The response of the Southern Ocean and Antarctic sea ice to fresh water from ice shelves in an Earth System Model

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ABSTRACT

The possibility that recent Antarctic sea ice expansion resulted from an increase in fresh water reaching the Southern Ocean is investigated here. The freshwater flux from ice sheet and ice shelf mass imbalance is largely missing in models that participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5). However, on average P-E reaching the Southern Ocean has increased in CMIP5 models to a present value that is about 2600 Gt yr^{-1} greater than pre-industrial times and 5-22 times larger than estimates of the mass imbalance of Antarctic ice sheets and shelves (119 to 544 Gt yr^{-1}). Two sets of experiments were conducted from 1980-2013 in CESM1-CAM5, one of the CMIP5 models, artificially distributing fresh water either at the ocean surface to mimic iceberg melt, or at the ice shelf fronts at depth. An anomalous reduction in vertical advection of heat into the surface mixed layer resulted in sea surface cooling at high southern latitudes, and an associated increase in sea ice area. Enhancing the freshwater input by an amount within the range of estimates of the Antarctic mass imbalance did not have any significant effect on either sea ice area magnitude or trend. Freshwater enhancement of 2000 Gt yr^{-1} raised the total sea ice area by 1×10^6 km^2, yet this and even an enhancement of 3000 Gt yr^{-1} was insufficient to offset the sea ice decline due to anthropogenic forcing for any period of 20 years or longer. Further, the sea ice response was found to be insensitive to the depth of fresh water injection.

1. Introduction

Sea ice is a critical component of Earth's climate, controlling ocean-atmosphere heat exchange and driving deep ocean convection (Vaughan et al. 2013). It plays an important role in the global climate due to the sea ice-albedo feedback, which has been a major factor in the rapid decline in Arctic sea ice extent (Screen and Simmonds 2010). The Earth is warming (Vaughan et al. 2013), including the upper 700 m of the Southern Ocean (Gille 2008), although sea surface temperatures are not increasing everywhere (Fan et al. 2014). Observations show Antarctic sea ice extent has expanded around 75% of the continent's perimeter over the past three decades (Turner et al. 2009; Zunz et al. 2013). However, in contrast, CMIP5 (Coupled Model Intercomparison Project phase 5) models have a decline in Antarctic sea ice due to climate forcing over this period (Maksym et al. 2012; Zunz et al. 2013). Recently there has been some debate over the statistical significance of the observed increase in sea ice extent (Eisenman et al. 2014), because a change in the satellite sensor in December 1991 was not accounted for correctly in one of the main data products arising from use of NASA's Bootstrap algorithm. Nonetheless, the annual mean sea ice extent is certainly not decreasing in the Antarctic like it is in the Arctic.

Antarctic sea ice cover is strongly influenced by both winds and SST, and the coupled trio of sea ice, winds, and SST exhibit large interannual and decadal variability (e.g., Fan et al. 2014; Holland and Kwok 2012; Renwick et al. 2012). The sea ice variability is linked to distant regions through atmospheric teleconnections (e.g., Stammerjohn et al. 2008; Ding et al. 2011; Li et al. 2014). Some authors have argued that natural variability could be responsible for the recent sea ice expansion (e.g., Polvani and Smith 2013; Zunz et al. 2013). However, it is unclear if natural variability can explain the detailed pattern of sea ice trends correctly, or whether any one explanation can capture the sea ice trends in all regions at once.

Identification of a missing mechanism responsible for the inconsistency between models and observations has been the subject of much recent work. Mechanisms that have been explored include wind changes (Holland and Kwok 2012; Turner et al. 2013; Holland et al. 2014), ice-ocean feedback (Goosse and Zunz 2014) and the freshwater flux from ice shelf melt (Bintanja et al. 2013, 2015; Swart and Fyfe 2013), but none have conclusively explained the discrepancy.

Here we focus on the hypothesis that freshening the Southern Ocean could explain the recent Antarctic sea ice expansion. The effect of such surface freshening has been studied in coupled ocean-sea ice models (e.g., Beckmann and Goosse 2003; Hellmer 2004), and Earth System Models of intermediate complexity (e.g., Aiken and England 2008; Swingedouw et al. 2008). These studies have indicated that artificially enhancing the freshwater input to the Southern Ocean is effective at increasing ocean stratification, which inhibits the vertical transport of warmer water from depth to the ocean surface and in all cases SSTs cool, resulting in increased sea ice formation.

In more recent studies with an Earth System Model Bintanja et al. (2013, 2015) added freshwater amounts that were intended to replicate current sources from Antarctic basal ice shelf melt. In the first of the two studies, Bintanja et al. (2013) achieved increases of up to 10% in sea ice concentration over a 31 year period with the EC-Earth model under constant year 2000 forcing. Their freshwater flux of 250 Gt yr^{-1} was distributed nearly uniformly around the Antarctic coast, and uniformly throughout the year. Bintanja et al. (2015) then showed additional experiments required as little as 120 Gt yr^{-1} to reverse the modelled sea ice area trend in an RCP8.5 forcing scenario.

Swart and Fyfe (2013) used the UVic model (a coupled ocean-sea ice model with an energy balance model atmosphere) to investigate the effects of surface freshwater fluxes that increased from 0 to $\sim$ 740 Gt yr^{-1} and 0 to $\sim$ 890 Gt yr^{-1} over periods of 47 and 29 years respectively. With wind-forcing fixed to isolate the effects of the freshwater input, they performed each of these runs with fresh water either distributed uniformly around the Antarctic coast, or concentrated in the Amundsen Bay. They found that none of their freshwater scenarios reversed the sea ice loss in the model, although all of their scenarios reduced the amount of sea ice loss relative to their control integrations from 1970 to 2020 using historical and RCP8.5 forcing. This significantly different result from that of Bintanja et al. (2013) and Bintanja et al. (2015) suggests there are differences between models that produce very different responses to similar forcing.

The studies of Bintanja et al. (2013, 2015) and Swart and Fyfe (2013) based their artificial freshwater amounts on estimates of the mass imbalance of the grounded ice of Antarctica (see Fig. 1), citing recent altimetric and gravimetric estimates from satellites by Rignot et al. (2011); Shepherd et al. (2012) and King et al. (2012).[1] Such methods estimate the grounded ice loss to the ocean, and therefore Antarctica's contribution to sea level rise. Such data say nothing about the fate of the ice once it is afloat (as an ice shelf or iceberg), and therefore using only the values for the grounded ice sheet for ice shelf meltwater is an unusual assumption that neglects the additional freshwater input from the current mass imbalance of ice shelves (Shepherd et al. 2010; Rye et al. 2014; Paolo et al. 2015). Hence the studies of Bintanja et al. (2013, 2015) and Swart and Fyfe (2013) not only disagree, but the studies of Bintanja et al. (2013, 2015) managed to cause the sea ice to expand in response to far less freshwater than equals estimates of the current mass imbalance of Antarctica's grounded ice and ice shelves, as discussed later in this paper.

Perhaps even more surprising, we show in Section 4a that the freshwater enhancements used by Bintanja et al. (2013, 2015) and Swart and Fyfe (2013) are insignificant relative to the amount of precipitation minus evaporation (P-E) falling on the Southern Ocean, and much less than the

[1] It should be noted that Bintanja et al. (2013) justified their use of 250 Gt yr based on Rignot et al. (2011). Interestingly, the value given by Rignot et al. (2011) for Antarctic ice sheet loss in 2006 was 200 $\pm$ 150 Gt yr^{-1} using the mass budget method (250 $\pm$ 40 Gt yr^{-1} is the net imbalance for Greenland.)

increase in P-E over the Southern Ocean and Antarctica from pre-industrial times to present day in these same models. Furthermore, in reality about half of the meltwater leaving Antarctica enters the Southern Ocean at the depth of the ice shelf front (Rignot et al. 2013; Depoorter et al. 2013). The potential mixing as the buoyant meltwater rises from the ice shelf front depth ($\sim$ 100 - 200 m) has been ignored in these studies and in many other artificial freshwater enhancement studies.

In this paper, we first discuss the differences between the model representation of the Antarctic mass budget and reality, and cast the mass budget calculations in a new, consistent notation. We discuss what is known about the freshwater input to the Southern Ocean from Antarctica and the current mass imbalance of the grounded ice versus the ice shelves. We compare plausible trends in these sources to precipitation (minus evaporation) falling directly into the Southern Ocean.

We examine the influence of ice shelf processes on Antarctic sea ice extent through introduction of fresh water to the Community Earth System Model version 1 - Community Atmosphere Model version 5 (CESM-CAM5), which is a fully-coupled Earth System Model and a member of the CMIP5 ensemble. We conduct a set of experiments that artificially enhance freshwater input to the model to investigate the effect on the local ocean and sea ice. It is important to note that this work is purely an experiment to determine the response of the climate system to an additional forcing, rather than an attempt to bring the model closer to reality. Two different sets of experiments are presented: one with the fresh water added at the ocean surface and distributed according to the meltwater input from icebergs in the GFDL model (Martin and Adcroft 2010), and the other with the fresh water added north of Antarctic ice shelves and at the depth of the ice shelf front. Finally, we discuss whether the model sensitivity to fresh water is plausible.

2. Antarctic mass budget for ice shelves and grounded ice

The mass budget of Antarctica's grounded ice and ice shelves are governed by processes shown in Figures 1a and b. Only the mass imbalance of the grounded ice can directly influence sea level rise. Due to its importance to society it has been measured by many recent studies (see Table 1), and we consider this portion first. This is the only contribution considered by Bintanja et al. (2013, 2015) and Swart and Fyfe (2013). However, later we show that although it is relevant to sea level rise, it is currently an insignificantly small source of fresh water to the Southern Ocean.

The mass budget for the grounded ice sheet (see Fig. 1a), including all the sources and sinks of mass, yields the equation:

$$\dot{M}_{SM} + \dot{M}_{GL} + \rho_I A_G \dot{H} = 0, \tag{1}$$

where $\dot{M}_{SM}$ is the air-ice surface mass exchange rate (taking into account meltwater refreezing), $\dot{M}_{GL}$ is the mass flux across the grounding line, ρ_I is the density of ice, A_G is the horizontal area of the grounded ice, and $\dot{H}$ is the rate of change of height of the grounded ice. At present the surface meltwater is thought to mostly refreeze within the snow cover (Liston and Winther 2005). The term $\rho_I A_G \dot{H}$ is considered the mass imbalance, and it may be positive or negative depending on whether the ice sheet is gaining or losing ice, respectively. In a steady climate, the mass imbalance may be near zero if the averaging period is long enough (i.e. over several centuries) to make the contribution from natural variability negligible.

Recent estimates of the mass imbalance of the grounded ice of Antarctica range from -31 to -256 Gt yr^{-1}, where negative values indicate mass loss, and are summarized in Table 1. The very wide range of estimates, even for similar averaging periods, indicates the difficulty in obtaining these numbers. Nonetheless, Sutterley et al. (2014) note the imbalance of the grounded ice is accelerating, suggesting this imbalance will play an increasingly important role in future global climate change.

While the grounded ice mass imbalance is key to sea level rise, neither it nor any other term in Eq. 1 directly reach the Southern Ocean as fresh water as almost all meltwater refreezes. To influence the freshwater influx, the grounded ice mass must first cross the grounding line and become part of the ice shelves.

Studies such as those of Depoorter et al. (2013) and Rignot et al. (2013) attempt to quantify each of the components that make up the mass budget for the Antarctic ice shelves. Their estimates are calculated using a combination of satellite data and modelling, and provide values for basal melt rates, iceberg calving rates, surface mass balance, dynamic thinning and flux of ice into the ice shelves at the grounding line. These studies both identify basal melting of ice shelves as the largest ice loss mechanism for the Antarctic ice shelves (1500 $\pm$ 237 Gt yr^{-1} and 1454 $\pm$ 174 Gt yr^{-1} respectively), closely followed by iceberg calving (1265 $\pm$ 141 Gt yr^{-1} and 1321 $\pm$ 44 Gt yr^{-1} respectively). These two loss mechanisms dominate the mass loss of the Antarctic continent. There is evidence that basal melt may have increased on some ice shelves in response to an increase in upwelling Circumpolar Deep Water (CDW) along the continental shelf, particularly near the Bellingshausen/Amundsen Sea region (e.g., Jacobs et al. 2011; Sutterley et al. 2014; Paolo et al. 2015). An increase in ice mass loss of the ice shelves is related to, but is by no means equal to, the mass imbalance of the grounded ice sheet.

The components of the mass budget for the Antarctic ice shelves are related by:

$$\dot{m}_{GL} + \dot{m}_{SM} + \dot{m}_{BM} + \dot{m}_{C} + \rho_I A_S \dot{h} = 0 \qquad (2)$$

where $\dot{m}_{GL}$ is the grounding line flux, $\dot{m}_{SM}$ the air-ice surface mass exchange rate, $\dot{m}_{C}$ the iceberg calving rate, $\dot{m}_{BM}$ the basal mass exchange rate with the ocean and $\dot{h}$ the dynamic ice thinning rate, given as the rate of change of height with time multiplied by the ice density (ρ_I) and the horizontal area of the ice shelf A_S. Positive (negative) values imply addition (removal) of mass to (from) the shelf, and the term $\rho_I A_S \dot{h}$ is considered the mass imbalance, as in Equation 1.

Estimates of the mass imbalance of Antarctic ice shelves are similarly varied as for the grounded ice. Using mixed methods, Shepherd et al. (2010) estimated the ice shelf imbalance at 88 $\pm$ 47 Gt yr^{-1} for 1994-2004, where we have multiplied their volume rate of change by the density of solid ice, $\rho = 0.930$ Gt km^{-3}. In contrast, Paolo et al. (2015) used only radar altimetry to estimate what they considered a lower bound for the ice shelf imbalance of 288 $\pm$69 Gt yr^{-1} for 2003-2012 (after applying the same unit conversion factor). Importantly, Paolo et al. (2015) also found more than an order of magnitude increase in the mass imbalance between 1994-2003 and 2003-2012.

If the mass imbalance of grounded ice and/or the ice shelves has increased over the last few decades or centuries, then the freshwater flux to the Southern Ocean from Antarctica would also have increased, by an amount equal to the increase in the total mass imbalance. To estimate an "extra" yearly freshwater input at present relative to a hypothetical time of ice balance, we sum the central values of the largest estimates of grounded ice and shelf imbalance to arrive at 544 Gt yr^{-1}. Likewise, if we sum the lowest estimates, the amount is 119 Gt yr^{-1}. The true increase in freshwater flux from Antarctica over the last few decades is clearly highly uncertain, and we do not claim that it lies within these rough estimates, although the study of Rye et al. (2014) calculates the same sum to get an estimate of $\sim$ 350 $\pm$100 Gt yr^{-1}, which lies within our range.

None of the Earth System Models in the CMIP5 ensemble include ice shelf cavities at present (Flato et al. 2013), and for many, the ice shelves are represented as land. The model we used in our experiments, Community Earth System Model version 1 - Community Atmosphere Model version 5 (CESM1-CAM5), has this simple representation, where the entire Antarctic continent, including ice shelves, is treated as land with a maximum allowed snow cover of 1 m. Figure 1c shows the model representation of the Antarctic continent and the components of its mass budget. When the snow thickness exceeds 1 m it is immediately dumped at the coast as runoff (Oleson et al. 2013). In fact, the model does not capture all the processes in Equation 2. Instead it represents the mass budget of Antarctica as:

$$\dot{M}_{SM} + \dot{M}_R + \rho_W A_T \dot{H} = 0 \tag{3}$$

where $\dot{M}_R$ is the runoff from the continent, $A_T = A_G + A_S$, and $\dot{H}$ the rate of change of height of snow water equivalent with respect to time, with ρ_W here denoting the density of water, and the constraint that $H \leq 1$ m. The grounding line flux and ice thinning rate are not represented since ice sheet dynamics are not included in the model, while the basal mass balance and calving flux are not included due to the lack of realistic ice shelves in the model. Because surface melt is rare, $\dot{H} \approx 0$, so we have:

$$\dot{M}_{SM} \approx -\dot{M}_R \tag{4}$$

In other words, an increase in P-E over Antarctica in CMIP5 models is essentially equal to an increase in freshwater flux to the Southern Ocean.

In summary, we have cast the mass budget calculations in a consistent notation, which makes comparison of values measured or calculated by different studies for different components easier to understand. The mass budget in Earth System Models represents a greatly simplified version of reality and means that the models are unable to capture any mass imbalance.

3. Methods

a. The Model

The model used in this study is the Community Earth System Model version 1 - Community Atmosphere Model version 5 (CESM1-CAM5, Hurrell et al. 2013). The simulations were run with the POP2 (Parallel Ocean Program) ocean model, the CICE4 (Community Ice CodE version 4) sea ice model, the CLM4 (Community Land Model version 4) land component, and the CAM5 (Community Atmosphere Model version 5) atmosphere component. These stand-alone components were coupled by the CPL7 coupling infrastructure. The model was run at approximately 1° horizontal resolution in all components for all simulations with 60 vertical layers in the ocean, and 30 in the atmosphere.

Our experiments were run from January 1980 to December 2013, with 20th century transient forcing until December 2005, and using the RCP8.5 (Representative Concentration Pathway, 8.5 W m^{-2} radiative forcing) thereafter. This represents the "high emissions scenario" for greenhouse gas emissions in the models (Taylor et al. 2012). We branch our experiments in 1980 from four different ensemble members of the CESM-CAM5 LENS (Large ENSemble) project (Kay et al. 2015). The 30 ensemble members of the LENS have the same model configuration and forcing scenarios as used in this study (without the extra freshwater forcing), where each ensemble member has the sea surface temperature (SST), in 1920 perturbed by $N \times 10^{-14}$ K, where N is the number of the ensemble member (i.e., $N = 1$ to 30). This perturbation is enough for the climate state to have diverged by 1980 to produce an ensemble with which statistical comparisons can be made. We show the 30 ensemble members in Figure 2, and the four randomly-chosen ensemble members (labelled A-D) that form our sensitivity experiments in Table 2. To compare the response to freshwater scenario independent of initial condition, we branched each of the freshwater scenarios that we tested (described next) from LENS member A. We also investigated the sensitivity to the initial conditions, by varying the LENS member from which we branched for select freshwater scenarios.

b. Surface Freshwater Experiments

To simulate freshwater input from either ice shelf basal melt or iceberg melt in excess of the normal way that CESM1-CAM5 deals with the mass balance of Antarctica (described in Figure 1c and Eq. 4), we enhanced the fresh water entering the Southern Ocean. In the first set of experiments, we added the water to the surface to investigate the response as if all the fresh water missing in our model (and other CMIP5 models) were from an increase in the iceberg flux. Since the ocean in CESM1-CAM5 conserves volume and direct addition of fresh water is not possible, we parameterize the freshwater input as a negative salinity forcing by multiplying the freshwater flux by minus the reference salinity of the ocean, -34.7 psu. After discovering our model had a very weak response to freshwater flux estimates of the current Antarctic mass imbalance, we chose to introduce larger amounts of freshwater enhancement, specifically we input 1000, 2000, or 3000 Gt yr^{-1} of additional fresh water in an attempt to determine how much fresh water is required to have a significant effect on the sea ice area trend. We acknowledge that these freshwater inputs are much larger than estimates of the combined ice shelf/ice sheet mass imbalance. Three experiments were conducted with 2000 Gt yr^{-1} to test for reproducibility (see Table 2). To distribute the fresh water realistically around the Antarctic coast we used the 100 year monthly mean global meltwater distributions from icebergs in the GFDL-ESM runs (Martin and Adcroft 2010), regridded onto the CESM grid (see Fig. 3a). The freshwater flux was introduced at a an annually periodic rate throughout the year using the GFDL iceberg distribution, due to the lack of current knowledge of the seasonality of freshwater flux from iceberg calving. Although several papers have shown that the latent heat associated with melting icebergs has a significant impact on the hydrography and sea ice in the Southern Ocean (e.g., Jongma et al. 2009), we have not taken it into account because our purpose is to isolate the effects of fresh water alone to compare more directly with the studies of Bintanja et al. (2013, 2015) and Swart and Fyfe (2013).

c. Interior Freshwater Experiments

In a second set of experiments, fresh water was added at the ice shelf fronts to investigate the response as if all the fresh water missing in our model (and other CMIP5 models) were from an increase in the basal melt of ice shelves. This applies a constant reduction in salinity to the specified vertical level. We injected the fresh water in front of ice shelves and at the depth of the front (see Fig 3b). The ice shelf location and depth were derived from the RTopo-1 dataset (Timmermann et al. 2010). These were then regridded onto the CESM1-CAM5 grid and checked for mismatches between the RTopo-1 and CESM bathymetry, which arose due to the large resolution difference between the dataset and the model (the RTopo-1 dataset is much higher resolution than the CESM1-CAM5 grid). In some cases the interpolated depth of the ice shelf front from RTopo-1 was deeper than the CESM1-CAM5 bathymetry. In these cases the problem was resolved by manually raising the vertical layer in the model into which the fresh water was input to the lowest level within the ocean. Other issues arose when islands were present in the middle of an ice shelf, causing false identification of the ice shelf front. These cells were manually inspected and removed. The freshwater flux was then divided evenly among the grid cells, and the forcing was input uniformly throughout the year.

Three interior freshwater experiments were conducted, denoted IFW167A, IFW2000A and IFW2000B (see Table 2). The IFW167A experiment simulated a freshwater input within our calculated range of estimates of present total ice mass imbalance for Antarctica. The IFW2000A and IFW2000B experiments were conducted after preliminary results from the surface freshwater experiments suggested this magnitude of freshwater input (2000 Gt yr^{-1}) was necessary in order to see a significant change in the annual mean sea ice area over the duration of the experiments.

Figure 4 shows a comparison of the depth of freshwater input with the modelled seasonal mixed-layer depth from the CESM1-CAM5 LENS mean. We see that for the shallower mixed-layer depths of summer and autumn, the depth of interior fresh water input is predominantly below the mixed layer, while in winter and spring about half the input cells lie within the mixed layer. This is important since fresh water that is input directly into the mixed layer will be immediately mixed with the ambient water, while input below the mixed layer will take longer to be mixed.

In summary, we have two sets of experiments to test the effect of freshwater input either due to iceberg calving (surface experiments), or basal melt (interior experiments). It should be noted that in both sets of experiments, we are only considering the freshening effect of the meltwater and that we do not apply any explicit cooling to the model.

4. Results

a. CMIP5 Freshwater Budget

To put the amount of artificial freshwater enhancement used in our experiments and those of others in context, we first examined the sources of fresh water to the Southern Ocean from P-E falling on the Antarctic continent and the Southern Ocean in the CMIP5 ensemble (Taylor et al. 2012) (http://cmip-pcmdi.llnl.gov/cmip5/) and in MERRA (Modern Era Retrospective Analysis for Research and Applications) and ERA (ECMWF Reanalysis) reanalyses. Recall that on the continent P-E is approximately equal to the amount of meltwater from the continent, which is the sole source of fresh water in the models (see Fig. 1c). On the Southern Ocean, P-E either adds fresh water directly to the ocean surface, or it accumulates on sea ice, and subsequently melts some time later.

To calculate P-E on Antarctica for CMIP5 models we summed over grid cells using the land masks from individual models. For the Southern Ocean, P-E was summed over all grid cells south of 50° S, then the values for the continent were subtracted to leave the total for the ocean.

Over the Southern Ocean, P-E on average from 1994-2013 was $21,000$ Gt yr^{-1} from the MERRA reanalysis and $27,700$ Gt yr^{-1} from the ERA-interim reanalysis. The CMIP5 models have an across-model ensemble mean of $23,108$ Gt yr^{-1} and a standard deviation of 2667 Gt yr^{-1} (Fig. 5a). Over Antarctica, P-E over the same period is an order of magnitude smaller; it is 2480 Gt/yr from the MERRA reanalysis and 2580 Gt/yr from the ERA-interim reanalysis. The across model mean for CMIP5 models for that period was 2608 Gt yr^{-1} with a standard deviation of 538 Gt yr^{-1} (Fig. 5b). If Antarctica's ice sheets and shelves were in mass balance, the meltwater from Antarctica (mainly from basal melt and iceberg calving) would equal P-E falling over Antarctica averaged over a few decades. Thus the mean combined freshwater input to the Southern Ocean from P-E and Antarctic meltwater in CMIP5 models is about $25,700$ Gt yr^{-1}. Further, the change in P-E since pre-industrial times over the Southern Ocean and Antarctic continent combined in CMIP5 models, taken as the difference between the average over 1994-2013 and the average over 1861-1890, is 2595 Gt yr^{-1}, with a standard deviation of 1409 Gt yr^{-1} (Fig. 5c). The contribution to the increase in P-E from over Antarctica alone in CMIP5 models is 623 Gt yr^{-1}, which lies above the wide-ranging estimates of the total present mass imbalance of Antarctic ice from observations (roughly 119-544 Gt yr^{-1}).

In summary, the largest source of fresh water to the Southern Ocean is the P-E falling directly onto the ocean. The P-E, and hence runoff (see Equation 4), from the Antarctic continent is an order of magnitude smaller, and is coincidentally of similar magnitude to the increase in P-E falling on the Southern Ocean since pre-industrial times and the largest of our artificial freshwater enhancement experiments (3000 Gt yr^{-1}).

b. Ocean Response Difference Between Interior and Surface Freshening

The freshwater input scenario in our experiments is quite different for the surface and interior cases (see Fig. 3). When fresh water is injected in the interior, it enters exclusively at the Antarctic coast, while at the surface it is introduced over a much wider area. In this section we present the ocean response to freshwater enhancement and describe the extent to which the point of origin of the freshening influences the results. We compare only the response of the ensemble means of surface freshwater experiments with ≥ 2000 Gt yr^{-1} freshwater enhancement and the 2000 Gt yr^{-1} interior freshwater experiments. With regard to the other experiments, the ocean response appears to be roughly linear in the magnitude of freshwater input, though the response to adding just 167 Gt yr^{-1} was not significant.

Examining all experiments with ≥ 2000 Gt yr^{-1} freshwater enhancement, it takes only a few years after we begin to artificially add fresh water in 1980 before the upper ocean salinity decreases substantially south of about 40° S (Fig. 6) (Here and henceforth we compare our experiments to the 30-member ensemble mean of the LENS at an equivalent point in time). The response within the mixed layer, which is from the surface to ~ 100 m depth, between $\sim 40-75°$ S shows little evidence of the point of origin of the freshening. The stabilizing effect of the desalination extends year round to the northernmost reach of the sea ice cover.

The increased stratification of the water column inhibits sinking near the coast of Antarctica and upwelling further north in the Southern Ocean. The resulting weaker meridional overturning circulation reduces the exchange of heat between the intermediate depth ocean and the surface mixed layer. The temperature response shows upper ocean cooling over a large domain, except for patches of warming below about 100 m south of $\sim 60^\circ$ S (Fig. 7). The maximum cooling in the zonal mean is over 0.5°C at the surface just beyond the winter sea ice extent. The sea surface temperature response is nearly the same for the surface and interior freshwater experiments. The temperature response at depth differs more between freshwater forcing scenarios. The coastal subsurface warming results from a reduction in sinking of cold continental shelf waters, while the subsurface warming at $\sim 70^\circ$ S results from a reduction in upwelling in the vicinity of a temperature inversion (i.e., the ocean is warmer below the mixed layer at $\sim 70^\circ$ S).

Because the interior freshwater experiments concentrate the freshwater flux near the coast of Antarctica, the coastal subsurface warming is greater, while the maximum warming in the surface freshwater experiments is at $\sim 70^\circ$ S. The apparent greater magnitude of warming in the interior freshwater experiments may be because signals are concentrated on smaller latitude circles at high southern latitudes.

We diagnose the cooling rate by this mechanism in an analysis similar to that used by Ferreira et al. (2015). A key component of the temperature tendency ($\partial T/\partial t$) is from advection by the residual mean vertical upwelling rate (w_{res}) and the sum of the Eulerian and parameterized eddy-induced vertical velocities acting on the mean vertical temperature gradient ($\partial\overline{T}/\partial z$). The reduction in upwelling results in an advective tendency response from the residual mean upwelling anomaly acting on the temperature gradient from the mean-state:

$$\frac{\partial \Delta T}{\partial t} \approx -\Delta w_{\mathrm{res}} \frac{\partial \overline{T}}{\partial z}. \tag{5}$$

where Δ indicates an anomaly. The expression in Eq. 5 does not include a vertical velocity gradient term which Ferreira et al. (2015) have demonstrated is of second-order importance.

Figure 8 shows the advective temperature tendency response (using Eq. 5 with $\partial\overline{T}/\partial z$ from the ensemble mean of the LENS) in our experiments. There is predominantly a cooling tendency in the

Southern Ocean at 100-200 m depth, which is evidence of the reduction in upwelling of warmer water from below. There is no clear dependence in the response of the advective temperature tendency on whether the freshwater is injected in the interior or added at the surface (see Fig. 8).

It is interesting to note that the most negative temperature tendencies by advection in Figure 8 appear far to the south of greatest cooling in Figure 7. We attribute this disparity to the fact that we have only examined the response to vertical advection. Heat transport occurs mainly along isopycnals, which are more horizontal in mid-latitudes. An anomalous northward ocean heat transport was found in support of this explanation (not shown).

An interesting result of our freshwater enhancement experiments is that fresh water added at the surface tends to reduce the mixed layer depth relative to the LENS mean at most times of the year, while the interior freshwater enhancement caused the mixed layer to become deeper as shown in Figure 9. As seen in Figure 4, when injected in the interior, most of the fresh water enters at the base of the mixed-layer. Since the density of the water is dominated by the salinity, the fresh water is buoyant, which drives convective overturning and deepens the mixed layer.

In summary, injecting fresh water at depth does drive greater mixing, which significantly deepens the mixed layer (see Fig. 9) and leads to a greater reduction in salinity at 100-200 m depth at the Antarctic coast. Nonetheless, to a large extent the upper ocean salinity and temperature response is independent of the two methods we employed for adding fresh water, especially in ways that are likely to be important to the sea ice cover.

c. Sea Ice Response to Artificial Freshwater Enhancement

Given the weak sensitivity of the surface ocean to the depth of freshwater injection, it is not surprising that the trend in sea ice area is also insensitive to the method by which we added fresh water. However, the response in the 1994-2013 annual mean of the total sea ice area does depend on the amount of fresh water input. After a 5-10 year adjustment period from the start of freshwater enhancement, only the total area in those cases enhanced by 2000 Gt yr^{-1} or more (SFW2000A, C, and D; IFW2000A and B; and SFW3000A) lie outside the spread of the LENS members (see Fig. 10). In each of these cases the total area is significantly larger than the distribution of the LENS in the last 20 years of the experiments (1994-2013) in every season. From 1994-2013 the total sea ice area in the ensemble mean of the $\geq$ 2000 Gt yr^{-1} freshwater enhancement cases compared to the LENS mean is significantly larger in winter and spring (by about a factor of two) than in summer and autumn. The response in the magnitude of sea ice area for the IFW167A experiment stays well within the range of the LENS.

Figure 11 shows the slope of a linear fit to the timeseries of seasonal mean sea ice area for each of our artificial freshwater enhancement experiments. These are plotted on a histogram of the slopes of a linear fit to each of the members of the LENS for the period 1994-2013. We see that the trends for all of the experiments fall well within the range of the ensemble trends. This suggests that the introduction of large artificial freshwater enhancement causes no significant change in the trend in seasonal mean sea ice area.

In the trend analysis just described, we eliminate the first six years of our experiments because during this time the sea ice in some of our experiments undergoes a rapid expansion before levelling off. We repeated our analysis for a range of different start and end dates with a period length of at least 20 years, and found the results were unchanged.

Figure 12 shows spatial maps of the sea ice trend in the freshwater enhancement experiments branched from LENS run A (see Fig. 2) and for the ensemble mean of $\geq$ 2000 Gt yr^{-1} enhancement experiments compared to the LENS mean in individual seasons. In agreement with the trends in total area response in Figure 11, there is no consistent spatial pattern in the trend response among the individual experiments in Figure 12. Many anomalies persist over the seasonal cycle, which is expected because sea ice concentration anomalies exhibit persistence and re-emergence for up to about a year (e.g. Holland et al. 2013). When averaged over a number of runs, these anomalies are removed.

5. Discussion

The freshwater inputs over the Southern Ocean in the CMIP5 ensemble (see Fig. 5), which includes P-E that falls directly into the ocean and that which falls on Antarctica and generally becomes meltwater input to the Southern Ocean according to Eq. 4, give a useful benchmark with which to compare our freshwater forcings, and those used in previous studies. It is also reassuring that these estimates agree well with the values obtained from the reanalyses. At most we are adding around 10% on top of the net amount of fresh water already received by the Southern Ocean from P-E. Our most aggressive freshwater forcings are of a similar magnitude (i.e. $\sim 100\%$) to the amount of additional P-E entering the Southern Ocean at present compared to pre-industrial values in CMIP5 models. In contrast, the previous studies of Bintanja et al. (2013, 2015) and Swart and Fyfe (2013) add at most 1%, 0.5% and 3% to the fresh water from P-E that is received by the Southern Ocean. Importantly, in the latter two studies, the freshwater inputs were added to models forced with 20th and 21st century scenarios, which therefore already have substantial increases in P-E compared to the pre-industrial period. Relative to this increase in P-E, the enhancement was at most about 5% in Bintanja et al. (2015) and 30% in Swart and Fyfe (2013).

In response to artificially adding fresh water in our model, the upper 100-200 m freshens and the upper 100 m cools south of about 65° S. The same near surface response is described by other recent studies (Bintanja et al. 2013; Swart and Fyfe 2013, suppl.). The peak surface cooling in the zonal mean in Bintanja et al. (2013) is within the winter sea ice covered region about 65° S, while in our study it is shifted north by about 5° of latitude, which is nearly always beyond the sea ice cover. Even larger differences in the pattern of subsurface temperature prevail among recent studies (including ours). In Bintanja et al. (2013), the peak warming in the zonal mean occurs at about 42° S at $\sim$ 300 m depth. In the other two studies (including ours), the peak warming in the zonal mean occurs south of 65° S at a similar depth.

It has been shown (Fig. 9) that the mixed layer response depends upon whether fresh water is added at the surface or interior, while sea ice and vertical advection do not. We suggest the dominant mechanism that limits the sea ice is the increased stratification of the ocean, where the density difference between the surface mixed layer and the ocean immediately below it is increased, inhibiting vertical transport of heat to the surface. Using salinity as a proxy for density, we see very little difference in this response between the two experiments (Fig. 6). We conclude that the behavior of the mixed layer depth, while interesting, does not determine the response in sea ice area.

Even though our model freshens and cools in the upper Southern Ocean, we see clearly in Figure 11 that the trends in all of our artificial freshwater enhancement experiments fall well within the range of the trends of the LENS members (which had no artificial freshwater forcing). This suggests that even a very large artificial freshwater enhancement introduced at a constant annual mean rate is not sufficient to reverse the model's trend in sea ice area over the last 34 years.

Although our artificial freshwater enhancement does not cause the sea ice to expand over time, our integrations do have a substantial ocean and 1994-2013 annual mean total sea ice area magnitude response. The sea ice total area is about 1 million square kilometers greater than in the LENS, and the sea surface temperature is cooler by as much as 0.5 °C in the zonal mean. Interestingly, the IFW167A experiment, with a freshwater input that lies within our calculated range of estimates of total Antarctic ice mass imbalance has no significant effect on the sea ice area trend or magnitude.

The sea ice response in our experiments is more consistent with Swart and Fyfe (2013). When we added an amount of fresh water of a similar magnitude to theirs, we found no significant response in the sea ice total area in any season. We had to more than double the amount of fresh water used by Swart and Fyfe (2013) before the sea ice total area response was significant. Our results also agree with those of Zunz and Goosse (2015), who concluded that while freshwater input from melting plays some role in determining sea ice area, it appears not to be the dominant mechanism.

In contrast Bintanja et al. (2013, 2015) had a significant response from an order of magnitude less freshwater forcing than was used in the artificial freshwater enhancement experiments in our model. In our experiments that have a significant sea ice response the salinity response in the mixed-layer also appears to be about 5-10 times greater than that of Bintanja et al. (2013). If we assume that no error was made in the estimate of freshwater inputs by Bintanja et al. or us, then it is difficult to understand why such a small freshwater enhancement had such a dramatic effect in the simulations presented in Bintanja et al. (2013, 2015). Our evaluation of the freshwater inputs into the Southern Ocean in Figure 5 gives no indication why the results should differ so dramatically since our model (CESM1-CAM5) and the model used by Bintanja et al. (EC-EARTH) are similar and both are in line with other CMIP5 models. We can only assume that the water column in the EC-EARTH model is weakly stratified so that the addition of a very small surface freshwater forcing is enough to cause significant surface cooling and thus reverse the trend in sea ice area.

6. Conclusions

We have investigated the hypothesis that recent freshening of the Southern Ocean might be the cause of recent Antarctic sea ice expansion. This mechanism has received attention in part because it involves meltwater from ice shelves and icebergs, which are not treated in GCMs, and therefore could be the missing mechanisms responsible for discrepancy in sea ice behavior in CMIP5 models and observations.

We began with an analysis of sources of fresh water that are included in CMIP5 from P-E over the Southern Ocean and Antarctica. Given the simplifications to the surface mass balance of Antarctica in CMIP5 models, P-E falling on Antarctica is roughly equal to the source of fresh water from Antarctica that reaches the Southern Ocean in CMIP5 models. We found P-E directly falling on the Southern Ocean is about an order of magnitude higher than the P-E that falls on Antarctica. Further, the *increase* (at present day relative to pre-industrial) in this freshwater source to the Southern Ocean in CMIP5 models is 2608 Gt yr^{-1} on average. Thus the increase in fresh water that has been accounted for in CMIP5 models is roughly 5-22 times larger than the sum of current estimates of the missing sources in CMIP5 models from the mass imbalance of the grounded ice sheet (-31 to -256 Gt yr^{-1}) and the ice shelves (-88 to -288 Gt yr^{-1}).

There are disagreements in the sensitivity of models to the missing freshwater sources from Antarctica among recent studies that have introduced artificial freshwater enhancements to the Southern Ocean. We not only explored the sensitivity in another model, but we ask how much freshening is needed to produce a significant response. We introduced freshwater enhancements to the Southern Ocean in the CESM1-CAM5 model that ranged from 167 to 3000 Gt yr^{-1}, which at the high end is much larger than observational estimates suggest is reasonable. Freshwater input within the range of estimates of combined Antarctic ice sheet/ice shelf imbalance caused no significant effect on either the annual mean sea ice area magnitude or trend. In response to larger freshwater enhancement (≥ 2000 Gt yr^{-1}), after an initial rapid adjustment, the sea ice area remained elevated by at most about 1 million square kilometers compared to integrations without freshwater enhancement. Despite the large freshwater input, the forcing we introduced was not sufficient to alter the trend in our model's annual mean sea ice area after the initial rapid adjustment. Our weak response in sea ice area to this large forcing suggests a constant annual mean freshwater input is not wholly responsible for the observed increase in sea ice area over recent decades.

In addition to investigating the amount of fresh water needed to produce a significant sea ice response, we also explored whether the response depended on whether the fresh water was distributed as if all the meltwater was from iceberg melt, or all from ice shelf basal melt. We anticipated that adding fresh water at depth might drive mixing that would compete with the ability of the fresh water to stratify the upper ocean. We found that injecting water at the depth of the front of ice shelf around Antarctica caused the ocean mixed-layer to deepen, while adding fresh water at the surface caused the mixed-layer to shoal. However, the overall response of the ocean and sea ice is not very sensitive to the difference, indicating that the likely mechanism by which Antarctica loses mass now and in the future will not affect the sea ice response.

A limitation of our experiments at depth is that we introduce fresh water at a constant rate in time over the length of the experiments, which is almost certainly not the case in nature. At present little is known about the seasonality of meltwater from ice shelf melt, and the sensitivity of response to the time of freshwater input could be a useful area of future work.

The inconsistent response to artificial freshwater enhancement among different modelling studies suggests important mechanisms in the interaction between the ocean and sea ice are being misrepresented in models. An investigation into these interactions in models is needed to account for this discrepancy in response. A comparison of CMIP5 model response to freshwater enhancement has been suggested by Bintanja et al. (2015), and seems a crucial step in identifying the source of discrepancy between models and observations, and between models themselves.

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LIST OF TABLES

Name	GMI (Gt yr^{-1})	IMI (Gt yr^{-1})	MI + IMI	Period
Zwally et al. (2005)	-31 ± 12	-	-	1992 - 2002
King et al. (2012)	-69 ± 18	-	-	2002 - 2010
Barletta et al. (2013)	-83 ± 36	-	-	2003 - 2011
Velicogna and Wahr (2013)	-83 ± 49	-	-	2003 - 2012
William et al. (2014)	-256 ± 22	-	-	2003 - 2012
McMillan et al. (2014)	-159 ± 48	-	-	2010 - 2013
	-83 ± 5	-	-	1992 - 2013
Sutterley et al. (2014)	-84 ± 10	-	-	2003 - 2009
	-102 ± 10	-	-	2003 - 2011
Shepherd et al. (2010)	-	-88 ± 47	-	1994 - 2004
Paolo et al. (2015)	-	-288 ± 69	-	2003 - 2012
Rye et al. (2014)	-	-	-350 ± 100	1992-2011

TABLE 1. Summary of recent gravimetry- and altimetry-based estimates of Antarctic grounded ice mass imbalance (GMI), ice shelf mass imbalance (IMI) and total mass imbalance (GMI + IMI).

Expt. Name	Mass (Gt yr^{-1})	Mask Source
SFW1000A	1000	GFDL Iceberg Dist.
SFW2000A,C,D	2000	GFDL Iceberg Dist.
SFW3000A	3000	GFDL Iceberg Dist.
IFW167A	167	Derived from RTopo-1
IFW2000A,B	2000	Derived from RTopo-1

TABLE 2. The experiments discussed in this paper. The A to D suffix on the experiment name indicates multiple ensemble members and the CESM1-CAM5 LENS member counterpart as shown in Figure 2. Mask source gives the data source used to construct the distribution of freshwater input.

LIST OF FIGURES

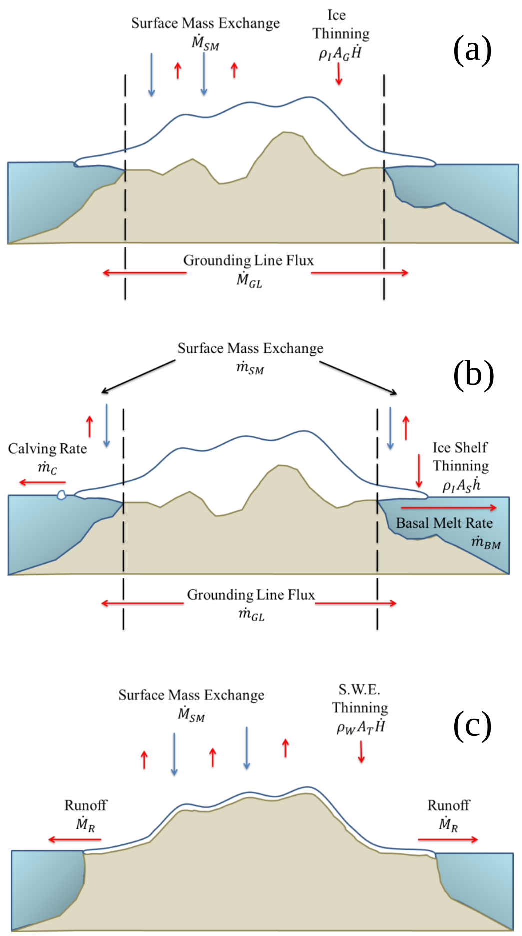


FIG. 1. The components of the mass budget for: (a) the grounded ice on Antarctica, (b) the Antarctic ice shelves, (c) the representation of Antarctica in CESM1-CAM5. S.W.E. denotes "snow water equivalent."

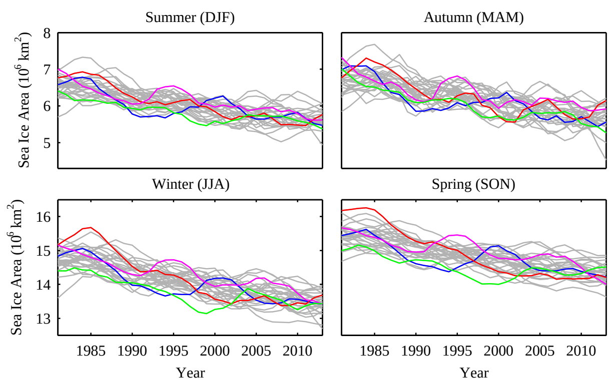
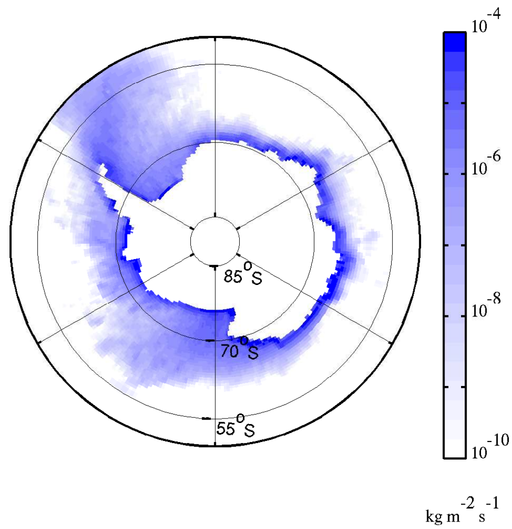


FIG. 2. Seasonal total sea ice area for the 30 members of the CESM1-CAM5 LENS. Our experiments were branched from the colored trajectories. We shall refer to the member highlighted in blue as run 'A', red as run 'B', pink as run 'C' and green as run 'D'. The interior freshwater (IFW) experiments were branched from 'A' and 'B', while the surface freshwater (SFW) experiments were branched from 'A', 'C', and 'D'. A, B, C and D correspond to members 25, 20, 26 and 27 of the ensemble respectively.



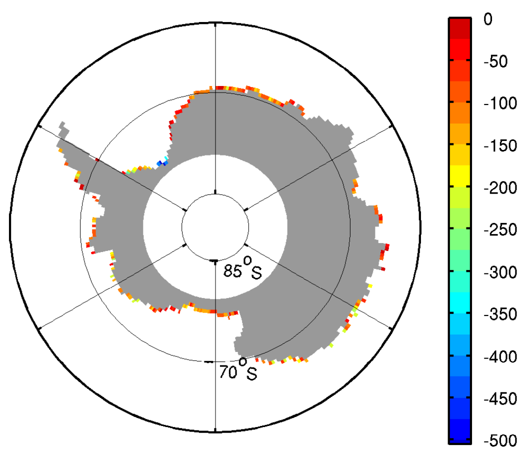


FIG. 3. Maps showing the surface freshwater (SFW) (top) and interior freshwater (IFW) (bottom) distributions. The surface freshwater distribution based on iceberg drift is on a logarithmic scale in order to resolve input far from the coast. The interior freshwater distribution based on ice shelf location shows the location of the grid cells in which the negative salinity forcing was input, the color scale indicates the depth at which the forcing was input.

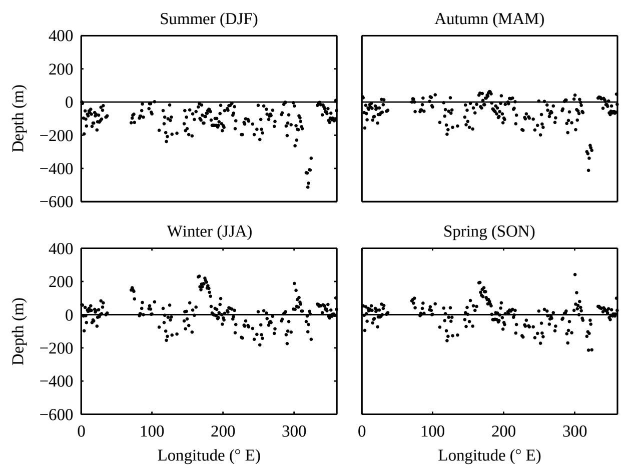


FIG. 4. Difference between the modelled mixed layer depth and the depth of freshwater input for the interior freshwater experiments for each season. A positive (negative) value indicates the depth of input is above (below) the mixed layer depth.

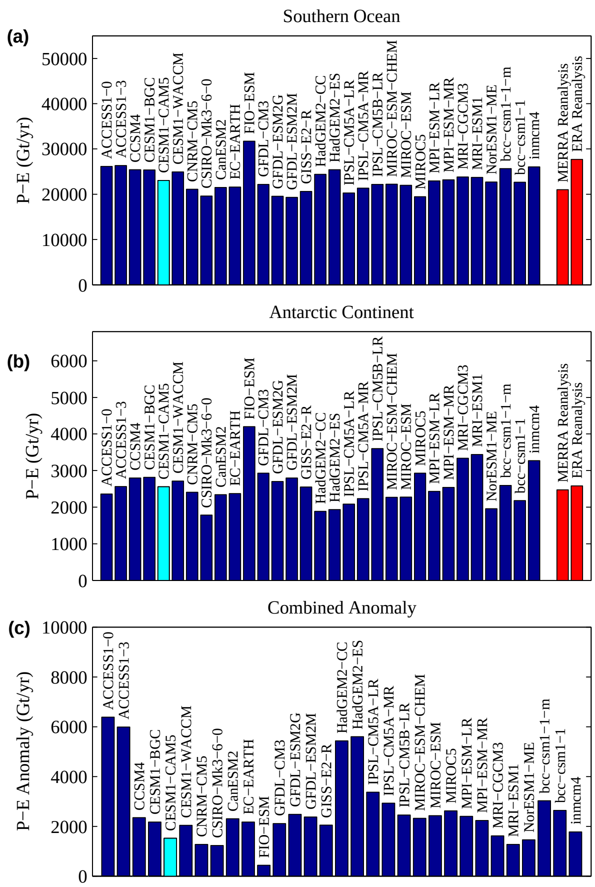


FIG. 5. The net precipitation (precipitation - evaporation) for a selection of the models used in the CMIP5 ensemble for: (a) the Southern Ocean averaged over 1994-2013, (b) the Antarctic Continent averaged over 1994-2013, and (c) the difference between (1994-2013) and (1861-1890) over the Southern Ocean and Antarctic continent combined. The 1994 to 2013 averages also include the ERA and MERRA reanalyses estimates of P-E over the Southern Ocean and Antarctica respectively (red). The CMIP5 model used in this study (CESM1-CAM5) is highlighted in cyan.

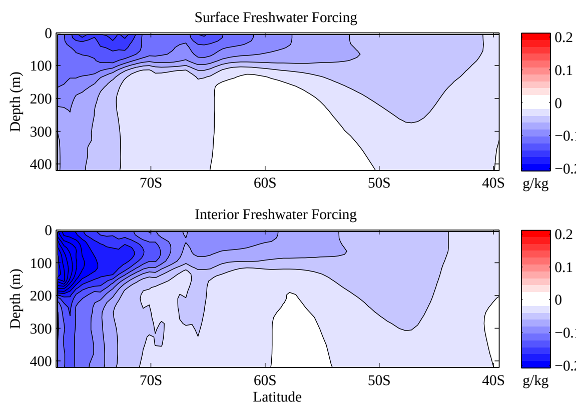


FIG. 6. The response of the zonal mean salinity in the ensemble mean of SFW2000A, C, and D (upper panel) and IFW2000A and B (lower panel) for 1994-2013 (all months) compared to the LENS. Blue/red colors denote a decrease/increase in zonal mean salinity relative to the LENS.

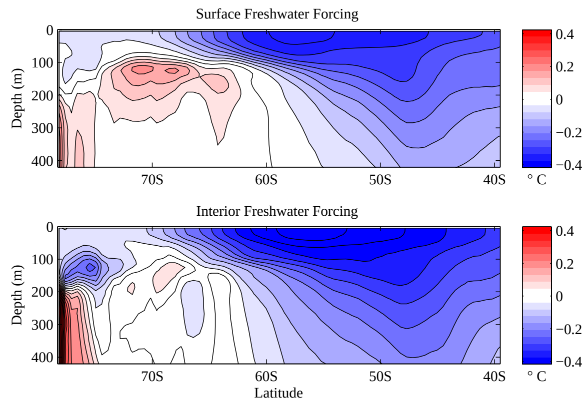


FIG. 7. The response of the zonal mean temperature in the ensemble mean of SFW2000A, C, and D (upper panel) and IFW2000A and B (lower panel) for 1994-2013 (all months) compared to the LENS. Blue/red colors denote a decrease/increase in zonal mean temperature relative to the LENS.

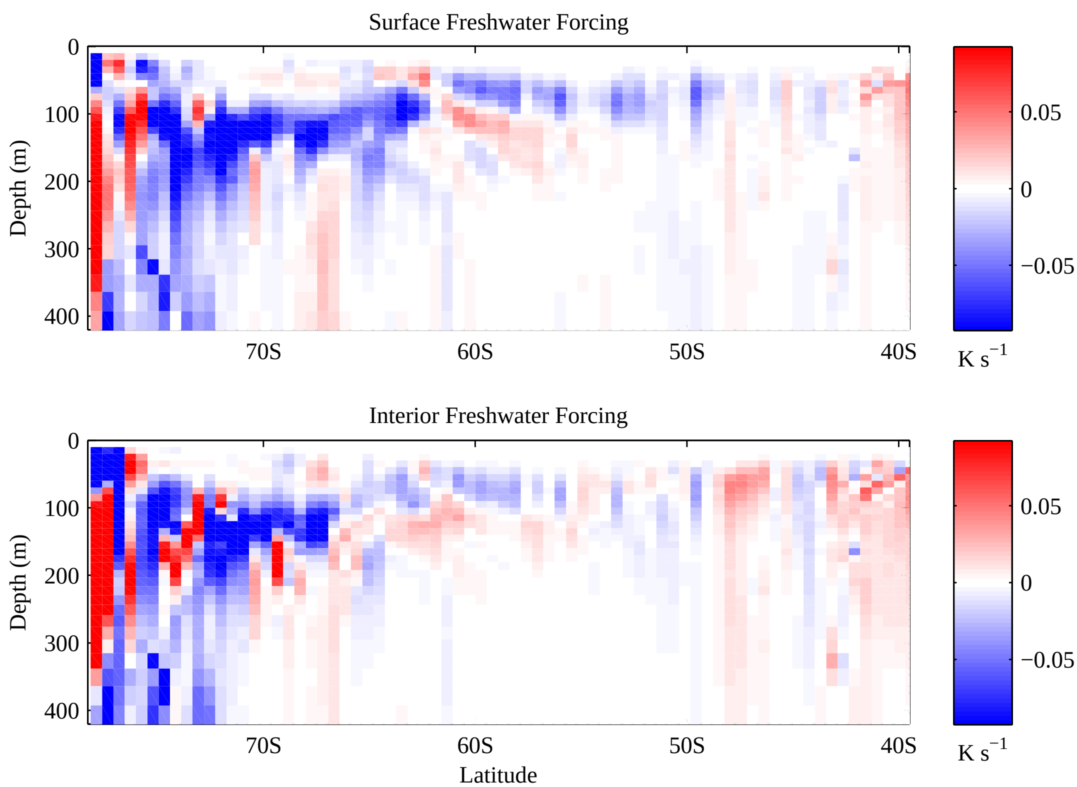


FIG. 8. The response in vertical advection for the SFW2000A, C, and D (top) and IFW2000A and B experiments (bottom) calculated from Eq. 5. Positive/negative values denote an increase/decrease in upwards advection.

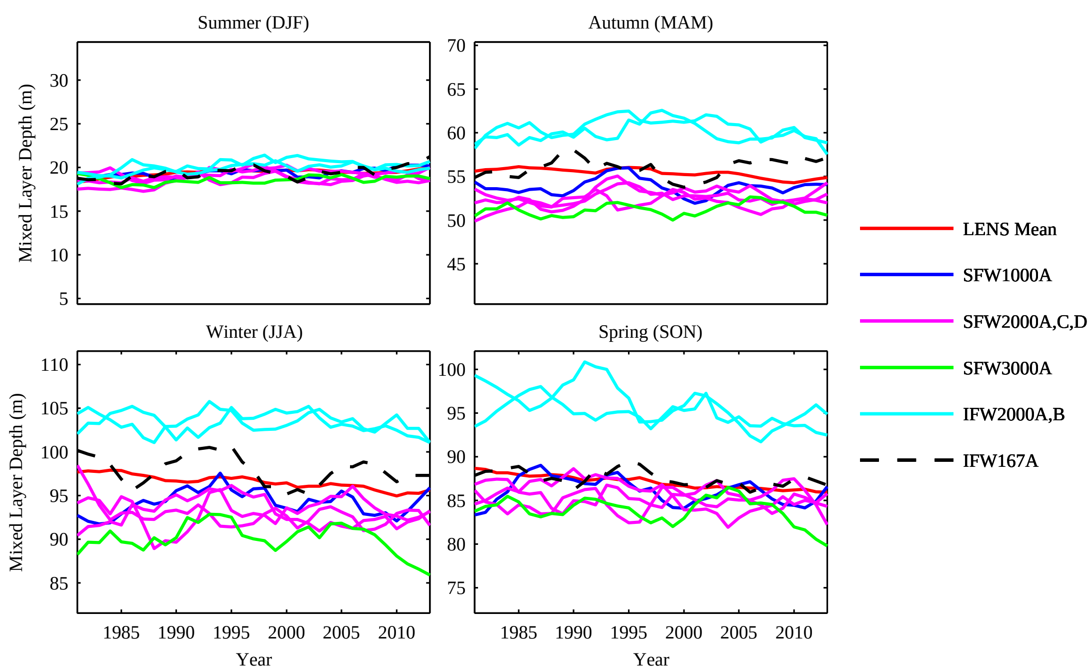


FIG. 9. Seasonal mean mixed layer depth, averaged over all longitudes and all latitudes south of 60° S.

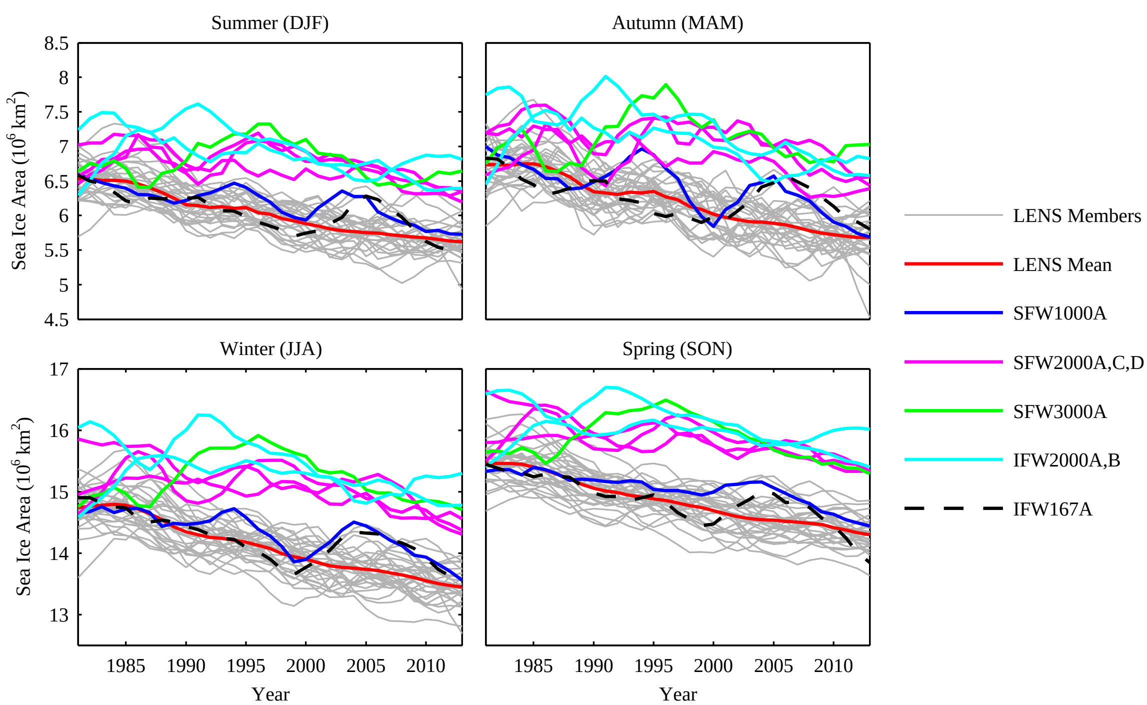


FIG. 10. The 5 year running mean total sea ice area for each of the experiments, as well as the 30 individual LENS members and their mean. Note the different vertical axis scale between Summer/Autumn and Winter/Spring.

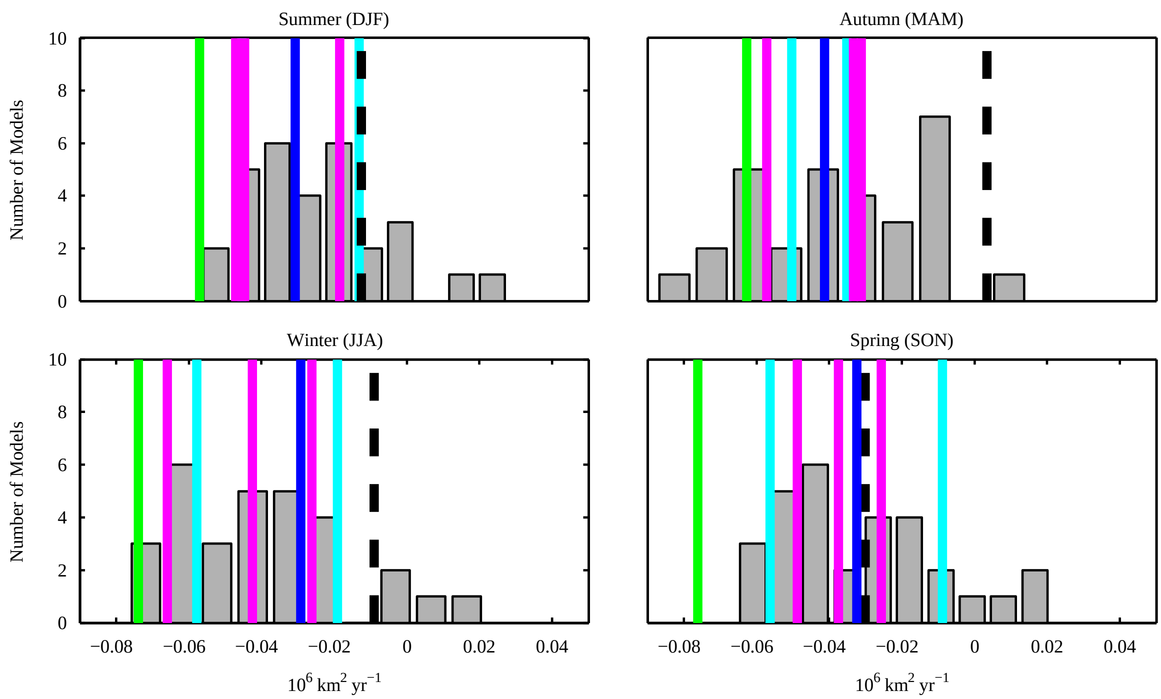


FIG. 11. Histogram of the slopes of a linear fit to the seasonal timeseries of total sea ice area for each of the CESM-CAM5 LENS overlaid with the IFW2000A and B (cyan), IFW167A (dotted black), SFW1000A (blue), SFW2000A, C, and D (pink), and SFW3000A (green) slopes. All were calculated as linear fits to the model output over the period 1994 to 2013, to avoid the transient initial response in the freshwater enhancement experiments.

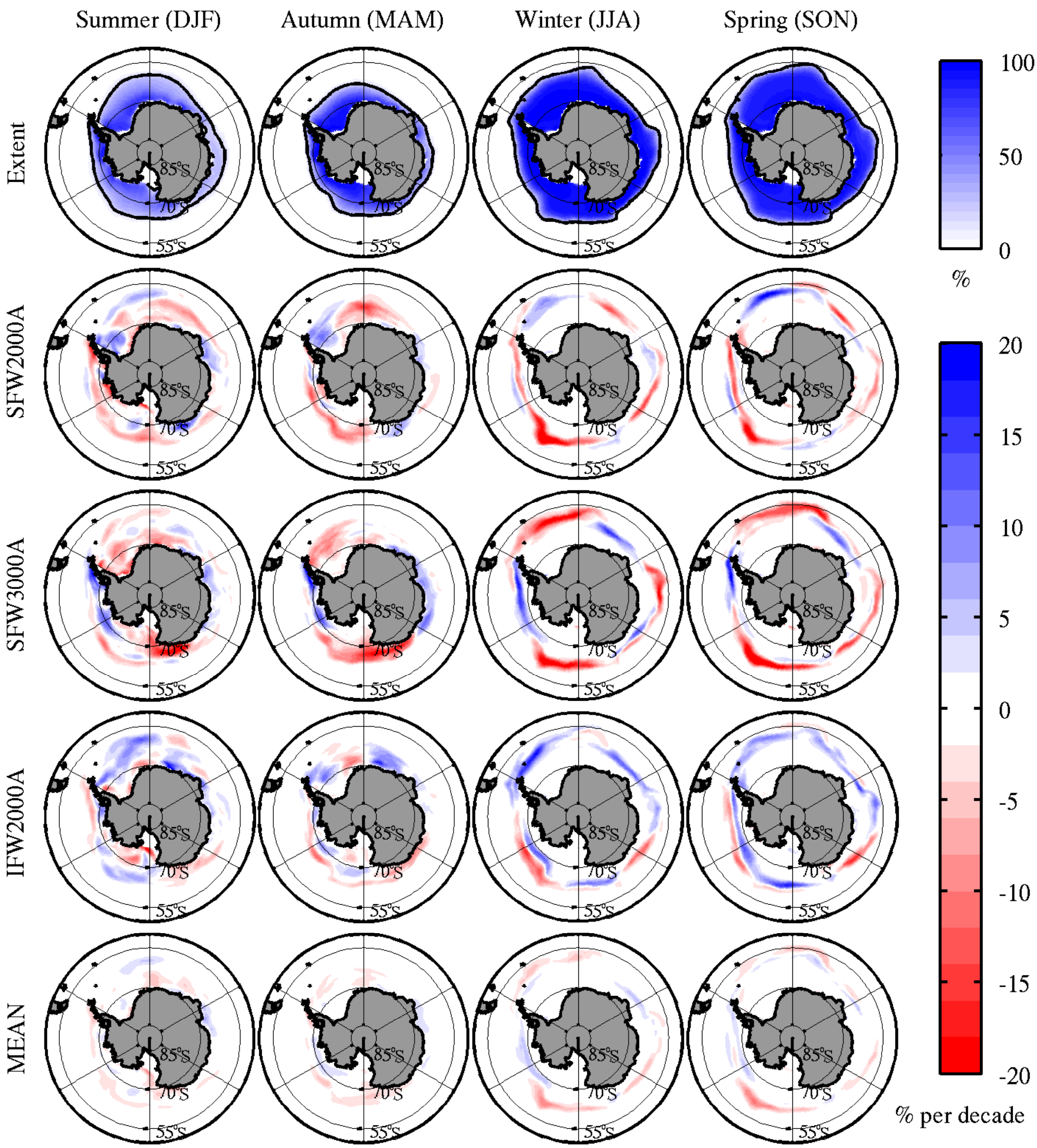


FIG. 12. The LENS mean sea ice concentration and extent for 1994-2013 (top), with the response to the freshwater forcing in sea ice concentration for the SFW2000A (second row), SFW3000A, (third row) and IFW2000A (fourth row) experiments. We also show the mean response of all experiments with ≥ 2000 Gt yr^{-1} (fifth row). The response is the slope of a linear fit to the difference between the experiment and the LENS mean over the period 1994-2013 of the experiments. Note the differing color scales for the top row and those below it. In the lower 4 rows, blue/red colors denote a increase/decrease relative to the LENS mean.