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Key Points:

- Sea ice biases dominate model uncertainty in CMIP5 precipitation projections
- Ratio of precipitation change to temperature change sensitive to sea ice bias
- Significant potential for improved precision in Antarctic climate projections

Supporting Information:

- Figures S1–S4 and Table S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4

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The importance of sea ice area biases in 21st century multimodel projections of Antarctic temperature and precipitation

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Abstract Climate models exhibit large biases in sea ice area (SIA) in their historical simulations. This study explores the impacts of these biases on multimodel uncertainty in Coupled Model Intercomparison Project phase 5 (CMIP5) ensemble projections of 21st century change in Antarctic surface temperature, net precipitation, and SIA. The analysis is based on time slice climatologies in the Representative Concentration Pathway 8.5 future scenario (2070–2099) and historical (1970–1999) simulations across 37 different CMIP5 models. Projected changes in net precipitation, temperature, and SIA are found to be strongly associated with simulated historical mean SIA (e.g., cross-model correlations of $r = 0.77$, 0.71, and −0.85, respectively). Furthermore, historical SIA bias is found to have a large impact on the simulated ratio between net precipitation response and temperature response. This ratio is smaller in models with smaller-than-observed SIA. These strong emergent relationships on SIA bias could, if found to be physically robust, be exploited to give more precise climate projections for Antarctica.

1. Introduction

Producing reliable projections of future climate change over the Antarctic continent is important for impact assessments relating to issues such as global sea level change and regional ecosystem change [*Kennicutt et al.*, 2014]. Increased precipitation (and resulting accumulation) under warming conditions is a robust feature of climate model simulations of Antarctic climate change, with the potential to offset projected future global sea level rise by altering the surface mass balance (SMB) of the Antarctic ice sheet [*Krinner et al.*, 2014; *Frieler et al.*, 2015]. *Frieler et al.* [2015] presented evidence for a consistent linear relationship between Antarctic accumulation and temperature changes both in paleoclimate reconstructions of past change and projections of future change. Such a relationship is potentially valuable since simulated and recorded Antarctic temperature change can be used to infer accumulation change, which is challenging to accurately simulate owing to the complex orography of parts of Antarctica. However, there is large uncertainty in Antarctic climate projections from global climate models (e.g., see Figure 1), which cascades down to regional assessments of 21st century SMB change under warming scenarios.

At high latitudes uncertainty in climate model projections of regional change is, at many locations, strongly tied to sea ice [*Raisanen*, 2007; *Bracegirdle and Stephenson*, 2013]. This is particularly clear at locations where atmospheric warming occurs in response to the transition from ice cover to open ocean. Over continental Antarctica, the nonlocal effect of sea ice change is also important and climate model sensitivity experiments show warming and increased precipitation in response to sea ice retreat [*Simmonds and Budd*, 1991; *Rind et al.*, 1995; *Bromwich et al.*, 1998; *Weatherly*, 2004; *Krinner et al.*, 2014]. Many of the current generation of global coupled climate models (specifically the Coupled Model Intercomparison Project phase 5 (CMIP5) multimodel ensemble (MME) [*Taylor et al.*, 2012]) exhibit large biases in Southern Hemisphere (SH) sea ice extent, with some simulating less than one third of the observed annual mean climatology [*Turner et al.*, 2013]. Therefore, there is an urgent need to assess the impacts of biases in simulated SH sea ice on future projections in MMEs such as CMIP5, which would potentially contribute to reducing uncertainty in climate change estimates derived from existing and future MMEs.

To address this issue, this study focuses on assessing the role of SH sea ice area biases in the CMIP5 MME on model uncertainty in projections of 21st century Antarctic precipitation change and how this relates to projections of Antarctic temperature and sea ice itself.

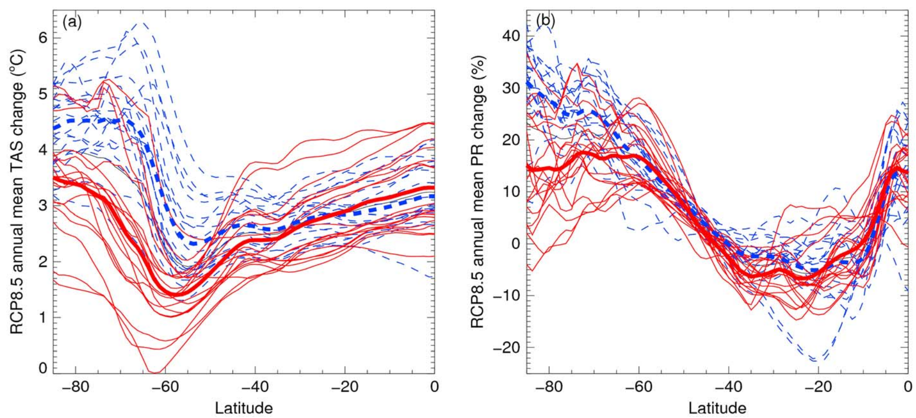

Figure 1. Projected 21st century change in (a) zonal mean annual mean TAS and (b) PR following the RCP8.5 scenario. The thin lines show output from individual CMIP5 models. The dashed blue lines identify a subset with more than the CMIP5 median historical SIA, and the solid red lines identify models with historical SIA below the median (the multimodel mean of each subset is shown by the thick lines).

2. Climate Model Data

The required data were available for 37 CMIP5 models (Table S1 in the supporting information). Output from the historical and Representative Concentration Pathway (RCP) 8.5 experiments was assessed. The main reason for focusing on the high emissions RCP8.5 scenario was that the intermodel differences in forced response will emerge most clearly from internal climate variability. However, to assess the sensitivity of the results to the choice of emissions scenario, the key analysis was also repeated using the medium emissions RCP4.5 stabilization scenario.

In this paper "historical" refers to time slice climatologies from the CMIP5 historical simulations over the period 1970–1999. Projections of change over the 21st century are defined as the difference between late 21st century time slice climatologies in the RCP simulations (2070–2099) and their respective historical time slice climatologies. The following variables were investigated: surface air temperature (TAS), precipitation rate (PR), precipitation minus evaporation (PME, also referred to as net precipitation), and Southern Hemisphere sea ice area (SIA). The CMIP5 variable "evaporation" used here includes the conversion of both liquid and solid water phases into water vapor. More detailed information on temporal and spatial averaging and interpolation are provided in the supporting information.

3. Results

Climate model projections of Antarctic temperature and precipitation show qualitatively similar increases, but across different models there is large uncertainty in the magnitude of change. Some key features of projected 21st century change in annual mean surface temperature (denoted hereinafter as ΔTAS) and precipitation (ΔPR) are evident in Figure 1. The large intermodel spread across the CMIP5 models over Antarctica (south of ~60°S) is most notable, with ΔTAS ranging from near zero to approximately 6°C. Similarly, proportional PR change ranges from near zero to approximately 40%. Therefore, even under the high emissions RCP8.5 scenario, some models give almost no change. This raises the question of whether such negligible changes are realistic. A clue that the answer may lie in regional processes specific to high Southern latitudes is that the magnitude of simulated ΔSIA in a given model is not particularly strongly related to globally averaged surface warming ($r = -0.40$ across all 37 models). Indeed, the correlation between temperature change in the subtropics (0°S–30°S) and ΔSIA is even smaller at only $r = -0.16$.

As discussed in section 1, changes in sea ice area are known to have a significant impact on the atmosphere, and therefore, biases in sea ice are likely to have major implications for Antarctic climate projections (by "bias" we mean the difference between the time mean of a variable in historical model simulations and the time mean from observations). The array of scatterplots shown in Figure 2 shows that this is indeed the case for the CMIP5 ensemble. Intermodel differences in annual mean ΔSIA are highly correlated with intermodel differences in ΔPME_{Ant} and ΔTAS_{Ant} ($r = -0.92$ and -0.91, respectively), where the subscript "Ant" denotes

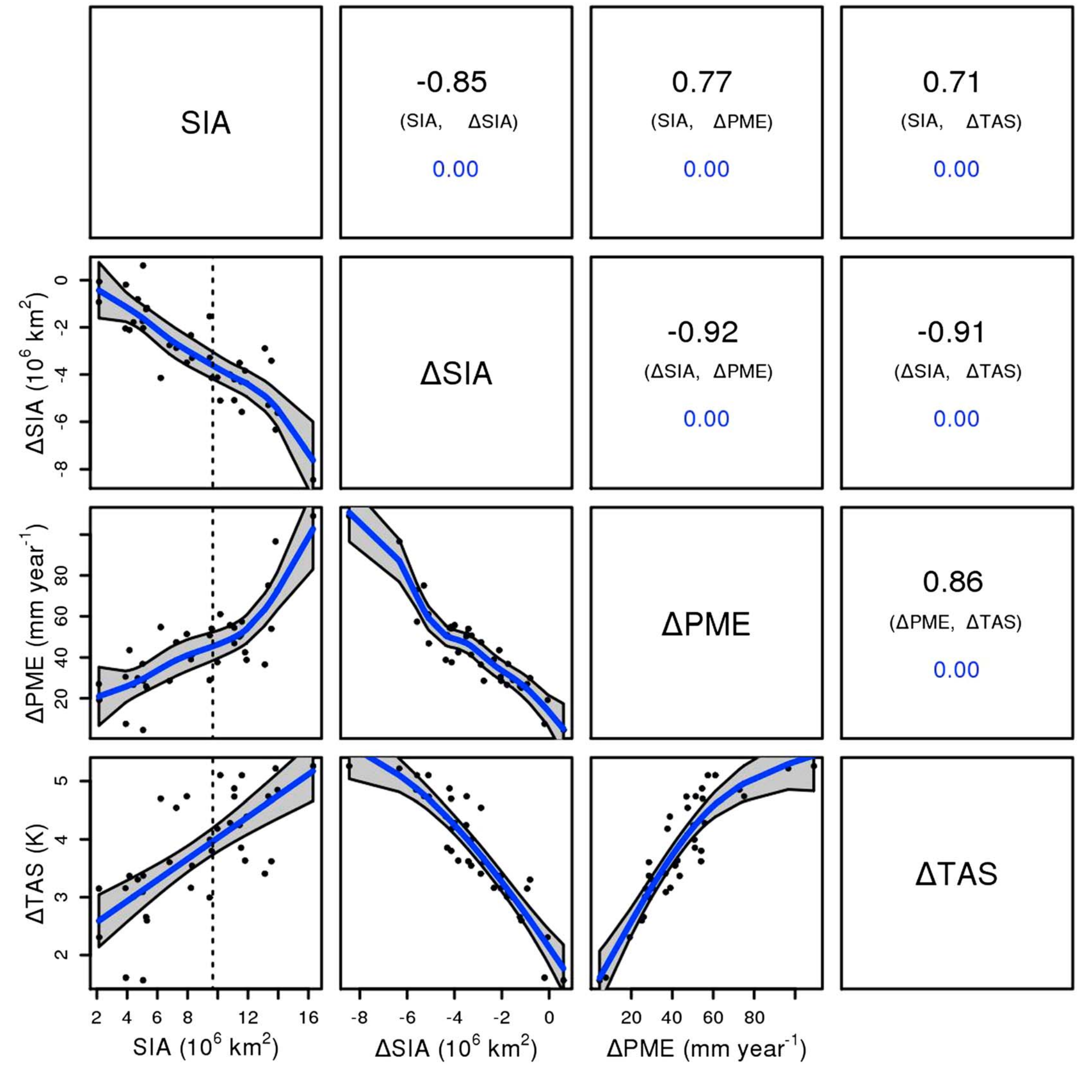

Figure 2. Array of scatterplots (pairs plot) showing the relationships between annual mean SIA, ΔSIA, ΔPME_{Ant}, and ΔTAS_{Ant} across the CMIP5 models, where each dot represents a different model. Smooth fits (blue curves) and 95% confidence intervals (grey shading) have been estimated using a Gaussian general additive model [*Scinocca et al.*, 2010]. The panels to the top right of the diagonal display the correlations (black text, with the correlated variables indicated in brackets) and *p* values (blue text) for a two-sided *t* test (using the *R* function "cor.test," which attempts to reject the null hypothesis that the test statistic $\sqrt{(n-2)r^2/(1-r^2)}$ is *t* distributed with *n*-2 degrees of freedom, where *n* is the sample size and *r* is the sample correlation). The correlation values relate to scatterplots at locations mirrored across the diagonal (e.g., the correlation value in the panel at the top right relates to the scatterplot at the bottom left). The dotted lines in the left column indicate the satellite-based estimate of historical annual mean SIA (1979–1999) from the NASA Bootstrap 2 sea ice concentration data set [*Comiso*, 2000].

spatial averages over the Antarctic continent. The fact that models with more warming and net precipitation increase also exhibit more sea ice retreat is not surprising, but the correlations are strong and this is important for considering the role of sea ice on model uncertainty. The use of a Gaussian general additive model to estimate smoothed fits in Figure 2 shows that the relationships are broadly either linear or near linear, thus justifying the use of correlation to quantify linear association. High correlations between ΔSIA and Antarctic warming were also identified by *Flato* [2004] in the CMIP1/CMIP2 MME (although net precipitation was not assessed), indicating some robustness across MMEs. *Flato* [2004] pointed out that in their analysis a linear regression fit to the relationship between sea ice extent change and Antarctic temperature change did not cross the origin, whereby some warming is still evident in models with negligible ice retreat. This can also be seen for the CMIP5 models (Figure 2), where approximately 2°C of warming occurs in models with near

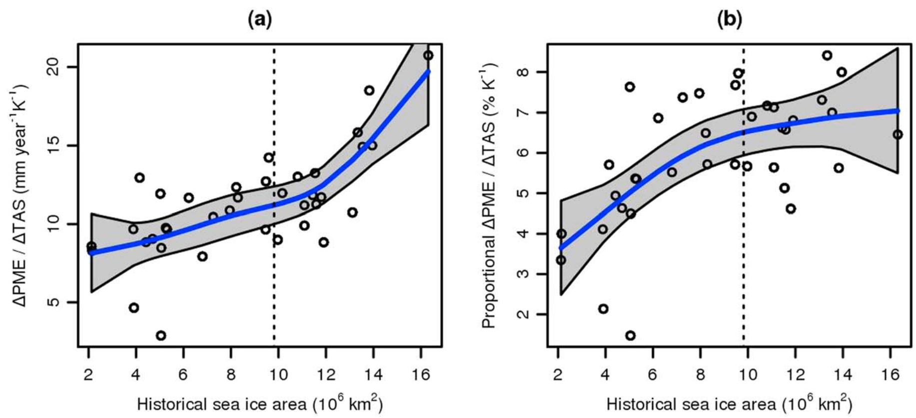

Figure 3. Scatterplots of historical SIA against the ratio of annual mean net precipitation change to annual mean temperature change with (a) showing a ratio based on absolute change in PME_{Ant} ($\Delta PME_{Ant}/\Delta TAS_{Ant}$) and (b) showing ratios based on PME_{Ant} change as a proportion of simulated historical mean PME_{Ant} ($100 \times (\Delta PME_{Ant}/PME_{Ant\_hist})/\Delta TAS_{Ant}$). The meaning of the various lines follows Figure 2.

zero ΔSIA. Interestingly, in contrast to this, the relationship between ΔSIA and ΔPME_{Ant} does approximately cross the origin. A consequence of this is that the ratio between net precipitation change and temperature change (i.e., $\Delta PME_{Ant}/\Delta TAS_{Ant}$) is smaller in models with small SIA values (Figure 3a). This appears to contradict the findings of *Krinner et al.* [2014], who found only weak warming in atmosphere-only simulations forced by greenhouse gas increases and with constant surface conditions (i.e., constant sea ice and sea surface temperature). However, a key difference between their study and this analysis is that CMIP5 models with negligible ΔSIA will still exhibit sea surface warming at lower latitudes which could potentially affect Antarctic temperature. Furthermore, different models may give different results from the model used by *Krinner et al.* [2014], who also appear not to have included 21st century recovery of stratospheric ozone. It would be of interest to determine the reasons for this apparent difference in future work.

The ratio of proportional Antarctic net precipitation change (i.e., change relative to simulated historical PME) to Antarctic temperature change is a key parameter in ice sheet modeling (referred to here as γ). Estimates of γ based on high-resolution modeling are given in chapter 13 of Working Group 1 of the fifth IPCC report [*Church et al.*, 2013] and range from 3.7% K^{-1} to 7% K^{-1}, with an estimate based on output from the CMIP3 models lying near the middle of this range (5.1 ± 1.5%K^{-1}) [*Gregory and Huybrechts*, 2006]. The best fit line in Figure 3b spans a similar range of values (with a mean of 5.9%K^{-1}). For the models with larger-than-observed SIA, γ appears relatively stable at an average of 6.6% K^{-1}. It is only models that simulate smaller historical SIA that give values at the lower end of the range. Therefore, a large part of the model uncertainty in γ can be traced to models with unrealistically small historical SIA. A key implication of this result is that the near-linear behavior of γ identified in paleoclimate records and simulations by *Frieler et al.* [2015] appears to be robust across most CMIP5 models apart from those with unrealistically small historical SIA.

With regard to projections of sea ice itself, it is found that simulated future change in annual mean sea ice area (ΔSIA) is strongly related to historical SIA ($r = -0.85$). This is higher than for the CMIP1/2 and CMIP3 MMEs, for which the only significant relationship found was for late summer in CMIP3 ($r = -0.83$) [*Flato*, 2004; *Arzel et al.*, 2006]. The major reason for this difference is the use of the high emissions RCP8.5 scenario, which gives higher correlations than the medium emissions RCP4.5 scenario ($r = -0.68$; see Figure S2), but other possible reasons are the absence of models with flux adjustments and the larger number of models in CMIP5 compared to earlier CMIPs.

The link between SIA and ΔSIA helps to explain why ΔPME_{Ant} and ΔTAS_{Ant} are strongly associated with simulated historical SIA across the models (correlations of $r = 0.77$ and 0.71, respectively) (Figure 2). Previous research also suggests that horizontal resolution could play a role in model uncertainty in ΔPME_{Ant}, whereby increased resolution leads to higher PME_{Ant} due to improved representation of orographic precipitation [*Genthon et al.*, 2009; *Frieler et al.*, 2015]. However, across the CMIP5 MME we found no correlation ($r = 0.03$) between horizontal grid spacing and ΔPME_{Ant} suggesting that the range of resolutions across the CMIP5 models is not large enough for this effect to become apparent.

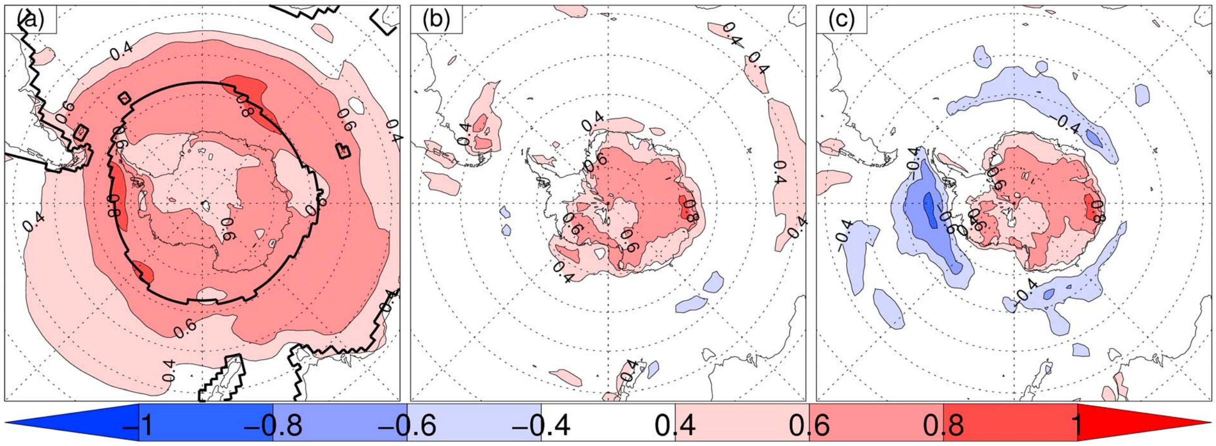

Figure 4. (a) Map of the cross-model correlations between simulated annual mean historical SH SIA and grid point ΔTAS (i.e., at each grid point a vector of *n* SIA values from the *n* = 37 models is correlated with a vector of *n* annual mean ΔTAS values at that grid point). Positive values indicate that models with larger historical SIA give more warming over the 21st century under RCP8.5. (b) Correlation between SIA and grid point ΔPR and (c) correlation between SIA and grid point ΔPME. The thick solid lines in Figure 4a show the 15% contour for the multimodel mean annual mean historical sea ice concentration.

To test the robustness of the results in a different scenario, Figure 2 was reproduced using projections from the RCP4.5 scenario (Figure S2). As might be expected correlations are slightly weaker, but they are still significant and the results are qualitatively unaffected. In particular correlations between historical SIA and ΔPME_{Ant} and ΔTAS_{Ant} are 0.67 and 0.55, respectively. A further test of the robustness was conducted by removing two models with both the largest historical SIA values and the largest changes in ΔPME_{Ant} (FIO-ESM and BNU-ESM). Correlations in this reduced ensemble between SIA and ΔSIA, ΔPME_{Ant}, and ΔTAS_{Ant} are also slightly weaker ($r = -0.81$, 0.73, and 0.66, respectively), but the main results are not affected.

Figure 4a shows a spatial map of the cross-model correlations between historical SIA and projected temperature change. The highest correlations occur near the multimodel mean historical sea ice edge. The high correlations extend over the Antarctic continent consistent with the nonlocal influence of sea ice change on Antarctic climate identified in sensitivity studies [e.g., *Weatherly*, 2004; *Krinner et al.*, 2014]. This nonlocal influence dominates correlations between historical SIA and projected ΔPR and ΔPME, which may be a consequence of additional water vapor associated with ice retreat being advected away from source regions and precipitating out over Antarctica. In Figure 4c, the negative correlations between SIA and ΔPME between 70°S and 55°S must be related to evaporation since there is no corresponding signal in ΔPR (Figures 1b and 4b).

Looking in more detail at intermodel differences in surface fluxes, it can be seen that the subset of models with larger than the median historical SIA generally exhibit increases in sensible heat flux with maximum values at around 70°S (Figure 5a), which is the approximate location of the Antarctic coastline. This is not unexpected since retreating ice at higher latitudes will expose the ocean to colder air masses. Equatorward of regions of historical sea ice cover in the models, there are consistent projected decreases in the sensible heat flux, which are likely to be mainly a result of the more rapid increase of atmospheric temperature compared to sea surface temperatures (SSTs) in the Southern Ocean. This increase in air-sea temperature difference helps to explain why there is no high-latitude increase in sensible heat flux in models with little present-day sea ice.

The impacts of projected sea ice retreat on latent heat flux show some key differences compared to impacts on sensible heat flux (Figure 5). In particular, the high-latitude maxima in projected latent heat flux change occur approximately 5° further equatorward than for sensible heat flux. This is a likely consequence of larger latent heat fluxes in warmer conditions at lower latitudes. A possible implication of this is that a given change in sea ice at lower latitudes could have more impact on Antarctic precipitation than a given change at higher latitudes. However, there is no clear evidence for this effect in the relationships shown in Figure 2, and therefore additional sensitivity studies would be required for a conclusive assessment.

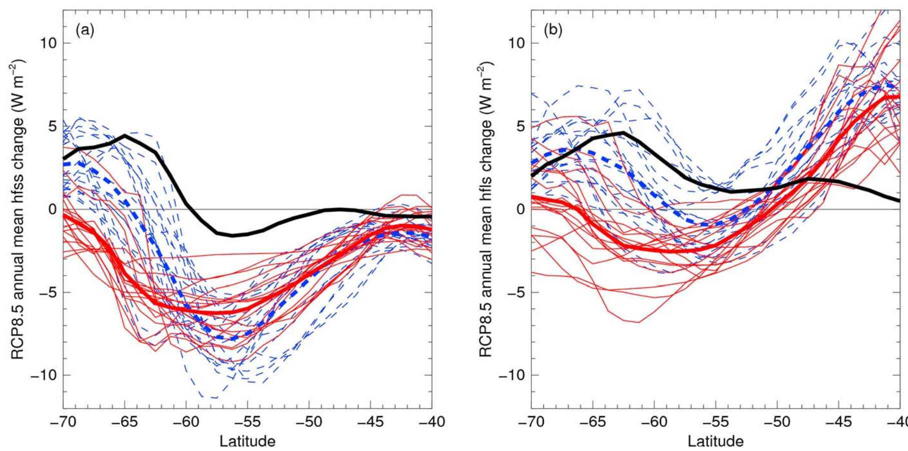

Figure 5. Projected 21st century change in (a) zonal mean annual mean sensible heat flux and (b) latent heat flux following the RCP8.5 scenario. The meaning of the color and line formatting follows Figure 1. The bold solid black lines show the difference between the multimodel means of the two subsets.

4. Conclusions and Discussion

This study has assessed the degree to which CMIP5 model biases in climatological historical sea ice area are related to intermodel differences in 21st century RCP8.5 projections of Antarctic temperature (ΔTAS_{Ant}), net precipitation (ΔPME_{Ant}), and sea ice itself (ΔSIA). The main conclusions are as follows:

1. Regional processes dominate uncertainty in Antarctic climate projections. In particular, CMIP5 models with a relatively large global surface warming response do not necessarily exhibit large ΔSIA.
2. Approximately half of the variance across the CMIP5 models in both ΔPME_{Ant} and ΔTAS_{Ant} can be statistically accounted for by historical SIA (Figure 2). This is in part a consequence of a strong intermodel relationship between historical SIA and ΔSIA.
3. Simulated ratios between net precipitation response and temperature response are lower in models with smaller SIA. Despite this, the near-linear relationship between proportional precipitation change and warming identified by *Frieler et al.* [2015] appears robust across most of the CMIP5 models with the exception of those with unrealistically low SIA.

A physical understanding of the statistical link between simulated historical SIA and ΔSIA is important for assessing implications for the robustness of projections. The simplest explanation is that models with a very small historical SIA are limited in how much retreat can occur in the future. However, it is not clear why the relationship remains strong for models with overly extensive sea ice. One possible reason is the fact that at lower latitudes a given retreat of sea ice implies a larger decrease in area than at high latitudes. Using an approach detailed in *Eisenman* [2010] to estimate ice edge latitude and its relationship to extent suggests that approximately 15–25% of the relationship could be caused by this effect (the larger estimate of 25% was found with FIO-ESM and BNU-ESM omitted). A clearer picture of the main processes involved will require an in-depth analysis of the mechanisms driving sea ice trends and associated trends within the Southern Ocean, which are both high priorities of current research.

The results presented highlight the fact that an accurate representation of SIA is a necessary condition for producing realistic projections of future Antarctic climate change. Specifically, under scenarios of retreating ice the transition from ice cover to open ocean would occur at the wrong location in models with too large or too small historical SIA. However, this is not by itself a sufficient condition since past-future correlations do not necessarily account for deficiencies shared across all models. For example, the CMIP5 models do not broadly capture the recent multidecadal increase in Southern Ocean sea ice extent. However, the post-1979 modern satellite era is too short to confidently assess the ability of climate models to replicate observed trends in sea ice area [e.g., *Meier et al.*, 2013; *Gagne et al.*, 2015]. A longer Antarctic temperature reconstruction is available back to 1958 [*Nicolas and Bromwich*, 2014], which was used to assess the emergent relationship between SIA and TAS_{Ant} trends in a historical context. However it was found that uncertainty associated with both the temperature reconstruction and internal climate variability was too large to make a conclusive evaluation (not shown). In addition, most global climate models do not include the regional orographic detail necessary to adequately capture precipitation over coastal Antarctica [*van Lipzig et al.*, 2004], which therefore requires some form of downscaling.

With regard to downscaling, recent studies suggest that the skill of global models used to drive regional climate model (RCM) simulations is the most important factor in determining the quality of their projections [*Racherla et al.*, 2012; *Di Luca et al.*, 2013]. In terms of global model forcing fields, the strong intermodel relationships between historical SIA and ΔTAS_{Ant} and ΔPME_{Ant} represent emergent relationships, whereby the simulated future changes across a multimodel ensemble can be related to an observable quantity (historical SIA in this case) [*Collins et al.*, 2012]. According to IPCC guidelines [*Flato et al.*, 2013, section 9.83], if the physical robustness of these emergent relationships could be established, then they would become emergent constraints that could be exploited to give more precise predictions of future change. It may then be possible to incorporate both RCM simulations and emergent constraints to produce more precise estimates of regional Antarctic climate change. For example, a hierarchy of statistical frameworks that take account of emergent constraints [e.g., *Bracegirdle and Stephenson*, 2012] could be used to constrain output from set of RCM simulations driven by a range CMIP5 model simulations.

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