Supplementary Materials for

Ice Shelf Melting Around Antarctica

E. Rignot,* S. Jacobs, J. Mouginot, B. Scheuchl

*Corresponding author. E-mail: erignot@uci.edu

Published 13 June 2013 on Science Express
DOI: 10.1126/science.1235798

This PDF file includes:

Supplementary Text
Figs. S1 to S4
Table S2
References

Other Supplementary Material for this manuscript includes the following:
(available at www.sciencemag.org/cgi/content/full/science.1235798/DC1)

Table S1 (Excel file)
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>§1</td>
<td>Ice shelf thickness</td>
<td>3</td>
</tr>
<tr>
<td>§2</td>
<td>Ice shelf velocity</td>
<td>4</td>
</tr>
<tr>
<td>§3</td>
<td>Drainage boundaries</td>
<td>4</td>
</tr>
<tr>
<td>§4</td>
<td>Ice-front positions</td>
<td>5</td>
</tr>
<tr>
<td>§5</td>
<td>Ice shelf areas, rises and islands</td>
<td>5</td>
</tr>
<tr>
<td>§6</td>
<td>Grounding line fluxes</td>
<td>5</td>
</tr>
<tr>
<td>§7</td>
<td>Surface mass balance (SMB)</td>
<td>5</td>
</tr>
<tr>
<td>§8</td>
<td>Basal melt rates</td>
<td>6</td>
</tr>
<tr>
<td>§9</td>
<td>Adjustments for ice shelf thickening</td>
<td>7</td>
</tr>
<tr>
<td>§10</td>
<td>‘Steady-state’ melt rates</td>
<td>8</td>
</tr>
<tr>
<td>§11</td>
<td>Characteristics of Antarctic Ice Shelves (Table S1)</td>
<td>9</td>
</tr>
<tr>
<td>§12</td>
<td>Comparison with other studies (Table S2)</td>
<td>9</td>
</tr>
<tr>
<td>§13</td>
<td>References</td>
<td>12</td>
</tr>
</tbody>
</table>
§1. Ice shelf thickness

Ice thickness (Fig. S1) is from BEDMAP-2 (1) and NASA Operation IceBridge (OIB) (18-19), which are available, respectively, at www.antarctica.ac.uk › Projects AZ › Bedmap2 and at the National Snow and Ice Data Center nsidc.org/data/icebridge/data_summaries.html. BEDMAP-2 merges measurements of ice thickness from airborne radio echo sounding with estimates derived from radar-altimetry observations of surface elevation from 1994 (20). The altimetry product uses the most inland grounding line positions from InSAR (21), MOA (36) or ASAID (37) to minimize the omission of floating sectors. Ice thickness may be erroneously high where ice is not in hydrostatic equilibrium, e.g. in a transition region. Along most glaciers, MOA and ASAID grounding lines (GL) have lateral errors up to 50 km (21), which impact the calculation of ice thickness, volume flux and basal melt rate. Here, we only rely a systematic, precise mapping of GL with InSAR (available at nsidc.org/data/docs/measures/nsidc0498_rignot/), and minimize the risk of including grounded ice sectors.

Special cases: As GL ice thickness is not well known on Larsen D-G, we use balance discharge from RACMO2 for the GL flux (Table S1). At the GL of Larsen C, Rayner/Thyer, Edward VIII and the thickest parts of Shackleton (Denman Glacier) and Moscow University Ice Shelves, ice thickness assumes hydrostatic equilibrium. For Larsen B, we use ice velocity from 2000 and ice-shelf thickness from 1994 - pre-dating its 2002 collapse. For the GL of Ross East, Nansen, Aviator, Mariner, Ninnis, Mertz, Dibble, Holmes, Totten, Wilma/Robert/Downer, Rayner/Thyer and Shirase in East Antarctica (EAIS), and Land, Nickerson, Sulzberger and Swinburne in West Antarctica (WAIS), we use (20); for David Glacier, we use OIB. For ice-front fluxes, we use BEDMAP-2, except for Rayner/Thyer where ice thickness uses hydrostatic equilibrium.
§2. Ice shelf velocity

Ice-shelf vector velocity data is from a mosaic of InSAR data from six sensors (22). Figure S2 shows the distribution of errors in a) speed and b) flow direction over the study area as discussed in (38). Flow speeds are highest along the coast and on ice shelves. The error in speed is lowest in fast-moving areas mapped with multiple sensors and highest in slow-moving areas mapped using only Advanced Land Observing System (ALOS) Polarimetric Advanced L-band Synthetic Aperture Radar (PALSAR) data. The average errors in flow speed and direction are, respectively, 4 m/yr and 1.7°. The velocity data are available online at nsidc.org/data/docs/measures/nsidc0484_rignot.

§3. Drainage boundaries

Drainage boundaries on continental ice are traditionally drawn using a digital elevation model of the ice sheet, assuming steady-state ice flow along the lines of steepest surface slope. This approach is not reliable on ice shelves due to their small surface slope. We use flow vector direction to delineate drainage boundaries between adjacent ice shelves. This approach helps to differentiate the ice flow into Filchner Ice Shelf (East Antarctica Ice Sheet (EAIS)) from Academy Glacier (not shown in Fig.~1) versus ice flow into Ronne Ice Shelf (West Antarctica Ice Sheet (WAIS)) from Foundation Ice Stream (not shown in Figure 1). We also separate ice flow into Ross West (WAIS) versus Ross East (EAIS) and ice flow into Brunt-Stancomb versus Riiser-Larsen ice shelves. The transition between EAIS and WAIS is thus defined at the boundaries between Foundation Ice Stream and Academy Glacier in the Weddell Sea sector, and Mercer Ice Stream and Scott Glacier (glaciers not shown in Fig. 1 and Table 1) in the Ross Sea sector.
§4. Ice-front positions

We identify ice-front positions in a radar mosaic of ALOS PALSAR data for the years 2007-2008 at a 150-m posting. The results are compared for consistency and quality control with MOA 2009 updated from (36). As an ice front migrates with ice flow and calving events, an exact agreement is not expected, but the comparison helps identify and resolve discrepancies. In the case of broken ice shelves, where icebergs are partially detached and glued together with an ice mélange of iceberg debris, sea ice and blown snow, ice front delineation uses clues from both radar and visible imagery.

The 2007-2008 ice-front positions do not coincide with the boundaries of BEDMAP-2 because the data sets are from slightly different time periods. As a result, our ice front flux gates are slightly upstream of the 2007-2008 ice front positions. The area in between the ice-front flux gates and the actual ice front positions is 2% of the total ice shelf area.

For ice walls and smaller ice shelves excluded from our survey, we assume a 50/50 partitioning between calving and basal melt to balance the incoming flux, as in the case of tidewater glaciers (39-40) (most listed below Table S1).

§5. Ice shelf areas, rises and islands

Inflow from ice rises ice islands along the ice shelf perimeter is included in the GL flux. Ice rises, rumples and islands within the ice shelf perimeters are included in the SMB input but excluded from the ice shelf area used to calculate total melt water production.

In Table 1 (and Table S1), we list the survey area of each ice shelf based on the locations of GL and ice-front flux gates. The survey area is used to calculate the melt rate in meters per year. Total melt water production is then obtained by multiplying this melt rate by the actual ice shelf area. Shape files of actual ice shelf perimeters used in this study will be made available at NSIDC under the Antarctic MEaSUREs project.

§6. Grounding line fluxes.

We have compared our GL fluxes with the balance fluxes calculated using RACMO2 (16). GL fluxes are within error bars of the balance fluxes except in a few areas known to be thinning rapidly (23). This verification provides an evaluation of the quality of the thickness data at the grounding line and helps justify the selection of alternative ice thickness estimates, as per the discussion in section 1, “Special cases”.

§7. Surface mass balance (SMB)

We employ SMB products from the University of Utrecht’s Regional Atmospheric Climate Model (RACMO2) validated with in-situ data (16). An error rate has been quantified for each basin based on error propagation (17), which we use in Table S1. We use an average $SMB$ for the time period 1979-2010 to obtain a long-term average SMB. Employing $SMB$ values for 2007-2008, the time period of velocity mapping, would
introduce significant noise and assume that ice shelf velocities respond instantaneously to annual fluctuations in snow input.

§8. Basal melt rates

The actual basal melt rate, $B$, in meters per year is deduced from the equation of mass conservation (15): $\frac{\partial H}{\partial t} = SMB - B - \nabla (H v)$, where $H$ is the ice thickness, $v$ is the ice velocity vector, $SMB$ the surface mass balance, and $\frac{\partial H}{\partial t}$ the rate of ice shelf thickening (positive for ice shelf growth).

To take into account the spatial resolution of the thickness data, we calculate the derivative terms of the mass conservation equation with a 10-km baseline, and the final melt rate map is smoothed with a 10-km filter. As a result, we miss points along the ice shelf perimeters when mapping the freeze/melt distribution; but this does not affect the estimation of area-average melt rates ($B$ expressed in Gt/yr in Table 1 and S1) because that calculation is based on the total inflow and outflow within the ice shelf perimeters, not the integration of point values.

We also calculate melt rates $B_{ss}$ for $\frac{\partial H}{\partial t} = 0$, i.e. the amount of freezing and melting that would be required to maintain the ice shelves in a steady state of velocity and thickness in 2007-2008. For this calculation, we still use velocity data for 2007-2008. In reality, some of these glaciers have been accelerating in recent decades, e.g. several glaciers draining into the Amundsen Sea. For these glaciers, it would have been preferable to use ice velocities from an earlier time period, e.g. 1975, when the system seemed closer to steady state. As we do not have complete velocity and thickness data for that time period, we focus instead on the most complete data set.

The spatial pattern of the melt rate $B$ appears noisy on some ice shelves, in particular on Brunt-Stancomb or Ross. Part of this signal is real and associated with rifts, cracks and vertical undulations in surface elevation present on those shelves. Part of the signal is caused by the time difference between ice thickness and ice velocity data and the advection of heterogeneities in ice thickness along flow. Furthermore, basal melting is expected to be non-uniform across such zones, with melting dominant along the rift sides and freezing dominant at the rift center.

We first calculate the basal melt rates in meters per year over the surveyed areas from the GL flux, ice front flux, $SMB$ and $\frac{\partial H}{\partial t}$. The result is then applied to the actual ice shelf area to deduce the total ice shelf melt water production. We then re-calculate $SMB$ and $\frac{\partial H}{\partial t}$ over the actual ice shelf areas instead of the surveyed area; the grounding line fluxes are unchanged because surveyed and actual areas share identical GL positions. The ice front fluxes are however corrected for the adjustment in $SMB$ and $\frac{\partial H}{\partial t}$ to insure closure of the mass balance equation. This correction amounts to 30 Gt/yr, i.e., < 3% of the total ice front flux, which covers 99.5% of the Antarctic ice shelf area.
§9. Adjustments for ice shelf thickening

Ice shelf thickening $\partial H/\partial t$ is derived using corrected ICESat-1 altimetry data for the period 2003-2008, and surface mass balance and firn correction data posted at dx.doi.org/10.1594/PANGAEA.775984. The analysis follows the method in (23). Firn depth corrections provided for 100 ice shelves are interpolated to all ice shelves using inverse distance weighting. The results (Fig. S3) are combined with the flux divergence and SMB data to calculate the melt rate $B$. The uncertainty in ice shelf thickening listed in Table S1 is from (23). Our results are consistent with (23).

Early in 2013, the National Snow and Ice Data Center reported an error of omission in the processing of ICESat data that introduces a 5-10 cm error on a pulse-by-pulse basis. Application of inter-campaign corrections and averaging over the entire time

Figure S3. Antarctic ice shelf thickening $\partial H/\partial t$ for years 2003-2008 derived from ICESat-1 data using the methodology of (23), overlaid on a 2009 MODIS mosaic of Antarctica (37).
period 2003-2008 reduce the impact of this correction, which should not affect the results of this study.

We have no estimates of ice shelf thickening for a few ice shelves (Table S1). For Wordie and Ferrigno, we use the rates for the adjacent Wilkins and Venable shelves, respectively. Zero thickening is assumed for Lillie, Wilma/Robert/Downer, Rayner/Thyer, Edward VIII and Shirase in East Antarctica. Ice shelf thickening for Larsen B is based on measurements collected over the remnant part of the ice shelf.

§10. ‘Steady-state’ melt rates

Figure S4 shows the steady state melt rates, i.e. assuming zero thickening. This map may be compared with actual melt rates in Figure 1 and Table 1. Some ice shelves are close to equilibrium, some are thinning and accelerating, and others are thickening. The results

Figure S4. Antarctic map of steady state ice shelf melting rate with ice shelf names overlaid on a MOA mosaic of Antarctica. Pie charts denote ‘steady-state’ ice shelf melt water production in Gigatonnes per year (black) versus calving fluxes (hatched) as in Figure 1.
show that ice shelves melt and freeze in a complex fashion even when they are in state of mass equilibrium with the atmosphere and the ocean.

§11. Characteristics of Antarctic Ice Shelves (Table S1)

Table S1 (Excel Spreadsheet) includes the list of names, center location, GL flux, ice front flux, surveyed area, actual area, $SMB$, thickening and associated uncertainties for all surveyed ice shelves. We also list 34 smaller ice shelves not included in the survey, for a combined total of 7,425 square kilometer, or 0.5% of our total surveyed area. See footnotes and comments for additional details.

§12. Comparison with other studies (Table S2)

From 1962-1994, seven estimates of total Antarctic ice shelf area, excluding ice rises, have ranged from 1.381 – 1.570 million km$^2$ (2, 3, 41). Differences between those areas and our 1.561 million km$^2$ (Table S1) could result from decadal-scale ice front advance and retreat, along with larger uncertainties in grounding line and ice front positions in prior surveys. Substantial changes have occurred around the Antarctic Peninsula (42). Areas and area-averaged basal melt rates for individual ice shelves in this study (Tables 1 and S1) reflect ice front locations in 2007-2008.

A thorough comparison of our results with other estimates from ocean measurements, ocean modeling and glaciological methods is problematical because of the different and not always specified ice shelf and model domains. Additional complications include various assumptions about ice shelf thickness and cavity morphology, uncertainties regarding total melting versus net melting, different time frames for parameters known to evolve on seasonal to decadal scales, and extrapolations from limited measurements. There has also been a scarcity of reference data, or its use, although some models are tuned to ice divergence calculations. For example, Table S2 shows a wide variety of estimates for a large, slow-melting ice shelf (Filchner-Ronne) and for a small, fast-melting ice shelf (Pine Island). Their listed melt rates, in some cases converted to Gt/yr, may slight the cited studies, which often provide qualifications, error estimates, sensitivity analyses and evaluations of prior work.

We treat the Filchner and Ronne ice shelves separately because of their different source regions (EAIS and WAIS), melt rates and grounding line thicknesses. Most basal mass balance studies have combined the two, but a few have focused on one or the other, portions of the Ronne, or have provided information that allows a rough division. Here our separate results are combined for comparison, and the error bars should be noted in Table S1. It is readily apparent that full Filchner-Ronne estimates vary widely, and that ocean tides can be a substantial factor in modeling studies (24). Our combined results are higher than most prior estimates, including a study employing similar glaciological methods (12), and the large ice shelf area magnifies the Gt/yr equivalent of m/yr. The rate from (6) is mainly derived from a Ronne
glaciological transect (15) incorporating a high-melting zone near the grounding line and flanking the large region of basal freezing in Figure 1, plus a near-ice front estimate. The large negative outlier from satellite radar altimeter data (45) would be equivalent to basal freezing of 0.5 m/yr, and may be caused by a rise in the radar reflection horizon due to changes in the firm associated with melt events, as in (46).

Since the discovery of rapid melting of the Pine Island Ice Shelf in 1994 (28), most estimates of its melt rate have focused on the fast-moving extension of the Pine Island Glacier in its southern part. Estimates of that area have ranged from 2,000 – 3150 km², and adding the adjacent slow-moving shelf ice has raised the full area by as much as 300%. Even larger total ice shelf areas (20; Table S1) result in part from a retreat of the glacier grounding line. We assume that most estimates are for net melting, noting that (45) also reported a steady state rate (24 Gt/yr). Reported melt rates for the more active southern portion have ranged from 6 – 85 Gt/yr, and a rise over time would be consistent with observed changes in ocean forcing and cavity dimensions (9). The rate sensitivity to cavity shape in ocean modeling can be seen in (29), where full ice shelf average rates are 40% higher with OIB than with BEDMAP data. The low 13 Gt/yr rate was discounted by its authors, based on modeled ‘warm’ deep water in Pine Island Bay ~2°C colder than observed.

While our tables show melting rates in Gt/yr and m/yr, the spatial and temporal distribution of basal melting is more important than its sum or areal average. Near ice shelf grounding lines, e.g., the melting has a larger impact on mass balance and glacier flow into the sea. At several regions near incoming glaciers to the Filchner and Ronne ice shelves, grounding zone rates of 2–14 m/yr have been estimated from glaciological methods (14), and peak rates of 2.5–18 m/yr from ocean modeling (24). Under the Pine Island ice shelf, grounding zone rates have ranged from ~44 to >100 m/yr (14, 47-48).
### Filchner and Ronne Ice Shelves

<table>
<thead>
<tr>
<th>Date (ref)</th>
<th>Type</th>
<th>Area</th>
<th>Melt rate</th>
<th>Notes</th>
<th>Date (ref)</th>
<th>Type</th>
<th>Area</th>
<th>Melt rate</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984 (49)</td>
<td>GM</td>
<td>473,000</td>
<td>443</td>
<td></td>
<td>1983 (58)</td>
<td>GM</td>
<td>3,150</td>
<td>6</td>
<td>[4]</td>
</tr>
<tr>
<td></td>
<td>GM</td>
<td>380,000</td>
<td>304</td>
<td>Ronne</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>GM</td>
<td>93,000</td>
<td>139</td>
<td>Filchner</td>
<td>1996 (28)</td>
<td>OO</td>
<td>3,000</td>
<td>28</td>
<td>[6]</td>
</tr>
<tr>
<td>1990 (44)</td>
<td>GT</td>
<td>530,000</td>
<td>126</td>
<td>[1]</td>
<td>1997 (53)</td>
<td>GM</td>
<td>2,500</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>1994 (43)</td>
<td>OO</td>
<td>500,000</td>
<td>46</td>
<td>[1]</td>
<td>1998 (47)</td>
<td>GM</td>
<td>2,000</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>1998 (50)</td>
<td>OM</td>
<td>71,800</td>
<td>23</td>
<td>Filchner</td>
<td>2004 (55)</td>
<td>GM</td>
<td>2,365</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GM</td>
<td>71,800</td>
<td>13</td>
<td>Filchner</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999 (51)</td>
<td>OM</td>
<td>450,000</td>
<td>37</td>
<td></td>
<td></td>
<td>OM, GM</td>
<td>3,010</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OM</td>
<td>450,000</td>
<td>49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OM</td>
<td>450,000</td>
<td>11</td>
<td>[3]</td>
<td>2010 (45)</td>
<td>GM</td>
<td>6,000</td>
<td>33</td>
<td>full ice shelf</td>
</tr>
<tr>
<td>2001 (10)</td>
<td>OO</td>
<td>470,000</td>
<td>86</td>
<td></td>
<td>2011 (56)</td>
<td>GM</td>
<td>2,775</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GM</td>
<td>340,456</td>
<td>72</td>
<td>Ronne</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003 (52)</td>
<td>OO</td>
<td>470,000</td>
<td>146</td>
<td></td>
<td>2012 (29)</td>
<td>OM</td>
<td>3,026</td>
<td>58</td>
<td>Bedmap</td>
</tr>
<tr>
<td></td>
<td>OM</td>
<td>408,000</td>
<td>120</td>
<td></td>
<td></td>
<td>OM</td>
<td>1,534</td>
<td>27</td>
<td>Bedmap</td>
</tr>
<tr>
<td></td>
<td>OM</td>
<td>1,534</td>
<td>33</td>
<td>OIB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010 (45)</td>
<td>GM</td>
<td>419,000</td>
<td>206</td>
<td></td>
<td>2011 (24)</td>
<td>OM</td>
<td>4,573</td>
<td>84</td>
<td>full Bedmap</td>
</tr>
<tr>
<td></td>
<td>OM</td>
<td>456,000</td>
<td>92</td>
<td>tidal forcing</td>
<td></td>
<td>OM</td>
<td>4,573</td>
<td>118</td>
<td>full OIB</td>
</tr>
<tr>
<td></td>
<td>OM</td>
<td>456,000</td>
<td>41</td>
<td>no tides</td>
<td>2012 (11)</td>
<td>OM</td>
<td>5,000</td>
<td>13</td>
<td>full ice shelf</td>
</tr>
<tr>
<td>2012 (11)</td>
<td>OM</td>
<td>438,000</td>
<td>141</td>
<td>[4]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**This Study**

| GM | 437,996 | 156 | Ronne |
| GM | 335,067 | 114 | Filchner |
| GM | 102,929 | 42 | Filchner |

### Pine Island Ice Shelf

<table>
<thead>
<tr>
<th>Date (ref)</th>
<th>Type</th>
<th>Area</th>
<th>Melt rate</th>
<th>Notes</th>
<th>Date (ref)</th>
<th>Type</th>
<th>Area</th>
<th>Melt rate</th>
<th>Notes</th>
</tr>
</thead>
</table>

---

**Table S2 notes:**

For simplicity melt rates are rounded to the nearest integer, without infrequently provided error bars (e.g., ~30% in (12, 52)). The comparisons above apply to the combined Filchner + Ronne and to the southern part of PIIS unless indicated otherwise. Melt rates in Gt/yr have in some cases been converted from other units in the cited studies.

- [1] Based on meltwater content in ‘Ice Shelf Water’ seaward of ice shelves.
- [2] Extrapolated from 2-D section of (15) and modified by added area near ice fronts.
- [4] A much higher rate could be inferred from other information in text.
- [5] Area estimated; rate is total minus freezing.
- [6] Revised to 51 Gt/yr in (9).
- [7] Full ice shelf area not specified within model domain of 9,720 km².

---

**Table S2: Comparison of melt rates from other studies for Filchner and Ronne Ice Shelves, and for Pine Island Ice Shelf (PIIS)**
§13. References


18. C. Allen, IceBridge MCoRDS L2 Ice Thickness. Boulder, Colorado USA: NASA DAAC at the National Snow and Ice Data Center (2010).


42. A. J. Cook, D. G. Vaughan, Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. *The Cryosphere* 4, 77 (2010). doi:10.5194/tc-4-77-2010


