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Key Points:

- Modeled Antarctic sea ice area decrease reversed with linearly increasing freshwater forcing: more positive trends when latent heat included
- Increase in the rate of change of freshwater input of ~45 Gt yr^{-2} sufficient to offset modeled sea ice area decreases in CESM1(CAM5)
- Increase in the rate of change of freshwater input required to offset decreasing sea ice area agrees with observed ice shelf melt increases

Supporting Information:

- Supporting Information S1

Correspondence to:
A. G. Pauling,
andrewpauling109@gmail.com

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Time-Dependent Freshwater Input From Ice Shelves: Impacts on Antarctic Sea Ice and the Southern Ocean in an Earth System Model

Andrew G. Pauling[1,2], Inga J. Smith[1], Patricia J. Langhorne[1], and Cecilia M. Bitz[2]

[1]Department of Physics, University of Otago, Dunedin, New Zealand, [2]Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA

Abstract Earth System Models do not reproduce the observed increase in Antarctic sea ice extent which may be due to the unrealistic representation of ice shelves. Here we investigate the response of sea ice to increasing freshwater input from ice shelves using the Community Earth System Model with the Community Atmosphere Model version 5 [CESM1(CAM5)]. We have conducted model experiments adding fresh water as if from ice shelf melt with a linear increase in the rate of input over the period 1980–2013. Including the effect of heat loss from the ocean to melt ice shelves resulted in significantly more positive trends in sea ice area. We found that an increase in the rate of change of freshwater input of ~45 Gt yr^{-2} was sufficient to offset the negative trend in sea ice area in CESM1(CAM5), although the freshwater input by the end of the experiment was larger than observed at that time.

1. Introduction

Satellite observations of Antarctic sea ice extent have shown an overall slight increase over time in recent decades (Parkinson & Cavalieri, 2012), in stark contrast to the rapid decline seen in the Arctic (Cavalieri & Parkinson, 2012). This increase has not been reproduced by models in the Coupled Model Intercomparison Project phase 5 (CMIP5) (Zunz et al., 2013). Proposed reasons for the discrepancy between models and observations include meridional wind (Holland & Kwok, 2012), stratospheric ozone depletion (Turner et al., 2009) (although the studies of Bitz and Polvani (2012) and Sigmond and amd Fyfe (2010) found that this caused sea ice loss), internal variability (Polvani & Smith, 2013; Turner et al., 2016; Zunz et al., 2013), and freshwater input from ice shelf melt (Bintanja et al., 2013, 2015) (although the studies of Swart and Fyfe (2013) and Pauling et al. (2016) found that this had no significant effect on the rate of change of sea ice area with respect to time). A consensus on the cause of sea ice expansion in recent decades is therefore lacking.

The model experiments of Bintanja et al. (2013, 2015) achieved a positive trend in Antarctic sea ice extent in the EC-Earth model with freshwater input around Antarctica at constant rates of 250 Gt yr^{-1} (Bintanja et al., 2013) and 120 Gt yr^{-1} (Bintanja et al., 2015) over a 40 year period, while the model experiments of Swart and Fyfe (2013) did not reverse the trend in sea ice area with freshwater input that increased linearly from 0 to 890 Gt yr^{-1} over a 29 year period (an increase in the rate of change of input of ~31 Gt yr^{-2}) in the UVic-ESCM (University of Victoria-Earth System Climate Model). Further, the study of Pauling et al. (2016) found an overall increase in the magnitude of sea ice area but no significant change in the trend, with freshwater input at a temporally constant annual mean rate of up to 3,000 Gt yr^{-1} over a 34 year period in the Community Earth System Model version 1 with the Community Atmosphere Model version 5 (CESM1(CAM5)). The studies of Swart and Fyfe (2013) and Bintanja et al. (2013, 2015) introduced fresh water at the ocean surface only. Pauling et al. (2016) tested the response to input both at the surface and at the depth of the front of the ice shelves around Antarctica and found that the sea ice response had little dependence on the depth of freshwater input.

These recent studies, where the freshwater input to the Southern Ocean is artificially enhanced, have been motivated by the unrealistic representation of ice shelves in Earth System Models at present (e.g., Pauling et al., 2016). For example, the Antarctic ice sheet, including ice shelves, is represented as land with a 1 m thick covering of snow in CESM1(CAM5) (Oleson et al., 2013), and if the net precipitation exceeds this limit, the excess is dumped at the coast as runoff. Interactive ice shelf cavities were absent from all the ESMs used

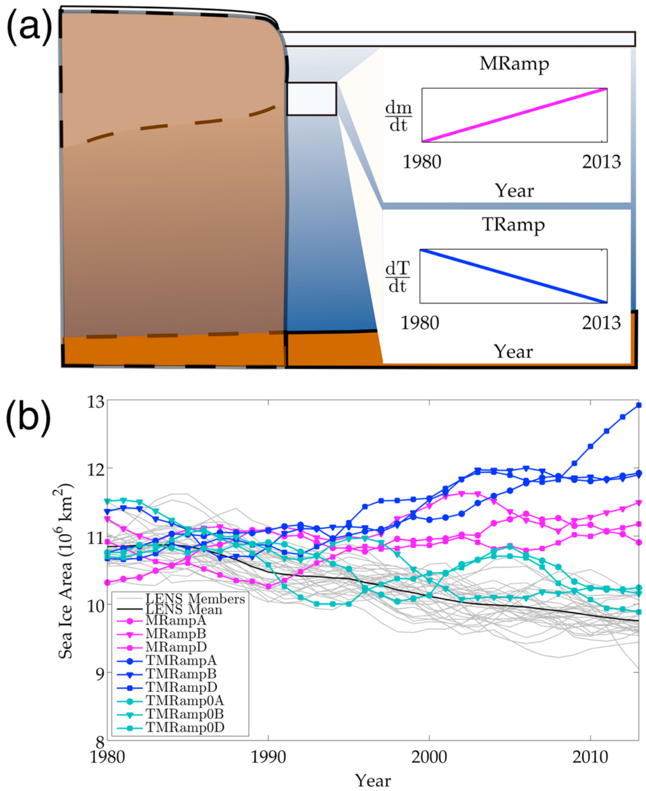

Figure 1. (a) Schematic of the freshwater enhancement implementation used for our experiments (top). The dashed line outlines the ice shelf-ocean-sea ice system in reality, while the solid line denotes the model representation of the system. The white rectangle denotes the grid cell where our forcing is introduced, with the two subplots showing the rate of freshwater input (magenta) and cooling (blue) applied. (b) Five year running mean sea ice area for each of the freshwater enhancement experiments, the individual CESM1(CAM5) LENS members, and the LENS mean.

in CMIP5 (Collins et al., 2013), meaning no basal melting of the ice shelf could occur (see Figure 1a), and so the continent loses mass via runoff only. The aim of artificial freshwater enhancement studies has been to investigate the response to the freshwater flux from ice shelf melt without the considerable undertaking of modifying the models to include an interactive ice sheet model.

While the rate of increase of Southern Ocean sea surface temperatures (SSTs) overall is lower than the global mean, the upper ~2 km has warmed over recent decades (Armour et al., 2016). It seems unlikely, then, that the rate of freshwater input to the Southern Ocean from the continent has remained constant over this period, as was assumed in the studies of Bintanja et al. (2013, 2015) and Pauling et al. (2016). Indeed, Paolo et al. (2015) estimated the increase in the rate of change of Antarctic mass loss to be 47 $\pm$ 30 Gt yr^{-2} (calculated assuming an ice density of 0.917 Gt km^{-3} (CESM Online Code Browser, http://www.cesm.ucar.edu/models/cesm1.2/cesm/cesmBbrowser/html_code/csm+share/shr_const_mod.F90.html [retrieved 21 September 2017])) over the period 2003–2012. Not only is this rate of increase highly uncertain, but it is substantially larger than that over the period 1994–2012 (28 $\pm$ 9 Gt yr^{-2}) (Paolo et al., 2015). Recent studies have either focused on introducing a "realistic" amount of freshwater to the Southern Ocean, based on estimates of Antarctic mass imbalance (Bintanja et al., 2013, 2015), or used increasingly large amounts of fresh water in an attempt to understand the physical mechanisms involved (Pauling et al., 2016; Swart & Fyfe, 2013). However, given the large uncertainty in, and short timespan of, our knowledge of the increase in the rate of change of Antarctic mass loss, it is not possible to say how realistic the freshwater inputs used in these previous studies are. In this paper we instead ask the question: what linear increase in the rate of freshwater input is required to minimally offset the modeled decrease in Antarctic sea ice area over time?

2. Methods

For the experiments in this study we use the Community Earth System Model version 1 (Hurrell et al., 2013) with the Community Atmosphere Model version 5 (Neale et al., 2010), referred to as CESM1(CAM5). CESM1(CAM5) uses the Parallel Ocean Program version 2 (POP2) (Smith et al., 2010), the Community Ice Code version 4 (CICE) (Hunke et al., 2013), and the Community Land Model version 4 (CLM) (Oleson et al., 2013), which are coupled together by the Coupling Infrastructure version 7 (CPL7). The model uses ~1° horizontal resolution in all components, with the north pole of the sea ice and ocean components displaced onto Greenland, with 60 vertical layers in the ocean and 31 in the atmosphere. We conducted experiments where we input fresh water in front of Antarctic ice shelves, at the depth of the ice shelf front, using the same spatial distribution as in the interior freshwater enhancement experiments of Pauling et al. (2016). This distribution introduces all of the fresh water at depth, as though it resulted only from basal melting of ice shelves. However, Pauling et al. (2016) showed that the response to freshwater input had little dependence on the depth of input. Since CESM1(CAM5) conserves ocean volume, direct addition of fresh water to the ocean was not possible, so the freshwater flux was parametrized as a negative salinity tendency. We also accounted for the latent heat that must be taken from the ocean to melt the ice, which was parametrized as a negative temperature tendency and applied in the same grid cell and depth as the salinity tendency.

In this paper we present results from nine experiments where we introduced time-dependent freshwater forcing to the Southern Ocean. The first six experiments were designed to isolate the response of Antarctic sea ice to increasing freshwater input from ice shelves. In these experiments we introduced fresh water at a rate that increased linearly from 0 to 4,000 Gt yr^{-1} over the period 1980–2013. This high input was chosen because in our previous study (Pauling et al., 2016) we found that CESM1(CAM5) was relatively insensitive to

Table 1
The Trends in Annual Mean Antarctic Sea Ice Area for the Period 1994–2013

Experiment	Trend (m^2 $decade^{-1}$)	*p* value[a]	Acceleration (Gt yr^{-2})	Input method
MRampA	2.2×10^{11}	0.04	118	Freshening only
MRampB	1.8×10^{11}	0.18	118	Freshening only
MRampD	1.4×10^{11}	0.09	118	Freshening only
TMRampA	5.6×10^{11}	<0.01	118	Freshening and latent heat
TMRampB	5.2×10^{11}	<0.01	118	Freshening and latent heat
TMRampD	7.2×10^{11}	<0.01	118	Freshening and latent heat
TMRamp0A	0.4×10^{11}	0.80	45	Freshening and latent heat
TMRamp0B	-4.7×10^{11}	<0.01	45	Freshening and latent heat
TMRamp0D	-0.9×10^{11}	0.55	45	Freshening and latent heat
LENS	-3.4×10^{11}	<0.01	-	-

[a]The *p* values result from a two-tailed Student's *t* test with the null hypothesis that the trends are nonzero.

temporally constant freshwater input. The period was chosen to coincide with the highest anthropogenic forcing and availability of satellite observations. It should be noted that in an effort to isolate the response to freshwater input from the variability of the system, the rate of freshwater input later in the runs exceeded recent estimates of the Antarctic mass imbalance (e.g., Paolo et al., 2015). However, it is the change in mass which leads to an increase in the rate of change of freshwater input that is important to freshening the Southern Ocean. Based on the results of the first six experiments, we then conducted three further experiments using an increase in the rate of change of freshwater input designed to minimally offset the modeled decrease in Antarctic sea ice area (discussed further in section 3).

The experiments were branched from three members of the CESM1(CAM5) Large Ensemble (LENS) (Kay et al., 2015), a 30 member ensemble of the period 1920–2100. Each member began from the same initial state except that each had the surface air temperature perturbed by $N \times 10^{-14}$ K, where N is the number of the ensemble member. The nonlinear nature of the system is such that by 1980, the climate trajectories have diverged enough that the 30 members are normally distributed and can be used as a base from which statistical comparisons may be made. The model was forced with time-varying concentrations of atmospheric greenhouse gases, ozone, aerosols, solar insolation, and volcanic activity from 1980 to 2005, as in the transient historical forcing strategy used for CMIP5 (Taylor et al., 2012). From 2006 to 2013 the forcing was the RCP8.5 scenario (Moss et al., 2010), which is a high-emissions scenario for anthropogenic greenhouse gases.

Among our branch experiments (see Table 1), the first three, referred to as "MRampA," "MRampB," and "MRampD," respectively, accounted for the freshening effect of ice shelf melt only, where "M" denotes that the mass tendency is changing, and "Ramp" refers to the linearly increasing freshwater input. The latter six experiments are referred to as "TMRampA," "TMRampB," "TMRampD," "TMRamp0A," "TMRamp0B," and "TMRamp0D." "TM" denotes that both the mass and temperature tendencies are changing; in these the loss of heat from the ocean that would be required to melt the ice is included in addition to the linearly increasing freshening. The "0" denotes the experiments designed to minimally offset the modeled decrease in Antarctic sea ice area. The "A," "B," and "D" suffixes on the names of each of the two types of experiments refer to the member of the CESM1(CAM5) LENS from which the run was branched, as in Pauling et al. (2016). We also conducted experiments to test the response to isolating the freshwater input to either the winter or summer half of the year, which are discussed in the supporting information.

3. Results

The ensemble mean trend in sea ice area for the CESM1(CAM5) LENS over the period 1994–2013 is -3.4×10^{11} m^2 $decade^{-1}$ and is statistically significant at the 99% confidence level ($p < 0.01$). The six freshwater enhancement experiments with freshwater input that increases linearly from 0 to 4,000 Gt yr^{-1} show an increase in sea ice area over time (see Figure 1b as well as Table 1 for the trends and associated p values). The sea ice area trends of the ensemble members within each of the MRamp and TMRamp experiments are similar to one another, and there is a significant difference in the ensemble means of the trends between the experiments with the freshening effect only (MRamp) and those with both freshening and heat loss (TMRamp).

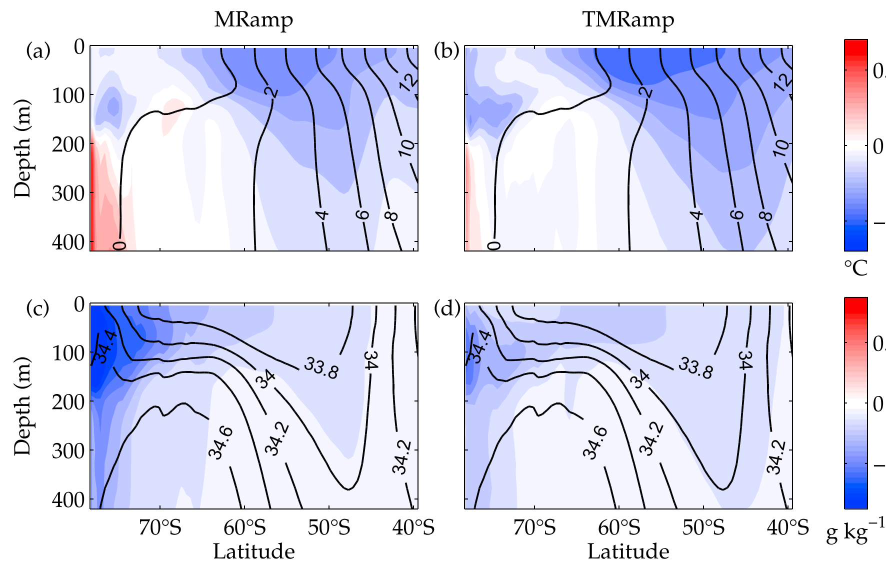

Figure 2. (a, b) The zonal mean temperature response for the mean of the three MRamp experiments (Figure 2a) and the mean of the three TMRamp experiments (Figure 2b). Contours denote the LENS ensemble mean temperature. (c, d) The zonal mean salinity response for the mean of the three MRamp experiments (Figure 2c) and the mean of the three TMRamp experiments (Figure 2d). Calculated as the mean anomaly between each experiment and the LENS averaged over the period 1994–2013. Contours denote the LENS ensemble mean salinity. Results for individual experiments in the supporting information.

The trends of the three MRamp experiments are significantly different from the three TMRamp experiments, discriminated by a two-tailed Student's *t* test with pooled variances (see supporting information). In contrast, the ensemble mean trend of the TMRamp0A experiments is not significantly different from zero by construction, so we exclude it from any further analysis until the end of this section, where we explain our rationale for conducting it. On average over the period 1994–2013, the ensemble mean Antarctic sea ice area of the TMRamp experiments is 0.6×10^{12} m^2 greater than the MRamp experiments and 1.6×10^{12} m^2 greater than the LENS.

Figures 2c and 2d show the zonal mean salinity anomaly with respect to the CESM1(CAM5) LENS for each type of experiment. We see that there is considerably less freshening in the experiments where the ocean heat loss is taken into account. There is also substantially weaker enhancement of the net southward meridional salt transport (see supporting information). We attribute this to the increased sea ice production near the coast resulting in more brine rejection into the surface mixed layer, which partially offsets the freshening induced by the artificial freshwater enhancement (see supporting information). It is also worth noting that the negative salinity anomaly extends further north in the TMRamp experiments, which can also be attributed to the increased sea ice area. The larger sea ice area in the TMRamp experiments results in sea ice melt farther north than in the LENS or MRamp experiments, causing fresher near-surface waters there.

We also see a substantially different response in the meridional overturning circulation (MOC) computed along surfaces of constant density (Döös & Webb, 1994). In Figure 3 we show the LENS ensemble mean isopycnal MOC plotted as a function of depth ($\psi(\rho(z)) \rightarrow \psi(z)$), as well as the anomaly in the time-mean ($\bar{\psi}$) and eddy-induced (ψ^*) components between each type of experiment and the LENS. There is a reduction in circulation strength of the lower cell of the mean component of the isopycnal MOC (the large region of anticlockwise circulation centered at approximately 65°S) in both types of experiment. However, the response is much (~32%) weaker in the TMRamp experiments. Since the response in the eddy component is weak and very similar for both types of experiment, the response of the total or "residual mean" isopycnal MOC ($\psi_{res} = \bar{\psi} + \psi^*$) can be well approximated by the mean component response.

Assuming that the trend in annual mean Antarctic sea ice area depends linearly on the increase in the rate of change of freshwater input to the Southern Ocean, we estimate that the increase in the rate of change of freshwater input required to minimally offset the negative ensemble mean sea ice trend of the LENS is ~45 Gt yr^{-2} (see supporting information). Hence, by design the experiments with this amount of freshwater

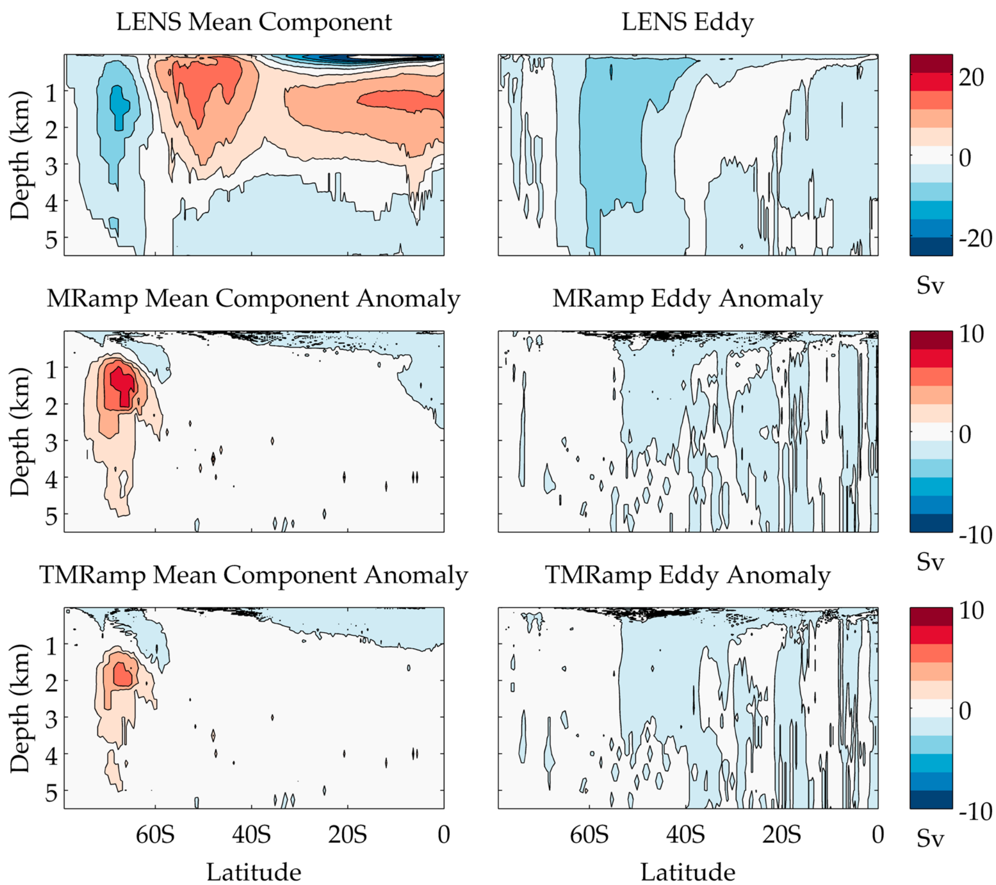

Figure 3. The mean and eddy-induced components of the CESM1(CAM5) LENS mean isopycnal MOC stream function (where 1 Sv = 10^6 m^3 s^{-1}), computed across all basins by taking the zonal mean in potential density, averaged over the period 1994–2013 (top), and the mean response of the three MRamp experiments (middle) and the three TMRamp experiments (bottom) calculated as the average anomaly between each experiment and the LENS averaged over the period 1994–2013. The stream function is shown as a function of depth, by converting the zonal average potential density to an average depth. Note the difference in color scale between the LENS mean and the responses.

(the TMRamp0 experiments in Figure 1 and Table 1) should have an insignificant trend in sea ice area. Indeed, the ensemble mean of the trend in the sea ice area of the TMRamp0 experiments is not significantly different from zero at the 95% confidence level. While the ensemble mean of the trends of the TMRamp0 experiments is not significantly greater than the ensemble mean of the trends of the LENS at the 95% confidence level, it is at 90%. Consequently, we have less confidence that these experiments offset the sea ice area trend in the LENS than we do for our earlier results.

4. Discussion

We conducted new experiments to test the response of the trend in Antarctic annual mean sea ice area to time-dependent freshwater forcing in CESM1(CAM5) and to determine the increase in the rate of change of input required to minimally offset the modeled decrease in Antarctic sea ice area. We first tested the response to freshwater input with a constant increase in the rate of change of input for the period 1980–2013, both with and without the heat loss from the ocean needed to melt the required amount of ice. The final magnitude of this forcing (4,000 Gt yr^{-1}) is much larger than recent estimates of the Antarctic mass imbalance. We do not claim that these experiments represent reality; rather, they are designed to isolate the response of Antarctic sea ice to increasing freshwater input from ice shelves. Due to the observational record of freshwater input to the Southern Ocean spanning only the last couple of decades, it is unknown when the mass imbalance began to ramp upward. We then estimated the increase in the rate of change of freshwater input required to minimally offset the modeled decrease in sea ice area to be ~45 Gt yr^{-2}. This agrees well with recent estimates of the rate of increase of Antarctic mass imbalance (47 ± 30 Gt yr^{-2}) (Paolo et al., 2015), although the final magnitude of input (∼1,500 Gt yr^{-1}) is much higher than estimates of present-day freshwater input.

Large, linearly increasing freshwater forcing resulted in increasing sea ice area over the period of the run, with the greatest rates of increase seen when the ocean heat loss was taken into account. This is in contrast to the insignificant sea ice response to temporally constant freshwater input distributed uniformly throughout the year (Pauling et al., 2016) (the major difference between that study and this paper being time constant versus increasing freshwater input) or isolated to a particular season (supporting information). The lack of response to seasonally isolated freshwater input can be explained by the 5 year residence time of the fresh water in CESM1(CAM5) (supporting information). We showed that the sea ice response in the experiments that accounted for the latent heat required to melt the ice shelves was significantly different to those that did not. The direct cooling effect of the latent heat associated with ice melt removed from the ocean, combined with the cooling induced by the more stratified water column inhibiting vertical advection of warmer water from depth into the surface mixed layer, resulted in greater cooling of the near-surface ocean in the TMRamp experiments.

Our results show that CESM1(CAM5) is relatively insensitive to large freshwater input. The study of Sallée et al. (2013) showed that the Southern Ocean in CESM1(CAM5) is too stratified compared to observations, and thus, the addition of fresh water near the ocean surface is less able to stratify the water column. The study of Ferreira et al. (2015) found that the response of CCSM3.5 (an older version of CESM1(CAM5)) to a poleward shift and strengthening of the westerly winds around Antarctica is to rapidly transition from an initial SST cooling response due to northward Ekman transport, to SST warming due to advection of warm water from depth into the surface mixed layer. Greenhouse gases and ozone force such a wind anomaly over the period 1980–2013 in CESM1(CAM5), which enhances surface warming due to greenhouse gases. Several other factors influence the growth and decay of sea ice, such as increasing P−E (Pauling et al., 2016) and snowfall (Lenaerts et al., 2016) over Antarctica and the Southern Ocean, and the salinity changes from sea ice growth and melt (Haumann et al., 2016). The observed increasing trend in Antarctic sea ice extent is likely due to a combination of these processes, as well as the natural variability of the climate system.

The response of the MOC is consistent with previous studies that have shown that freshwater enhancement causes the lower cell to weaken (e.g., Morrison et al., 2015) owing to the increased ocean stability associated with surface freshening (see Figure 3). Because the TMRamp experiments have substantially less surface freshening, the lower cell has more modest weakening. The greater weakening of the circulation in MRamp might be expected to permit the freshwater anomaly to expand farther northward and remain closer to the surface compared to TMRamp. Because this is not what we find in Figure 2, we conclude that the sea ice production and sea ice area differences are more important factors to explain the differing salinity response between the two experiments.

5. Conclusions

We have conducted experiments introducing linearly increasing freshwater input to the Southern Ocean, with the aim of determining the increase in the rate of change of freshwater input required to minimally offset the modeled decrease in Antarctic sea ice area. We first used large, linearly increasing freshwater input both with and without the effect of the latent heat required to melt ice shelves, to isolate the sea ice response to this forcing. We found that a combination of the inhibition of vertical advection of heat into the surface mixed layer due to stratification of the water column, and direct cooling due to the latent heat associated with ice melt removed from the ocean caused the most sea ice growth. While by the end of these freshwater ramping experiments the input in a given year far exceeds recent estimates of the magnitude of current Antarctic mass imbalance, the rate of change of input with respect to time (i.e., the slope of the freshwater ramp) appears more important to the trend in sea ice. This is consistent with the results of Swart and Fyfe (2013), who offset the modeled decrease in sea ice area in the UVic Model with an increase in the rate of change of freshwater input of 32 Gt yr^{-2}. Due to the large uncertainty and short timespan over which estimates of this rate of increase are available, it is not possible to say what a realistic value for the increase in the rate of change over the period of our experiments might be. We found that the increase in the rate of change of freshwater input required to minimally offset the modeled decrease in sea ice area in the CESM1(CAM5) LENS (∼45 Gt yr^{-2}) agrees with observations of the current rate of change of mass imbalance (47 ± 30 Gt yr^{-2}), although the final magnitude of input still substantially exceeds recent estimates of freshwater input from Antarctic ice shelves to the Southern Ocean.

Recent studies that have conducted freshwater enhancement experiments have used a wide range of input scenarios and obtained contradictory responses in Antarctic sea ice. This highlights the consequences of a lack of historical Antarctic mass balance data, as well as model uncertainty regarding the response to freshwater forcing. One source of model uncertainty is likely from different representations of the latent heat associated with ice melt in the freshwater input implementation. Our results suggest that the increase in the rate of change of freshwater input to the Southern Ocean may be more important than the absolute magnitude at present. If, for example, the mass balance of the Antarctic continent was positive at the start of the satellite era, the change in freshwater input to the Southern Ocean over recent decades may be much larger than the estimates of its current magnitude. However, even in the absence of historical Antarctic mass balance data, more progress can be made on understanding the reasons for the vastly different model responses to freshwater input. As yet, there has been no model intercomparison with a standardized freshwater forcing scenario to investigate the reason for model discrepancies. Until such a set of experiments is conducted, the reason for differing responses remains unresolved. If these processes are not correctly represented, the response of the Southern Ocean and Antarctic sea ice will be inaccurate regardless of whether or not ice sheet models that include interactive ice shelves are implemented in the future.

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