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- Antarctic Bottom Water formation rate highly sensitized to freshwater input
- Ocean stratification leads to reduced vertical mixing and warming at depth
- Warming occurs in sectors of Antarctic ice sheet sensitized to ocean forcing

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Corresponding author:
C. J. Fogwill, c.fogwill@unsw.edu.au

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Sensitivity of the Southern Ocean to enhanced regional Antarctic ice sheet meltwater input

C. J. Fogwill[1], S. J. Phipps[1,2,3], C. S. M. Turney[1], and N. R. Golledge[4,5]

[1]Climate Change Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW, Australia, [2]ARC Centre of Excellence for Climate System Science, University of New South Wales, Sydney, NSW, Australia, [3]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia, [4]Antarctic Research Centre, Victoria University of Wellington, Wellington, New Zealand, [5]GNS Science, Lower Hutt, New Zealand

Abstract Despite advances in our understanding of the processes driving contemporary sea level rise, the stability of the Antarctic ice sheets and their contribution to sea level under projected future warming remains uncertain due to the influence of strong ice-climate feedbacks. Disentangling these feedbacks is key to reducing uncertainty. Here we present a series of climate system model simulations that explore the potential effects of increased West Antarctic Ice Sheet (WAIS) meltwater flux on Southern Ocean dynamics. We project future changes driven by sectors of the WAIS, delivering spatially and temporally variable meltwater flux into the Amundsen, Ross, and Weddell embayments over future centuries. Focusing on the Amundsen Sea sector of the WAIS over the next 200 years, we demonstrate that the enhanced meltwater flux rapidly stratifies surface waters, resulting in a significant decrease in the rate of Antarctic Bottom Water (AABW) formation. This triggers rapid pervasive ocean warming (>1°C) at depth due to advection from the original site(s) of meltwater input. The greatest warming is predicted along sectors of the ice sheet that are highly sensitized to ocean forcing, creating a feedback loop that could enhance basal ice shelf melting and grounding line retreat. Given that we do not include the effects of rising CO_2—predicted to further reduce AABW formation—our experiments highlight the urgent need to develop a new generation of fully coupled ice sheet climate models, which include feedback mechanisms such as this, to reduce uncertainty in climate and sea level projections.

1. Introduction

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change highlights that current and future anthropogenic greenhouse gas emissions are likely to affect climate for millennia to come, due to the long equilibrium response time scales of Earth's oceans and ice sheets [*Collins et al*., 2013; *Stocker et al*., 2013]. One major uncertainty, however, is how the marine-based West Antarctic Ice Sheet (WAIS) will respond to future climate change, and particularly how it may contribute to future global mean sea level (GMSL) [*Lenton et al*., 2008; *Pritchard et al*., 2012; *Vaughan et al*., 2013; *Golledge et al*., 2015]. In part, this question arises from analogy with past interglacial periods when, despite only small apparent increases in mean atmospheric and ocean temperatures, GMSL is predicted to have been far higher than present [*Dutton et al*., 2015; *Dutton and Lambeck*, 2012; *Kopp et al*., 2009]. To achieve these levels, undefined mechanisms must have been at work that substantially increased the net contribution of the Earth's ice sheets to global sea level [*Fogwill et al*., 2014].

One such mechanism could have been through ice-ocean feedbacks that arose as a consequence of enhanced meltwater discharge to the Southern Ocean. This has been highlighted in recent studies investigating the apparent coupling between Antarctic ice sheet change and atmospheric temperatures during past interglacials [*Holden et al*., 2010]. In conclusion, this detailed study of the Last Interglacial demonstrated that feedbacks from WAIS retreat were required to simulate the magnitude of the observed warming within Antarctic ice core records. Therefore, here we focus on the future impacts of increasing Antarctic meltwater input on ocean circulation on a localized time-transgressive basis. While previous studies have examined the effects of Southern Ocean wide sea ice and meltwater feedbacks [*Bintanja et al*., 2013; *Golledge et al*., 2014; *Menviel et al*., 2010; *Swingedouw et al*., 2008; *Weaver et al*., 2003; *Weber et al*., 2014], we project future changes driven by sectors of the WAIS, delivering spatially and temporally variable

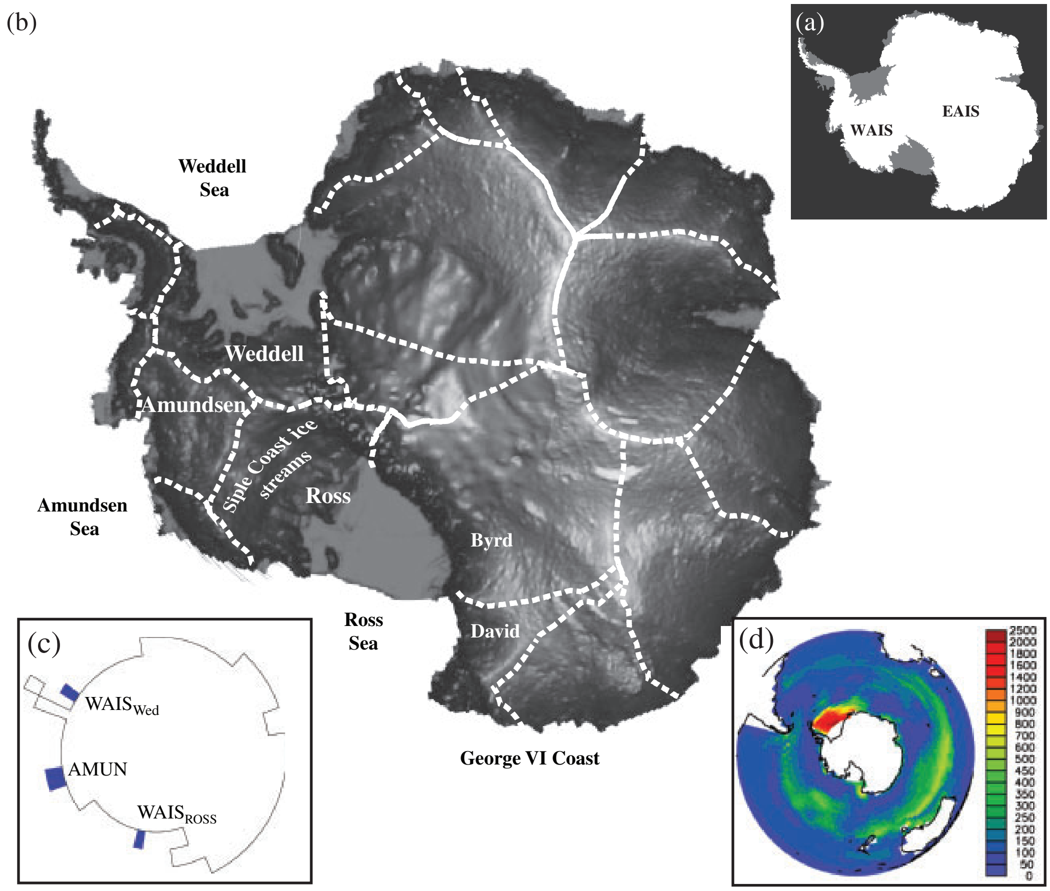

Figure 1. Location map. (a) Overview map of WAIS and EAIS outlining areas of grounded ice (white) and floating ice shelves (grey). (b) The Antarctic ice sheet with key locations and the sectors of the WAIS from which the grounded ice is sourced is labeled (Weddell, Amundsen, and Ross), represented by the RADARSAT-1 synthetic aperture radar mosaic of the ice sheet surface from the Antarctic Mapping Mission (AMM-1) © CSA 2001. The image is overlaid with the modern ice divides of the WAIS and EAIS. (c) CSIRO Mk3L Antarctic land/sea mask with grid squares of meltwater addition highlighted. Blue boxes define the locations of meltwater input for each sector. (d) Convective depth (m) of the pre-industrial control simulation, showing regions of Southern Ocean downwelling and deepwater formation predicted by CSIRO Mk3L.

meltwater flux into the Amundsen, Ross, and Weddell embayments over future centuries (Figure 1). Given that the WAIS has been demonstrated to be a key source of rapid sea level rise during the last deglaciation [*Deschamps et al*., 2012; *Golledge et al*., 2014; *Weber et al*., 2014], and has recently been suggested to have passed a threshold in apparent stability [*Joughin et al*., 2014], the need to understand ice sheet-ocean feedbacks that may alter future ice sheet dynamics is imperative.

The importance of feedbacks is highlighted by recent studies that have demonstrated the Southern Ocean has warmed and freshened substantially over the last four decades [*Purkey and Johnson*, 2013; *Schmidtko et al*., 2014; *van Wijk and Rintoul*, 2014], leading to increased stratification and a reduction in Antarctic Bottom Water (AABW) formation [*de Lavergne et al*., 2014]. The exact drivers of these changes, however, remain uncertain. Possible causal mechanisms range from increased ocean heat uptake to changes in regional hydroclimate or shifts in atmospheric fronts or entrainment of warm deep water [*Fogwill et al*., 2014; *Rhein et al*., 2013; *Spence et al*., 2009; *Spence et al*., 2014; *van Wijk and Rintoul*, 2014]. A potentially major driver of this trend is increasing direct meltwater input from one or more sectors of the Antarctic ice sheets [*Rye et al*., 2014], leading to a reduction in the production of dense shelf water, the precursor to AABW.

Of particular concern is that WAIS retreat in the Amundsen Sea embayment may have passed a threshold in stability and may now be unstoppable [*Joughin et al*., 2014]. This sector of the WAIS has an associated global sea level rise of around ~1.2 m, adding uncertainty to 21st century sea level rise projections and ocean circulation changes, and suggesting that current upper estimates of ~1 m sea level rise over the next century may be conservative [*Joughin et al*., 2014; *Stocker et al*., 2013]. In addition, based on palaeoclimate records and ice sheet modeling studies, it appears that anthropogenic climate change today may be replicating conditions that in the past triggered significant shifts in the stability of the Antarctic ice sheet through positive feedback mechanisms that are not currently included in future projections [*Golledge et al*., 2014]. This uncertainty has been highlighted by several recent studies that have demonstrated changes in the circulation pattern of the Southern Ocean led to rapid melting of sectors of the Antarctic ice sheets [*Golledge et al*., 2014; *Weber et al*., 2014], potentially leading to abrupt rises in global sea level during the last deglaciation [*Deschamps et al*., 2012].

In light of the above questions, we analyze a suite of model simulations that examine the potential impact of Antarctic meltwater on the Southern Ocean over future centuries and millennia. In order to explore the effects of meltwater discharge on ocean circulation, we undertake a number of simulations using a fully coupled climate system model that provide new insights into the effects of spatially and temporally variable meltwater fluxes from Antarctica. We examine the response of the atmosphere, ocean, and sea ice to variable and time-transgressive meltwater input from specific locations at the periphery of the ice sheet to better understand both contemporaneous and potential future interactions between the ice sheet and the ocean around Antarctica. We do not include the effects of rising CO_2—predicted to further reduce AABW [*Phipps et al*., 2012]—so as to explore the role of meltwater alone on Southern Ocean circulation, a factor that may play a role in freshening and contraction of AABW today [*van Wijk and Rintoul*, 2014].

2. Data and Methods

We use CSIRO Mk3L version 1.2, a fully coupled atmosphere-ocean general circulation model, to carry out multi-centennial simulations. The model comprises fully interacting ocean, atmosphere, land surface, and sea ice components, and is designed for millennial-scale climate simulations [*Phipps et al*., 2011; *Phipps et al*., 2012]. The ocean model has a horizontal resolution of 1.6° latitude × 2.8° longitude and 21 vertical levels, while the atmosphere model has a horizontal resolution of 3.2° latitude × 5.6° longitude and 18 vertical levels. Importantly, CSIRO Mk3L has demonstrated utility for simulating past and future changes in the climate system, including the millennial-scale response to anthropogenic forcing [*Phipps et al*., 2013; *Phipps et al*., 2012]. We chose CSIRO Mk3L for this study because it includes full dynamic complexity in its sub-models, and yet is sufficiently computationally efficient to allow us to explore the long-term evolution of the Southern Ocean to meltwater fluxes.

Our experiments consider a range of idealized hypothetical scenarios, from collapse of discrete sectors of the WAIS, as suggested by remote sensing and model estimates [*Joughin et al*., 2014; *Rignot et al*., 2014], through to a complete collapse of the entire ice sheet. Meltwater is added in specific sectors, close to modern grounding lines, over varying periods of time (Table 1). We focus on the WAIS given that, as the only marine-based ice sheet on the planet, it represents one of the key potential tipping elements in the Earth's climate system [*Lenton et al*., 2008]. While we acknowledge that there is a growing body of evidence that suggests sectors of the East Antarctic Ice Sheet (EAIS) may also be at risk from marine ice sheet instability (MISI) [*Mengel and Levermann*, 2014], the WAIS has the potential to respond on centennial timeframes [*Hellmer et al*., 2012; *Joughin et al*., 2014; *Lenton et al*., 2008]. We divide the WAIS into three sectors, Weddell, Ross, and Amundsen, based on the modern ice sheet geometry and ice divides (Figure 1); while these could evolve over time due to rapid changes such as those recorded in the Amundsen Sea region [*Joughin et al*., 2014], it provides a means of dividing the potential meltwater input of the modern ice sheet into sectors.

We employ an ensemble modeling approach. For each experiment, the model was integrated three times. Each of these simulations was identical except for the fact that it is initialized from a different year of a pre-industrial control simulation. Such an approach allows us to better distinguish between natural internal climate variability and the forced response to the meltwater fluxes. The results reported here represent the ensemble mean for each experiment, with any anomalies being calculated relative to the pre-industrial control simulation. Extensive analysis demonstrates that CSIRO Mk3L reproduces pre-industrial climatology faithfully [*Phipps et al*., 2011; *Phipps et al*., 2012], and it has been used extensively to examine decadal and centennial changes in climate phenomena including El Niño and the Southern Annular Mode [*Abram et al*., 2014; *McGregor et al*., 2013]. Critically, CSIRO Mk3L reproduces broader scale Southern Ocean dynamics well, predicting rates of pre-industrial simulation AABW formation of ~6.8 Sv, a value close to Southern Ocean

Table 1. Southern Ocean Freshwater Pulse Experiments: Seawater Equivalent (SWE), Time of Meltwater Input for Each Experiment, Freshwater Flux (Sv) Based on Time Frame, and Key Reference

Scenario	Total SWE (m)	Time (years)	Freshwater Flux (Sv)	Description	Principal Reference
AMUN	1.2	200	0.069	Loss of Amundsen Sea sector of the WAIS over 200 years	*Rignot et al.* [2014]
$WAIS_{MAX}$	3.6	(i) 200 (ii) 400	(i) 0.139 (ii) 0.070	Loss of Amundsen Sea sector over 200 years, plus loss of Ross and Weddell Sea sectors over 400 years	*Rignot et al.* [2014]; *Bamber et al.* [2009]
$WAIS_{MIN}$	3.6	(i) 900 (ii) 1000	(i) 0.044 (ii) 0.028	Loss of Amundsen Sea sector over 900 years, plus Ross and Weddell Sea sectors over 1,000 years	*Rignot et al.* [2014]; *Bamber et al.* [2009]

observations of between 8.1 and 9.4 Sv [*Orsi et al*., 1999]. In addition, it reproduces the subduction of Southern Ocean surface waters just north of the Antarctic Circumpolar Current (ACC), where it forms Sub-Antarctic Mode Water and Antarctic Intermediate Water, the building blocks of the global ocean shallow-overturning circulation [*Connolley and Bracegirdle*, 2007]. These features can clearly be seen in our pre-industrial climatology, apparent from the projected depth of convection in the simulated pre-industrial control simulation (Figure 1d).

We deliberately choose not to increase CO_2 in our experiments. While we acknowledge that the combined effects of elevated CO_2 have substantial implications for both sea ice production and AABW formation [*Phipps et al*., 2012], our aim is to disentangle, in detail, the effects of localized meltwater flux delivery at the periphery of the Antarctic ice sheets to examine potential feedback loops independent of past or future CO_2 changes [*Collins et al*., 2013; *Holden et al*., 2010; *Joughin et al*., 2014; *Swingedouw et al*., 2008].

Our simulations focus on the three hypothetical "end member" scenarios: AMUN, $WAIS_{MAX}$, and $WAIS_{MIN}$. These are summarized in Table 1. AMUN reflects a hypothetical collapse of the Amundsen Sea sector of the WAIS over the next two centuries [*Joughin et al*., 2014]. This was implemented as a freshwater flux of 0.069 Sv into the Southern Ocean through the Amundsen Sea embayment for 200 years, equivalent to an increase of ~1.2 m in the global sea level. $WAIS_{MAX}$ provides an extreme scenario of a collapse of the Amundsen Sea sector of the WAIS over 200 years, combined with an additional collapse of the Weddell and Ross Sea sectors of the WAIS over a total of 400 years [*Bamber et al*., 2009]. Finally, $WAIS_{MIN}$ represents a hypothetical collapse of the Amundsen Sea sector of the WAIS over 900 years, combined with an additional collapse of the Weddell and Ross Sea sectors of the WAIS over 1000 years. As such, the only difference between $WAIS_{MIN}$ and $WAIS_{MAX}$ is the timing of meltwater delivery to the ocean. The locations of the sources of grounded ice and resultant meltwater input for each experiment are shown in Figure 1.

Past studies have considered simple scenarios, hosing large sectors of the Southern Ocean [*Bintanja et al*., 2013; *Holden et al*., 2010; *Menviel et al*., 2010; *Morrison et al*., 2015; *Weaver et al*., 2003], but we are not aware of any that have considered the direct effects of localized time-transgressive meltwater input on ice sheet dynamics. Recent studies have shown that Antarctic meltwater input can be highly localized [*Shepherd et al*., 2004], and yet still have important implications for the Southern Ocean circulation, atmospheric processes, sea ice regimes, and potentially ice sheet dynamics [*Pritchard et al*., 2012; *Rhein et al*., 2013; *Vaughan et al*., 2013]. Importantly, we choose not to include the additional effects of rising CO_2 in our simulations due to the extremely strong impact that predicted increases in CO_2 will have on sea ice formation, brine rejection, and therefore AABW formation over forthcoming decades and centuries [*Phipps et al*., 2012], which potentially contradict contemporary observations of Southern Ocean sea ice expansion and AABW contraction and freshening [*Rhein et al*., 2013; *van Wijk and Rintoul*, 2014]. Thus, while our experiments represent hypothetical idealized scenarios, they allow us to examine the response of the Southern Ocean to both limited localized meltwater additions (i.e., AMUN) and more extensive time-transgressive collapse scenarios (i.e., $WAIS_{MAX}$ and $WAIS_{MIN}$). These scenarios are critical for better understanding the evolution and response of the Southern Ocean to meltwater input that is predicted to be highly spatially and temporally variable [*Rignot et al*., 2014].

3. Results

Here we discuss the response of the Southern Ocean to the meltwater forcing simulations, and the driving mechanisms involved.

3.1. Southern Ocean Response

Each model simulation reveals rapid and pervasive impacts on the Southern Ocean circulation from the imposed freshwater flux. To understand the impacts on AABW formation and other climate variables, we compare changes to the climatology of the pre-industrial control simulation. While there is some variability in the structure, due to the evolving model response to each individual experiment, the 50 year running mean of each simulation clearly demonstrates the strong effect that meltwater has on AABW formation, with the rate decreasing by 25–50% within decades in comparison to the control situation (Figure 2a). Importantly, the levels of AABW remain reduced throughout the hosing period and, while there is apparent structure within the 50 year running mean in the first 200 years of the $WAIS_{MAX}$ and AMUN experiments, this structure, which reflects the model's evolving response to forcing, is lost when we examine the 10 year running means over this period (Figure 2b). The extremely rapid nature of the freshwater flux's impact on AABW formation causes far-reaching, rapid, and pervasive changes within the Southern Hemisphere climate system.

Through comparison between the scenarios, it is possible to assess the impact of an increased freshwater flux in different regions of the Southern Ocean; this is particularly important when considering potential feedback effects on the Antarctic ice sheets [*Golledge et al*., 2014; *Rye et al*., 2014]. Figure 2 demonstrates the effect on the rate of AABW formation within each experiment. While each scenario leads to rapid reductions in AABW formation, their signatures vary markedly. AMUN experiences a rapid decline from a mean rate of 6.9 Sv in the pre-industrial control simulation to a minimum of about 3.6 Sv by the end of the 200 year hosing period (Figure 2b). $WAIS_{MAX}$ experiences a similar magnitude of change, with a rapid initial decline to around 3.2 Sv, followed by a gradual recovery, and then further stepped recoveries after 200 and 400 years as the meltwater flux ceases. These simulations both contrast with $WAIS_{MIN}$ which, while exhibiting a strong and pervasive response to the hosing, only experiences a reduction in AABW formation of ~1.7 Sv at a broadly constant level over the 900 years, with a recovery to levels above background after a further 100 years prior to returning to pre-industrial levels by the end of the 1500 year experiment. The apparent bounce back and variability of the $WAIS_{MIN}$ experiment post-hosing reflects the evolving model response to forcing, and it is important to note that the values in Figure 2 are the 50 year running means of the simulations. More detail of both the reduction and increase in the rate of AABW formation can be seen in Figure 2a where the 10 year running mean is presented for the first 250 years of hosing.

3.2. Driving Mechanisms

The model outputs show that these increased freshwater fluxes rapidly reduce the mixing of the cold surface waters with the underlying warmer waters and lead to cooling of the surface and warming at depth in all simulations. This can be seen clearly in Figure 3, which depicts the evolving temperature anomaly in response, over each 50 year period of the 200 year experiment (Figures 3a–3d), to the reduction in the rate of AABW formation (Figure 3e) for the AMUN simulations. This results from density-driven stratification of the upper ocean by the increased freshwater, with increased freshwater fluxes rapidly reducing the rate of AABW formation. This results in a rapid initial freshening of the surface waters, which is apparent as a reduction in the sea surface salinity (SSS; Figure 4) and a concomitant reduction in the sea surface density (SSD; Figure 5). As would be expected, these changes are strongest in the regions where the freshwater fluxes are applied. The SSS is reduced by up to 6 psu in the Amundsen Sea during the first 200 years of the experiment, but then rapidly recovers as soon as the hosing ceases. The SSS is also reduced by up to 4 psu in the Ross and Weddell Seas (Figure 4). The reduction in SSD leads to increases in the stratification of the upper ocean, reducing the depth of convection markedly in some locations (Figure 6). It is worth noting that, regardless of the internal redistribution of heat within the ocean, the response of the surface climate is negligible with, for example, only insignificant changes in the latitude and/or intensity of core westerly airflow (Figure 7).

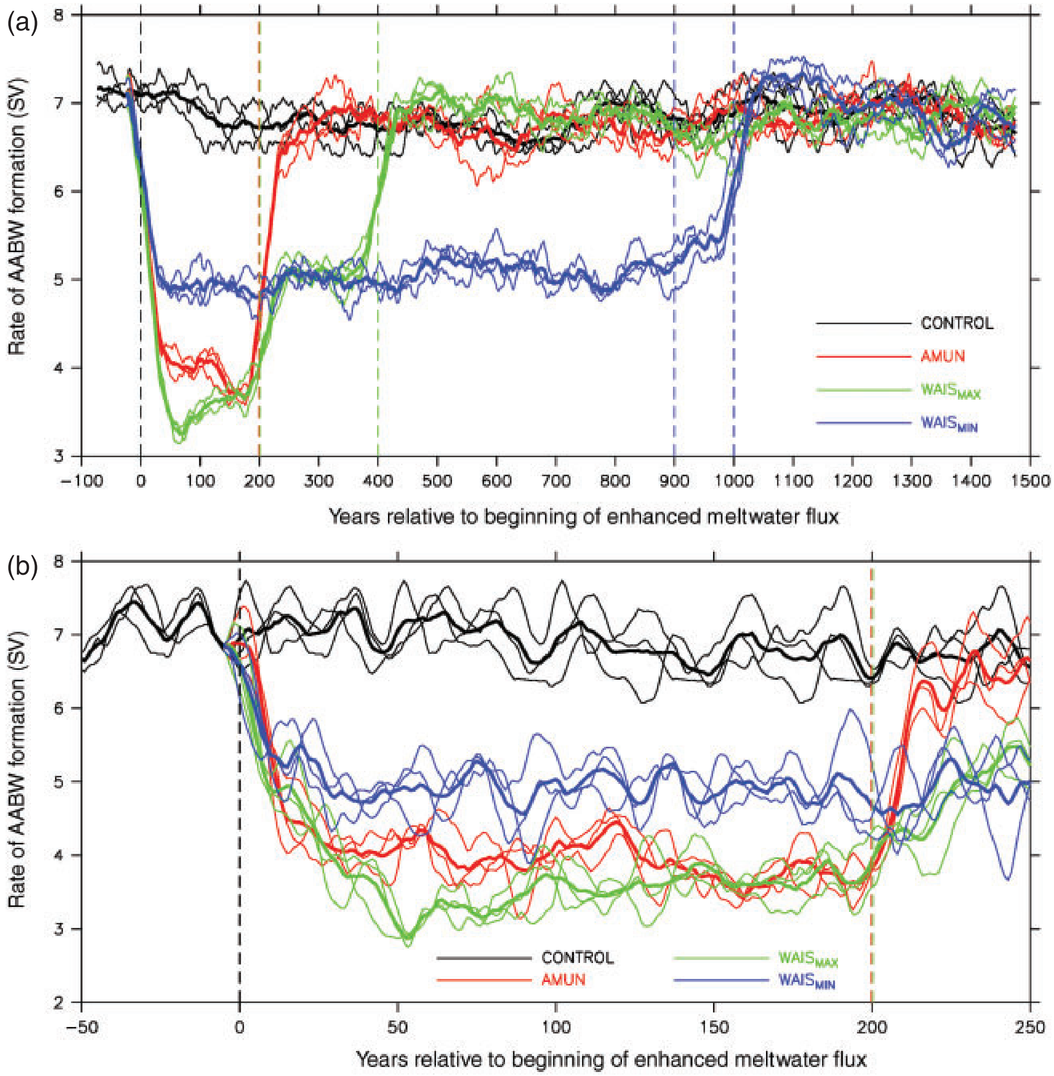

Figure 2. The changes in the rate of AABW formation predicted from experiments AMUN, WAIS$_{MIN}$, and WAIS$_{MAX}$, plotted against the pre-industrial control simulation to demonstrate the background variability. The thin lines indicate the rate of AABW formation from individual simulations; thick lines indicate the ensemble mean. (a) Evolution of AABW formation over the full period of the regional experiments from −100 to 1500 model years. It should be noted that the values shown are 50 year running means. (b) Evolution of the period −50 to 250 model years. It should be noted that the values shown are 10 year running means. The vertical dashed lines indicate the end(s) of the hosing phase(s) for each experiment.

These changes in the Southern Ocean are most apparent in the regions of strong contemporary AABW formation in the Ross and Weddell Seas, as the sudden decrease in the rate of AABW formation drives the pronounced temperature differences through the water column (Figure 3). The magnitude of the warming at depth varies spatially depending on the location and magnitude of the imposed meltwater flux; however, the pattern of warming simulated in response to each of our scenarios is remarkably similar. This can be seen in Figure 8, which compares each of the experiments 101–200 years after the initiation of hosing.

While all of the experiments predict warming at depth (400–700 m) around the entire continent, the focus of intense warming stretches from the western Antarctic Peninsula, along the Amundsen Sea Embayment and into the Ross Sea extending to George V Coast (Figures 8a–8c). The degree of warming in these regions is remarkable, ranging from 0.5°C to in excess of 1°C between 400 and 700 m within the first 200 years of each experiment. The sites of intense warming at depth correlate with regions of marked changes in convective depth (Figures 8d–8f). Given that changes in convective depth are seen in all regions of AABW formation in all simulations, advection of the meltwater input around the Southern Ocean in the coastal counter current

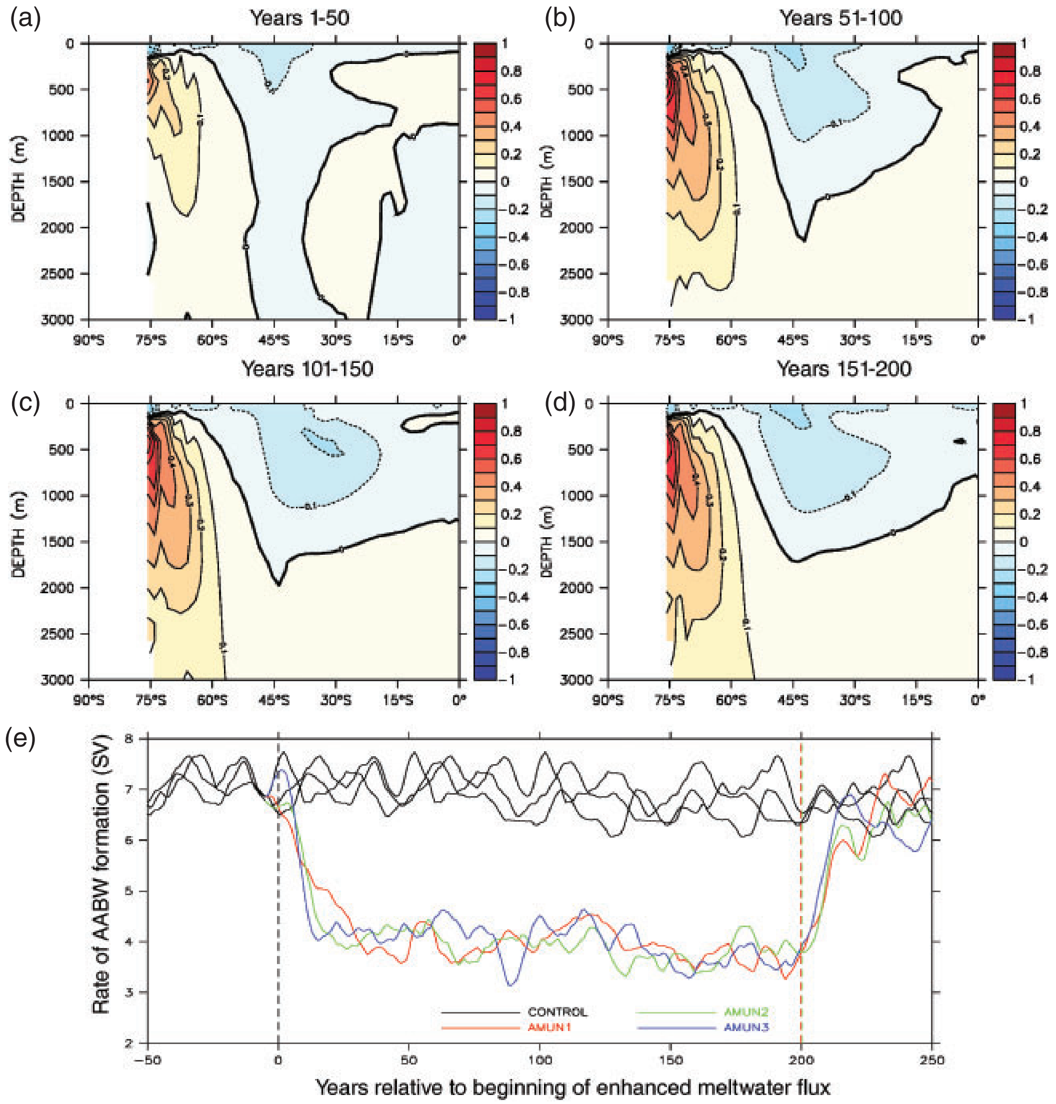

Figure 3. The average zonal mean ocean temperature anomaly (°C), relative to the equivalent years of a pre-industrial control simulation, across the Southern Hemisphere during hosing for experiment AMUN for years (a) 1–50, (b) 51–100, (c) 101–150, and (d) 151–200. (e) Lower panel depicts the evolution in the rate of AABW formation predicted from experiment AMUN, plotted against the pre-industrial control simulation to demonstrate the background variability and evolving model response. The thin lines indicate the rate of AABW formation from individual simulations evolution of the period −50 to 250 model years. It should be noted that the values shown are 10 year running means. The vertical dashed lines indicate the end of the hosing phase for experiment AMUN.

is clearly an important mechanism for communicating the meltwater signal and triggering stratification and concomitant warming around the periphery of the continent.

4. Discussion

The results of our three experiments clearly demonstrate a strong positive feedback mechanism between increased Antarctic meltwater flux and warming at depth in the Southern Ocean in all scenarios. By focusing meltwater flux in discrete locations in a time-transgressive way, we are able to demonstrate that the oceanic response is controlled not only by the volume or temporal evolution of the flux of freshwater into the ocean but also that the location plays a critical role in the impact that meltwater has on Southern Ocean dynamics.

While the effects of the freshwater input are strongest near the Antarctic continent, they are felt across the Southern Hemisphere (Figure 3), with the reduced AABW and increased stratification impacting the salinity and temperature structure across the oceans; however, the most intense changes are seen in the

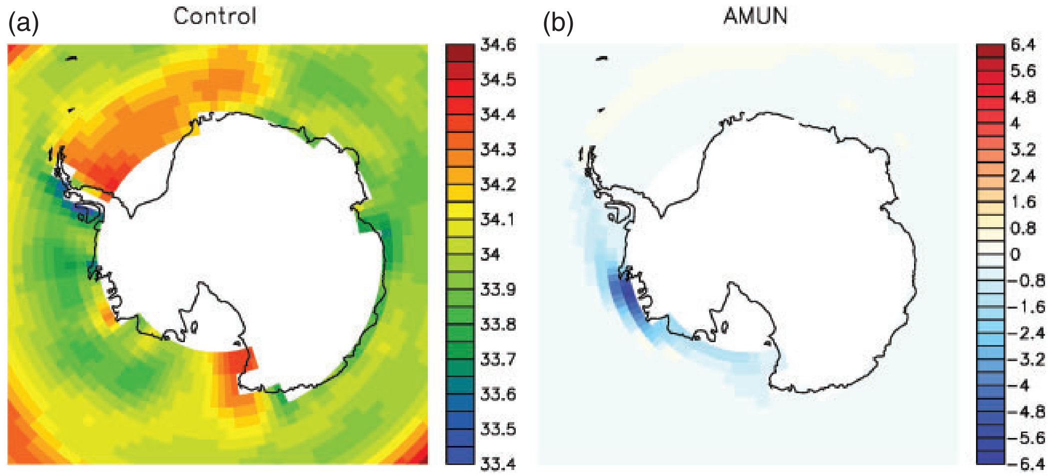

Figure 4. Average sea surface salinity (psu) during (a) a pre-industrial control simulation, and (b) years 151–200 of experiment AMUN, expressed as an anomaly relative to the control.

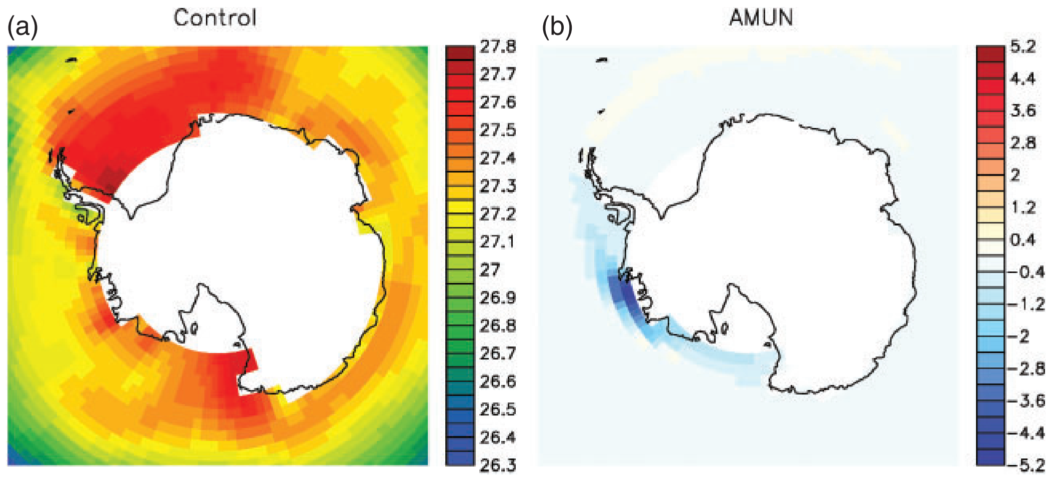

Figure 5. Average sea surface density (kg m^{-3}) during (a) a pre-industrial control simulation, and (b) years 151–200 of experiment AMUN, expressed as an anomaly relative to the control. In (a), 1000 kg m^{-3} has been subtracted from the values for convenience.

Southern Ocean, as suggested by other studies that use Southern Ocean sector wide freshwater forcing [*Menviel et al*., 2010; *Morrison et al*., 2015] (Figure 9). In reality, although possible increases in CO_2 are not included in our experiments, future fluxes of freshwater into the Southern Ocean due to melting of the WAIS may also change in response to increasing atmospheric concentrations of greenhouse gases; these increases, through a reduction in Antarctic sea ice formation, would cause an additional reduction in the rate of AABW formation [*Phipps et al*., 2012; *Swingedouw et al*., 2008]. These changes would act to exaggerate the response seen in our simulations. Our scenarios should therefore be regarded as conservative, and warming at depth in the Southern Ocean with increased CO_2 would likely exceed the values simulated. A detailed understanding of the interplay and feedbacks between meltwater and rising CO_2 should be seen as a priority for future modeling studies given the rises predicted over the coming decades [*Collins et al*., 2013].

With the recent evidence which suggests that the Amundsen Sea sector of the WAIS may have already passed a key threshold in stability [*Joughin et al*., 2014], our discussion focuses on the AMUN experiment, and the potential implications that this has for future Antarctic ice sheet stability and associated global sea level rise. The AMUN experiment shows a remarkable and rapid reduction in the rate of AABW formation, in common with each of the experiments (Figure 2). The resultant warming at depth is also remarkable, and

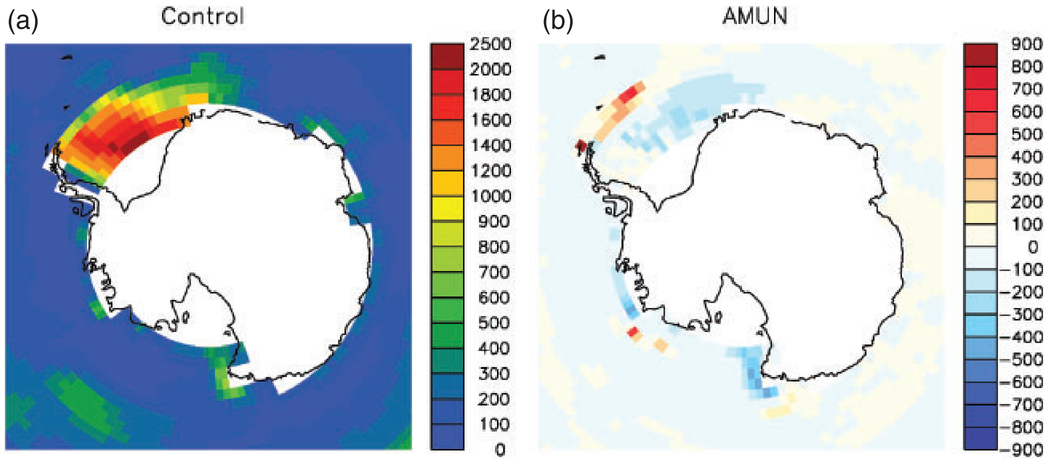

Figure 6. Average depth of convection (m) during (a) a pre-industrial control simulation, and (b) years 151–200 of experiment AMUN, expressed as an anomaly relative to the control.

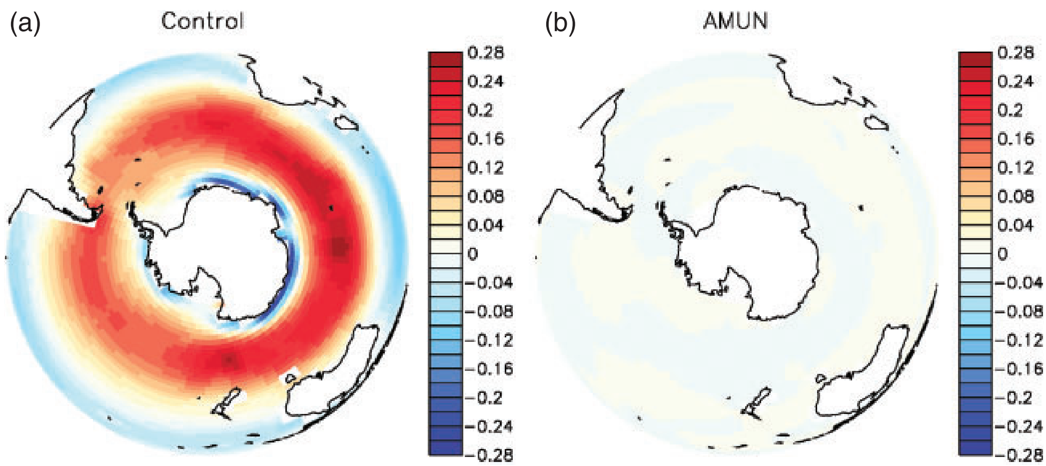

Figure 7. Average zonal component of surface wind stress (N m^{-2}) during (a) a pre-industrial control simulation, and (b) years 151–200 of experiment AMUN, expressed as an anomaly relative to the control.

is of a similar magnitude to the WAIS_{MAX} experiment, reflecting the importance of the location of the meltwater input (Figure 8). This is supported by the WAIS_{MAX} experiment, which shows a distinct recovery once hosing from the Amundsen Sea has ceased after 200 years (Figure 2). The magnitude of this response suggests that the Amundsen Sea is a critical location for meltwater input, a conclusion that is further supported by the marked recovery within the WAIS_{MAX} experiment as soon as the Amundsen Sea sector flux ends. The behavior of the AMUN experiment most likely reflects two factors: first, the instantaneous application of a freshwater flux of 0.069 Sv into the Amundsen Sea; second, strong transport through the Antarctic coastal counter current, which redistributes the enhanced freshwater toward the two important sectors of AABW formation, stratifying the ocean and rapidly reducing bottom water formation in both the Ross Sea and off George V Coast (East Antarctica) (Figure 8).

The reduced rate of exchange between the cold surface waters and the underlying warmer waters leads to a rapid early regional warming, with the strongest temperature increases occurring at the depths of the grounding lines. This can be seen clearly in Figure 9, which shows warming at depth and temperature changes in the Amundsen, Ross, and Weddell Seas predicted from the AMUN experiment. Importantly, the simulated warming is instantaneous and pervasive, remaining stable for several centuries throughout the water column (Figure 3). It is also noted that the magnitude of the warming is of the order of that recorded

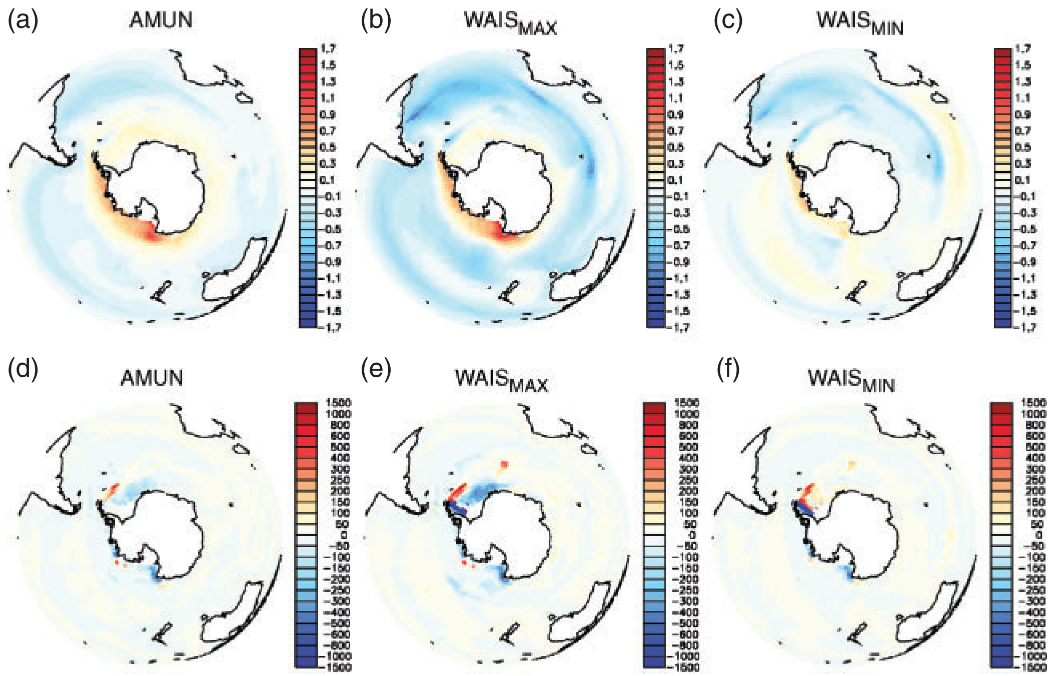

Figure 8. Upper panels: Average mean ocean temperature anomaly (°C), relative to the equivalent years of a pre-industrial control simulated, between 400 and 700 m for years 101–200 from experiment, (a) AMUN, (b) WAIS$_{MAX}$, and (c) WAIS$_{MIN}$. Lower panels: Average mean convective depth anomaly (m), relative to the equivalent years of a pre-industrial control simulated, for years 101–200 from experiment, (d) AMUN, (e) WAIS$_{MAX}$, and (f) WAIS$_{MIN}$.

in the ACC over recent decades [*Boning et al*., 2008], as well as locally in the Amundsen Sea. This is associated with rapid ice sheet drawdown triggered by marine ice sheet instability (MISI) [*Joughin and Alley*, 2011; *Shepherd et al*., 2004].

Although our simulations project warming at several localities around the Southern Ocean—including along the Antarctic Peninsula—it is the marked warming along the fringes of the WAIS including Marie Byrd Land and in the Ross Sea that have significant implications for future ice sheet stability (Figure 1). Through comparison of the resultant warming predicted by the model, and the outputs from high-resolution ice sheet modeling studies [*Fogwill et al*., 2014; *Golledge et al*., 2012; *Golledge et al.*, 2015], we can see that the foci of the ocean warming are adjacent to the sectors of the ice sheet that are predicted to respond most rapidly to ocean forcing. These sites correspond with sectors of the WAIS—and potentially the EAIS—that are drained by fast-flowing outlet glaciers, conduits which originate in the interior of the ice sheet.

Previous experiments suggest that these major arteries of the ice sheet are highly sensitive to changes in ocean temperature and sea level at the periphery of the continent, and are able to induce drawdown from the WAIS and EAIS, transmitting changes felt in the ocean rapidly to the interior of the ice sheet [*Golledge et al*., 2012]. The sensitivity of these sectors of the ice sheet relates to two major factors: the coincidence of ice sheet basins with concave ice sheet surface profiles [*Cuffey and Patterson*, 2010], and an individual basin's connectivity to the ocean [*Fogwill et al*., 2014]. These conditions exist—and importantly may well persist due to hysteresis within ice sheets [*Schoof*, 2007]—across much of the WAIS, including the Siple coast ice streams in the Ross Sea (Figure 1), but also in key sectors of the EAIS, namely the Byrd and David catchments of the western Ross Sea. In common with many of the WAIS catchments, the David and Byrd catchments currently exhibit concave profiles suggesting weakness at their bed and potential for high mass flux [*Fogwill et al*., 2014]. Importantly, flux changes in the David and Byrd catchments have the potential to cause drawdown within the extensive Wilkes sub-glacial basin, supporting past studies that highlight a potential contribution to future global sea level from the EAIS [*Fogwill et al*., 2014; *Fox*, 2010; *Mengel and Levermann*, 2014; *Miles et al*., 2013].

To summarize, the changes in the properties of AABW triggered by increasing freshwater input in the Southern Ocean surrounding Antarctica have critical implications for the dynamics of the Antarctic ice sheet.

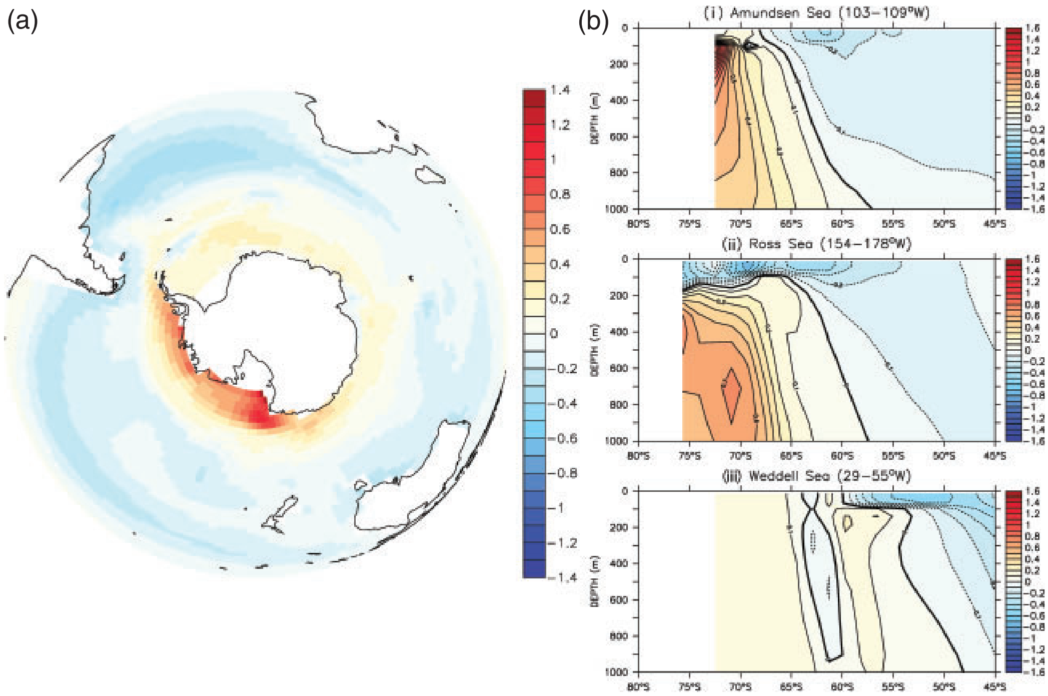

Figure 9. (a) Average ocean temperature anomaly (°C) between 400 and 700 m. (b) Detail of average zonal mean temperature anomaly (°C) across the (i) Amundsen, (ii) Ross and (iii) Weddell Seas. All values shown are the mean for years 101–200 of experiment AMUN, relative to the equivalent years of a pre-industrial control simulation.

Intriguingly, several recent studies provide growing evidence of rapid contemporary changes in the properties of AABW [*Jacobs et al*., 2002; *Rhein et al*., 2013; *van Wijk and Rintoul*, 2014]. Observations suggest that the AABW layer is warming, freshening, and contracting in volume [*Jacobs et al*., 2002], although the drivers of these changes are not yet clear. Our simulations and the mechanism described above suggests that contemporary Southern Ocean freshening may already be occurring as a result of increasing delivery of meltwater from Antarctic ice, with the possibility that a marked reduction in the rate of AABW production may be imminent [*Purkey and Johnson*, 2013; *Rhein et al*., 2013], triggering further warming at depth in the Southern Ocean. When combined with uncertainties regarding potential increases in ocean temperatures due to shifting winds and/or changing ocean circulation patterns, the potential for marked changes in ocean ice sheet dynamics over the next century is high [*Fogwill et al*., 2014; *Hellmer et al*., 2012; *Miles et al*., 2013; *Spence et al*., 2014]. Our experiments provide a unique insight into potential future changes in the Southern Ocean that have important implications for the stability of the Antarctic ice sheets. This study examines just one of a number of strong feedback mechanisms operating at the ocean ice sheet interface that question current sea level rise projections; clearly, modeling studies will need to integrate these feedbacks to gain a more realistic picture of future change.

5. Conclusions

Our idealized experiments demonstrate that the stability and rate of AABW formation is highly sensitized to surface salinity variations in the Southern Ocean at the periphery of the Antarctic ice sheets. Previous modeling studies have demonstrated that this sensitivity may have been crucial in driving periods of past rapid ice sheet change [*Fogwill et al*., 2014; *Golledge et al*., 2014]. Therefore, given current projections of ice sheet change, this mechanism must be assessed to explore the potential feedback mechanisms that may occur in the next century and beyond. This study demonstrates that the impact on the rate and volume of AABW formation due to enhanced localized meltwater is essentially instantaneous, experiencing significant reductions within decades of input, but with no apparent atmospheric response.

The simulated modeled rapid response of Southern Ocean circulation may explain the current reduction and contraction in AABW formation recorded since the 1950s [*Rhein et al*., 2013; *Stocker et al*., 2013; *van Wijk* *and Rintoul*, 2014]. This contrasts with the potential impacts of increasing CO_2, which, despite the strength of their forcing, are predicted to take some centuries to significantly impact AABW formation [*Phipps et al*., 2012]. Our experiments demonstrate clearly that even without CO_2 forcing, changes in circulation driven by surface salinity decreases in response to meltwater input lead to net warming in many sectors of the Southern Ocean, ranging from 0.4 to in excess of ∼1°C between 400 and 700 m within the first 200 years of each experiment (Figure 3; Figures S1 and S2, Supporting Information). With the location of this warming at the grounding lines of portions of both the WAIS and EAIS, which are already sensitized to marine-driven instability [*Fogwill et al*., 2014], this meltwater-ocean warming feedback provides an additional and important mechanism that increases the likelihood of marine instability of large sectors of the Antarctic ice sheets. To better constrain sea level rise projections, future coupled ice sheet-ocean models must include these nonlinear feedback mechanisms to better understand anomalous observations across the Southern Ocean today.

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