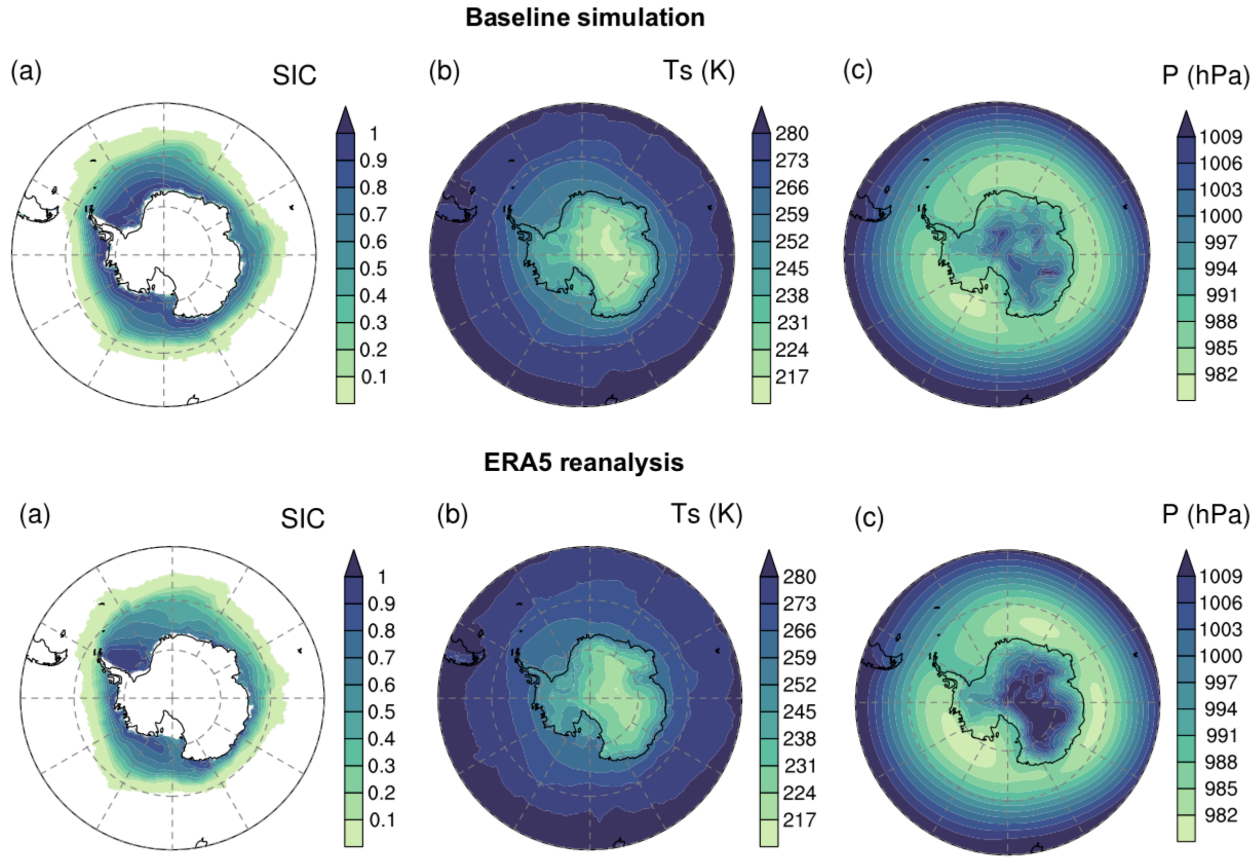


Fig. R1: Annual mean (a) sea ice concentrations, (b) surface temperature, and (c) sea level pressure based on the baseline simulation (top) and the ERA5 1979-2018 reanalysis (bottom).

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.

Following the referee's suggestion, we have now calculated the decadal variability (based on the 1100-year CESM-LENS control simulation) of all fields in the original Figures 3 and 10 by annual mean and seasonal (DJF and JJA) mean. The new analyses for comparison between the model results and decade variability are now included in in the Supplement (as new Figs. S6-S11). The figures are referred to in the manuscript to indicate the significance of differences in the relevant model variables between the “low” and “high” SIC cases.

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.

Changed as suggested. The original Fig. 10 has been revised and now becomes the new Fig. 4. The original Section 3.4 that describes the figure of circulation and moisture transport is moved up accordingly.

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?).

This has been included in the new 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.

We agree that the changes in circulation and moisture transport can be due to both SIC/SST differences and internal variability. As shown in the new Figs. S7 and S9, SIC differences in DJF is more widespread (e.g., large SIC changes near coastal areas) than in JJA, while the JJA SIC changes are concentrated at sea ice edges. The contrast in surface temperature and heat fluxes within the sea ice zone is much stronger in JJA than in DJF, so does the SLP over Southern Ocean and Antarctica. However, the decadal variability of these fields is also stronger in JJA than in DJF (See Figs. S8, S10 and S11). It indicates that decadal variability plays a more important role in JJA than in DJF, but it is still challenging to quantitatively compare the contributions by decadal variability vs. SIC/SST anomalies. We have included some discussions on this in the manuscript.

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.

We have now made new JJA and DJF figures, showing the difference in contributions to Antarctic precipitation between "low" and "high" SIC cases, to compare different regions. They are included in the Supplement (Figs. S14, S15, S17 and S18). The challenge is that SIC reduction is ubiquitous in the Southern Ocean. There is no clean contrast in the source contribution between changed and unchanged SIC regions. However, the DJF and JJA figures more clearly demonstrate the important role of meridional flow in bringing the additional moisture from SIC reduction to Antarctica. For example, with the decrease in SIC, contributions from the Weddell Sea increase near the Antarctic Peninsula in both DJF and JJA under the favorite change in meridional moisture transport, while there is a strong seasonal contrast in contribution to precipitation near the Queen Maud Land because of the difference in meridional flow. Similar seasonal contrast is also seen in the contributions from Cosmonauts Sea and Amundsen Sea. We have added such discussions to the manuscript.

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.

Added the reference and revised the sentence accordingly.

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.

Thanks for pointing out this reference. We have now incorporated the key finding of Kittel et al. (2018) in the introduction to provide a more appropriate context for our study. It is revised as follows:

The direct impact of sea ice anomalies on moisture flux and Antarctic precipitation is through air-sea interactions, but the associated feedback on atmospheric dynamics can also be significant, as shown in previous modeling studies of projected climate change (e.g., Menéndez et al.,1999; Bader et al., 2013). Kittel et al. (2018) conducted sensitivity experiments in a regional climate model, with atmospheric circulation nudged toward reanalysis, to study the impact of idealized or forced sea ice perturbations on AIS SMB. They found significant Antarctic precipitation and SMB anomalies for the largest perturbations. However, the impact of SO sea ice anomalies and accompanying sea surface temperature (SST) changes on Antarctic snowfall changes through changing atmospheric moisture sources and associated atmospheric circulation and moisture transport, in the absence of anthropogenic forcing that primarily originates from low and mid-latitudes, has not been clearly disaggregated.

Minor comments

Abstract

a climate model ↦ the global ocean-atmosphere coupled model

Changed to “general circulation model” since SST and SIC are prescribed to the model.

XXX SST: not introduced

Now defined.

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

Done.

S. ↦ replace by South or Southern in the abstract

Done.

/year ↦ year-1 (everywhere in the article)

Done.

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

Rephrased to “Comparing two experiments prescribed with high and low pre-industrial SIC, respectively, the annual mean Antarctic precipitation is about 150 Gt year^{-1} more in the lower SIC case than in the higher SIC case.”

« 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?

As indicated in the previous sentence and discussed more in the main text, the meridional and vertical transport of vapor is along moist isentropes (θe) that are largely shaped by local topography in Antarctica (see the original Fig. S5). More precisely, high elevation of coastal mountains can block the transport moisture from nearby sources.

« 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?

Revised this sentence and added a closing statement: "This study highlights the importance of better understanding changes in water transport toward Antarctica under natural variability."

Introduction

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

Removed "the vast majority of".

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

Added Shepherd et al. (2012).

P3 L5 Remove « this » and « profound »

Done.

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

Done.

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.

The sentence has been removed in response to the major comment #1.

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)

The sentence has been revised to "… most of the year (except for austral summer)."

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

Both "natural" and "internal" refer to "unforced" climate variability. To avoid confusion, it has been changed to "internal climate variability".

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 … »*

Revised as suggested.

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.

The fully coupled pre-industrial control simulation was conducted for 1500 years with years 400-1500 released. It's considered as one member of the Large Ensemble. Transient simulations (1920-2100) have 30 members but they are not so relevant to the control simulation used in this study. Nonetheless, we have added more details as follows:

"Three SIC (and corresponding SST) composites are constructed from the pre-industrial control simulation of the CESM Large Ensemble (hereafter CESM LENS; Kay et al., 2015), which was initialized with January mean present-day potential temperature and salinity from Polar Science Center Hydrographic Climatology dataset for ocean and a previous CESM 1850 control run for atmosphere, land and sea ice. It was run for 1500 years with years 400-1500 released, giving a continuous time series of over 1000 years to perform our composite analysis of SIC and SST."

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)

Yes, it means across all years for the baseline simulation and about 100 years for the two sensitivity simulations. The mean SIC/SST was obtained from monthly means to preserve the seasonal cycle. We have now clarified this in the paper.

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

Set to which values? pre-industrial?

Pre-industrial conditions.

P6 L9 « Antarctic/SO » SO defined latter in the text.

Fixed it.

P6 L10 « CESM LENS »

Not defined, what is LENS?

It stands for Large Ensemble simulations. Now defined in Section 2.2.

P6 L15 « CESM »

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

Yes, it has been changed to CAM5.

P6 L15 « Southern Ocean (SO) »

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

Done. Southern Ocean (SO) refers to the geographical region. S. Ocean is used for the tagged source region.

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 ?)

The mean precipitation is 2500 Gt year^{-1}, as noted later in the parentheses later in the same sentence. It was calculated for the entire Antarctic using the land mask from the same model.

P7 L26 « contributed » contribution?

It means S. Ocean contribution (i.e., the amount of precipitation contributed by the S. Ocean tag). It's now clarified.

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.

The sentence has been simplified to "As indicated in the previous section (Fig. 5), the horizontal transport pathways of atmospheric water from individual source regions to a receptor are largely determined by large-scale atmospheric circulations.”

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

This reference has been added to the list.

P9 L16 « mean moist isentropes moist » Typo

Corrected.

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

We agree with the referee that there is a causal relationship between atmospheric circulation and large-scale precipitation, but not necessarily for meridional moisture flux and total precipitation over the broad area. Also, here we don’t want to make the generic claim without providing concrete analysis. Later in the same paragraph we tried to pinpoint a causal relationship between lower SIC, reduced meridional moisture flux, and precipitation decrease for specific regions.

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?

Please also see our response to major comment #3. We agree that we cannot rule out the impact of internal variability on the changes in circulation and moisture transport, but the comparison with decadal variability indicate that the SIC reduction plays a role here too. The sentence has been revised to *“Decreases in precipitation in the “low” SIC case over the King Haakon VII Sea and coastal areas can be traced to the reduction in meridional flow and related moisture fluxes from the north in part due to the SIC decrease and internal variability (Fig. 4a). A Student’s t-test and the comparison of changes to decadal variability (Fig. 4 and S11) suggest that the reduction of meridional moisture flux (F_{VQ}) in that area is primarily determined by the SIC decrease in JJA but more likely due to internal variability in DJF.”*

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.

The sentence doesn't add much here, so it has been removed.

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.

As we discussed earlier, the circulation changes cannot be quantitatively attributed to SIC/SST or the internal variability. The sentence has been revised to "*Therefore, the impact of sea ice anomalies and corresponding SST changes on Antarctic precipitation stem both from their thermodynamic impact on moisture sources and from the dynamic changes that accompany the different SIC and SST patterns as well as internal variability.*"

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.

The significance has been tested against the decadal variability for DJF and JJA. In JJA, the reduced SLP over the ABSL region is larger than the computed decadal 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.

We mean to say that the atmosphere and land are coupled. It has been revised to avoid confusion.

P11 L23 « 1800 » Typo? 1000?

Corrected.

P11 L25-26 « are used as prescribed boundary conditions for atmosphere- only simulations. » Add the length of simulations: 10 years

Done.

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.

The significance has been tested against the decadal variability. It is indeed more significant in JJA. The sentence is revised accordingly.

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

Not entirely. Changes in evaporation also contribute to the moisture flux into Antarctica.

P12 L7-8 « This is qualitatively consistent with the source attribution change in response to warming from CO_2 doubling (Singh et al., 2017). » Explain more.

It is in terms of the annual mean. Seasonal source attribution could be different between the two studies. It has been clarified.

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?

The decadal variability of precipitation for the entire Antarctica from the CESM LENS is 49 Gt year^{-1}, which is even smaller. For reference the interannual variability calculated from the ERA5 reanalysis (1979-2018) is 113 Gt year^{-1}.

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

Agreed. We didn't mean to go into the quantitative details, especially, in the summary here.

Figures

Figure 1
Don't use a divergent colorbar for sea ice concentration. Use a sequential colorbar instead.

The diverging color bar is kept for the difference plots, but sequential colors are now used for the mean SIC.

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)

The top panel has been removed as suggested by Referee #2.

Figure 3
Use symmetric colorscales around 0 (for Fsh, E, and P) Change unit for E and P: kg m-2 year-1

Color scales and units are changed as suggested.

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.

Changed as suggested.

Figure 5, 6 and 7
Don't use divergent colorbars.

Changed as suggested.

Figure 10
Use symmetric colorscales around 0.

Changed as suggested.

Same remarks for supplement

Changed as suggested.

Harald Sodemann (Referee #2)

Review of "Influence of Sea Ice Anomalies on Antarctic Precipitation Using Source Attribution" by Wang et al., submitted to The Cryosphere.
The authors present a sensitivity study of the global water cycle, testing the response of precipitation origin over Antarctica to combined sea ice cover and sea surface temperature changes, using a climate model capable of water vapour tagging. The results are interesting and novel, and fit well into the scope of TC. However, some aspects need further clarification, concerning the more general implications of the findings and the relation to previous results. In addition, the presentation quality of some figures can be improved, as detailed below.

Major comments

1. The findings should be placed more clearly into the wider scientific context to make their significance more obvious. This concerns the abstract, introduction and conclusions.

In response to some comments from referee #1 and the specific comments below, we have revised the manuscript to include a wider context and more comparisons to previous studies (e.g., Krinner et al., 2014; Frieler et al, 2015; Kittel et al., 2018; …).

2. The relation to previous studies should be more clearly specified. The present study is based on a long control run, whereas previous studies mostly used reanalysis data. What are the differences? How valid is the control run for the present-day simulation? And, more specifically, how do the uppermost and lowermost percentiles used here compare to observed natural variability?

Previous studies using reanalysis data mostly also consider climate change signals and more realistic atmospheric circulations for a specific time period but don't allow **interactive** dynamical feedback from oceanic changes to the atmosphere. To some extent, the prescribed sea ice and SST are disconnected from the atmospheric response (based on the reanalysis data).

By design our experiments are conducted for the purpose of sensitivity analysis. The oceanic conditions (sea ice concentration and sea surface temperature) are based on a long CESM pre-industrial control run, which enable assessment of unforced internally generated climate variability. The prescribed sea ice anomalies may not be representative of present-day natural variability that is challenging to quantify from short-term observations in the presence of anthropogenic forcing. However, in some regions the pre-industrial sea ice anomalies are comparable to observations during the recent decades (Hobbs et al., 2016). In response to comments from the Referee #1, we have now included a comparison of baseline simulations to ERA5 reanalysis and tested the significance of the model sensitivity to SIC/SST changes against decadal variability. Please see also our responses to Referee #1.

3. The tagging setup should to be modified, or justified more clearly, and be documented more comprehensively. The Antarctic land mass is currently part of a general land tracer in the tagging setup. It would be interesting to specify an Antarctic-land only tracer, to allow for distinguishing local from remote contributions. In addition, the Southern Ocean tag appears

specified in a confusing way, with a narrow stripe going around the globe, and some boxes for the Weddell Sea and others placed inside. It should be stated more clearly why this specific setup has been chosen. Furthermore, a table or other form of description of the exact box coordinates are needed in order to compare and reproduce results.

The total contribution to Antarctic precipitation from global land is small (less than 5%). The lower tropospheric moisture over Antarctica attributed to the land tag is predominantly from the local continent, and the remote contributions from lower latitude land are mostly in the upper troposphere (Fig. 6). The difference in land contribution due to sea ice anomalies is seen in the lower troposphere (Fig. 8). On the other hand, since the focus of this study is on ocean and sea ice, we didn't want to add more land tags to increase the computational burden. Regardless, we agree with the referee that this design is not ideal.

The tagged regions are defined by latitude-longitude coordinates in the model. Smaller regions are used for the Southern Ocean because it is in close proximity to Antarctica and the surface evaporation is more affected by sea ice variations. Therefore, we use regular latitude-longitude boxes to define the Southern Ocean and five some source regions. The remaining area (irregular shape) of the Southern Ocean is constructed by differencing between the entire Southern Ocean tag and the sum of the five regular boxes. The irregular stripe is not a focus of our analysis. The tagged regions are independent of each other. They can have overlaps without an issue of double counting. We have now included a table (Table S1; see below) the describe the tagged regions in the Supplement.

Table S1: The latitude-longitude coordinates for the tagged water source regions. Land mask (and land fraction for coastal areas) in the model is used to define the "land" tag and mask land in the oceanic boxes.

Source region	**Latitude S**	**Latitude N**	**Longitude W**	**Longitude E**
Land	-90	90	0	360
Subtropical N. Pacific	10	30	105	260
Gulf of Mexico	10	30	260	300
Subtropical N. Atlantic	10	30	300	360
Northern Indian Ocean	10	30	35	105
Pacific Warm Pool	-10	10	25	190
Equatorial Pacific	-10	10	190	285
Equatorial Atlantic	-10	10	290	25
Southern Indian Ocean	-50	-10	25	130
South Pacific	-50	-10	130	290
South Atlantic	-50	-10	290	25
Southern Ocean	-90	-50	0	360
Amundsen Sea	-90	-60	210	285
Cosmonauts Sea	-70	-53	30	60
Mawson Sea	-90	-55	90	120
Weddell Sea	-90	-55	285	360
Ross Sea	-90	-55	120	210

4. The findings in some figures should be condensed further to facilitate grasping the main findings, as detailed in the specific comments

Please see our responses to the specific comments below.

Specific comments

Abstract

Pg. 2, L. 1: highlight the relevance to other research, now it is just described as a sensitivity study in the first sentence.

It is indeed a sensitivity study but with more realistic sea ice and SST anomalies (in terms of unforced internal variability), compared to previous studies (e.g., Kittel et al., 2018) with prescribed homogeneous perturbations or SIC/SST from different CMIP5 models. More detailed context is provided in the introduction.

Pg. 2, L. 6: "but": consider splitting into two sentences

Done.

Pg. 2, L. 11: A percent number could be more informative here

Added the percent change.

Introduction

Pg. 3, L. 1: "SMB ... plays a role... by supplying" does not make sense

Revised.

Pg. 3, L. 10-13: Not sure the exact mechanism is assessed quantitatively in this study. May need rephrasing.

Rephrased.

Pg. 3, L. 17: "Because of..." ultimate meaning/logic of this sentence not clear. "Relies" for what purpose? Maybe it helps to rephrase in terms of mean temperature?

Revised. It means to highlight the importance of moisture transport to local precipitation over Antarctica.

Pg. 3, L. 20: The relevance of knowing the moisture source could be highlighted here.

Yes, it is highlighted at the end of the paragraph.

Pg. 3, L. 24 onward: Some link to the state of the Antarctic hydrologic system from observation or reanalysis data would be useful here (e.g., Papritz et al., 2014).

Thanks for the suggestion. The following two sentences have been added. *Sodemann and Stohl (2009) showed that the source regions for Antarctic precipitation over the SO vary greatly between the ocean basins. Based on reanalysis datasets Papritz et al. (2014) found that extratropical cyclones and fronts are key to the spatial distribution of evaporation and* *precipitation over the SO as well as moisture fluxes toward Antarctica.*

Pg. 4, L. 1: Clarify the distinction between internal and natural climate variability

Both “natural” and “internal” refer to “unforced” climate variability. To avoid confusion, it has been changed to “internal climate variability”.

Pg. 4, L. 2: "such responses": unclear what exactly is referred to

It is referred to the sea ice changes in the past few decades. This has now been clarified.

Pg. 4, L. 10: "and/or" - rephrase

Done.

Pg. 4, L. 17: "unacceptably" - I think this depends on the approach and purpose. One frequently used countermeasure is to consider the problem stochastically, by calculating many trajectories, as is done in Sodemann and Stohl (2009). Interpreting single trajectories beyond 10 days in contrast may be meaningless. On the other hand, tracer studies suffer from numerical diffusion and the uncertainty of parameterisation processes, and do not provide the spatial detail of source contributions available from backward trajectories. A more balanced discussion would be justified here.

Done.

Pg. 4, L. 20 onward: The relevance for ice core studies could be included as an additional motivation, see for example Winkler et al., 2012, Wang et al., 2013, Masson- Delmotte et al., 2011, Buizert et al., 2018 and references therein.

Added. Both back-trajectory and GCM water tracer approaches along with ice core records of water isotopic composition have been used to attribute water sources at Antarctic ice core sites and study their historical changes (e.g., Masson- Delmotte et al., 2011; Wang et al., 2013, Buizert et al., 2018).

Pg. 4, L. 22: "such studies" - which ones specifically?

Referred to the aforementioned back-trajectory and water tracer studies. This has now been clarified.

Methods

Pg. 5, L. 3: Are all 5 references needed as reference to the method, or rather example applications? Please clarify.

These are mostly example applications. This has now been clarified.

Pg. 6, L. 3: "assuming" - has it been checked that the simulation stabilises after 1 year?

Yes, it has been checked. With the prescribed SST and sea ice, the atmospheric model stabilizes within a year.

Pg. 6, L. 13: It would be helpful to more convincingly illustrate and quantify this aspect.

Figures are now shown in Figs. S1-S2.

Pg. 6, L. 23: tags -> tag

Corrected.

Pg. 6, L. 25: remove "well"

Done.

Pg. 6, L. 26: "differencing": rephrase, e.g. distinguishing?

Rephrased to refer to the difference between the Southern Ocean and the sum of the five sub-regions.

Pg. 6, L. 15 onward: SST mean and anomalies should be shown/discussed and placed in relation to observations/reanalysis.

Comparison to ERA5 reanalysis are now included in Figs. S1-S4.

Pg. 6, L. 15: see major comment 3.

Revised accordingly.

Results

Pg. 7, L. 11: "echoing the finding" - what aspect specifically?

The positive correlation between moisture convergence and precipitation, as described in the preceding sentence. Revised to "echoing the same finding of…".

Pg. 7, L. 20: This number could be useful to include in the Abstract

Added.

Pg. 7, L. 22 onward: would be helpful to put these numbers into the context of observation /reanalysis data

It's a good idea, but the comparison could be misleading because different reanalysis products give quite different precipitation results according to Bromwich et al. (2011). Nonetheless, for reference the interannual variability of Antarctic precipitation calculated from the ERA5 reanalysis (1979-2018) is 113 Gt year^{-1}.

Bromwich, D. H., Nicolas, J. P., and Monaghan, A. J.: An Assessment of Precipitation Changes over Antarctica and the Southern Ocean since 1989 in Contemporary Global Reanalyses. J. Climate, 24, 4189–4209, https://doi.org/10.1175/2011JCLI4074.1, 2011.

Pg. 7, L. 27: what is meant by "more significant"?

The sentence has been revised to "The contrast in Antarctic precipitation contributed by S. Ocean between the "low" and "high" SIC cases, 102 Gt year^{-1}, is much larger than the interannual variability of 35 Gt year^{-1} in precipitation that originates from the S. Ocean…".

Pg. 8, L. 1: It would be interesting to know what land region contributes, in particular anything from Antarctica.

Please see the response to major comment #3.

Pg. 8, L, 2 onward: it would be helpful to collect these results in a table.

The manuscript and Supplement are already quite long. We don't see a need to add another table to repeat the information.

Pg. 8, L. 8: The discussion could be more comprehensive. My take is that the overall results are quite similar, and specific numbers depend on how the ocean sectors have been defined here and in Sodemann and Stohl (2009). That itself is a useful finding that should be stated clearly. Part of the differences may then be due to the fact that Sodemann and Stohl (2009) based their results on ECMWF analyses for a specific period, while you consider a control run of a climate model. Comparison to reanalysis data may therefore be helpful to better explain the differences found here. Furthermore, a table or other form of description of the exact box coordinates are needed in order to compare (and reproduce) results.

We agree that the quantitative difference in the annual mean contribution from results of Sodemann and Stohl (2009) based on reanalysis for a specific time period may be due to internal variability (rather than the source attribution tools). The seasonal cycle of the S. Ocean contribution, especially from regions such as the Amundsen and Bellingshausen Seas, might be due in part to the SIC/SST conditions and/or circulation difference between the two models. We have revised the text to reflect this.

A table (Table S1) describing the exact latitude-longitude coordinates has been added to the Supplement.

Pg. 8, L. 30: Fig S4 seems to contain useful results but the information needs to be condensed more (see below).

Addressed below (Figures)

Pg. 9, L. 9: See, for example, Stohl and Sodemann (2010), which also clearly illustrates the thermodynamic transport barrier to low-level airmasses from the Southern Ocean (their Fig. 3).

Added.

Pg. 9, L. 9: "at the source" - or underways!

Revised.

Pg. 9, L. 17: The presentation of the results can be improved, see comments on figures below.

Addressed below (Figures)

Pg. 9, L. 25 onward: The discussion here is quite vague, and could be made more specific

Revised.

Pg. 10, L. 4 onward: What is the region for the apparently substantial changes in the NH? Maybe better to only show the SH.

Those are regions with differences in SST. Figures are revised to only show NH since the SIC change is the focus.

Pg. 10, L. 30: It appears you imply a direct and indirect impact from the SIC and SST anomalies - if this is a main result, this should be introduced more prominently already in the Introduction. Is it really possible to separate both aspects, as dynamic changes can also affect evaporation of the source regions?

The current results suggest that both evaporation and dynamical feedback have an impact on the difference in moisture source attribution between the low and high SIC cases. However, we agree with the referee that it is impossible to clearly separate the effect of evaporation and dynamical feedback in the current simulations. Therefore, we choose to illustrate the changes in moisture flux and transport but cannot quantify their relative contributions, not even mentioning the higher order effect (e.g., thermodynamic and dynamic feedback on evaporation).

Pg. 11, L. 15: The takeaway from this paragraph is not fully clear.

This is basically to provide a context of the complicated circulation changes and dynamic feedback from the SIC/SST anomalies, which could have affected the moisture transport to Antarctica. We admit their existence but cannot separate the impact from the direct effect of SO evaporation on Antarctic precipitation. A future study with more carefully designed series of experiments (e.g., with specified large-scale circulations, surface wind stress, evaporation and heat fluxes) is needed to address this. We have added a sentence to clarify.

Summary

Pg. 12, L. 15: It could be helpful to state whether or not this confirms earlier findings (to my understanding it does)

Done.

Pg. 12, L. 34: "intuitively" - may not be applicable to all readers

Removed.

Pg. 13, L. 1-5: Would be useful to highlight the wider implications of this study in the end.

Added.

Figures

Fig. 1: In Antarctica, seasons are more commonly defined as JFM and ASO, in line with the sea ice seasonality. Maybe it would probably be sufficient to show these seasons only along with the annual mean.

We have taken the suggestion to only show austral summer (DJF) and winter (JJA) along with the annual mean. DJF and JJA are still preferred for the consistency with other results that consider seasonality in lower latitudes.

Fig. 2: The E panel does not appear to be relevant here, but could be part of a "validation" figure where you compare SH plots of annual mean P and E from the model simulation with reanalysis/observation data.

We have removed the top panel for evaporation. Both E and P are now evaluated against ERA5 reanalysis in Figs. S1 and S2.

Fig. 4: This figure could be made more easily readable by either showing bars for 3- month periods, or by removing the white space in between the individual monthly bars. Similarly, Fig. S4 could be made into a much simpler figure that only compares the annual mean or summer/winter differences for the 3 regions.

We appreciate the thoughtful suggestions. The plots are a little complicated but still readable, and we do like to keep the monthly information. Nonetheless, we have reduced much of the white spaces in between the color bars.

Fig. 5: Panel a is method validation and could be removed in this context, the big red spot draws a lot of attention, and prevents a more useful color scale to be used. For the purpose of the paper, it seems it would be more useful to highlight the contributions to precipitation in Antarctica only, by masking the tracer contribution over the Oceanic regions, and zooming in on Antarctica.

Panel (a), which is not the sum of all source regions, does make a point that the five major source regions together account for over 95% of total Antarctic precipitation. We have taken the suggestion to zoom in more to highlight Antarctica.

Fig. 6: Instead of a zonal mean covering all latitudes, it would be more useful to highlight the Southern Hemisphere only. In fact, Fig. 6 may be dropped altogether, and be replaced by Fig. S5.

Revised.

Fig. 7: Similarly, the figure would be improved by showing the SH part only.

Changed as suggested.

Fig. 8: May be dropped in favour of Fig. 9

Figure 8 has been moved to the Supplement and Figure 9 is kept in the manuscript.

Fig. 9: Show SH section only (or discuss the NH changes which are in general larger or as large as the NH changes)

Changed as suggested.

Fig. 10: Busy figure with 15 panels and the SLP difference contours. Consider removing panel c and d, and e, or keeping e and removing the contours from the other panels.

Changed as suggested. The original Fig. 10 has been moved up, becoming the new Fig. 4, as suggested by Referee #1.

References

Buizert, Christo; Sigl, Michael; Severi, Mirko; Markle, Bradley; Wettstein, Justin; Mc- Connell, J; Pedro, Joel; Sodemann, H.; Goto-Azuma, Kumiko; Kawamura, Kenji; Fujita, Shuji; Motoyama, Hideaki; Hirabayashi, Motohiro; Uemura, Ryu; Stenni, Barbara; Par- renin, Frederic; He, Feng; Fudge, T.J.; Steig, Eric J., 2018: Abrupt ice-age shifts in southern westerly winds and Antarctic climate forced from the north, Nature 563: 681- 685.

Masson-Delmotte, V., Buiron, D., Ekaykin, A., Frezzotti, M., Gallée, H., Jouzel, J., Krin- ner, G., Landais, A., Motoyama, A., Oerter, H., Pol, K., Pollard, D., Ritz, C., Schlosser, E., Sime, L. C., Sodemann, H., Stenni, B., Uemura R., and Vimeux, F., 2011: A comparison of the present and last interglacial periods in six Antarctic ice cores Clim. Past, 7, 397-423.

Papritz, L., Pfahl, S., Rudeva, I., Simmonds, I., Sodemann, H., and Wernli, H., 2014: The role of extratropical cyclones and fronts for Southern Ocean freshwater fluxes, J. Climate 27: 6205–6224, doi:10.1175/JCLI-D-13-00409.1.

Stohl, A., and Sodemann, H., 2010: Characteristics of atmospheric transport into the Antarctic troposphere, J. Geophys. Res., 115, D02305, doi:10.1029/2009JD012536.

Wang, Y., Sodemann, H., Hou, S., Masson-Delmotte, V. Jouzel, J. and Pang, H., 2013: Snow accumulation and its moisture origin over Dome Argus, Antarctica. Clim. Dyn., 40:731-742, doi: 10.1007/s00382-012-1398-9.

Winkler, R., Landais, A., Sodemann, H., Dümbgen, L., Priéa, F., Masson-Delmotte, V., Stenni, B., and Jouzel, J., 2012: Deglaciation records of 17O-excess in East Antarctica: reliable reconstruction of oceanic relative humidity from coastal sites. Clim. Past 8, 1- 16.

Anonymous Referee #3

General Comments:

As far as it goes, this exploration of the impact of sea ice extent anomalies on Antarctic precipitation within the climate model context is competently done and the findings are interesting and valuable. Unfortunately, there are many things left dangling that require some effort to rectify before publication.

1. This is a model study and the title should reflect this.

The title has been changed to "Influence of sea ice anomalies on Antarctic precipitation using source attribution in the Community Earth System Model"

2. There is very little effort made to relate the results to the real world, rather the manuscript seems to assume that the results must be realistic. What constraints can you apply throughout the manuscript to the results to verify their credibility? In the background, stable water isotope studies are relevant, so it would be nice to see explicit discussion of relevant results.

We did compare our results with the CESM LENS pre-industrial control simulation. We have also considered suggestions from the other two referees to compare some of our results to ERA5 reanalysis products. Please see Figs. S1-S4 and relevant responses to their comments.

3. Explain why you used a pre-industrial control as the basis for your atmospheric sensitivity studies. What difference does this make to today? Do you think that fixed SST and sea ice distort your results in contrast to having an interactive ocean?

The model experiments were designed to isolate the impact of Southern Ocean SIC/SST anomalies on source–receptor relationships for moisture and precipitation over Antarctica from the anthropogenic warming (e.g., associated with GHGs). Thus we took the SIC and SST anomalies from the pre-industrial control simulation of CESM Large Ensemble simulations (LENS), which enable assessment of unforced internally generated climate variability. The prescribed SIC/SST anomalies may not be representative of present-day natural variability that is challenging to quantify from short-term observations in the presence of anthropogenic forcing.

Kittel et al. (2018) did similar sensitivity experiments using homogeneously perturbed SIC or SIC/SST from different CMIP5 models. We are using more realistic SIC/SST anomalies (in terms of unforced internal variability in the same model). With an interactive ocean, the model would take a long time to stabilize and generate the internal variability in SIC/SST or, alternatively, by introducing a strong external forcing (e.g., 2xCO_2) to attain the desired change in SIC/SST. It is almost undoable with the many water tracers enabled in the simulations.

4. There are some unexplained results for low versus high sea ice. What is the reason large PW increase north of 55S between 90E and 120E (Fig. 3c)? Why does the surface sensible heat flux decrease north of 55s (Fig. 3d)? Why does the latent heat flux decrease north of 55S between 90E and 170E (Fig. 3e)? This impacts the precipitation (Fig. 3f). You could discuss/explain these results after presenting Fig. 10.

These are all good questions. In addition to evaporation and precipitation, an important factor that affect the column-integrated water (PW) is the moisture convergence/divergence. For the specific location, the increase in PW appears to be consistent with the reduction in northward meridional moisture fluxes (new Fig. 4a). The large differences in sensible heat flux and evaporation over the northern latitudes of the SO between the two cases are due to meteorological responses (e.g., wind speed, temperature, and humidity) to the SIC/SST anomalies. For example, the decrease of wind speed (north of 55S) is clearly shown in Fig. S5. Following the suggestion, we have now discussed more along with the Fig. 10 (new Fig. 4).

5. You use unusual units for P, g/m*m/h, in contrast to the frequent mm/d or mm/yr. The latter units allow the reader to evaluate the magnitude of the simulated changes.

In response to a similar comment from Referee #1, units for P and E have been changed to kg m^{-2} $year^{-1}$ that are equivalent to mm $year^{-1}$.

Smaller Comments.

6. Page 3, line 17: Palerme et al. (2016) as per reference list?

Corrected it in the reference list.

7. Page 4, line: Difference between natural and internal climate variability?

Both "natural" and "internal" refer to "unforced" climate variability. To avoid confusion, it has been changed to "internal climate variability".

8. Page 5, line 2: Need Hurrell et al. (2013) reference.

Added to the reference list.

9. Page 6, line 8: "further" than what?

It's not being used as a comparative adverb. It can be removed.

10. Page 6, line 10: What is "CESM LENS"?

Now defined.

11. Page 7, line 11: Must be "anomalous meridional moisture transport divergence" to fit with the atmospheric water balance equation.

Yes, it is meant to be "meridional moisture flux divergence" term in the water budget equation. It has been corrected.

12. Page 7, line 18: Fall and spring are when the low-pressure trough around Antarctica is closest to the continent, known as the semi-annual oscillation.

Thanks for pointing this out.

13. Page 8, line 1: "Evaporation/sublimation over land". This is a quite surprising result. Do you mean primarily over Antarctica in summer?

It does have a peak in austral summer (December and January, see new Fig. 5) but we cannot tell whether it is primarily over Antarctica since the 'land' tag represents the global land.

14. Page 8, line 24: Why do you think that the remote sources mostly lead to precipitation decreases?

We didn't mean to suggest that the remote sources mostly lead to Antarctic precipitation decreases. The annual mean Antarctic precipitation is 150 Gt $year^{-1}$ more in the low SIC case than in the high SIC case, among which 102 Gt $year^{-1}$ is explained by the difference in Southern Ocean contributions and thus less by the remote sources. Therefore, there is indeed a decrease in the fractional contribution by the remote sources in the low SIC case relative to the high SIC case. The sentence has been revised to avoid confusion*: "This arises because small increases in precipitation originating from remote sources can be overwhelmed by large increases from local sources."*

15. Figs. 3, 8-10, S2, S3: Statistical significance should be tested for these figures.

Done.

16. Fig. 10f: Please use the more physically meaningful hPa rather than Pa for SLP differences.

Changed as suggested.

Influence of Sea Ice Anomalies on Antarctic Precipitation Using Source Attribution in the Community Earth System Model

Hailong Wang[1*], Jeremy G. Fyke[2,3], Jan T. M. Lenaerts[4], Jesse M. Nusbaumer[5,6,8], Hansi Singh[1], David Noone[7], and Philip J. Rasch[1], Rudong Zhang[1]

(1) Pacific Northwest National Laboratory, Richland, WA

(2) Los Alamos National Laboratory, Los Alamos, NM

(3) Associated Engineering, Vernon, British Columbia, Canada

(4) Department of Atmospheric and Oceanic Sciences, University of Colorado at Boulder, Boulder, CO

(5) NASA Goddard Institute for Space Studies, New York, NY

(6) Center for Climate Systems Research, Columbia University, New York, NY

(7) Oregon State University, Corvallis, OR

(8) Now at National Center for Atmospheric Research, Boulder, CO

[*]Correspondence to: Hailong.Wang@pnnl.gov

Abstract

We conduct sensitivity experiments using a general circulation model that has an explicit water source tagging capability forced by prescribed composites of pre-industrial sea ice concentrations (SIC) and corresponding sea surface temperatures (SST) to understand the impact of sea ice anomalies on regional evaporation, moisture transport, and source–receptor relationships for precipitation over Antarctica. Surface sensible heat fluxes, evaporation, and column-integrated water vapor are larger over Southern Ocean areas with lower SIC. Changes in Antarctic precipitation and its source attribution with SICs have a strong spatial variability. Among the tagged source regions, the Southern Ocean (south of 50°S) contributes the most (40%) to the Antarctic total precipitation, followed by more northerly ocean basins, most notably the South Pacific Ocean (27%), South Indian Ocean (16%) and South Atlantic Ocean (11%). Comparing two experiments prescribed with high and low pre-industrial SIC, respectively, the annual mean Antarctic precipitation is about 150 Gt year^{-1} (or 6%) more in the lower SIC case than in the higher SIC case. This difference is larger than the model-simulated interannual variability of Antarctic precipitation (99 Gt year^{-1}). The contrast in contribution from the Southern Ocean, 102 Gt year^{-1}, is even more significant, compared to the interannual variability of 35 Gt year^{-1} in Antarctic precipitation that originates from the Southern Ocean. The horizontal transport pathways from individual vapor source regions to Antarctica are largely determined by large-scale atmospheric circulation patterns. Vapor from lower latitude source regions takes elevated pathways to Antarctica. In contrast, vapor from the Southern Ocean moves southward within the lower troposphere to the Antarctic continent along moist isentropes that are largely shaped by local ambient conditions and coastal topography. This study also highlights the importance of atmospheric dynamics in affecting the thermodynamic impact of sea ice anomalies associated with natural variability on Antarctic precipitation. Our analyses of the seasonal contrast in changes of basin-scale evaporation, moisture flux and precipitation suggest that the impact of SIC anomalies on regional Antarctic precipitation depends on dynamic changes that arise from SIC/SST perturbations along with internal variability. The latter appears to have a more significant effect on the moisture transport in austral winter than in summer.

Deleted: climate

Deleted: SSTs

Deleted: (SO)

Deleted: , but changes

Deleted: reflect

Deleted: S.

Deleted: S.

Deleted: S.

Deleted: The

Deleted: /

Deleted: “low”

Deleted: “high”

Deleted: /

Deleted: S.

Deleted: /

Deleted: /

Deleted: S.

Deleted: , so the contribution of nearby sources also depends on regional

Deleted: The

Deleted: also

Deleted: atmospheric circulation

Deleted: result

Deleted: the prescribed composite SIC

Deleted: . 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.

1. Introduction

Antarctic surface mass balance (SMB), which plays a critical role in determining the evolution of the Antarctic Ice Sheet (AIS), controls the positive mass component of the overall AIS mass balance through precipitation (e.g., Lenaerts et al., 2012; Shepherd et al., 2012). Variations of AIS SMB, dominated by changes in precipitation (and to a lesser degree by sublimation), have implications for global mean sea level change. Modeling and experimental evidence suggests that AIS SMB increases in a warming climate due to increased precipitation as snowfall (e.g., Frieler et al., 2015; Zwally et al., 2015; Grieger et al., 2016; Lenaerts et al., 2016; Medley and Thomas, 2019). Previous studies have also attempted to attribute the increase in Antarctic moisture flux and precipitation to both thermodynamics (i.e., the increase in atmospheric moisture content) and dynamics (i.e., changes in the atmospheric circulation). Krinner et al. (2014) showed that changes in circulation patterns have a significant impact on Antarctic precipitation, but thermodynamic changes associated with ocean warming play a more important role in the projected increase in Antarctic precipitation. Grieger et al. (2016) quantified the thermodynamical and dynamical contributions to the increase of moisture flux and Antarctic precipitation by climate change projected in a multimodel ensemble and showed a decrease in dynamical contribution.

Observations and modeling have also shown strongly heterogeneous spatial patterns and temporal variability in AIS SMB and its trends (e.g., Thomas et al., 2017; Lenaerts et al., 2018; Medley and Thomas, 2019), suggesting the presence of regional precipitation variability over the AIS, which has been confirmed by previous studies using reanalysis and observational data (e.g., Bromwich et al., 2011; Behrangi et al., 2016; Palerme et al., 2017). Because of the extremely low atmospheric moisture content and low local moisture flux from the ice sheet surface, the formation of precipitation over Antarctica relies on moisture transport from the surrounding oceans (e.g., Tietäväinen and Vihma, 2008). By analyzing long quasi-equilibrium global climate model simulations, Fyke et al. (2017) identified statistically significant relationships in Antarctic basin-scale precipitation patterns that are driven by internal variability in large-scale atmospheric moisture transport. Sodemann and Stohl (2009) showed that the source regions for Antarctic precipitation over the Southern Ocean (SO) vary greatly between the ocean basins. Based on reanalysis datasets, Papritz et al. (2014) found that extratropical cyclones and fronts are key to the spatial distribution of evaporation and precipitation over the SO as well as moisture fluxes toward Antarctica. The impact of sea ice anomalies in the SO associated with internal variability on Antarctic moisture source apportionment as well as their feedback on atmospheric circulation remain unclear.

Deleted:)

Deleted:) by supplying the vast majority of

Deleted:) through precipitation as snow.

Deleted: this

Deleted: profound

Deleted: Zwally et al., 2015;

Deleted: This SMB

Deleted: 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). However, the exact coupled-climate mechanisms driving this

Deleted: have not been well elucidated. In particular, the role of sea surface temperature (SST) changes,

Deleted: sources/transport/carrying capacity, sea ice loss, and …

Deleted: dynamical

Deleted: snowfall

Deleted: has not been clearly disaggregated.

Deleted: local

Deleted: , Antarctic

Deleted: However,

Deleted: origin

Deleted: moisture (i.e.,

Deleted: source) and the

Deleted: Southern Ocean on

Deleted: availability

Sea ice has long been recognized as being highly sensitive to both forced changes and internal variability. Much of the SO is seasonally covered by sea ice. Oceanic areas close to the Antarctic coast are ice-covered most of the year, but the sea ice pack can be broken up by strong winds originating from the ice sheet, generating coastal polynyas that expose open ocean to the atmosphere. Variations in sea ice cover and/or the polynyas not only affect local surface heat and moisture fluxes from the ocean (e.g., Weijer et al., 2017) but also shift the latitudes of the mid-latitude storm track (e.g., Kidston et al., 2011). In contrast to the Arctic sea ice loss observed in recent decades, sea ice cover in the Antarctic (Southern Ocean) has increased over the last few decades (Turner and Overland, 2009), followed by a strong decline from 2016 (https://nsidc.org/data). While many coupled climate models are able to reproduce Arctic sea ice trends, these same models have difficulty simulating observed trends in sea ice cover over the Southern Ocean (e.g., Holland and Raphael, 2006; Meehl et al., 2016; Turner et al., 2013a). It is still unclear whether this trend in the Southern Ocean is due to internal climate variability, but there is no convincing mechanistic explanation for such responses of the SO sea ice cover to the warming caused by anthropogenic forcing. Given the connections between sea ice and Antarctic precipitation, this suggests a corresponding uncertainty in the projection of precipitation changes over Antarctica (Agosta et al., 2015; Bracegirdle et al., 2015) and, by consequence, AIS SMB and global sea level rise. Understanding the impact of sea ice anomalies on AIS SMB therefore presents an important scientific challenge (e.g., Kennicutt et al., 2015).

The direct impact of sea ice anomalies on moisture flux and Antarctic precipitation is through air-sea interactions, but the associated feedback on atmospheric dynamics can also be significant, as shown in previous modeling studies of projected climate change (e.g., Menéndez et al.,1999; Bader et al., 2013). Kittel et al. (2018) conducted sensitivity experiments in a regional climate model, with atmospheric circulation nudged toward reanalysis, to study the impact of idealized or forced sea ice perturbations on AIS SMB. They found significant Antarctic precipitation and SMB anomalies for the largest perturbations. However, the impact of SO sea ice anomalies and accompanying sea surface temperature (SST) changes on Antarctic snowfall changes through changing atmospheric moisture sources and associated atmospheric circulation and moisture transport, in the absence of anthropogenic forcing that primarily originates from low and mid-latitudes, has not been clearly disaggregated.

Moisture contributions from different source regions to local Antarctic precipitation cannot be quantified from direct measurements. Indirect approaches have to be used to derive such source–receptor relationships, characterize moisture history, and identify precipitation origins. Air parcel back-trajectory approaches tend to attribute more vapor sources to the high-latitude regions in the Southern Ocean (e.g., Helsen et al., 2007), likely due to the use of relatively short backward trajectories, which cannot trace water vapor originating from the distant low latitudes. A longer tracking time (e.g., 20 days) allows for

Deleted: Much of the Southern Ocean

Deleted: break

Deleted: Coupled

Deleted: that

Deleted: the

Deleted: difficulties

Deleted: the increasing trend of

Deleted: in

Deleted: natural or

Deleted: and

Deleted: high-latitude climate system

Deleted: potential

Deleted: future

Deleted: such

Moved (insertion) [1]

Deleted: /or

the identification of more distant moisture sources of Antarctic precipitation that are generally consistent with isotope-based source reconstructions and general circulation model (GCM) results (Sodemann and Stohl, 2009). However, for tracking times beyond 10 days, the single trajectory calculation error can become large due to the reduced coherency of air parcels (Sodemann et al., 2008), which might be overcome stochastically by calculating many trajectories (Sodemann and Stohl, 2009). Despite their limitations (e.g., coarse resolution, numerical diffusion and biases in physics), atmospheric GCMs with moisture tracking capability using water isotope or tagged water tracers provide a powerful means to determine the origin of moisture sources of precipitation over receptor regions such as Antarctica (e.g., Koster et al., 1986; Delaygue et al., 2000; Noone and Simmonds, 2002; Singh et al., 2016a). These back-trajectory and water tracer studies have shown that moisture sources for precipitation over the AIS are primarily from the Southern Ocean (south of 50°S) and the Southern Hemisphere mid-latitude oceans. Both back-trajectory and GCM water tracer approaches, along with ice core records of water isotopic composition, have been used to attribute water sources at Antarctic ice core sites and study their historical changes (e.g., Masson- Delmotte et al., 2011; Wang et al., 2013; Buizert et al., 2018).

In this study, we aim to understand the impact of SO sea ice anomalies associated with internal variability on local evaporation, moisture transport and source–receptor relationships for moisture and precipitation over Antarctica using a GCM that has an explicit water source tagging capability. Section 2 describes the GCM with water tagging capability and the experimental design. Main results and related discussions are presented in Section 3. Section 4 summarizes key conclusions drawn from these sensitivity experiments and water source attribution analysis.

2. Methodology

2.1 Model description

The climate model employed in this study is a coupled atmosphere-land version of the Community Earth System Model (CESM1-CAM5, CESM hereafter; Hurrell et al., 2013) that has an atmospheric water tagging capability. This modeling tool has been used in several recent studies to quantify source-receptor relationships for the aerial hydrologic cycle (e.g., Singh et al., 2016a; Singh et al., 2016b; Singh et al., 2017; Nusbaumer and Noone, 2018; Tabor et al., 2018). 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 with an interactive land component (CLM4, Oleson et al., 2010), which includes the evolution of ice and snow over land. Snow cover over sea ice still evolves in the model, although SSTs and SICs are prescribed. CAM5 has relatively comprehensive

Deleted: reconstruction

Deleted: unacceptably

Deleted:). Atmospheric

Deleted: Such

Deleted: Southern Ocean

Deleted: The

Deleted: can also be run

Deleted: Sea ice thickness and snow

Deleted: evolve

representations of surface evaporation, clouds, precipitation, and atmospheric circulation (Neale et al., 2010).

The atmospheric water tagging capability in CAM5 can be used to track water that enters the atmosphere through surface evaporation in any given region, moves with the air mass, condenses into liquid or ice clouds, and forms precipitation (rain or snow). A set of new water variables (designated as a tagged water tracer set) is defined in CAM5 to capture the mass mixing ratio of vapor, cloud liquid, cloud ice, stratiform rain, stratiform snow, convective rain, and convective snow for each water source region of interest. Each water tracer set undergoes the same atmospheric processes as the corresponding standard water variables in the model. The tracked water cycle starts with surface evaporation/sublimation and ends when water returns to the Earth's surface in the form of condensate or precipitation. Thus, the destiny of the tracer water is lost once it returns to the surface.

2.2 Experimental design

We use the water tagging capability along with a set of sensitivity experiments to examine the impact of changes in sea ice concentration (SIC) in the Southern Ocean on moisture transport, Antarctic snowfall, and the AIS SMB. Here SIC is defined as the fractional area of ocean in a model grid that is covered by sea ice. Three SIC (and corresponding SST) composites are constructed from the pre-industrial control simulation of the CESM Large Ensemble (hereafter CESM LENS; Kay et al., 2015), which was initialized with January mean present-day potential temperature and salinity from the Polar Science Center Hydrographic Climatology dataset for the ocean and a previous CESM 1850 control run for the atmosphere, land and sea ice. The CESM LENS control simulation was run for 1500 years with years 400-1500 released, which provides a continuous time series of over 1000 years to perform our composite analysis of SIC and SST based on monthly mean model output. 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. All other forcing conditions (e.g., solar, greenhouse gases, anthropogenic aerosols) are identical across simulations. Although these sensitivity simulations are not designed to represent present-day conditions, several essential model fields from the baseline simulation are compared to the fifth generation ECMWF reanalysis (ERA5, 1979-2018). The main purpose is to provide a context for the interpretation of model results that might also be valid for the recent historical period in terms of internal climate variability. The large-scale patterns of SIC, surface temperature, circulation (sea level pressure), precipitation, precipitable water, and horizontal moisture fluxes in the baseline simulation are comparable to those in the ERA5 reanalysis, as shown in Figs. S1-S4.

Deleted: large ensemble (

Deleted: gives

The three simulations (hereafter referred to as "mean", "low" and "high" according to the prescribed SICs) are conducted at a horizontal grid spacing of 0.9° × 1.25° with 30 vertical levels for 11 years. Results from the last 10 years are analyzed, assuming that the first simulation year is for model spin up. Figure 1 shows the anomalies of the two SIC composites with respect to the annual and seasonal (DJF and JJA) mean SIC. The most widespread SIC anomalies are found in the Weddell sea and the Bellingshausen and Amundsen seas in austral summer (DJF). The largest reduction in the "low" SIC case is along the east coast of the Antarctic Peninsula in DJF, while the most positive anomalies in the "high" SIC case are in the Amundsen sea away from the coastal zone in JJA. SIC anomalies are relatively small in the eastern Antarctic/SO sectors where the mean sea ice extent and SIC are also smaller. The regional difference in SIC anomalies adapted from the CESM LENS simulations is likely related to the key role of the Amundsen-Bellingshausen Seas Low (ABSL) in controlling the regional climate variability (e.g., Hosking et al., 2013). Although the magnitude and location of prescribed SIC anomalies are comparable to the observed SIC changes during recent decades (Hobbs et al., 2016), the prescribed seasonal SIC anomalies associated with internal variability under the CESM LENS pre-industrial conditions are likely to be different from future changes. Here the widespread anomalies occur in austral summer (DJF) and JJA anomalies concentrate at sea ice edges, while sea ice reductions by the end of the 21st century or in response to CO_2-doubling and the resulting global warming are expected to be dominated by winter (JJA) changes (e.g., Singh et al., 2017). Therefore, the simulations designed here are to examine Antarctic precipitation changes and moisture transport pathways dominated by natural variability, as opposed to the projected future changes driven by the increase in atmospheric moisture content related to temperature increases (e.g. Krinner et al., 2014, Frieler et al, 2015).

To use the water tracer tagging capability of CESM, we need to predefine water vapor source regions, where surface evaporation/sublimation of water provides the initial source of water vapor entering the atmospheric hydrologic cycle for the corresponding source region tags (Table S1). Figure 2 shows the water source regions, including major tropical, subtropical and mid-latitude ocean basins, land (all continents) and several finer sectors in the SO, that are tagged in all three simulations. According to Singh et al. (2017), the more distant lower-latitude oceans (i.e., 30°S equatorward) are much less efficient in contributing to Antarctic precipitation, and there is no seasonal sea ice over in the lower-latitude oceans, so each of these tagged regions is set up to cover a quite large area to economize computing time. Much finer divisions are used for the S. Ocean tags because they are in close proximity to the Antarctic and their surface evaporation is more affected by SIC variations. Five regular latitude-longitude boxes are defined. The remaining area (irregular shape) of the SO was constructed by subtracting the sum of the five regular regions from the entire S. Ocean tag.

Deleted: the
Deleted: autumn (MAM) and
Deleted: MAM and
Deleted: further
Deleted: and SON
Deleted: The
Moved (insertion) [2]
Deleted: the recent decades (Hobbs et al., 2016).
Deleted: .
Deleted: global annual mean evaporation/sublimation rate from the "mean" SIC case and
Deleted: Southern Ocean (SO),
Deleted: tags
Deleted: SO
Deleted: well
Deleted: differencing between the entire S. Ocean tag and

3. Results and Discussions

3.1 Responses of surface fluxes, precipitable water and precipitation to the SIC and SST anomalies

Although the three SIC composites were based on annual mean sea ice data, there are also large and consistent seasonal differences in SIC prescribed in the "low" and "high" sea ice cases (Fig. 1). The most widespread SIC differences are in the Weddell Sea and the King Haakon VII Sea where the reduction in "low" SIC extends to north of 60°S, while the largest difference (over 20%) occurs in the Bellingshausen and Amundsen Seas (Fig. 3a), indicating the role of the ABSL in dominating the overall internal variability of sea ice cover in the Southern Ocean (e.g., Hosking et al., 2013). Compared to the "high" SIC case, the "low" SIC case also has much warmer SSTs and higher surface sensible heat flux and evaporation over the areas where SIC is lower (Figs. 3b, d and e). The sensible heat flux and evaporation over the northern latitudes of the SO also show large differences between the two cases due to meteorological responses (e.g., changes in winds as shown in Fig. S5; also changes in temperature and specific humidity) to the SIC/SST differences. The total precipitable water (PW) in the low SIC case is greater over most of the SO, while the precipitation is greater over most of the coastal areas except for the King Haakon VII Sea (Fig. 3c and f). Comparison to the corresponding decadal variability of these annual mean fields (Fig. S6), along with a Student's t-test at 90% confidence, suggests that the significant regional differences in surface temperature, evaporation and precipitable water are mostly due to SIC/SST perturbations while changes in precipitation is influenced more by internal variability.

There are seasonal contrasts between DJF and JJA that can be an indication of the relative importance of SIC anomalies and internal variability. As shown in Figs. S7 and S9, SIC differences in DJF are more widespread (e.g., large SIC changes near coastal areas) than in JJA when SIC changes are concentrated at the sea ice edge. The differences in surface temperature and heat fluxes within the sea ice zone is much larger and more definite in JJA than in DJF, which is similar for the seasonal contrast in SLP over SO and Antarctica (Fig. 4). However, the decadal variability of these fields is also stronger in JJA than in DJF (See Figs. S8, S10 and S11). It indicates that decadal variability plays a more important role in determining the moisture flux and precipitation differences in JJA than in DJF. Comparing the regional changes in seasonal evaporation and precipitation (Figs. S7 and S9), positive evaporation anomalies in the SO can only translate to a positive impact on Antarctic basin-scale precipitation when there is a strong meridional moisture flux towards the basin (Fig. S3). This is consistent with the finding of Fyke et al. (2017) that large-scale moisture transport is the main driver of basin-scale precipitation variations over Antarctica. For example, evaporation anomalies are significant and positive in both DJF and JJA over the Amundson Sea, but the meridional flux (F_{VO}) is much stronger in JJA than in DJF, leading to a more significant positive impact on the downwind Antarctic coastal precipitation in JJA.

Deleted: 'low'
Deleted: 'high'
Deleted: Sea
Deleted: the
Deleted: Sea
Deleted: interannual
Deleted: .
Deleted: mean SST
Deleted: SIC areas
Deleted: , likely
Deleted: wind,
Deleted: ,
Deleted: The coastal area that has less precipitation in
Deleted: low SIC case,
Deleted: occurring
Deleted: austral winter (JJA) when SIC
Deleted: regions is almost the same in the two cases (Fig. 1),
Deleted: characterized by anomalous
Deleted: divergence (figure not shown), echoing

3.2 Changes in meridional transport and circulation patterns

Moved (insertion) [3]

SIC changes between the “low” and “high” cases can be closely related to large-scale circulation changes over the SO. Previous studies identified complex large-scale interactions between the atmosphere and Antarctic sea ice cover that depend on the geographic location of sub-sectors in the SO (e.g., Lefebvre and Goose, 2008; Hobbs et al., 2016). Meridional winds can drive the exchange of dry/cold air over the AIS with moist/warm air from lower-latitude oceans. In the annual mean, moisture from the north moves to Antarctica over the entire SO, while southerly katabatic outflow associated with the polar high brings relatively dry air back to the ocean. The meridional moisture flux (F_{VQ}) that is largely determined by meridional winds is also significantly different between the “low” and “high” SIC cases (Fig. 4a). Changes in meridional winds can be explained by the sea level pressure change using the geostrophic balance approximation (Fig. S5 and Fig. 4c). The pattern of variations in meridional moisture flux (Fig. 4a) is consistent with precipitation differences (Fig. 3f). Decreases in precipitation in the “low” SIC case over the King Haakon VII Sea and coastal areas can be traced to the reduction in meridional flow and related moisture fluxes from the north in part due to the SIC decrease and internal variability (Fig. 4a). A Student’s t-test and the comparison of changes to decadal variability (Fig. 4 and S11) suggest that the reduction of meridional moisture flux (F_{VQ}) in that area is primarily determined by the SIC decrease in JJA but more likely due to internal variability in DJF. Therefore, the impact of sea ice anomalies and corresponding SST changes on Antarctic precipitation stem both from their thermodynamic impact on moisture sources and from the dynamic changes that accompany the different SIC and SST patterns as well as internal variability.

Moved (insertion) [4]

Moved (insertion) [5]

Comparing the “low” and “high” cases also reveals a strengthening of the Hadley Cell and weakening of the polar vortex in the southern hemisphere accompanying the “low” SIC (figure not shown). Variations in zonal flow and moisture fluxes over much of the SO (Fig. 4b and Fig. S5) can affect Antarctic precipitation through redistribution of moisture among the different sectors/basins and indirect changes in northward moisture transport. Regional westerlies can also drive changes in upper-ocean heat storage and sea ice formation by affecting Ekman pumping and thus the sea ice extent (e.g., Turner et al., 2013b). The southern annular mode, which dominates the variability of the large-scale atmospheric circulation in the Southern Hemisphere, has been found to co-vary with tropical SST variability (e.g., Ding et al., 2012) and respond to SIC changes (e.g., Menéndez et al., 1999; Bader et al., 2013; Smith et al., 2017). The ABSL, which plays an important role in bringing warm/moist air into the Bellingshausen Sea and Antarctic Peninsula region and moving cold/dry air equatorward through the Ross Sea region, strongly influences winds, near-surface temperature, precipitation and SIC over the Amundsen-Bellingshausen Seas (e.g., Hosking et al., 2013). Conversely, the strength and location of the ABSL (in JJA) can also be affected by

Moved (insertion) [6]

Moved (insertion) [7]

Deleted:).

the sea ice and temperature changes along with internal variability, as depicted in Fig. 4c. Therefore, variability in atmospheric circulation and SIC/SST anomalies indirectly influence moisture transport and regional precipitation over Antarctica. Here we cannot elaborate more on causes of CESM-simulated SO SIC/SST anomalies in the Large Ensemble that promulgate the resulting circulation changes when prescribed in our sensitivity experiments. To further separate the direct impact of changes in evaporation from the indirect impact of changes in circulation and moisture transport associated with SIC/SST anomalies as well as internal variability, a future dedicated study using a series of carefully designed experiments (e.g., with specified atmospheric circulations and/or regional evaporation) is needed.

3.3 Seasonal variation of Antarctic precipitation and source attribution

As expected, there are strong seasonal variations in total Antarctic precipitation, with a distinct minimum in austral summer months (Fig. 5), which is opposite to the PW seasonal cycle (Fig. S12). Although the seasonal pattern itself changes very little with the SIC/SST anomalies, the magnitude of seasonal precipitation has relatively larger changes, as well as larger interannual variability (indicated by the longer error bars), in spring and fall than the other months, which is consistent with SIC changes between the "low" and "high" cases (Fig. 1). The annual mean precipitation is about 150 Gt year^{-1} more in the "low" SIC case than in the "high" SIC case, representing a 6% increase relative to the total precipitation (2500 Gt year^{-1}) in the "mean" SIC case. This difference is larger than the interannual variability of Antarctic precipitation (99 Gt year^{-1}) that is characterized by one standard deviation of annual mean precipitation within the 10 years of the "mean" SIC case. Note that the standard deviation of annual mean Antarctic precipitation for the entire CESM LENS time series is 98 Gt year^{-1}, which is smaller than the variability of 122 Gt year^{-1} for recent historical precipitation simulated in CESM (Fyke et al., 2017). For reference interannual variability in Antarctic precipitation calculated from the ERA5 reanalysis (1979-2018) is 113 Gt year^{-1}. The contrast in Antarctic precipitation contributed by the S. Ocean between the "low" and "high" SIC cases, 102 Gt year^{-1}, is much larger than the interannual variability of 35 Gt year^{-1} in precipitation that originates from the S. Ocean, although it is a small fraction of the increase in evaporation (870 Gt year^{-1}) from the S. Ocean (again comparing the "low" SIC case to the "high" SIC case).

Among the tagged source regions, the S. Ocean (including the 6 sub-sectors) contributes the most (40%) to the Antarctic total precipitation in the "mean" SIC case, followed by S. Pacific Ocean (27%), S. Indian Ocean (16%) and S. Atlantic Ocean (11%), with the remaining mostly coming from evaporation/sublimation over land. The other oceans in the tropics and northern hemisphere have a negligible contribution to Antarctic moisture and precipitation. The fractional contribution by the S.

Deleted: and
Deleted: 4
Deleted: S1
Deleted: /
Deleted: /
Deleted: /
Deleted: /
Deleted: /
Deleted: contributed by the S. Ocean
Deleted: /
Deleted: more significant, compared to
Deleted: /
Deleted: /

Ocean has a 1.7% increase (comparing the "low" SIC case to the "high" SIC case), while there is a small decrease from the S. Atlantic (-0.7%) and S. Pacific (-1%). The contribution by the S. Ocean, Land and some remote oceans (e.g., S. Indian Ocean and S. Pacific Ocean) has a relatively strong seasonal variation. There is a seasonal peak contribution from the S. Ocean in fall and spring (MAM and SON), when the SIC anomalies make a relatively large difference to the total Antarctic precipitation (Fig. 5), while the peak is in boreal summer (JJA) for the remote oceans and in austral summer (DJF) for land sources. The annual mean contribution of 40% by the S. Ocean is larger than the estimate (30%) by Sodemann and Stohl (2009) using the 20-day back trajectory method for a specific historical time period (1999-2005). Also different from the finding of Sodemann and Stohl (2009), the seasonal cycle of the S. Ocean contribution to Antarctic precipitation in our study is not mainly determined by the SIC seasonality. These may be due in part to differences in SIC/SST conditions and atmospheric circulations (rather than the tools being used), especially for the JJA source attribution to evaporation over the Amundsen and Bellingshausen Seas, where the internal variability of relevant fields is large (Figs. S10 and S11).

As shown in Fig. (3f), the responses in Antarctic precipitation to SIC/SST anomalies along with internal variability have a strong spatial variability, as does the source attribution. Figure 6 shows the spatial distribution of fractional contributions to annual mean Antarctic precipitation by individual and combined source tags. The five major source regions together account for over 95% of total Antarctic precipitation, with individual regions dominating in certain areas as determined by geographical location and atmospheric circulation patterns (Fig. S3). The S. Ocean tag as a whole dominates precipitation over most of the coastal areas except for the segment (90–150°E) located at the south of the S. India Ocean. The sub-sector sources in the SO primarily affect nearby coastal areas as well as downwind coastal and inland regions. There is also a strong regional variation in the annual and seasonal changes of absolute precipitation and corresponding fractional contribution from individual source regions related to the SIC anomalies (Figs. S13-S18). The higher fractional contribution in the lower SIC case from the S. Ocean and sub-sectors is mostly due to increased coastal precipitation, while changes in the fractional contribution by the remote sources do not correspond well with the absolute precipitation change over the SO and Antarctica. This arises because small increases in precipitation originating from remote sources can be overwhelmed by large increases from local sources. Such compensating effects occur not only between the local source region (S. Ocean) and remote source regions but also amongst the remote region contributions themselves. Another reason is that the long-range moisture transport from remote source regions towards Antarctica is more likely affected by internal variability in atmospheric circulations. A Student's t-test suggests that S. Ocean has a more significant impact on the response of Antarctic

Deleted: 4

Deleted: .

Deleted: SIC/SST-driven changes

Deleted: 5

Deleted: .

Deleted: S2 and S3

Deleted: more

Deleted: changes

Deleted: changes

precipitation to the SIC/SST anomalies than the remote oceans do. The total response from all major sources are less robust than S. Ocean alone for annual and seasonal mean results (i.e., comparing "Sum" to "S. Ocean" in Figs. S13-S18). Similarly, smaller source regions such as the sub-sectors of S. Ocean tend to impose more robust signals than the S. Ocean as a whole, indicating that the quantified response of Antarctic precipitation to SIC/SST anomalies in the S. Ocean subsectors has minimal interference from internal variability.

To further look at spatial variations in precipitation and its source attribution, we divide Antarctica into three broad sectors: eastern Antarctica (0, 180°E; 65°S, 80°S), western Antarctica (0, 180°W; 65°S, 80°S), and interior Antarctica (80°S, 90°S). The contribution of the entire S. Ocean source tag to the annual mean precipitation dominates over all three and has a small interannual variation, although seasonal variations of contribution have large differences (Fig. S19). The S. Ocean has a larger contribution to precipitation over western Antarctica than eastern Antarctica, which is due in part to higher elevation in the east. Subsectors of the S. Ocean in the west (e.g., Amundsen Sea, Weddell Sea, and part of Ross Sea) can have a discernable impact on precipitation over interior Antarctica (Fig. S19), which shows a significant response to SIC/SST anomalies in these source regions as well (Figs. S13-S18). Among the major remote source regions, the S. Indian Ocean and S. Atlantic dominate the contribution to precipitation over eastern Antarctica, while the S. Pacific Ocean dominates over western and interior Antarctica, especially in austral winter (JJA).

3.4 Transport pathways of water to Antarctica

As indicated in the previous section (Fig. 6), the horizontal transport pathways of atmospheric water from individual source regions to a receptor are largely determined by large-scale atmospheric circulations. Localized or large-scale vertical lifting at the source region or along the transport pathway is an important factor in determining the extent to which water vapor can penetrate to the Antarctic interior before precipitating. Stohl and Sodemann (2010) illustrated the thermodynamic transport and lifting barrier for SO low-level airmasses to move to the Antarctic interior. Figure 7 shows the vertical distribution of fractional contribution to zonal mean water vapor mixing ratio from the major source regions. In general, vapor originating from remote source regions at lower latitudes takes elevated pathways to Antarctica while vapor from the nearby sources in the SO moves southward within the lower troposphere, as also noted in previous studies (e.g., Noone and Simmonds, 2002; Sodemann and Stohl, 2009; Stohl and Sodemann, 2010; Kittel et al., 2018). The meridional and vertical transport of vapor is along zonal mean moist isentropes (θ_e) that are largely shaped by local airmass temperature and topography in Antarctica, especially, for water vapor originating from the individual SO sub-sectors (Fig. 8; see also Bailey et al 2019). As a result, a large portion (up to 70% for the zonal mean) of the vapor below 700 mb comes from

Deleted: S4

Deleted: in part due to higher elevation in the east.

Moved up [2]: Singh et al., 2017

Deleted: As shown in previous studies (e.g., Wang et al., 2014; …

Deleted:), as well as

Deleted: 5

Deleted: constituents such as vapor and aerosol particles

Deleted: this

Deleted: 6

Deleted: by

Deleted: for Antarctic precipitation.

Deleted: and northern hemisphere

Deleted: tags

Deleted:).

Deleted: moist

Deleted: S5

the S. Ocean source tag, which also contributes a significant amount (10-40%) to vapor in the mid-troposphere (700–400 mb). Vapor in the upper troposphere (above 400 mb) predominantly comes from remote oceans through elevated pathways, although evaporation from lower-latitude continents also contribute a discernible fraction (up to 20%). Vapor originating from the equatorial oceans, lifted by deep convection in the ITCZ, can have a substantial contribution (up to 40%) at very high levels (above 200 mb).

We have shown in the previous section that the SO SIC reduction substantially increases the atmospheric column-integrated water vapor (Fig. 3). Vertical distributions of water vapor changes show that the increase occurs mostly in the lower troposphere over the SO and coastal areas (Fig. S20), where water vapor sources include the S. Pacific, S. Indian Ocean and S. Atlantic in addition to the primary contributor, the S. Ocean (Fig. 7). However, two of the three major remote ocean source regions (S. Pacific and S. Atlantic), Equatorial Oceans and land contribute significantly less water vapor further inland in the "low" SIC case (Fig. S20), which leads to a discernable and significant reduction in their fractional contribution to water vapor in the lower and mid troposphere (Fig. 9). The contribution by the entire S. Ocean tag increases substantially south of 50°S in the "low" SIC case, compensating for the reduced contribution from remote oceans. Note that the changes in fractional contribution in the upper troposphere and lower stratosphere (Fig. 9) are more likely related to SST and deep convection changes in the lower latitudes than to the SIC changes.

4. Summary and Conclusions

In this study, we use the Community Atmosphere Model version 5 (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. A set of sensitivity experiments are conducted to understand the impact of SIC and SST variations on regional evaporation, moisture transport, and source–receptor relationships for Antarctic precipitation. Three composites of sea ice concentration (SIC), which were constructed from the 1000-year fully-coupled pre-industrial control simulation of the CESM Large Ensemble Project using mean, 10% lowest, and 10% highest SIC years (and corresponding SSTs), respectively, are used as prescribed boundary conditions for 10-year atmosphere-only simulations. Moisture originating from individual geographical regions is explicitly tracked using separate water tracers throughout the atmospheric water cycle that closes with surface precipitation.

Because of the prescribed changes in the SIC and SST, surface sensible heat fluxes and evaporation over lower SIC areas in the SO increase significantly in the "low" SIC case, compared to the "high" SIC case, especially in JJA. Column-integrated water vapor also increases over much of the SO, while changes in

Deleted: at

Deleted: Clouds over Antarctica are dominated by the ice phase or mixed phase (containing supercooled liquid), especially at high altitudes (above 600 mb). Figure 7 shows the vertical distribution of fractional contributions to zonal mean ice water mixing ratio by the major source regions. It is generally consistent with that for water vapor but with differences in the magnitude and spatial patterns, presumably, due to different cloud-formation mechanisms. For instance, the large contribution by the S. Ocean tag between 50°S and 70°S are related to Southern Ocean storm dynamics and the strong orographic lifting of local moisture. The contribution by remote sources in the middle and upper troposphere is more likely determined by large-scale dynamics and local ambient conditions.¶

Deleted: . The

Deleted: is

Deleted: 8

Deleted: 6

Deleted: 8

Deleted: As expected, the

Moved up [3]: <#>Changes in meridional transport and circulation patterns¶
<#>SIC changes between the "low" and "high" cases can be closely

Deleted: <#>associated with large-scale circulation changes over the SO. Previous studies identified complex large-scale interactions between the atmosphere and Antarctic sea ice cover, which are dependent on sub-sectors in the SO (e.g.,

Moved up [4]: <#>Lefebvre and Goose, 2008; Hobbs et

Deleted: <#>Moisture from the north moves to Antarctica... [1]

Moved up [5]: <#>3f).

Deleted: <#>As a result, decreases in precipitation in the... [2]

Moved up [6]: <#> a strengthening of the Hadley Cell and

Deleted: <#>10b, d

Moved up [7]: <#>) can affect Antarctic precipitation

Deleted: <#>The Amundsen-Bellingshausen Seas Low... [3]

Moved up [1]: <#> et al., 2013).

Deleted: <#>Conversely, the strength and location of the... [4]

Deleted: a coupled atmosphere-land version of

Deleted: Earth System

Deleted: (CESM1-

Deleted: concentrations

Deleted: 1800

Deleted: the

Deleted: Southern Ocean (

Deleted:) have a large

Antarctic precipitation with SICs have a strong spatial variability, as does the source attribution. The prescribed SIC anomalies in DJF are more widespread than in JJA when SIC changes are concentrated at the sea ice edge. Our analysis indicates that decadal variability plays a more important role in determining the moisture flux and precipitation differences in JJA than in DJF. Comparing the regional changes in seasonal evaporation and precipitation, positive evaporation anomalies in the SO can only translate to a positive impact on Antarctic basin-scale precipitation when there is a strong meridional moisture flux towards the basin.

Among the tagged source regions, the S. Ocean (including all six sub-sectors) contributes the most (40%) to the Antarctic total precipitation, followed by the S. Pacific Ocean (27%), S. Indian Ocean (16%) and S. Atlantic Ocean (11%), with the remaining contributions mostly from evaporation or sublimation over global land. The major remote source regions have a reduced absolute contribution to water vapor further inland in the "low" SIC case, which leads to a significant reduction in their fractional contribution, especially, in the lower and mid troposphere. With lower SIC, the relative contribution to water vapor south of 50°S by the S. Ocean tag increases substantially, compensating the reduction in the relative contribution from remote oceans. This is qualitatively consistent with the annual mean source attribution change in response to warming from CO_2 doubling (Singh et al., 2017). The annual mean total Antarctic precipitation is approximately 150 Gt year^{-1} more in the "low" SIC case than in the "high" SIC case. This difference is larger than the interannual variability of Antarctic precipitation (characterized by one standard deviation of annual mean precipitation) estimated from the CESM LENS control experiment and the ERA5 reanalysis (1979-2018), 98 and 113 Gt year^{-1}, respectively. The contrast in precipitation between the "low" and "high" SIC cases contributed by the S. Ocean, 102 Gt year^{-1}, is even more significant, compared to the interannual variability of 35 Gt year^{-1} in precipitation that originates from the S. Ocean.

Deleted: three

Deleted: discernable

Deleted: /

Deleted: within the 10 years of the "mean" SIC case as well as over 1000 years of

Deleted: /

Deleted: /

The horizontal transport pathways from individual vapor source regions to Antarctica are largely determined by the large-scale atmospheric circulation, which confirms earlier findings (e.g., Stohl and Sodemann, 2010; Singh et al., 2017). Localized or large-scale vertical lifting is important in determining the heights at which vapor is transported and forms cloud. Thus the source contribution is primarily determined by their geographical location (and atmospheric dynamical setting) and atmospheric circulation patterns, as well as the local elevation over Antarctica. Vapor from source regions at lower latitudes takes elevated pathways to Antarctica while vapor from the nearby tags in the SO moves southward within the lower troposphere. The entire S. Ocean source tag is the primary contributor to the annual mean precipitation over all defined Antarctic sub-regions - eastern Antarctica (0, 180°E; 65°S, 80°S), western Antarctica (0, 180°W; 65°S, 80°S), and interior Antarctica (80°S, 90°S). However, it has

Deleted: circulations.

Deleted: .

a larger contribution to precipitation over western Antarctica than eastern Antarctica, which is in part due to higher elevation in the east. The S. Ocean contribution also has large seasonal differences among the three. Among the remote source regions, the S. Indian Ocean and S. Atlantic dominate the contribution to precipitation over eastern Antarctica, while the S. Pacific Ocean dominates over western and interior Antarctica, especially in austral winter (JJA).

In addition to direct thermodynamic effects, the impact of sea ice anomalies on regional precipitation over Antarctica also depends on atmospheric circulation changes that result from the SIC/SST perturbations prescribed to the simulations along with internal variability. Regional anomalies in zonal and meridional winds combine with surface evaporation changes to determine regional shifts in zonal and meridional moisture fluxes. The resultant changes in meridional moisture fluxes from the Southern Ocean to the Antarctic continent can explain some of the precipitation differences between the "low" and "high" SIC cases. Variations in zonal moisture fluxes can also affect Antarctic precipitation indirectly through the redistribution of moisture among the different sectors/basins. The seasonal contrast between DJF and JJA in basin-scale moisture flux and precipitation changes can be used as an indication of the relative importance of SIC anomalies versus internal variability. However, the experiment design of this study doesn't allow us to isolate the impact of SIC anomalies from internal variability on circulation-driven changes in Antarctic precipitation. A future dedicated study with specified large-scale circulations or fixed regional evaporation might be helpful in this regard.

Deleted: .

Deleted: intuitively

Deleted: potentially

Code and data availability. The CESM model code can be obtained from http://www.cesm.ucar.edu/ and https://github.com/NCAR/iCESM1.2. Directions for obtaining CESM Large Ensemble data are available at www.cesm.ucar.edu/projects/community-projects/LENS/. ERA5 reanalysis products were downloaded from the Climate Data Store https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview. The model simulations will be made available upon request to the corresponding author.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgments. This research is based on work supported by the U.S. Department of Energy (DOE), Office of Science, Biological and Environmental Research as part of the Regional and Global Model Analysis (RGMA) program. Jan T. M. Lenaerts acknowledges support from the National Aeronautics and Space Administration (NASA) through project 80NSSC18K1025. Jesse Nusbaumer was supported by the NASA Post-doctoral Program (NPP) fellowship. The Pacific Northwest National Laboratory (PNNL) is operated for DOE by Battelle Memorial Institute under contract DE-AC05-76RLO1830. The CESM project is supported by the National Science Foundation and the DOE Office of Science. We would like to acknowledge high-performance computing support from Yellowstone (ark:/85065/d7wd3xhc) provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation.

References

Agosta, C., Fettweis, X., and Datta, R.: Evaluation of the CMIP5 models in the aim of regional modelling of the Antarctic surface mass balance, The Cryosphere, 9, 2311-2321, https://doi.org/10.5194/tc-9-2311-2015, 2015.

Bader, J., Flügge, M., Kvamstø, N. G., Mesquita, M. D. S., and A. Voigt, A.: Atmospheric winter response to a projected future Antarctic sea-ice reduction: A dynamical analysis. Climate Dyn., 40, 2707–2718, doi:https://doi.org/10.1007/s00382-012-1507-9, 2013.

Bailey AR, Singh HA, Nusbaumer J. "Evaluating a Moist Isentropic Framework for Poleward Moisture Transport: Implications for Water Isotopes over Antarctica", Geophysical Research Letters, 2019, 46 (13), pp 7819-7827, doi: 10.1029/2019GL082965.

Behrangi, A., Christensen, M., Richardson, M., Lebsock, M., Stephens, G., Huffman, G. J., Bolvin, D., Adler, R. F., Gardner, A., Lambrigtsen, B., and Fetzer, E.: Status of high-latitude precipitation estimates from observations and reanalyses, J. Geophys. Res. Atmos., 121, 4468– 4486, doi:10.1002/2015JD024546, 2016.

Deleted: 10.1002/2015JD024546

Bracegirdle, T. J., Stephenson, D. B., Turner, J., and Phillips, T.: The importance of sea ice area biases in 21st century multimodel projections of Antarctic temperature and precipitation. Geophys. Res. Lett. 42, 10,832–810,839, 2015.

Bromwich, D. H., Nicolas, J. P., and Monaghan, A. J.: An Assessment of Precipitation Changes over Antarctica and the Southern Ocean since 1989 in Contemporary Global Reanalyses. J. Climate, 24, 4189–4209, https://doi.org/10.1175/2011JCLI4074.1, 2011.

Buizert, C., Sigl, M., Severi, M., Markle, B., Wettstein, J., McConnell, J., Pedro, J., Sodemann, H., Goto-Azuma, K.,;Kawamura, K., Fujita, S., Motoyama, H., Hirabayashi, M., Uemura, R., Stenni, B., Parrenin, F., He, F., Fudge, and T.J., Steig, E.J. : Abrupt ice-age shifts in southern westerly winds and Antarctic climate forced from the north, Nature 563: 681- 685, 2018.

Delaygue, G., Masson, V., Jouzel, J., Koster, R. D., and Healy, R. J.: The origin of Antarctic precipitation: A modelling approach, Tellus, Ser. B, 52, 19– 36, 2000.

Ding, Q., Steig, E. J., Battisti, D. S., and Wallace, J. M.: Influence of the Tropics on the Southern Annular Mode. J. Climate, 25, 6330–6348, https://doi.org/10.1175/JCLI-D-11-00523.1, 2012.

Frieler, K., Clark, P. U., He, F., Buizert, C., Reese, R., Ligtenberg, S. R. M., van den Broeke, M. R., Winkelmann, R., and Levermann, A.: Consistent evidence of increasing Antarctic accumulation with warming, Nature Climate Change, 5, 348–352, https://doi.org/10.1038/nclimate2574, 2015.

Fyke, J., Lenaerts, J., and Wang, H.: Basin-scale heterogeneity in Antarctic precipitation and its impact on surface mass variability. The Cryosphere, 11(6), 2595-2609, 2017.

Grieger, J., Leckebusch, G.C. and Ulbrich, U.: Net precipitation of Antarctica: thermodynamical and dynamical parts of the climate change signal. Journal of Climate, 29, 907-924, 2016.

Helsen, M. M., van de Wal, R. S. W., and den Broeke, M. R. V.: The isotopic composition of present-day Antarctic snow in a Lagrangian atmospheric simulation, J. Clim., 20, 739– 756, 2007.

Hobbs, W.R., Massom, R., Stammerjohn, S., Reid, P., Williams, G. and Meier, W., 2016. A review of recent changes in Southern Ocean sea ice, their drivers and forcings. Global and Planetary Change, 143, 228-250, 2016.

Holland, M. and Raphael, M.: Twentieth century simulation of the southern hemisphere climate in coupled models, Part II: sea ice conditions and variability, Clim. Dynam., 26, 229–245, doi:10.1007/s00382-005-0087-3, 2006.

Hosking, J.S., Orr, A., Marshall, G.J., Turner, J., and Phillips, T.: The influence of the Amundsen–Bellingshausen Seas Low on the climate of West Antarctica and its representation in coupled climate model simulations. J. Climate, 26, 6633–6648, https://doi.org/10.1175/JCLI-D-12-00813.1, 2013.

Hurrell, J. W., Holland, M., Gent, P., Ghan, S., Kay, J., Kushner, P., Lamarque, J.-F., Large, W., Lawrence, D., Lindsay, K., Lipscomb, W., Long, M., Mahowald, N., Marsh, D., Neale, R., Rasch, P., Vavrus, S., Vertenstein, M., Bader, D., Collins, W., Hack, J., Kiehl, J., and Marshall, S.: The Community Earth System Model: A framework for collaborative research, Bulletin of the American Meteorological Society, 94, 1339–1360, doi:10.1175/BAMS-D-12-00121, 2013.

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J. M., Bates, S. C., Danabasoglu, G., Edwards, J., Holland, M., Kushner, P., Lamarque, J.-F., Lawrence, D., Lindsay, K., Middleton, A., Munoz, E., Neale, R., Oleson, K., Polvani, L., and Vertenstein, M.: The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability, B. Am. Meteorol. Soc., 96, 1333–1349, https://doi.org/10.1175/BAMS-D-13-00255.1, 2015.

Kennicutt, M.C., Chown, S.L., Cassano, J.J., Liggett, D., Peck, L.S., Massom, R., Rintoul, S.R., Storey, J., Vaughan, D.G., Wilson, T.J. and Allison, I.: A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond. Antarctic Science, 27, 3–18. http://dx.doi.org/10.1017/S0954102014000674, 2015.

Kidston, J., Taschetto, A.S., Thompson, D.W.J., England, M.H.: The influence of Southern Hemisphere sea-ice extent on the latitude of the mid-latitude jet stream. Geophys. Res. Lett., 38, L15804, http://dx.doi.org/10.1029/2011gl048056, 2011.

Kittel, C., Amory, C., Agosta, C., Delhasse, A., Doutreloup, S., Huot, P.-V., Wyard, C., Fichefet, T., and Fettweis, X.: Sensitivity of the current Antarctic surface mass balance to sea surface conditions using MAR, The Cryosphere, 12, 3827–3839, https://doi.org/10.5194/tc-12-3827-2018, 2018.

Koster, R., Jouzel, J., Suozzo, R., Russell, G., Broecker, W., Rind, D., and Eagleson, P.: Global sources of local precipitation as determined by the NASA/GISS GCM. Geophysical Research Letters, 13, 121-124, 1986.

Krinner, G., Largeron, C., Ménégoz, M., Agosta, C., and Brutel-Vuilmet, C.: Oceanic forcing of Antarctic climate change: A study using a stretched-grid Atmospheric General Circulation Model. J. Climate, 27, 5786–5800, https://doi.org/10.1175/JCLI-D-13-00367.1, 2014.

Lefebvre, W. and Goosse, H.: An analysis of the atmospheric processes driving the large-scale winter sea ice variability in the Southern Ocean, J. Geophys. Res., 113, doi:10.1029/2006JC004032, 2008.

Lenaerts, J.T.M., Van den Broeke, M.R., Van de Berg, W.J., Van Meijgaard, E., and Kuipers Munneke, P.: A new, high-resolution surface mass balance map of Antarctica (1979–2010) based on regional atmospheric climate modeling. Geophysical Research Letters, 39, L04501, doi:10.1029/2011GL050713, 2012.

Lenaerts, J. T. M., Vizcaino, M., Fyke, J., van Kampenhout, L., and van den Broeke, M. R.: Present-day and future Antarctic ice sheet climate and surface mass balance in the Community Earth System Model, Clim. Dynam., 47, 1–15, https://doi.org/10.1007/s00382-015-2907-4, 2016.

Lenaerts, J. T. M., Fyke, J., and Medley, B.: The signature of ozone depletion in recent Antarctic precipitation change: A study with the Community Earth System Model. Geophysical Research Letters, 45, 12,931–12,939. https://doi.org/10.1029/2018GL078608, 2018.

Masson-Delmotte, V., Buiron, D., Ekaykin, A., Frezzotti, M., Gallée, H., Jouzel, J., Krin- ner, G., Landais, A., Motoyama, A., Oerter, H., Pol, K., Pollard, D., Ritz, C., Schlosser, E., Sime, L. C., Sodemann, H., Stenni, B., Uemura R., and Vimeux, F.: A comparison of the present and last interglacial periods in six Antarctic ice cores, Clim. Past, 7, 397-423, 2011.

Medley, B., and Thomas, E. R.: Increased snowfall over the Antarctic Ice Sheet mitigated 20th century sea-level rise. Nature Climate Change, 9, 34-39. https://doi.org/10.1038/s41558-018-0356-x, 2019.

Meehl, G.A., Arblaster, J.M., Bitz, C.M., Chung, C.T. and Teng, H.: Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. Nature Geoscience, 9, 590–595. doi:10.1038/ngeo2751, 2016.

Menéndez, C. G., Serafini, V., and Le Treut, H., 1999: The effect of sea-ice on the transient atmospheric eddies of the Southern Hemisphere. Climate Dyn., 15, 659–671, 1999.

Neale, R.B., Chen, C.C., Gettelman, A., Lauritzen, P.H., Park, S., Williamson, D.L., Conley, A.J., Garcia, R., Kinnison, D., Lamarque, J.F. and Marsh, D.: Description of the NCAR community atmosphere model (CAM 5.0). NCAR Tech. Note TN-486, 274 pp, 2012.

Noone, D. C., and Simmonds, I.: Annular variations in moisture transport mechanisms and the abundance of $\delta^{18}O$ in Antarctic snow, Journal of Geophysical Research: Atmosphere, 107(D24), 4742, doi:10.1029/2002JD002262, 2002.

Noone, D. C., and Simmonds, I.: Sea ice control of water isotope transport to Antarctica and implications for ice core interpretation, Journal of Geophysical Research: Atmospheres, 109, D7, 2004.

Nusbaumer, J., and Noone, D.C.: Numerical Evaluation of the Modern and Future Origins of Atmospheric River Moisture Over the West Coast of the United States, Journal of Geophysical Research: Atmospheres, 123(12), 6423-6442, doi: 10.1029/2017JD028081, 2018.

Oleson, K. W., Lawrence, D. M., Bonan, G. B., Flanner, M. G., Kluzek, E., Lawrence, P. J., Levis, S., Swenson, S. C., Thorn- ton, P. E., Dai, A., Decker, M., Dickinson, R., Feddema, J., Heald, C. L., Hoffman, F., Lamarque, J., Mahowald, N., Niu, G., Qian, T., Randerson, J., Running, S., Sakaguchi, K., Slater, A., Stockli, R., Wang, A., Yang, Z., Zeng, X., and Zeng, X.: Technical Description of version 4.0 of the Community Land Model (CLM), NCAR Technical Note NCAR/TN-478+STR, doi:10.5065/D6FB50WZ, 2010.

Palerme, C., Genthon, C., Claud, C., Kay, J. E., Wood, N. B., and L'Ecuyer, T.: Evaluation of current and projected Antarctic precipitation in CMIP5 models, Clim. Dynam., 48: 225, https://doi.org/10.1007/s00382-016-3071-1, 2017.

Papritz, L., Pfahl, S., Rudeva, I., Simmonds, I., Sodemann, H., and Wernli, H.: The role of extratropical cyclones and fronts for Southern Ocean freshwater fluxes, J. Climate 27: 6205–6224, doi:10.1175/JCLI-D-13-00409.1, 2014.

Shepherd, A., Ivins, E. R., A, G., Barletta, V. R., Bentley, M. J., Bettadpur, S., Briggs, K. H., Bromwich, D. H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M. A., Lenaerts, J. T. M., Li, J., Ligtenberg, S. R. M., Luckman, A., Luthcke, S. B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J. P., Paden, J., Payne, A. J., Pritchard, H., Rignot, E., Rott, H., Sørensen, L. S., Scambos, T. A., Scheuchl, B., Schrama, E. J. O., Smith, B., Sundal, A. V., van Angelen, J. H., van de Berg, W. J., van den Broeke, M. R., Vaughan, D. G., Velicogna, I., Wahr, J., Whitehouse, P. L., Wingham, D. J., Yi, D., Young, D., and Zwally, H. J.: A reconciled estimate of ice-sheet mass balance, Science, 338, 1183–1189, https://doi.org/10.1126/science.1228102, 2012.

Singh, H. A., Bitz, C. M., Nusbaumer, J., and Noone, D. C.: A mathematical framework for analysis of water tracers: Part 1: Development of theory and application to the preindustrial mean state, J. Adv. Model. Earth Syst., 8, 991–1013, doi: 10.1002/2016MS000649, 2016a.

Deleted: , 1–15

Deleted: 2016

Singh, H. A., Bitz, C. M., Donohoe, A., Nusbaumer, J., and Noone, D. C.: A Mathematical Framework for Analysis of Water Tracers. Part II: Understanding Large-Scale Perturbations in the Hydrological Cycle due to CO_2 Doubling, J. Climate, 10.1175/JCLI-D-16-0293.1, 29, 6765-6782, 2016b.

Singh, H. A., Bitz, C. M., Donohoe, A., and Rasch, P. J.: A source–receptor perspective on the polar hydrologic cycle: Sources, seasonality, and Arctic–Antarctic parity in the hydrologic cycle response to CO_2 doubling, J. Climate, 30, 9999-10017, 2017.

Smith, D. M., Dunstone, N. J., Scaife, A. A., Fiedler, E. K., Copsey, D., and Hardiman, S. C.: Atmospheric response to Arctic and Antarctic sea ice: The importance of ocean–atmosphere coupling and the background state. J. Climate, 30, 4547–4565, https://doi.org/10.1175/JCLI-D-16-0564.1, 2017.

Sodemann, H., Schwierz, C., and Wernli, H.: Interannual variability of Greenland winter precipitation sources: Lagrangian moisture diagnostic and North Atlantic Oscillation influence, J. Geophys. Res., 113, D03107, doi:10.1029/2007JD008503, 2008.

Sodemann, H., and Stohl, A.: Asymmetries in the moisture origin of Antarctic precipitation. Geophys. Res. Lett., 36, L22803, doi:10.1029/2009GL040242, 2009.

Stohl, A., and Sodemann, H.: Characteristics of atmospheric transport into the Antarctic troposphere, J. Geophys. Res., 115, D02305, doi:10.1029/2009JD012536, 2010.

Tabor, C., Otto-bliesner, B., Brady, E. C., Nusbaumer, J., Zhu, J., Erb, M. P., Wong, T. E., Liu, Z., and Noone, D. C.: Interpreting precession-driven $\delta^{18}O$ variability in the South Asian monsoon region, 123(11), 5927-5946, doi: 10.1029/2018JD028424., 2018.

Thomas, E. R., van Wessem, J. M., Roberts, J., Isaksson, E., Schlosser, E., Fudge, T. J., Vallelonga, P., Medley, B., Lenaerts, J., Bertler, N., van den Broeke, M. R., Dixon, D. A., Frezzotti, M., Stenni, B., Curran, M., and Ekaykin, A. A.: Regional Antarctic snow accumulation over the past 1000 years, Clim. Past, 13, 1491-1513, https://doi.org/10.5194/cp-13-1491-2017, 2017.

Tietäväinen, H., and Vihma, T.: Atmospheric moisture budget over Antarctica and the Southern Ocean based on the ERA-40 reanalysis. Int. J. Climatol., 28, 1977–1995, 2008.

Turner, J. and Overland, J.: Contrasting climate change in the two polar regions", Polar Research, 28, 146-164. doi:10.3402/polar.v28i2.6120, 2009.

Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J., Hosking, J. S.: An initial assessment of Antarctic sea ice extent in the CMIP5 models. J. Clim., 26, 1473–1484. http://dx.doi.org/10.1175/Jcli-D-12-00068.1, 2013a.

Turner, J., Maksym, T., Phillips, T., Marshall, G. J., and Meredith, M. P.: The impacts of changes in sea ice advance on the large winter warming on the western Antarctic Peninsula. Int. J. Climatol., 33, 852–861, doi:https://doi.org/10.1002/joc.3474, 2013b.

Moved (insertion) [8]

Wang, Y., Sodemann, H., Hou, S., Masson-Delmotte, V. Jouzel, J. and Pang, H., 2013: Snow accumulation and its moisture origin over Dome Argus, Antarctica. Clim. Dyn., 40:731-742, doi: 10.1007/s00382-012-1398-9.

Weijer, W., Veneziani, M., Stössel, A., Hecht, M. W., Jeffery, N., Jonko, A., Hodos, T., and Wang, H.: Local atmospheric response to an open-ocean polynya in a high-resolution climate model. J. Climate, 30, 1629–1641, https://doi.org/10.1175/JCLI-D-16-0120.1, 2017.

Zwally, H.J., Li, J., Robbins, J.W., Saba, J.L., Yi, D., Brenner, A.C. and Zwally, C.H.J.: Mass gains of the Antarctic ice sheet exceed losses. J. Glaciol, 61, 1019-1036, 2015.

Deleted: H., Rasch, P. J., Easter, R. C., Singh, B., Zhang, R., Ma, P.-L., Qian, Y., Ghan, S. J., and Beagley, N. Using an explicit emission tagging method in global modeling of source-receptor relationships for black carbon in the Arctic: Variations, sources, and transport pathways. J.

Moved up [8]: Geophys. Res

Deleted: . Atmosphere, 119, 12888–12909, 2014

Deleted: Winkelmann, R., Levermann, A., Martin, M. A., and Frieler, K.: Increased future ice discharge from Antarctica owing to higher snowfall, Nature, 492, 239–242, doi:10.1038/nature11616, 2012. ¶

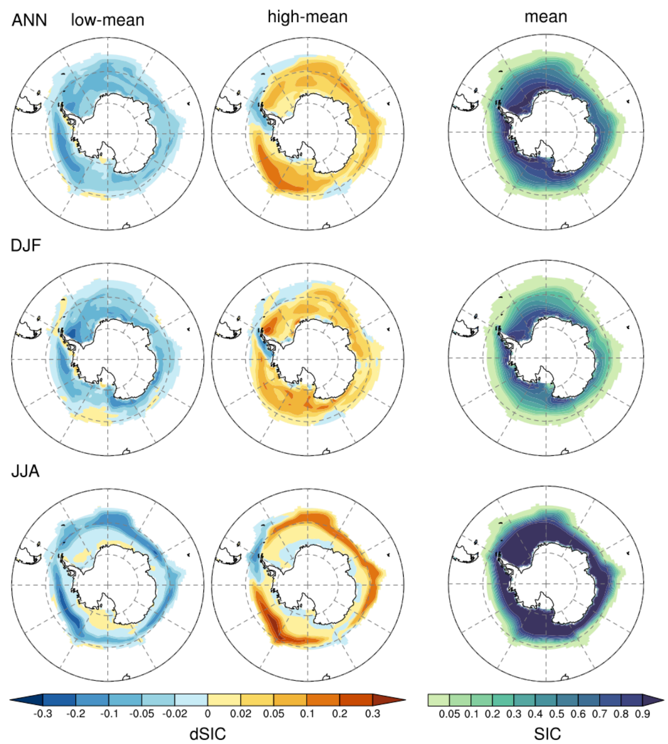
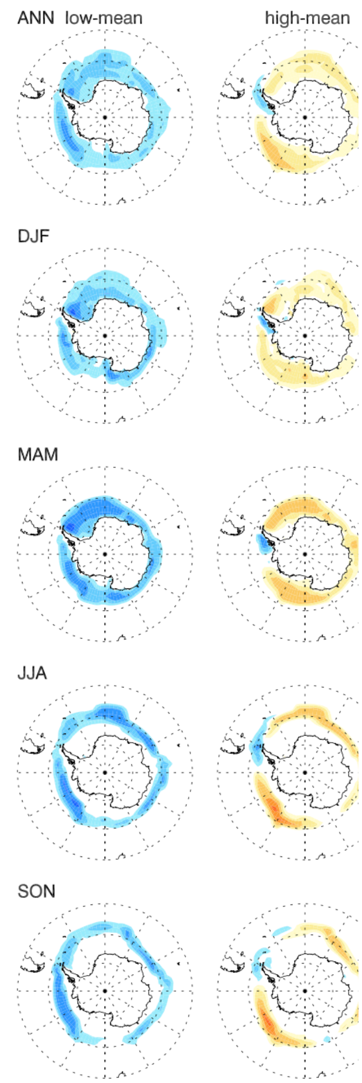


Figure 1: the anomalies of the two SIC composites ("low" and "high") with respect to the annual and seasonal mean SIC ("mean" in the right-most column).



Deleted:

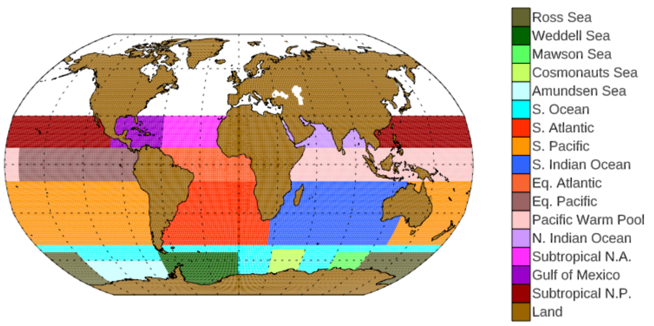
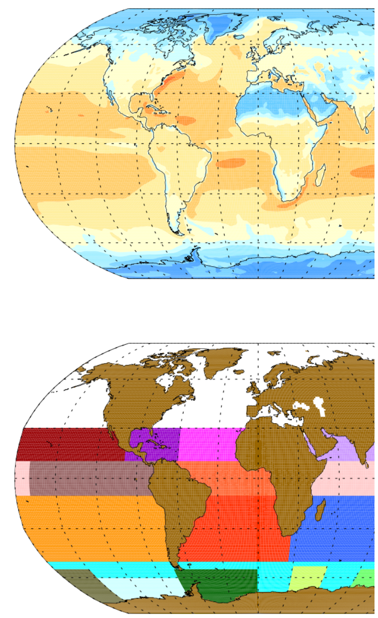


Figure 2: Tagged water source regions that are potentially important for Antarctic precipitation, including all major tropical/subtropical and mid-latitude ocean basins (Subtropical N. Pacific, Subtropical N. Atlantic, Gulf of Mexico, Pacific Warm Pool, Equatorial Pacific, Equatorial Atlantic, N. Indian Ocean, S. Indian Ocean, S. Pacific, S. Atlantic, and S. Ocean), five finer sectors (Amundsen Sea, Cosmonauts Sea, Mawson Sea, Weddell Sea, and Ross Sea) in the Southern Ocean, and land (all continents). All remaining oceanic areas (white) are also tagged.



Deleted:
Figure 2: (top) Annual mean net evaporation/sublimation (positive values) at the surface. (bottom)

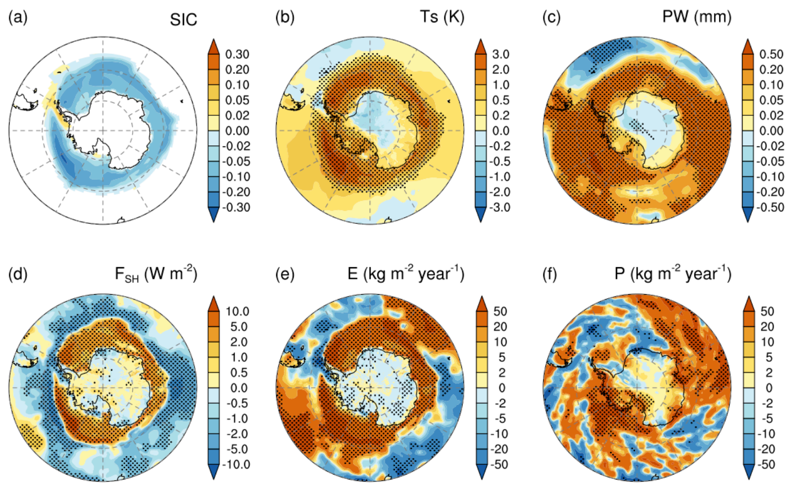
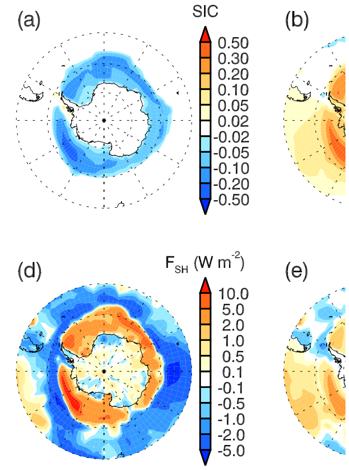


Figure 3: Annual mean differences in (a) sea ice concentrations (SIC), (b) surface temperature (Ts), (c) total precipitable water (PW), (d) surface sensible heat flux (F_{sh}), (e) surface evaporation/sublimation (E), and (f) surface precipitation (P) between the "low" and "high" SIC cases. Stippling on the maps indicates that the differences are statistically significant at the 90% confidence level based on Student's *t*-test.



Deleted:

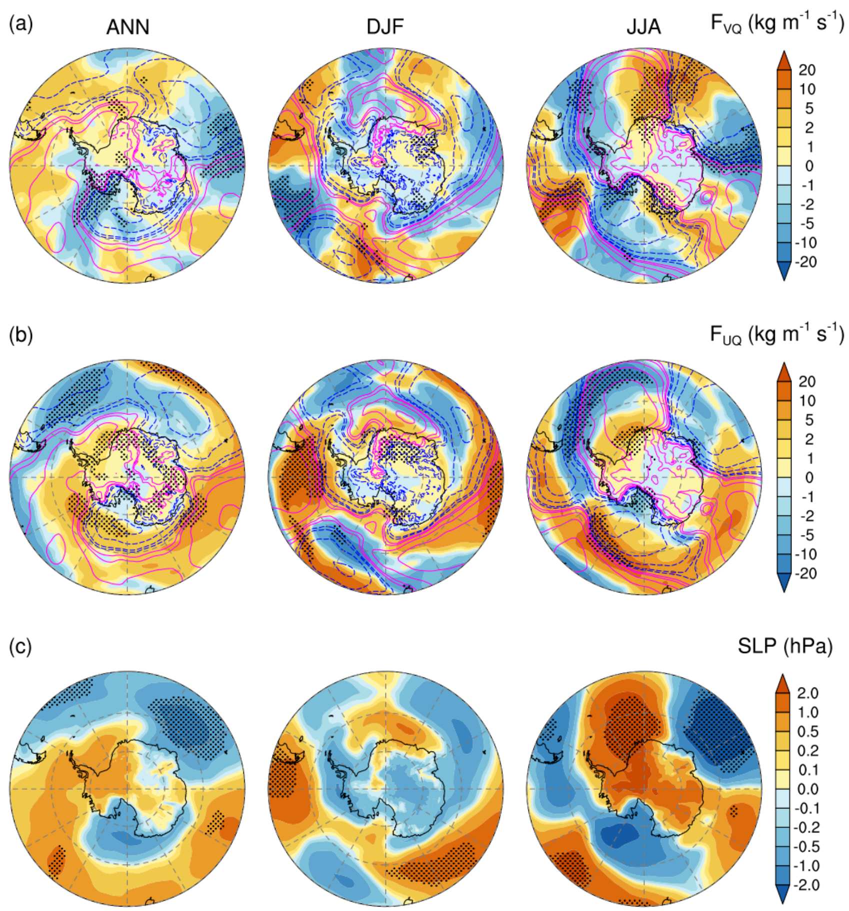


Figure 4: Spatial distribution of differences ("low" minus "high") in annual (left) and seasonal (DJF and JJA) mean column-integrated (a) meridional and (b) zonal moisture flux, and (c) sea level pressure (SLP). The superimposed contour lines represent SLP differences (magenta for positive and blue for negative with the same intervals as in the SLP color bar in hPa). Stippling on the maps indicates that the differences are statistically significant at the 90% confidence level based on Student's *t*-test.

Deleted: Page Break

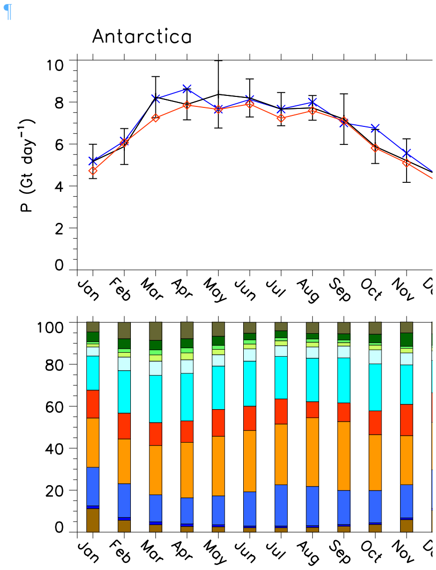


Figure 4

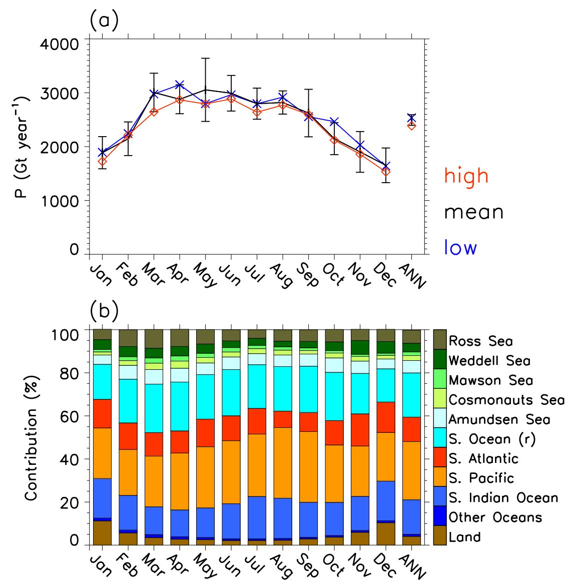
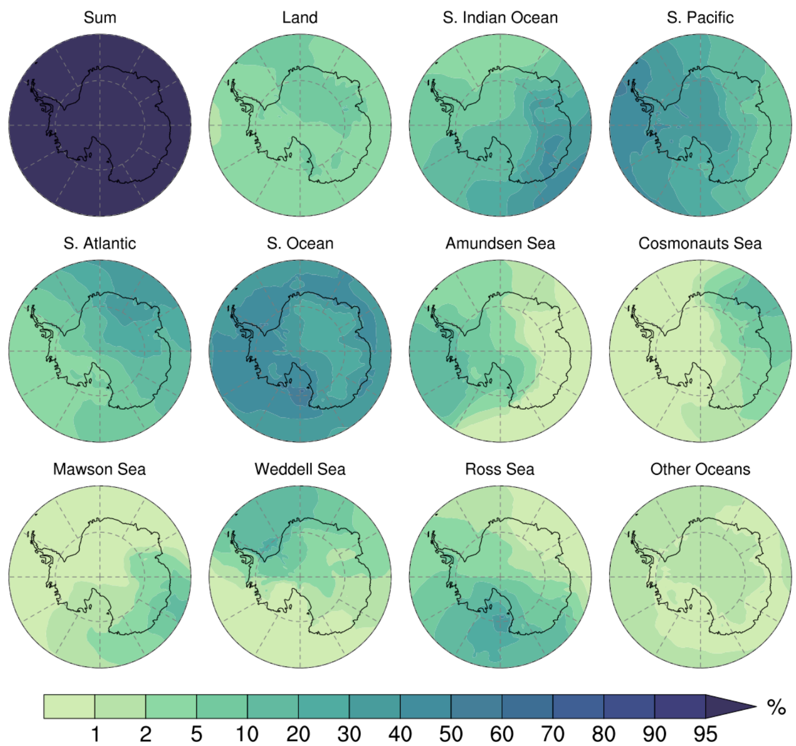


Figure 5: seasonal variation (January-December) and annual mean (ANN) precipitation over Antarctica in the three simulations (top) and the corresponding fractional contributions by the tagged source regions from the "mean" (bottom). Error bars represent one standard deviation of corresponding results from 10 individual years of the "mean" case. Note that the S. Ocean (r) tag plus the five sub-sector tags represent the entire Southern Ocean. Contributions from tropical oceans and northern hemisphere oceans are combined to the "Other Oceans".



Deleted: ¶
¶

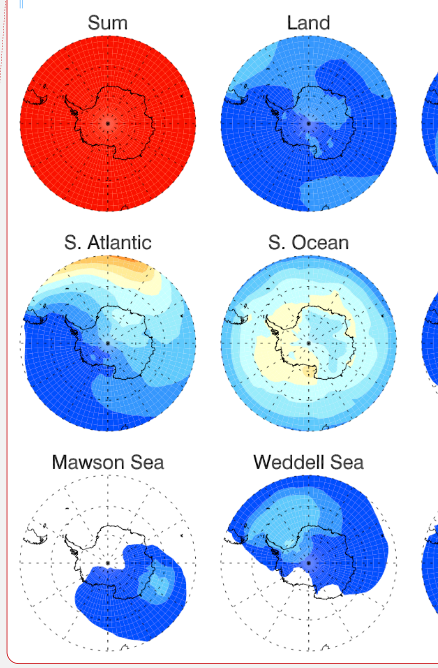


Figure 6: Spatial distribution of fractional contribution (%) to annual mean precipitation at the surface from individual source regions in the "mean" case. The "Sum" (upper-left panel) represents contributions from the five major source regions, including Land, S. Indian Ocean, S. Pacific, S. Atlantic and S. Ocean. Contributions from tropical oceans and northern hemisphere oceans are combined to the "Other Oceans".

Deleted: 5

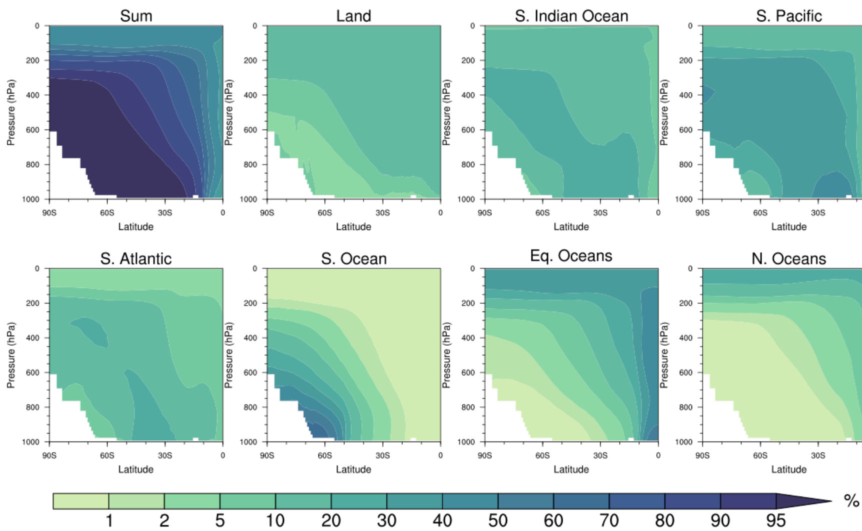
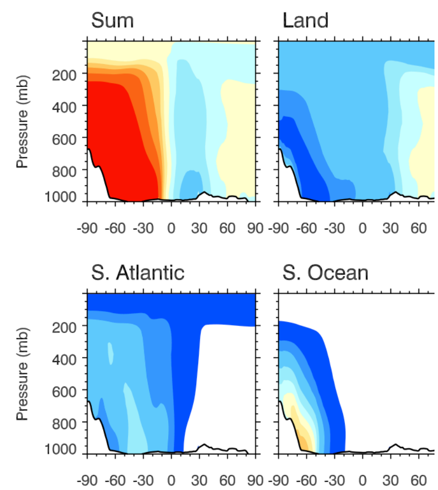


Figure 7: Vertical distribution of fractional contribution (%) to annual and zonal mean water vapor mixing ratio from individual source regions in the "mean" case. The "Sum" (upper-left panel) represents contributions from the five major source regions, including Land, S. Indian Ocean, S. Pacific, S. Atlantic and S. Ocean. The S. Ocean tag here includes all six sub-sectors. The Eq. Oceans includes the three equatorial ocean tags, and the N. Oceans includes the remaining ocean tags in the northern hemisphere.

Deleted: ¶

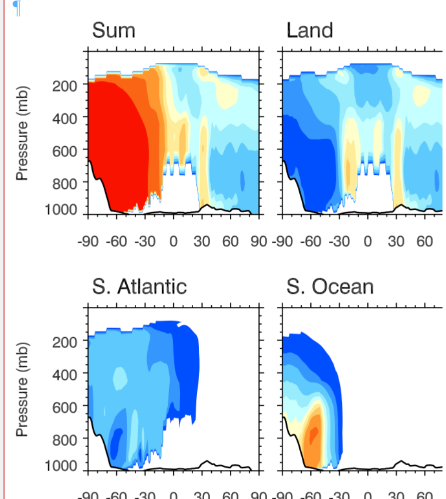


Deleted: 6

Deleted: ¶

Page Break

¶



¶

Figure 7: Same as Fig. 6 but for fractional contributions to zonal mean ice water mixing ratio.¶

Page Break

¶

¶

¶

... [5]

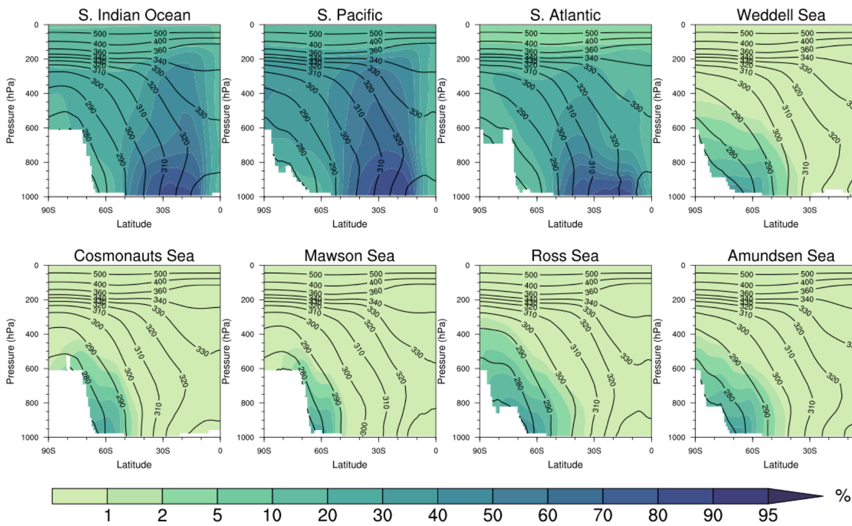


Figure 8: Vertical distribution of fractional contribution (%) to annual and zonal mean water vapor mixing ratio from individual source regions in the "mean" case. Contour lines are zonal mean equivalent potential temperature (θ_e). Zonal mean in each panel is taken along the corresponding longitude band of the source region.

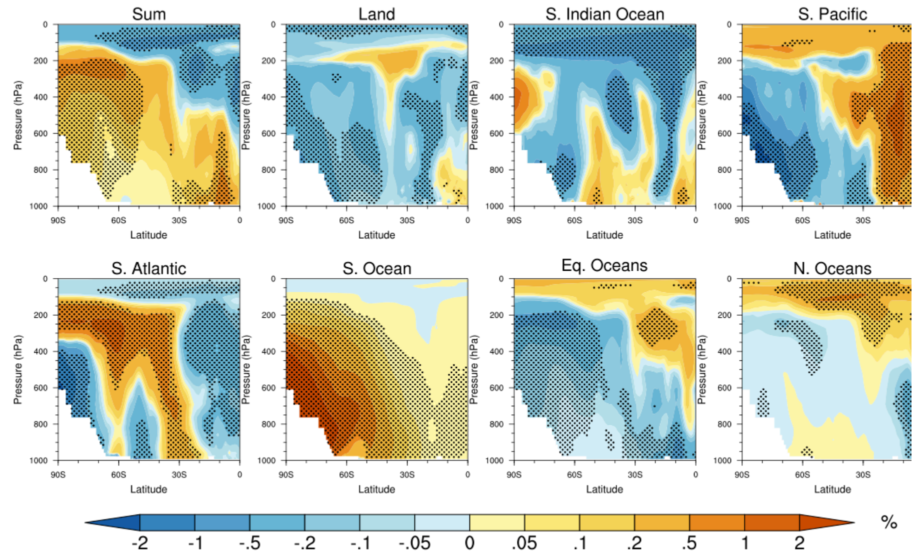


Figure 9: Vertical distribution of differences in fractional contribution to annual and zonal mean water vapor mixing ratio between the "low" and "high" SIC cases. Note that the contour intervals are non-uniform. Stippling indicates that the differences are statistically significant at the 90% confidence level based on Student's *t*-test.

Deleted: Page Break

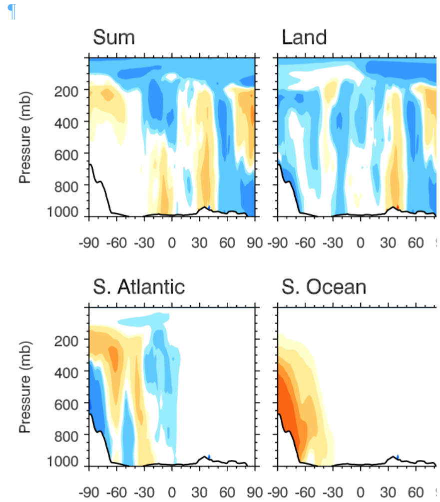


Figure 9: Same as Fig. 8 but for differences in fractional contribution to annual and zonal mean water vapor mixing ratio between the "low" and "high" SIC cases. Note that the contour intervals are non-uniform.

Page Break

... [6]