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Recent loss of floating ice and the consequent sea level contribution

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[1] We combine new and published satellite observations and the results of a coupled ice-ocean model to provide the first estimate of changes in the quantity of ice floating in the global oceans and the consequent sea level contribution. Rapid losses of Arctic sea ice and small Antarctic ice shelves are partially offset by thickening of Antarctic sea ice and large Antarctic ice shelves. Altogether, 746 ± 127 km^3 yr^{-1} of floating ice was lost between 1994 and 2004, a value that exceeds considerably the reduction in grounded ice over the same period. Although the losses are equivalent to a small (49 ± 8 μm yr^{-1}) rise in mean sea level, there may be large regional variations in the degree of ocean freshening and mixing. Ice shelves at the Antarctic Peninsula and in the Amundsen Sea, for example, have lost 481 ± 38 km^3 yr^{-1}. **Citation:** Shepherd, A., D. Wingham, D. Wallis, K. Giles, S. Laxon, and A. V. Sundal (2010), Recent loss of floating ice and the consequent sea level contribution, *Geophys. Res. Lett.*, *37*, L13503, doi:10.1029/2010GL042496.

1. Introduction

[2] A principal objective of global climate assessments [e.g., *Bindoff et al.*, 2007; *Church and Gregory*, 2001; *Warrick et al.*, 1996] has been to quantify the rate of global sea level rise, and to resolve differences between the observed rate and the sum of known contributions due to potential sources and sinks of water. In the most recent report of the Intergovernmental Panel on Climate Change (IPCC) [*Bindoff et al.*, 2007], only a small (about 0.3 mm yr^{-1}) discrepancy remained between these two estimates, the difference reflecting either measurement uncertainties or contributions due to known processes (e.g., groundwater extraction, impoundment of water in reservoirs, wetland drainage, and deforestation) that remain un-quantified. However, IPCC reports [*Bindoff et al.*, 2007; *Church and Gregory*, 2001; *Warrick et al.*, 1996] have failed to consider the sea level contribution due to changes in the quantity of ice floating in the global oceans in the form of sea-ice and ice shelves - a recently identified source [*Jenkins and Holland*, 2007; *Noerdlinger and Brower*, 2007] of ocean volume which may explain some of the unaccounted sea level rise. Moreover, the sea level contribution due to floating ice will increase substantially in a warming climate - it is estimated [*Jenkins and Holland*, 2007], for example, that global sea levels would rise by between 4 and 6 cm (7 to 33% of the projected 21st century change [*Meehl et al.*, 2007]) if all of the present-day floating ice were to melt - and so the timescale over which such changes may occur is a matter of considerable concern.

[3] The melting of floating ice contributes to the rate at which global sea level changes due to differences in the density and temperature of fresh- and sea-water [*Jenkins and Holland*, 2007]. If ice is added to an ocean, there is an initial rise in sea level equal to the volume of displaced water. As the ice melts, the ocean freshens and cools and, according to the rates at which these opposing processes take place, a concommital change in ocean volume occurs. The process may be reversed, so that the formation of floating ice from sea water leads to a fall in sea level. Provided the changes in density are sufficiently small, whether the water masses are mixed or not has no effect on the thickness of the total column. The change in ocean volume (ΔV) associated with melting (or freezing) of floating ice may be written as

$$\Delta V = V_{fw} \frac{(\rho - \rho_{fw})}{\rho} \quad (1)$$

where V_{fw} and ρ_{fw} are the volume and density of freshwater melted (or frozen), and ρ is the density of sea water [*Jenkins and Holland*, 2007]. Equation (1) assumes hydrostatic balance between floating ice and the surrounding ocean. Taking values of 1000 kg m^{-3} and 1026 kg m^{-3} for the densities of fresh- and sea-water, respectively, ice melting (or freezing) affects a change in sea level of about 2.6% of the volume of displaced water.

2. Method and Results

[4] The vast majority (over 99%) of ice shelves are located in Antarctica, and there have been well-documented examples of secular changes in their area [e.g., *De Angelis and Skvarca*, 2003] and thickness [e.g., *Shepherd et al.*, 2003] over recent decades. According to a study of optical imagery [*Cook and Vaughan*, 2009], for example, there has been a 28,117 km^2 reduction in the area of ice shelves at the Antarctic Peninsula since the late 1940's due to episodes of ice shelf collapse that have been attributed to changes in regional climate [e.g., *Vaughan and Doake*, 1996]. In addition to these abrupt events, other Antarctic ice shelves have experienced unsteady net melting at their base [e.g., *Shepherd et al.*, 2004] that have been attributed to enhanced ocean-driven melting. We examined changes in the volume of Antarctic ice shelves using repeat observations of their area and thickness.

[5] To estimate changes in the volume of ice shelves associated with episodic retreat, we analysed published records of the area [*Cook and Vaughan*, 2009], thickness [*Lythe and Vaughan*, 2001], and elevation [*Bamber and Bindschadler*, 1997] of those situated in Antarctica where

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Table 1. Area, Volume Rate, and Steric Sea Level Contribution of Floating Ice[a]

Region	Area (10^3 km^2)	Volume Rate (km^3 yr^{-1})	Sea Level Contribution (μm yr^{-1})
Ice Shelf Thickness Change (1994 to 2008)			
Filchner-Ronne ice shelf (FIL)	419	225 ± 3	−14.9 ± 0.2
Ross ice shelf (ROS)	473	71 ± 3	−4.7 ± 0.2
Amery ice shelf (AME)	61	56 ± 6	−3.7 ± 0.4
Brunt ice shelf (BRU)	80	46 ±5	−30. ± 0.3
Bach ice shelf (BAC)	4	35 ± 10	−2.3 ± 0.6
Moscow University ice shelf (MOS)	5	27 ± 9	−1.8 ± 0.6
George VI ice shelf (GEO)	31	−25 ± 8	1.7 ± 0.5
Fimbul ice shelf (FIM)	61	−31 ± 11	2.1 ± 0.7
Thwaites Glacier ice shelf (TWG)	4	−33 ± 1	2.2 ± 0.1
Pine Island Glacier ice shelf (PIG)	6	−36 ± 4	2.4 ± 0.2
Getz ice shelf (GET)	24	−44 ± 3	2.9 ± 0.2
Venable ice shelf (VEN)	3	−48 ± 22	3.2 ± 1.4
Larsen C ice shelf (LAC)	73	−62 ± 4	4.1 ± 0.3
Crosson/Dotson ice shelf (CRO)	8	−69 ± 5	4.6 ± 0.3
31 other ice shelves	328	−29 ± 33	1.9 ± 2.2
Unsurveyed ice shelves[b]	34	3 ± 1	−0.2 ± 0.1
All ice shelf thickness changes	**1517**	**115 ± 43**	**−7.6 ± 2.8**
Ice Shelf Retreat (1998 to 2008)			
Wordie ice shelf (WOR)	1	−7 ± 4	0.5 ± 0.3
Prince Gustav Channel (PGC)	1	−9 ± 2	0.6 ± 0.1
Larsen A ice shelf (LAA)	3	−44 ± 13	2.9 ± 0.9
Wilkins ice shelf (WIL)	16	−50 ± 6	3.3 ± 0.4
Larsen B ice shelf (LAB)	12	−100 ± 22	6.6 ± 1.5
All ice shelf retreat	**33**	**−210 ± 27**	**13.9 ± 3.1**
All Floating Ice			
Ice shelves	1483	−95 ± 50	6.3 ± 3.0
Arctic sea ice (1994−2007)		−851 ± 110	56.4 ± 7.3
Antarctic sea ice[c] (1979−2004)		200 ± 40	−13.2 ± 2.6
All floating ice		**−746 ± 127**	**49.4 ± 8.4**

[a]The full period of the observations spans 1986 to 2009; the overlap between the various datasets spans 1994 to 2004.
[b]Estimated from average elevation rate of all ice shelves.
[c]Based on a model simulation [*Zhang*, 2007].

a record of progressive retreat has been documented. Although there have been notable examples of ice shelf retreat elsewhere, the associated changes in volume are either small [e.g., *Mueller et al.*, 2003] or are part of the natural cycle of iceberg calving [e.g., *Arrigo et al.*, 2002]. Using the data of *Cook and Vaughan* [2009], we delimited the area of five Antarctic ice shelves (Table 1), each on four separate occasions. Their combined area reduced from 33,416 km^2 in the mid 1980's to 14,098 km^2 in the late 2000's. We estimated the thickness of the lost ice using a collection of airborne ice penetrating radar measurements [*Lythe and Vaughan*, 2001] and satellite altimeter elevation observations [*Bamber and Bindschadler*, 1997] (coupled with an assumption of hydrostatic balance [*Vaughan et al.*, 1995]) which provided between 100 and 693 independent estimates of ice thickness for each shelf. These data show that, between 1988 and 2008, the volume of Antarctic ice shelves decreased by 210 ± 27 km^3 each year through episodic retreat (Table 1).

[6] To estimate changes in the volume of Antarctic ice shelves associated with fluctuations in their thickness, we processed a continuous record of data acquired by the ERS-2 and Envisat satellite radar altimeters between 1994 and 2008. Using multiple orbit reference cycles, we calculated ice shelf elevation changes at 11,963 crossing-points of the satellites' ground tracks [*Wingham et al.*, 1998]. Elevation changes from each satellite were cross-calibrated during periods in which both instruments were operational (ERS cycles 78 to 84). We delimited fixed ice shelf boundaries using grounding lines determined from interferometric synthetic aperture radar [*Rignot et al.*, 2008] and other geodetic surveys [*British Antarctic Survey*, 1993], and ice shelf barriers determined from optical satellite imagery (2005). From these data, we computed the average rate of elevation change of 42 (98% of all) Antarctic ice-shelves (Figure 1 and Table 1), and we estimated the elevation change of the remainder based on the average rate of those surveyed. We adjusted the elevation trends for signals associated with other potential sources of vertical motion during the period of the altimeter survey. To account for the effects of snowfall variability and its associated error, we used a model prediction [*Helsen et al.*, 2008] of firn depth anomalies (and the associated uncertainty) over a similar period (1993–2005), and we assumed that any changes in accumulation occurred at a density of 350 kg m^{-3}. We also adjusted the elevation trends to account for non-steric changes in the rate of global sea level rise (1.2 mm yr^{-1} [*Bindoff et al.*, 2007]). The elevation time-series were sufficiently long and dense to obviate the need for an ocean tide correction [*Shepherd et al.*, 2003]. We used a hydrostatic relationship [*Vaughan et al.*, 1995] to estimate rates of ice shelf thickness change from the adjusted elevation trends, assuming values of 917 and 1026 kg m^{-3} for the densities of ice and ocean water, respectively. Changes in ice thickness were then attributed to either unsteady basal ice melting or freezing according the sign of the trend. Between 1994 and 2008, the volume of Antarctic ice shelves decreased by 115 ± 43 km^3 yr^{-1} due to changes in their thickness.

[7] We estimated the trend in volume of Arctic sea ice by considering the effects of changes in both area and thickness. According to ERS and Envisat satellite altimeter observations, the 1993–2001 (average wintertime) thickness of Arctic sea ice was estimated to be 273 cm [*Laxon et al.*, 2003], the thickness decreased by 6.7 ± 1.9 cm yr^{-1} between 1992 and 2001 [*Laxon et al.*, 2003], and the thickness decreased by 4.8 ± 0.5 cm yr^{-1} between 2003 and 2008 [*Giles et al.*, 2008]. We combined these datasets to produce a new estimate of the 1994–2008 thickness change. Published satellite microwave imager observations [*Comiso et al.*, 2008] show that the 1996–2007 Arctic sea ice area trend was $-111 \pm 8 \times 10^3$ km^2 yr^{-1} and, based upon our own analysis of these data, we estimate that the 1990–1999 average wintertime area of Arctic sea was 11.9×10^6 km^2. The combined reductions in Arctic sea ice area and thickness amount to a decrease in volume of 851 ± 110 km^3 yr^{-1} during the period 1994 to 2007, with changes in thickness and area accounting for 65% and 35% of the overall loss, respectively.

[8] Although the area of Antarctic sea ice has increased steadily since 1978 [*Cavalieri and Parkinson*, 2008], satellite observations of thickness trends are lacking due to uncertainties in, among other parameters, the densities of snow and ice, which complicate retrieval algorithms based on measurements of ice freeboard. Moreover, direct observations of Antarctic sea ice thickness are limited to a handful of sparse surveys from ship, aircraft, submarine, and satellite platforms, and records of thickness trends are absent alto-

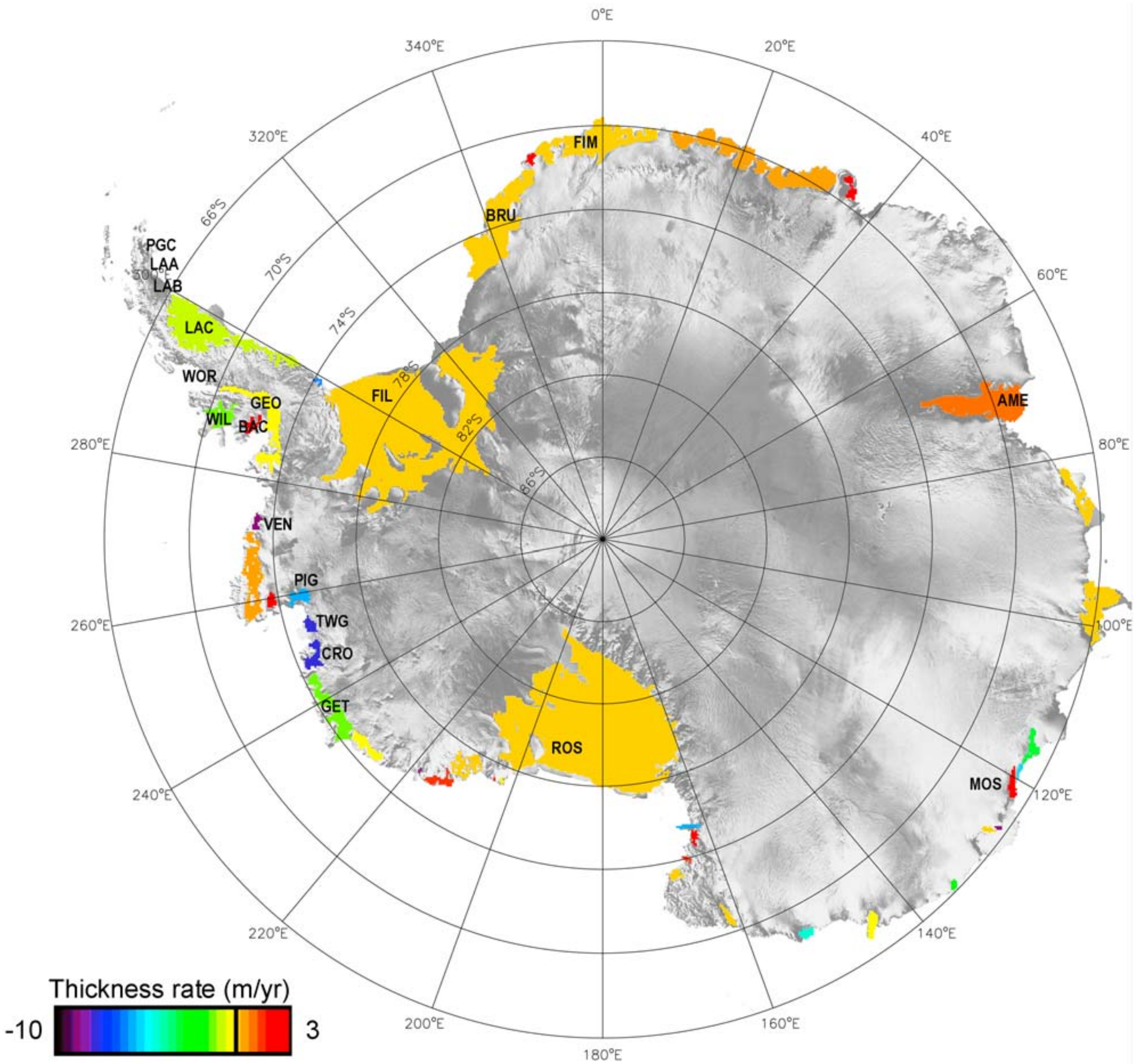

Figure 1. Average rate of Antarctic ice shelf thickness change, 1994 to 2008, determined from ERS and ENVISAT radar altimetry and a model of accumulation fluctuations [*Helsen et al.*, 2008].

gether. A global sea ice model forced by climate reanalyses [*Zhang*, 2007] has, however, simulated changes in Antarctic sea ice area (8.4×10^3 km^2 yr^{-1}) associated with increased thermohaline stratification within the near-surface ocean that are in remarkable agreement with the estimate ($9.6 \pm 2.4 \times 10^3$ km^2 yr^{-1}) derived from satellite observations [*Cavalieri and Parkinson*, 2008]. In the absence of satellite observations, we use the published results of the model study [*Zhang*, 2007] to assess the recent trend in Antarctic sea ice volume: during the period 1979–2004, it is estimated that the volume of Antarctic sea ice increased by 200 ± 40 km^3 yr^{-1}.

3. Discussion

[9] We present the first estimate of the total change in the mass of Earth's floating ice, and the associated impact on global sea level (Table 1 and Figure 2). The assessment is based upon satellite altimeter observations of Antarctic ice shelf and Arctic sea ice thickness trends and an analysis of published records, including ice shelf thickness [*Lythe and Vaughan*, 2001], elevation [*Bamber and Bindschadler*, 1997] and area trends [*Cook and Vaughan*, 2009], Arctic sea ice area trends [*Comiso et al.*, 2008], and Antarctic sea ice volume trends [*Zhang*, 2007]. Overall, increases in sea level due to the loss of Arctic sea ice and the collapse of several Antarctic ice shelves have been mitigated by gains in Antarctic sea ice and an overall thickening of the remaining Antarctic ice shelves. The detailed pattern of ice shelf change varies considerably. Although the rate of ice loss at the Antarctic Peninsula and in the Amundsen Sea is high (481 ± 38 km^3 yr^{-1}), this trend is offset by small increases in the thickness of the vast Filchner-Ronne, Ross, and Amery ice shelves. The combined change in mass of Earth's

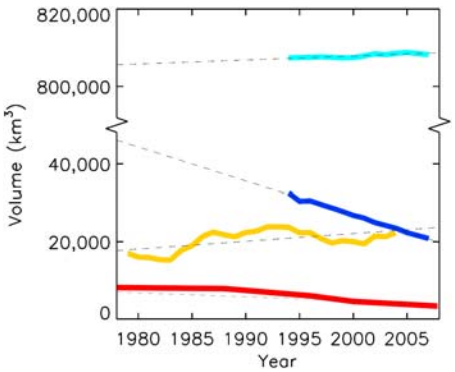

Figure 2. Changes in the volume of floating ice, including Antarctic ice shelves (due to change in thickness = cyan and area = red), Antarctic sea ice (orange), and Arctic sea ice (blue). The datasets overlap during the period 1994 to 2004.

floating ice is equivalent to an average rise in global sea level of 49 ± 8 μm yr^{-1}. Observations suggest, however, that freshwater released through ice melting is confined to the polar regions over decadal timescales [*Serreze et al.*, 2006] and so there may be substantial regional variations in the sea level contribution due to losses of floating ice because the Southern and Arctic Oceans constitute s small (10%) fraction of the global ocean area.

[10] Our estimates of floating ice mass trends may be compared to the results of shorter-term regional studies. The rate of Antarctic ice shelf growth through thickness changes (115 ± 43 Gt yr^{-1} between 1994 and 2009) is double that of an earlier study (47 ± 21 Gt y^{r-1} between 1992 and 2002) of satellite radar altimeter data that failed to account for accumulation fluctuations [*Zwally et al.*, 2005]. Although there is some evidence (Figure 2) of increased thickening since 2002, the discrepancy may alternatively be attributed to the effects of changes in snowfall or measurement uncertainties. In contrast, the near-constant rate of Arctic sea ice loss (−851 ± 110 km^3 yr^{-1} between 1994 and 2008) demonstrates that the recent trend (−862 km^3 yr^{-1} between 2003 and 2008) identified in a short study of satellite laser altimetry [*Kwok et al.*, 2009] is part of a long-term signal of decline.

4. Conclusions

[11] Today, the steric change in global sea level associated with trends in floating ice mass amounts to just 1.6% of the measured rate of sea level rise (3.1 ± 0.7 mm yr^{-1} [*Bindoff et al.*, 2007]), and is considerably smaller than contributions due to other components of the cryosphere [*Lemke et al.*, 2007] or thermal expansion of the oceans [*Bindoff et al.*, 2007]. However, there are large regional variations; the rapid and progressive loss of ice shelves at the Antarctic Peninsula and in the Amundsen Sea (481 ± 38 km^3 yr^{-1} in total), for example, has implications for the stability of the grounded ice which they abut [*Pollard and DeConto*, 2009]. Moreover, floating ice is sensitive to small changes in the temperature of the oceans [*Shepherd et al.*, 2003] and atmosphere [*Vaughan and Doake*, 1996] and, because the recent trend of global warming is expected to continue [*Meehl et al.*, 2007], the sea level contribution due to floating ice may rise. According to a range of climate models and future climate scenarios [*Meehl et al.*, 2007], the expected contributions to global sea level over the 21st century due to fluctuations in the rate of ocean thermal expansion, the mass of glaciers and ice caps, and the mass of the Antarctic and Greenland ice sheets (excluding rapid changes in ice dynamics) fall in the range 130–340 mm, 26–58 mm, –120 to –20 mm, and 10 to 70 mm, respectively [*Meehl et al.*, 2007]. By way of comparison, a 0.1 °C rise in ocean temperature beneath Antarctic ice shelves alone would lead to a 1 m yr^{-1} increase in their rate of melting, and an estimated 10 mm steric rise in global sea level over the same period [*Jenkins and Holland*, 2007] - a contribution of comparable magnitude to those already considered. On the other hand, it has been suggested [*Zhang*, 2007] that the warming of the southern oceans has led to *gains* in Antarctic sea ice mass through increased thermohaline stratification. Either way, changes in the mass of floating ice should be considered in future assessments of global sea level rise.

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