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Impact of Antarctic ice shelf basal melting on sea ice and deep ocean circulation

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Abstract. An approximation of Antarctica's rocky and icy coastline normally forms the southern boundary in global climate models. Such a configuration neglects extensive ice shelf areas where ocean-ice interaction initiates a net freshwater flux to the circumpolar continental shelf equal to ∼75% of the annual mean net precepitation in coastal seas. The results of a numerical model for the Southern Ocean using two contrasting configurations with and without caverns beneath major Antarctic ice shelves are compared. They show that the freshwater flux due to deep basal melting significantly stabilizes the shelf water column in front of an ice shelf as well as downstream due to advection by the coastal current. If the freshwater from the caverns is absent, sea ice is thinner, shelf waters are warmer and saltier, and the Southern Ocean deep basins are flushed by denser waters.

1. Introduction

Freshwater fluxes in the Southern Ocean have been studied in relation to the mass balance of the Antarctic ice sheet [*Jacobs et al.*, 1992; *Jacobs et al.*, 1996] and the freshwater budget of the Weddell Sea [*Timmermann et al.*, 2001]. The only flux, however, considered to be significant for the large-scale circulation is due to sea-ice melting [*Goosse and Fichfet*, 1999; *Shin et al.*, 2003]. Precipitation deposited on the Antarctic ice sheet is ultimately released as freshwater to the ocean, either locally as basal melting of floating ice shelves, or remotely as melting of drifting icebergs. The importance of the former source today is evidenced by extensive caverns underlying the ice shelves which represent ∼11% of the ice-sheet area and ∼50% of the Antarctic coastline [*Fox and Cooper*, 1994]. Modification of dense shelf water in the caverns due to melting and freezing at deep glacial bases is directly linked to the formation of bottom water at the continental shelf break [*Foldvik et al.*, 1985] and the ventilation of the world ocean abyss [*Orsi et al.*, 2001]. Warmer flows underneath the ice shelves and melting at shallower bases [*Hellmer et al.*, 1998; *Makinson and Nicholls*, 1999] freshen the surface waters, contributing to a stabilization of the weakly stratified water column. Changes in the export of freshwater from the caverns are likely to affect shelf water characteristics and thus deep convection, the main oceanic process for bringing heat to the surface and dense water to lower strata.

2. Experiment

Aside from snapshot realizations, continous long-term monitoring is difficult to conduct along ice-shelf fronts due to their inaccessibility and the threat of iceberg calving. Consequently, the coupled ice-ocean model BRIOS-2.2 [*Timmermann et al.*, 2002a; *Assmann et al.*, 2003] is used here to quantify the freshwater originating from melting ice shelf bases (Figure 1) and to study its influence on the Southern Ocean. The model includes state-of-the-art representation of the processes of air-sea ice/ice shelf-ocean interaction, deep convection, and deep-water formation at the continental margin. With a grid size of 1.5° zonally and $1.5° \times \cos\phi$ meridionally (∼110 km at the northern boundary (50°S) and ∼25 km at the southern boundary (82°S)) the model domain includes the major ice-shelf caverns listed in Table 1, representing 74% of the total floating ice body. For the set-up without caverns the land mask was extended to the ice-shelf front. Both configurations were forced for 20 model years with a 20-year (1978–1997) climatology using NCEP 10-m winds, 2-m air temperature, specific humidity, cloudiness, and net precipitation [*Kalnay et al.*, 1996].

3. Model Results

The total sub-ice freshwater flux (FWF; Table 1) of 28.42 mSv (1 mSv = $10^3 m^3 s^{-1}$) represents a significant contribution to the freshwater budget of the Antarctic continental shelf, even if basal melting of Eastern Weddell Ice Shelves (5.19 mSv) and Fimbulisen (12.95 mSv) might be overestimated. Iceberg calving at a rate of 2016×10^{12} kg yr^{-1} [*Jacobs et al.*, 1992] results in a freshwater flux of ∼70 mSv which mainly affects surface waters remote from the continent. Net precipitation in the coastal seas yields 38.62 mSv based on the NCEP 20-year annual mean. This figure, biased by high values in the Indian sector [e.g., *Bromwich*, 1988], reduces to 11.64 mSv for the continental shelves of the Weddell and Ross Seas. In addition, most precipitation falls in winter mainly as snow transported off the continental shelf with the sea ice. The magnitude of the basal mass loss (BML; Table 1) is comparable to previous estimates [*Jacobs et al.*, 1996] which indicated a shrinking of the Antarctic ice sheet. The modeled BML might further increase with even smaller ice-shelf caverns added, e.g., Pine Island Glacier (100°W, 75°S), or might decrease with increasing resolution of the continental shelf accentuating topographic features which restrain open ocean waters from direct interaction with glacial bases (e.g., Fimbulisen).

Neglecting the sub-ice freshwater input has various implications for the Southern Ocean. These are most pronounced in the Weddell and Ross Seas where large caverns are connected to broad continental shelves. Here, winter sea-ice thickness decreases by more than 0.2 m (Figure 1), a reduction of 10-25%, outside of the wind-induced coastal polynyas. Since identical atmospheric forcing is applied to both model configurations, these areas of low sea-ice concentration and thickness remain at the same place. Thinner sea ice also moves with the general drift to cover the deep ocean and adjacent continental shelves, e.g., in the western Ross Sea. A separate area of thinning sea ice is located in the northwestern Weddell Sea. This region near the recently decayed northern Larsen Ice Shelf [*Skvarca et al.*, 1999] hosts important formation sites of deep and bottom water which spread into the Scotia Sea and beyond [*Gordon*, 1998; *Schodlok et al.*, 2002]. In the vicinity of smaller ice shelves (Amery and Getz; Figure 1) with less freshwater input, thinning of the sea-ice cover is not so drastic. No change or thicker ice occurs in front of the small ice shelves (EWIS, Fimbulisen, Shackleton; Table 1) where the close proximity to the coastal current causes a rapid transport of their meltwater to the west.

The continental shelf waters become warmer and saltier if the caverns' freshwater is absent (Figure 2). Cooling, together with salt enrichment, happens only in the western Ross Sea where the closing of the cavern reduces the southward flow of warmer open ocean mixtures [*Assmann et al.*, 2003]. Although differences in temperature are otherwise positive and scattered over a wider range than in salinity, the density of the deep layers on the continental shelf generally increases (Figure 3) as salinity determines the density at low sea-water temperatures. Consequently, denser water masses escape from the continental shelf spreading as newly formed bottom water ($\sigma_2 > 37.16$) north in to basins beyond the ocean ridges which confine most of the current deep and bottom water formation sites in the Southern Ocean (Figure 3). The comparison of near-bottom density distribution for the model years 10 to 20 shows that, in addition, the density signal implemented on the continental shelf of the Weddell and Ross Seas travels near-coast westward with a speed of ~2 cm s^{-1}. The Weddell Sea signal soon attenuates on passing the eastern South Pacific while the Ross signal is still detectable as it enters the eastern Weddell Sea. This interconnection is possibly related to the dynamics of the coastal current and seems to be identical with the so-called Antarctic Circumpolar Coastal Wave [*Beckmann and Timmermann*, 2001].

The response to the missing ~28 mSv of freshwater is unequally distributed along Antarctica's periphery. This is not necessarily a consequence of the asymmetric arrangement of ice shelves melting at different rates. Instead, it can be related to the dynamics of the coastal current, continental shelf topography and the interaction between both. A broad continental shelf stores salty shelf water but can as well collect the freshwater of upstream basal melting. A reduction or lack of the latter thus amplifies the salinisation of the shelf waters and the destabilisation of the water column. The changes in sea-ice thickness (Figure 1) and bottom salinity (not shown) are more pronounced in the inner Weddell Sea despite the Ross Ice Shelf providing more freshwater than the Filchner-Ronne Ice Shelf (FWF in Table 1). Due to a bifurcation of the coastal current, however, melt-water from the eastern ice shelves is added to the Filchner-Ronne melt in the southern

Weddell Sea. The sources east of the Ross Sea in the Amundsen and Bellingshausen Seas are less productive (Abbot, Getz, and George VI; Table 1) and their freshwater signal rapidly attenuates toward the coastal current due to mixing with Circumpolar Deep Water penetrating onto the continental shelf [e.g., *Hellmer et al.*, 1998]. Therefore, consideration of the strong melting Pine Island Glacier would add 28 Gt a^{-1} [*Jacobs et al.*, 1996] to the total BML, but the amount of freshwater added to the coastal current and consequently to the Ross Sea would be insignificant.

4. Discussion and Conclusions

This study indicates that the influence of today's ice shelf basal melting on the Antarctic coastal seas is two-fold. The sub-ice freshwater cools and freshens the shelf waters, which are supplied by warm and salty open ocean components. It also contributes to the stabilization of the shelf water column reducing its susceptibility to deep convection driven by sea-ice formation and related brine release. Compared to the scenario without ice shelf caverns, less vertical exchange forms less dense shelf water and reduces the heat transfer to the surface inceasing the sea ice thickness. This result qualitatively agrees with a similar numerical experiment by *Beckmann and Goosse* [2003] in which the addition of basal meltwater to a global ice-ocean model caused sea-ice thickening in front of the major Antarctic ice shelves. Ice shelf basal melting in that model, however, was parameterized as a function of shelf geometry and temperature distribution at the continental shelf break.

The salinisation of the continental shelf due to the missing sub-ice freshwater (~28 mSv) is mitigated by less sea-ice formation. The comparison of winter (JAS) ice volumes of the 20th model year reveals that the net ocean freshwater loss amounts to 12 mSv. This figure indicates that the availability of basal meltwater is the key element in determining the shelf water characteristics (Figure 2). However, deep convection, initiated by a less stable water column, causes the sea-ice thinning (Figure 1) and the accumulation of denser waters at the bottom of the continental shelf (Figure 3). Thinner sea ice disintegrates faster allowing for an extended seasonal warming of the ocean surface. This adds to a new equilibrium state of the ice-ocean system with thinner sea ice, as shown by the time series of modeled ice thicknesses.

Results from earlier model studies indicate that freshwater fluxes to the ocean surface influence the sea-ice thickness distribution in the Southern Ocean [*Marsland and Wolff*, 2001]. They, however, affect the coastal seas only during summer, while in winter precipitation is transported northward with the sea ice. In contrast, the sub-ice shelf freshwater flux, though subject to temporal changes [*Timmermann et al.*, 2002b], dilutes the continental shelf water year-round with only minor spatial variability. This flux can only be compensated at the ocean surface if reduced sea-ice growth acts in concert with enhanced precipitation in coastal seas. Ice shelf basal melting depends on shelf water characteristics [*Nicholls*, 1997] which are controlled by the seasonal sea-ice cycle. The sensitivity of this self-regulating process in a key region of the global thermohaline circulation has yet to be determined. The results of this study, however, indicate that any reduction of the present ice-shelf area at Antarctica's periphery in combination with reduced basal melting changes the shelf water characteristics and decreases the stability of the water column, enhancing deep convection and the formation of denser bottom water. A comprehensive treatment of the sub-ice shelf environment and the related freshwater fluxes thus seems essential for future models designed to explore the Southern Ocean's role in past and future climates.

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Table 1. List of ice-shelf areas as represented in the model and as calculated by Giovinetto and Bentley [1985] (in parentheses), simulated annual means (20^{th} year) of freshwater flux (FWF), spatial average basal ice mass flux (BMF), and total basal mass loss (BML) assuming an ice density of 917 kg m^{-3}.

Ice Shelf	Area [$\times 10^5$ km^2]	FWF [mSv]	BMF [m a^{-1}]	BML [Gt a^{-1}]
Abbot [1]	0.36 (0.51)	0.57	0.55	18.16
Amery [2]	0.55 (0.75)	0.55	0.35	17.65
E-Weddell [3]	0.76 (0.82)	5.19*	2.38	165.9
Filchner-Ronne [4]	4.08 (5.48)	3.73	0.32	119.7
Fimbulisen [5]	0.54 (0.58)	7.76*	4.91	243.1
George VI [6]	0.57 (1.21)	0.69	0.43	22.48
Getz [7]	0.30 (0.66)	1.66*	1.95	53.64
Larsen [8]	0.66 (n.a.)	1.19	0.63	38.13
Ross [9]	4.01 (5.83)	5.61	0.49	180.2
Shackleton [10]	0.50 (0.82)	1.47	1.04	47.68
TOTAL	12.33 (16.66)	28.42		906.6

Due to model resolution and choice of the southern boundary (82°S), and the calculation based on drainage systems rather than on ice-shelf fronts [*Giovinetto and Bentley*, 1985], the model's total ice-shelf size is ∼25% less than the calculated size. FWFs marked with (∗) might be overestimated because of an insufficiently resolved narrow continental shelf allowing the coastal current to interact directly with ice-shelf bases. For the location of ice shelves compare numbers in brackets with Figure 1. 1 mSv=1×10^3 $m^3 s^{-1}$, 1 Gt=10^{12} kg.

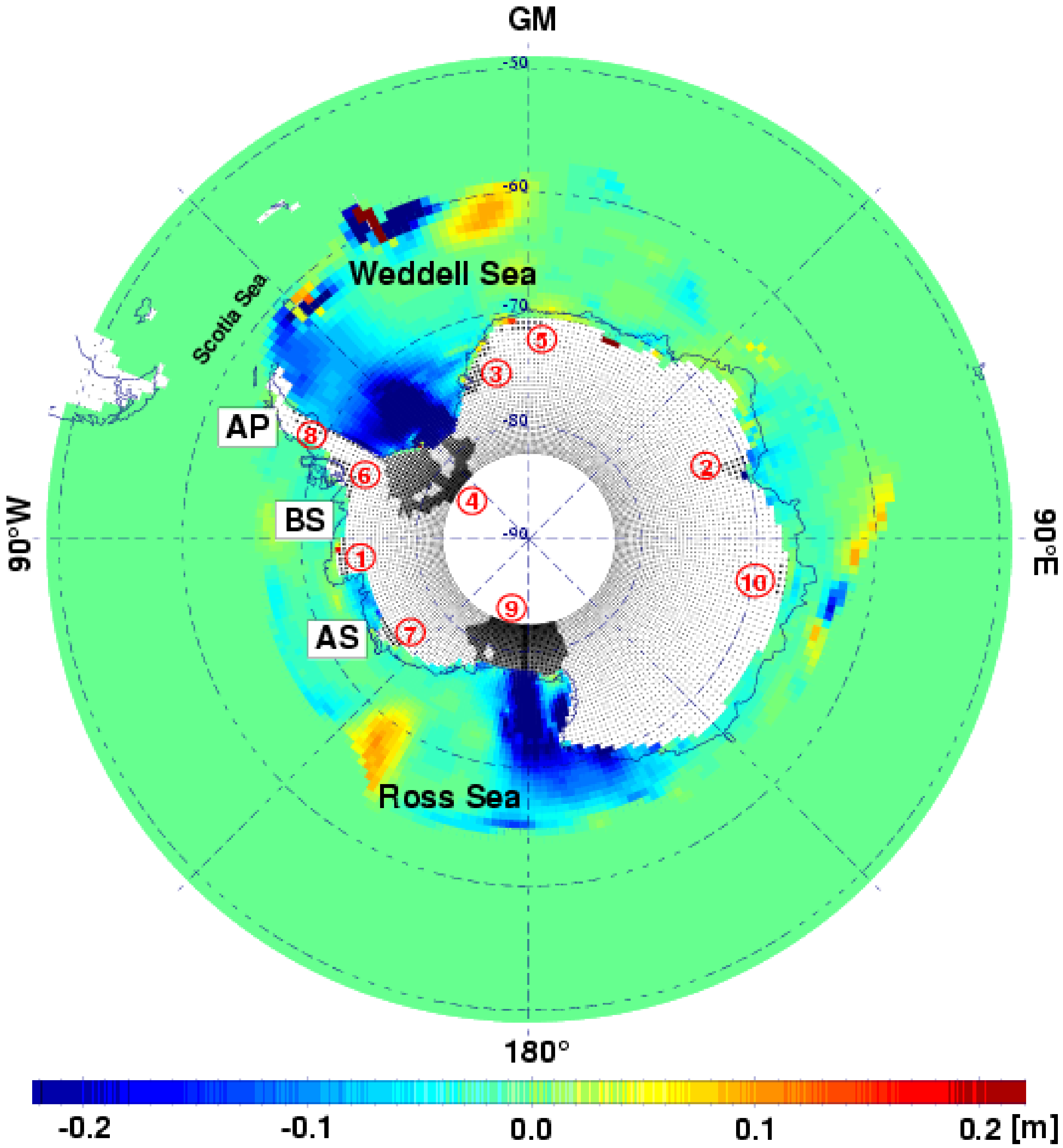

Figure 1. Difference in sea-ice thickness distribution for September of the 20^{th} model year in the Southern Ocean between two model configurations without ice-shelf caverns *minus* with ice-shelf caverns. Extreme values around South Sandwich Islands (∼30°W) are due to an insufficient resolution of island passages. Circled numbers represent locations of ice shelves (dark shaded) listed in Table 1. AP: Antarctic Peninsula, BS: Bellingshausen Sea, AS: Amundsen Sea.

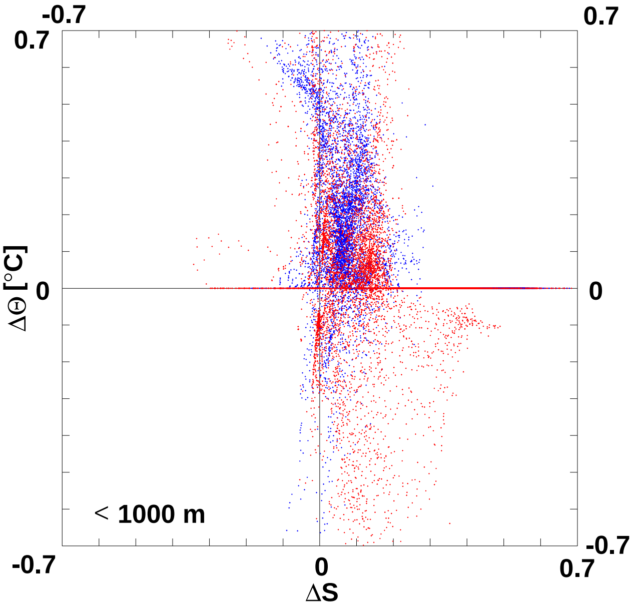

Figure 2. Annual mean (20^{th} model year) potential temperature vs. salinity diagram as difference (Δ) between the model configurations without ice-shelf caverns *minus* with ice-shelf caverns separated for water column thickness less than 1000 m in the Weddell (blue) and Ross (red) Seas. Though the southern continental shelf is generally less than 500 m deep, the 1000-m threshold was chosen to include the troughs of Weddell and Ross Seas.

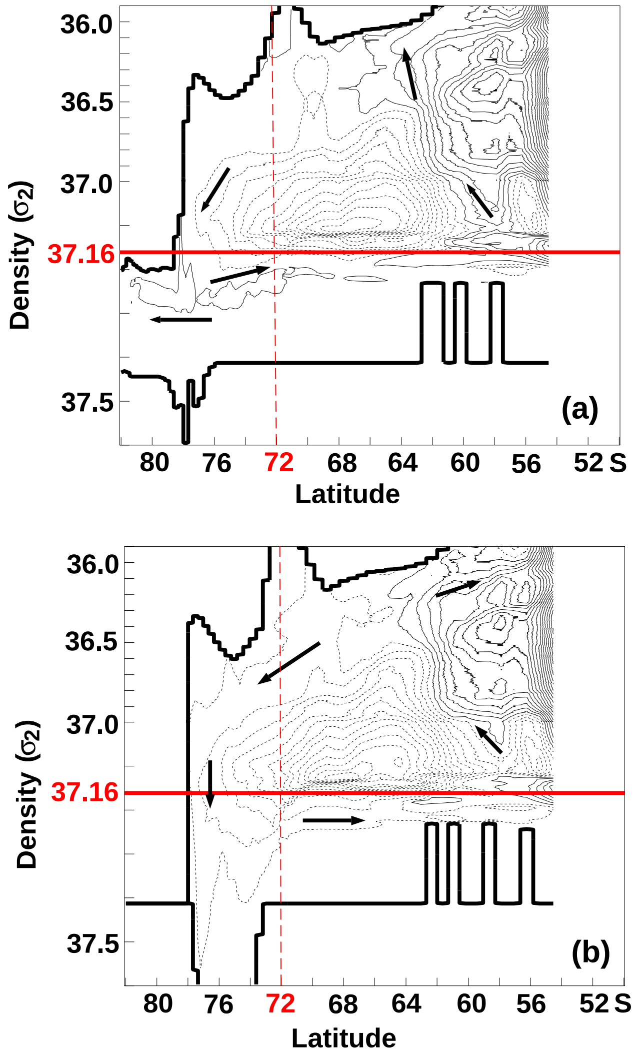

Figure 3. Annual mean (20^{th} model year) overturning transport streamfunction for the Southern Ocean south of 54°S for model configurations (a) with and (b) without ice-shelf caverns. For densities $\sigma_2 \geq 37.0$ kg m^{-3}, the vertical scale is stretched to better present the dense water transport. Red lines mark the density $\sigma_2 = 37.16$ kg m^{-3} defined as upper bound for Antarctic Bottom Water formed south of the Antarctic Circumpolar Current [*Orsi et al.*, 1999] (horizontal), and the approximate position of the continental shelf break in Weddell and Ross Seas (vertical). Dashed contours indicate counter-clockwise, solid contours clockwise circulations (see arrows). Bold solid lines represent the minimum (upper) and maximum (lower) density value for each latitudinal band. Contour spacing is $1{\times}10^6$ m^{3}s^{-1} starting from $\pm 1 \times 10^6$ m^{3}s^{-1}.