Contribution of giant icebergs to the Southern Ocean freshwater flux

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[1] In the period 1979–2003 the mass of "giant" icebergs (icebergs larger than 18.5 km in length) calving from Antarctica averaged 1089 ± 300 Gt yr⁻¹ of ice, under half the snow accumulation over the continent given by the Intergovernmental Panel on Climate Change (2246 \pm 86 Gt yr⁻¹). Here we combine a database of iceberg tracks from the National Ice Center and a model of iceberg thermodynamics in order to estimate the amount and distribution of meltwater attributable to giant icebergs. By comparing with published modeled meltwater distribution for smaller bergs we show that giant icebergs have a different melting pattern: An estimated 35% of giant icebergs' mass is exported north of 63°S versus 3% for smaller bergs, although giant bergs spend more of the earlier part of their history nearer to the coast. We combine both estimates to produce the first iceberg meltwater map that takes into account giant icebergs. The average meltwater input is shown to exceed precipitation minus evaporation (P - E) in certain areas and is a nonnegligible term in the balance of freshwater fluxes in the Southern Ocean. The calving of giant icebergs is, however, episodic; this might have implications for their impact on the freshwater budget of the ocean. It is estimated that over the period 1987-2003 the meltwater flux in the Weddell and Ross seas has varied by at least $15,000 \text{ m}^3 \text{ s}^{-1}$ over a month. Because of the potential sensitivity of the production of deep waters to abrupt changes in the freshwater budget, variations in iceberg melt rates of this magnitude might be climatologically significant.

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1. Introduction

[2] The Antarctic ice sheet produces tens of thousands of icebergs every year. Very large, tabular icebergs calve from ice shelves and glacier tongues (the floating portions of the Antarctic ice sheet). Some of these large bergs are more than 100 km long and can take more than a decade to melt as they slowly drift in the counterclockwise coastal current. Such large masses of ice can affect water circulation in their vicinity [*Grosfeld et al.*, 2001], block sea ice movements [*Markus*, 1996], and, consequently, cause disruption to marine ecosystems [*Arrigo et al.*, 2002], and they can cause other icebergs to calve through collision with the ice front [*Swithinbank et al.*, 1977]. The amount of ice transported by giant icebergs is thought to be, on average, comparable to the amount transported by the whole population of smaller icebergs [*Jacobs et al.*, 1992].

[3] The effect of the melting of icebergs (and ice shelves) differs from precipitation or sea ice melting in that the fresh water can be released below the very cool surface Winter Water, and by mixing with the warmer Circumpolar Deep

Water it may increase its buoyancy and cause warm water intrusions at the surface [*Jenkins*, 1999]. This has the effect of warming the surface, potentially reducing sea ice formation and increasing the water column stability. On the other hand, as *Jenkins* [1999] points out, if the mixing of the iceberg meltwater occurs above the pycnocline, the result would be to cool the upper layer water, favoring the thickening of sea ice. Accordingly, the inclusion of an ice shelf basal melting parameterization in a global ice-ocean model produced a thickening of sea ice in the Weddell and Ross seas and in front of the Amery ice shelf [*Beckmann and Goosse*, 2003]. Another effect in this simulation was the freshening and cooling of the shelf waters. Freshening of the coastal waters has also been related to intensification of the shelf break current [*Hellmer and Beckmann*, 1998].

[4] The melting of giant icebergs alone added, on average, 21 mSv (1 mSv = 10^3 m³ s⁻¹) of fresh water to the Southern Ocean south of 63° S, although it has a large temporal and spatial variability which can make it more significant locally. *Gladstone et al.* [2001] used an iceberg trajectory model seeded with climatological calving fluxes to calculate the climatological pattern of meltwater injection around Antarctica. They estimated that the rate of injection could be higher than 0.5 m m⁻² yr⁻¹ in some locations around the coast, comparable to the precipitation minus evaporation (*P* – *E*) contribution calculated by *Turner et al.* [1999]. The simulation by *Gladstone et al.* [2001] only

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considered icebergs up to 2.2 km in length. As they noted, very large icebergs appear to have different dynamics. For instance, *Lichey and Hellmer* [2001] used an iceberg drift model to show that the trajectory of giant iceberg C17 in the Weddell Sea was more dependent on sea ice than previously thought. Here we present the meltwater distribution estimated from observed giant iceberg tracks for the period 1987–2003, study its temporal variability, and discuss its relevance to the freshwater flux of the Southern Ocean and, in particular, to the Weddell Sea.

2. Iceberg Observations

[5] The National Ice Center (NIC) maintains a database of "giant icebergs," i.e., bergs larger than 10 n. mi (1 n. mi \approx 1.853 km) in the long axis, which is freely available from their Web site (see http://www.natice.noaa.gov). The unique identifier, position, and approximate measurements for the long and short axes are recorded every 9 days (median value). Icebergs larger than 10 n. mi or smaller than 10 n. mi but resulting from the breakup of a larger iceberg are recorded in the database for as long as they stay south of 60°S. The database spans from 1979 to the present.

[6] The NIC uses several types of satellite imagery, depending on the iceberg size and position. These include optical imagery, microwave radiometry, and synthetic aperture radar. In 1986 the NIC started using the Operational Line Scan sensor onboard the Defense Meteorological Satellite Program series. This wide-swath optical radiometer improved the available satellite coverage and resulted in a larger number of icebergs being tracked [Long et al., 2002]. As this gave longer and more complete iceberg tracks, we restricted the data set used in our analysis of iceberg melting to the period 1987-2003. The complete 1979-2003 data set is used, however, for the calculation of yearly average calving mass and numbers. Numerous errors in the data, which became apparent by plotting the trajectories, were corrected from the database. We include a table with a summary of the iceberg data as auxiliary material.

[7] The NIC database contains information about both the iceberg position and changes in its horizontal size. However, the size measurements (in n. mi) are coarse and updated infrequently. In order to find out if these reductions corresponded to abrupt changes in size or to progressive melting we used freely available advanced very high resolution radiometer and Moderate Resolution Imaging Spectroradiometer satellite images with resolutions of 1 km in summer and 4 km in winter [Scambos et al., 2001] to analyze the size reductions recorded in the database. In 15 out of the 90 recorded reductions in size it was possible to find satellite images of the target iceberg before and after the date of the size reduction on the NIC database. In 12 of these, there were no measurable observed changes in size, indicating a progressive melting or breakup of icebergs below the image resolution combined with infrequent updating of the iceberg size measurements.

[8] We estimated the spread of meltwater resulting from this progressive reduction by smoothing the size observations, resampling each iceberg dimension every 365 days,



Figure 1. Area of iceberg D17 estimated from observations (solid curve) and smoothed to simulate spreading of meltwater from smaller icebergs along its trajectory (dashed curve).

and interpolating it onto the observed dates using a piecewise cubic Hermite function. This procedure yields a continuous, monotonically decreasing, smoothed version of the size measurements; it is equivalent to spreading the meltwater associated with a reduction in the measurements along the iceberg tracks over a period of 1 year (Figure 1). We also used resampling periods of 100 and 1000 days, and only slight changes in meltwater distribution were observed. For a conservative estimate of rate of change of local meltwater injection for the Weddell and Ross seas an extreme smoothing was used by interpolating linearly between the first and last observations.

3. Calving and Drifting of Giant Icebergs

[9] The calving of a giant iceberg is an infrequent event for any ice shelf. In what might be an extreme example an iceberg of 10,000 km² in area broke from the Amery ice shelf in 1964, and Fricker et al. [2002] estimated that it would take 60-70 years for another such iceberg to be produced by the same ice shelf. Furthermore, only a small number of ice shelves and glacier tongues can produce icebergs of this size. This leads to a large variation in the number but especially the mass of giant icebergs calved each year, as can be seen in Figure 2. There are two prominent peaks in the calving history of giant icebergs for the period 1979-2003, and these are attributed to a small number of very large calving events: In 1986, iceberg A20 calved from the Larsen ice shelf and icebergs A22, A23, and A24 calved from Filchner ice shelf; icebergs A43 and A44 calved from Ronne ice shelf and iceberg B15 calved from the Ross ice shelf in 2000. For comparison, the final collapse of the remains of Larsen B ice shelf in 2002 only involved ~500 Gt of ice [Shepherd et al., 2003], although the icebergs resulting from this highly crevassed ice shelf were mostly too small to be tracked by the NIC. According to these data the average freshwater mass calved annually as giant icebergs in the period 1979-2003 was 1089 ± 300 Gt yr⁻¹ of ice. This was calculated by approximating the iceberg as an ellipsoid parallelepiped with the long axis L_a and short axis L_b , as given by the NIC [Jacobs et al., 1992]. The basal area

A

$$\mathbf{1}_B = -\frac{\pi}{4} L_a L_b \tag{1}$$

¹Auxiliary material is available at ftp://ftp.agu.org/apend/jc/2004JC002843.



Figure 2. Number and mass of giant icebergs (>10 n. mi or \approx 18.5 km) recorded by the National Ice Center from 1979 to 2003. "Calved" icebergs are considered to be the icebergs first detected in a specific year, while "tracked" icebergs are all "mother" icebergs observed in the same year. The mass was calculated by approximating each iceberg as an ellipsoidal parallelepiped, assuming an initial thickness of 250 m and an average ice density of 850 kg m⁻³.

was multiplied by an initial iceberg thickness of 250 m [*Jacobs et al.*, 1992] and by an average density of 850 kg m⁻³ [*Keys et al.*, 1990; *Keys and Fowler*, 1989] to obtain the total ice mass. The error margin of 300 Gt yr⁻¹ was estimated taking into consideration the possible range of average ice density and ice shelf thickness.

[10] A complementary iceberg drift database covering the period from 1992 to the present [*Long et al.*, 2002] lists several tens of additional icebergs missed by the NIC in recent years. *Long et al.* [2002] were able to detect these additional bergs by using an improved resolution algorithm applied to frequent large-coverage but low-resolution microwave scatterometer images. The extra observations were not included in our survey as they constitute a shorter time series and do not include iceberg size measurements. Although not including these extra icebergs might result in underestimating the total mass of giant icebergs, most of those missing from the NIC database are icebergs too small to be detected by the NIC that resulted from the large calving events of 1999–2000 [*Long et al.*, 2002].

[11] The calving flux of icebergs smaller than 10 n. mi bears more uncertainties as these are not detected in the daily low-resolution satellite imagery. Previous sources of iceberg drift include the Soviet Antarctic Survey [Bakavev, 1966], icebergs tracked using satellite beacons [Tchernia and Jeannin, 1984], and modeled trajectories [Gladstone et al., 2001]. These sources show that the pattern of drift of smaller bergs differs from that of giant icebergs (Figure 3) in that giant icebergs generally stay closer to the coast. This is because the Coriolis force, which pushes icebergs flowing counterclockwise in the coastal current toward the coast, is proportional to the iceberg's mass and hence volume. For an increasing iceberg size the Coriolis force will grow faster than the drag from water and wind, which is proportional to the area over which the respective drag acts. For the same reason, smaller bergs are more likely to drift away from the coast around the Kerguelen plateau in East Antarctica, as

the topographic steering more easily overcomes the weaker Coriolis force. As we will in section 4, by comparing the simulation output for smaller bergs [*Gladstone et al.*, 2001] with the present study, another difference becomes evident: Only 3% of the mass of smaller icebergs pass north of 63° S, compared with an estimated 35% for giant icebergs. Again, this is because of the smaller area:volume ratio for larger icebergs leading to slower attrition.

4. Iceberg Melting

4.1. Observations and Modeling

[12] We combined the observations of giant icebergs' drift and size with modeling of basal melting to calculate meltwater injection in the ocean. The sidewall melting was also simulated to compare with the observations. In addition to the NIC database we also used several climatological forcing fields for the simulations. Fields of ocean temperature and currents were obtained from the averages of years 8-11 of the Ocean Circulation and Climate Advanced Modelling project (OCCAM) ocean model output [de Cuevas et al., 1999]. For each of the top layers of the model, ocean temperatures were averaged monthly, and currents were averaged seasonally. The 0.25° spatial resolution was averaged to 1° as giant icebergs can be thousands of square kilometers in area. Monthly averages of surface winds were obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) 2.5° ERA-40 reanalysis data, averaged over the period 1987–2003. The monthly average sea ice concentrations were taken from remote sensing derived data (scanning multichannel microwave radiometer and Special Sensor Microwave Imager) averaged over the period 1973-1991 [Schweitzer, 1993].

[13] In the iceberg modeling studies by *Bigg et al.* [1997] and by *Gladstone et al.* [2001] the icebergs are treated as



Figure 3. Trajectories of giant icebergs (>18.5 km) as tracked by the National Ice Center for the period 1987–2003. Circles mark where tracks end.

rectangular parallelepipeds with a fixed length:width ratio of 1.5. Here, considering the bergs to be rectangular in shape using the maximum length and width measurements from NIC would result in overestimating their areas. Hence we treat icebergs as ellipsoid parallelepipeds with the long and short axes as given by the NIC (see equation (1)). There is no closed-form formula for the perimeter of an ellipse, so we used an approximation multiplied by the thickness (Z) to calculate the side area,

$$A_S \approx \pi \sqrt{2\left(L_a^2 + L_b^2\right)}Z.$$
 (2)

Two melting processes are included in the model: turbulent melting at the submerged surfaces and wave erosion on the sides. Buoyant convection on the submerged sides, solar heating, sublimation, and sensible heating were not included as these are negligible for the Southern Ocean [*Gladstone et al.*, 2001]. Turbulent heat transfer results from the movement of seawater past the iceberg, creating turbulence that transports heat to its surfaces. We calculated the turbulent melt rate using the three equation formulations of *Holland and Jenkins* [1999], assuming a neutral boundary layer with no effect of melting on the stratification. The temperature at the interface between the iceberg base and the ocean T_B is given by the local freezing point

$$T_B = aS_B + b + cp_B,\tag{3}$$

where the equation of state was linearized and the following constants were used: $a = -5.73 \times 10^{-2}$ °C psu⁻¹, $b = 8.32 \times 10^{-2}$ °C, and $c = -7.61 \times 10^{-4}$ °C dbar⁻¹. S_B is the salinity at the iceberg base, and p_B is the pressure at the base. The remaining two equations result from the conservation of heat and salt,

$$|u|\gamma_T(T_{\infty} - T_B) = -M_T \frac{L + \Delta T c_i}{c_w}$$
(4)

$$|u|\gamma_S(S_\infty - S_B) = -M_T S_B,\tag{5}$$

respectively, where |u| is the water speed relative to the iceberg surface; $\gamma_T = 6 \times 10^{-4}$ and $\gamma_S = 2.2 \times 10^{-5}$ are coefficients of heat and salt transfer from water to ice, respectively; S_{∞} and S_B are the far-field and basal salinities and, equivalently, T_{∞} and T_B are the far-field and basal temperatures; $L = 3.35 \times 10^5$ J kg⁻¹ is the latent heat of fusion of ice; $c_w = 4000$ J kg⁻¹ °C⁻¹ and $c_i =$ 2010 J kg⁻¹ °C⁻¹ are the specific heat capacities of water and ice, respectively; $\Delta T = 20^{\circ}$ C is an average value for the temperature difference between the iceberg core and the bottom surface [*Weeks and Mellor*, 1978]; and M_T is the turbulent melt rate. S_B and T_B can be eliminated from equations (3), (4), and (5), resulting in a quadratic equation for M_T . The solution of the quadratic gives M_T as a function of water speed and of superheating, here defined as

$$T_{sh} = T_{\infty} - (aS_{\infty} + b + cp_B). \tag{6}$$

This is the difference between the far-field in situ water temperature and its freezing point, the latter being

Table 1. Yearly Averages of Freshwater Mass Lost by Giant Icebergs for 1987-2003 South of $63^{\circ}S^{a}$

	Mass Flux, Gt yr ⁻¹		
	Measured	Corrected for Incomplete Tracks	
Calved giant icebergs	1035	_	
Mass lost south of 63°S	493 (48%)	668 (65%)	
Observed side reduction	241	327	
Modeled bottom melting	252	341	
Transport north of 63°S	271 (26%)	533 (35%)	
Incomplete tracks	272 (26%)		
Modeled side melting	43.7	59.2	
Wave erosion	39.0	52.9	
Turbulent melting	4.6	6.3	

^aThe observed iceberg sizes were smoothed by resampling every 365 days and were interpolated as described in the text. Corrected terms assume that icebergs with interrupted tracks melted in the same proportion as the ones with tracks that reach north of 63°S. Modeled side melting is included for comparison with the observed reduction but was not included in the remaining results.

calculated using the pressure at the ice base and the farfield salinity. Of the two solutions to the quadratic, only one is physically meaningful as it shows melting (negative values of M_T) for positive values of T_{sh} . Far-field values are taken as the OCCAM model values for the layer below the iceberg base; e.g., for an iceberg draft of 200 m the model layer below is centered at 244 m.

[14] Waves are responsible for eroding the iceberg sides both below and above the water line as overhanging slabs are also considered to fall. *Gladstone et al.* [2001] parameterized an empirical term [*Bigg et al.*, 1997] to take into account the dependence of erosion on the water temperature and the damping effect of the sea ice. The wave erosion M_W (in m d⁻¹) is given by

$$M_W = \frac{1}{12} S_S \left[1 - \cos(C^3 \pi) \right] (T_W + 2), \tag{7}$$

where S_s is the sea state on the Beaufort scale calculated from the wind speed and C is sea ice concentration (in %).

[15] In order to calculate the meltwater flux these two terms must be multiplied by the appropriate iceberg surface areas. Turbulent melting is applied to both the bottom of the iceberg and to the submerged sides, and wave erosion is applied to half the side area (the half exposed to the wind). The NIC observations are generally spaced days apart, so we linearly interpolated the iceberg's position and resampled it at daily intervals. For each day we calculated the meltwater injection for each different term and updated the iceberg thickness.

4.2. Spatial Variability

[16] Since we are mostly interested in the impact of meltwater injection on the stability of the Southern Ocean's shelf waters, we calculated the observed and modeled mass loss from giant icebergs south of 63°S (Table 1). Our estimate of the total dissolution south of 63°S is obtained by summing the observed horizontal size reduction with the modeled basal melting. This is, on average, 48% of the calved mass. Twenty-six percent of the ice mass is transported north of 63°S. Many NIC tracks terminate south of 63°S because of a lack of satellite coverage, because of icebergs becoming too small to be tracked, or because the icebergs still existed in 2004; these bergs amount to 26% of



Figure 4. Distribution of iceberg meltwater in the Southern Ocean calculated from (a) giant iceberg trajectories for the period 1987–2003 in this study, (b) climatological run of a model for icebergs up to 2.2 km in size [*Gladstone*, 2001], and (c) the combination of the giant and small icebergs (see text for details).

the calved mass. Incomplete tracks are spread all around the coast (Figure 3), and we assume that these icebergs will eventually melt south of 63° S and be transported north in the same proportion as the remaining icebergs. This results in an estimated 65% of the giant icebergs' mass melting south of 63° S and 35% being transported farther north (Table 1), compared with only 3% in the simulations performed for smaller bergs [*Gladstone et al.*, 2001]. Observed reductions in size were more than 5 times the modeled side melting, and we attribute at least some of this difference to breakup into smaller icebergs, the latter not being accounted for by the model. The turbulent basal melting was comparable in size with the observed size reduction. Within the side melting terms the wave erosion is by far the most important.

[17] Existing estimates of the total number of smaller icebergs rely on ship-based observations [Hamley and Budd, 1986; Orheim, 1988], which are biased by the location of ships' routes. Also, these estimates do not take into account the fact that a portion of the small bergs results from the breakup of giant icebergs. O. Orheim (personal communication with S. S. Jacobs et al., 1991, as discussed by Jacobs et al. [1992]) estimated the calving flux of small icebergs as 1200 Gt yr⁻¹, although Jacobs et al. [1992] chose to use a more conservative estimate of 1008 Gt yr This incorrectly includes in the calving flux small icebergs resulting from the breaking up of giant icebergs. Assuming that the side melting is correctly represented in our model, the difference between observed size reduction and side melting $(327 - 59 = 268 \text{ Gt yr}^{-1})$ is the outcome of breakup. Subtracting this term from the ship-based estimates of 1200 Gt yr⁻¹ results in a small iceberg calving flux of 932 Gt yr⁻¹ of fresh water. The total iceberg meltwater (Figure 4c) is the combination of three terms: giant icebergs scaled to take into account the incomplete tracks so that 668 Gt yr⁻¹ will melt south of 63°S (see Table 1), small icebergs [from Gladstone et al., 2001] scaled down to the calving flux of 932 Gt yr⁻¹, and small icebergs resulting

from giant bergs taken to be the *Gladstone et al.* [2001] map scaled down to a total of 268 Gt yr⁻¹. This simplification ignores the fact that small icebergs resulting from the breakup of giant icebergs will generally "calve" farther away from the coast and farther west than assumed by *Gladstone et al.* [2001].

[18] The average giant berg meltwater distribution (Figure 4a) differs from the simulations performed for smaller icebergs (Figure 4b); as a consequence of greater longevity many giant icebergs reach the Weddell Sea and are often transported farther north. Smaller bergs tend to melt closer to their sources. In East Antarctica, for example, smaller bergs drift farther away from the coast, entering warmer waters that accelerate their decay.

[19] The small iceberg simulations used a different model for turbulent melting which does not take into account the diffusivity of heat and salt across the water boundary layer. For comparison purposes we applied this simpler scheme to the giant iceberg drifts and obtained a similar basal meltwater distribution but observed, on average, half the amount of melting compared to the *Holland and Jenkins* [1999] model. The latter has been validated for ice shelves' basal melting [*Nicholls and Makinson*, 1998]. This suggests that the small icebergs' meltwater distribution might extend less far north around East Antarctica and have an even smaller transport of ice mass north of 63°S. Nevertheless, the agreement between the simulated trajectories and the observed northernmost iceberg limits lends some credibility to the small iceberg results [*Gladstone et al.*, 2001].

4.3. Temporal Variability

[20] Whereas we expect only relatively weak interannual variation in the production of small icebergs [*Orheim*, 1985, 1990], the high spatial and temporal variability observed in giant iceberg production will cause significant variability in meltwater flux. We calculated the meltwater injection from giant bergs in the Weddell Sea, Ross Sea, and the entire Southern Ocean south of 63°S for the period 1987–2003



Figure 5. Monthly averaged meltwater flux from giant icebergs (1 mSv = 10^3 m³ s⁻¹). Total flux is the sum of observed side reductions and modeled bottom reductions. Changes in total meltwater injection in the Ross and Weddell seas are as high as 20 mSv over a month.

(Figure 5). The Weddell Sea is here defined as the ocean area south of 65° S and between 63° W and 12° W, while the Ross Sea is defined as being south of 72° S and between 165° E and 150° W. The overall observed rate of change will vary considerably with the choice of resampling period used to interpolate the iceberg sizes. For this calculation we opted for a conservative estimate by using a constant mass loss during the iceberg's life (from a linear interpolation of size observations) instead of resampling and function fitting as we did for Figure 4.

[21] In early 2000 the monthly average meltwater input changed by 20 and 15 mSv in the Ross and Weddell seas, respectively. The high concentration of melting in some coastal areas will amplify the effects on water column stability and sea ice formation. *Richardson et al.* [2005] used a fully coupled global climate model (GCM) to simulate present-day climate and to test the effect of abruptly adding a much larger amount of fresh water (1.677 $\times 10^{14}$ m³) to the Southern Ocean surface waters. They found this to inhibit the ventilation of deep waters, with a rapid response in global climate. The freshwater perturbation in *Richardson et al.'s* [2005] simulation is 2 orders of magnitude larger than the total iceberg meltwater flux, and, furthermore, the fresh water is added instantaneously. Nevertheless, the large variability in iceberg melt-

water input induced by glaciological processes will potentially modulate sea ice development and deep water formation through the same mechanisms.

[22] The meltwater peaks observed in the Weddell and Ross seas in 2000 were caused by independent groups of icebergs. These included newly calved icebergs such as A43 and A44 in the Weddell Sea and B15 and B17 in the Ross Sea, together with older bergs such as A22 and A23. Other abrupt variations were observed in other regions in different years, as can be seen in the meltwater injection for the whole area south of 63°S (Figure 5). No melting occurred in the Ross Sea during the 1990s because few giant icebergs were tracked in the region and no size reduction occurred. It is also worth noting that there is very little modeled sidewall melting in the Weddell Sea during winter; the high sea ice concentration dampens waves and reduces wave erosion.

4.4. Contribution to the Freshwater Flux

[23] Sea ice forms mostly in open leads near the coast and is transported by wind and currents farther north, exporting very large amounts of fresh water from the Southern Ocean's shelf seas. Added to this fresh water is the sinking and export off the shelf of fresh and cold surface waters. These two terms are balanced by the precipitation minus evaporation (P - E) over the ocean, the difference between the ice shelf basal melting and refreezing deep in the cavity, and the melting of icebergs.

[24] The total contribution of the ice shelves to the Southern Ocean was estimated by *Hellmer* [2004] as 28.4 mSv (Table 2). We used 2.5° ERA-40 ECMWF reanalysis data for the period 1987–2003 to produce a P - E map. This term was responsible for a freshwater flux over the Southern Ocean south of 63°S of 76.3 mSv. Giant and small bergs together are responsible for an average freshwater flux in the same area of 50.7 mSv. This already large term has special significance in some areas. We compared the importance of the sum of giant and small iceberg meltwater (resampled to 2.5°) with P - E by mapping the meltwater for areas where it was at least the same order of magnitude (Figure 6). This is especially strong in the Scotia Sea, the western Weddell Sea, and Pridz Bay, facing the Amery ice shelf.

[25] We have studied the Weddell Sea in more detail and calculated its freshwater balance. *Harms et al.* [2001] used hydrographic observations, satellite passive microwave data, and moored upward looking sonar from 1990 to 1994 to study the flux of sea ice in the Weddell. They estimated an average net export of fresh water of 50 ± 19 mSv. *Harms et al.* [2001] did not take iceberg meltwater

Table 2. Freshwater Fluxes for the Southern Ocean South of 63° S and for the Weddell Sea^a

	South of 63°S, mSv	Weddell Sea, mSv
Icebergs (total)	50.7	11.9
Giant icebergs	21.2	7.0
Small icebergs	29.2	4.9
$P - E^{b}$	76.3	6.1
Ice shelf melting	28.4	10.1 to 17.9
Sea ice (net input)	_	-50 ± 19

^aIce shelf melting was obtained from *Hellmer* [2004], and sea ice transport was obtained from *Harms et al.* [2001].

^bPrecipitation minus evaporation from European Centre for Medium-Range Weather Forecasts reanalysis data.



Figure 6. Climatological precipitation minus evaporation (P - E) from ECMWF ERA-40 data (contours in m m⁻² yr⁻¹) and total iceberg meltwater injection at 2.5° resolution. The latter is shown only where it is at least of the same order of magnitude as P - E (meltwater > 0.2(P - E)).

into account, and the P - E estimate did not rely on reanalysis or model output data. We estimated the flux due to all icebergs to be 11.9 mSv, and the ECMWF data yielded a P - E flux of 6.1 mSv. Harms et al. [2001] omitted iceberg meltwater, but by using an older and much larger estimate for P - E of 20 mSv they ended up with a value comparable to our estimate of 18 mSv for iceberg meltwater plus P - E. The Larsen, Ronne-Filchner, and eastern Weddell ice shelves all contribute fresh water to the Weddell Sea. Some of the water from the Fimbul ice shelf, farther NE, will also enter the Weddell. Hellmer [2004] used an ice-ocean model to estimate the contribution of these ice shelves to be 17.9 and 10.1 mSv with and without the Fimbul contribution, respectively. The figures for the Fimbul and eastern Weddell ice shelves were overestimated because of the absence from the model of the narrow continental shelf, which allowed the modeled coastal current to interact directly with the ice shelves. Assuming that the salinity of the Weddell Sea is in balance, there is a net export of -14 to -22 mSv attributable to the difference between newly ventilated bottom water and the flow of fresh water from the east. Harms et al. [2001] had estimated a similar 19 mSv for this term, albeit using an overestimate for P - E and ignoring iceberg meltwater.

5. Conclusions

[26] In the last 25 years, giant icebergs have represented approximately half the mass loss of the Antarctic ice sheet (1089 Gt yr⁻¹). We have demonstrated the need to take

giant icebergs into account when studying Antarctic iceberg drifting and melting as these differ from the smaller bergs in both spatial distribution and temporal variability. The differences in drifts are mostly explained by giant icebergs' large volume:area ratio, which causes greater longevity and a stronger Coriolis force in relation to the water, sea ice, and wind drag. This causes three observed phenomena: concentration of both icebergs and meltwater very close to coastal areas around most of Antarctica, high concentration of iceberg tracks in the Weddell Sea, and higher transport of mass north of 63°S that will go mostly into the Antarctic Circumpolar Current (an estimated 35% of calved mass as compared to 3% for small modeled icebergs).

[27] The temporal variability of the distribution of meltwater from giant icebergs might be as important for its effects on the oceans as the amount injected. For the Ross Sea we made a conservative estimate of changes in the local meltwater injection of up to 20 mSv over a month for the period 1987–2003. Smaller variations of the same order of magnitude were also observed in the Weddell Sea. Our estimates of iceberg meltwater, taking into account giant icebergs, are shown to be significant in the freshwater balance of both the Southern Ocean overall, where it exceeds ice shelf basal melting, and for the Weddell Sea, where it is larger than P - E.

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