Overview and Assessment of Antarctic Ice-Sheet Mass Balance Estimates: 1992–2009

H. Jay Zwally · Mario B. Giovinetto

Abstract Mass balance estimates for the Antarctic Ice Sheet (AIS) in the 2007 report by the Intergovernmental Panel on Climate Change and in more recent reports lie between approximately +50 to −250 Gt/year for 1992 to 2009. The 300 Gt/year range is approximately 15% of the annual mass input and 0.8 mm/year Sea Level Equivalent (SLE). Two estimates from radar altimeter measurements of elevation change by European Remote-sensing Satellites (ERS) (+28 and −31 Gt/year) lie in the upper part, whereas estimates from the Input-minus-Output Method (IOM) and the Gravity Recovery and Climate Experiment (GRACE) lie in the lower part (−40 to −246 Gt/year). We compare the various estimates, discuss the methodology used, and critically assess the results. We also modify the IOM estimate using (1) an alternate extrapolation to estimate the discharge from the non-observed 15% of the periphery, and (2) substitution of input from a field data compilation for input from an atmospheric model in 6% of area. The modified IOM estimate reduces the loss from 136 Gt/year to 13 Gt/year. Two ERS-based estimates, the modified IOM, and a GRACE-based estimate for observations within 1992–2005 lie in a narrowed range of +27 to −40 Gt/year, which is about 3% of the annual mass input and only 0.2 mm/year SLE. Our preferred estimate for 1992–2001 is −47 Gt/year for West Antarctica, +16 Gt/year for East Antarctica, and −31 Gt/year overall (+0.1 mm/year SLE), not including part of the Antarctic Peninsula (1.07% of the AIS area). Although recent reports of large and increasing rates of mass loss with time from GRACE-based studies cite agreement with IOM results, our evaluation does not support that conclusion.

Keywords Antarctica · Ice sheet · Mass balance · ERS · GRACE · ICESat · Input output fluxes

H. J. Zwally (✉)
Cryospheric Sciences Branch Code 614. 1, NASA Goddard Space Flight Center,
Greenbelt, MD 20771, USA
e-mail: zwally@icesat2.gsfc.nasa.gov

M. B. Giovinetto
SGT Inc, Cryospheric Sciences Branch Code 614. 1, NASA Goddard Space Flight Center,
Greenbelt, MD 20771, USA

1 Introduction

A perspective on the contributions of ice sheets to sea-level rise relative to other sources and the different contributions of each ice sheet (Table 1, Figs. 1 and 2) emphasizes the necessity to discriminate on the role played by each ice sheet, as well as among the drainage regions in each ice sheet. Estimates of ice sheet contributions to the observed rise have practically doubled from 1961–2003 to 2003–2007. The overall contributions from each of Greenland and Antarctica were considered equal in 1993–2003 (Lemke et al. 2007 in Inter-Governmental Panel on Climate Change; IPCC07). Although reports of larger Antarctic contributions for 2002–2008 are assessed in this paper, the contribution of 0.24 mm/year from Antarctica listed in Table 1 from Wu et al. (2010) is smaller than the recent contribution of 0.38 mm/year (136 Gt/year) from southeast Greenland alone (c.f. Fig. 1a, b).

Table 1 Recent compilations of contributions to observed sea level rise (mm/year)

Origin/causes	1961–2003a[a]	1961–2003b[a]	1961–2003c[a]	1993–2003a[a]	1993–2003b[a]	Selected
Observed Sea Level	1.8 ± 0.5	1.6 ± 0.2	1.8 ± 0.3	3.1 ± 0.7	3.1 ± 0.4	3.3 ± 0.4[b]
Thermosteric	0.42 ± 0.12	0.7 ± 0.1	0.4 ± 0.06	1.6 ± 0.5	1.6 ± 0.25	0.75 ± 0.1[c]
Glaciers and Ice Caps	0.50 ± 0.18	0.5 ± 0.2	0.5 ± 0.1	0.77 ± 0.22	0.8 ± 0.11	1.1 ± 0.25[a]
Ice sheets:	–	–	0.2 ± 0.2	–	0.4 ± 0.2	$0.72 \pm$? [d]
Antarctica	0.14 ± 0.41	0.2 ± 0.4	–	0.21 ± 0.35	–	0.24 ± 0.12[d]
Greenland	0.05 ± 0.12	0.1 ± 0.1	–	0.21 ± 0.07	–	0.48 ± 0.01[d]
Unassigned	0.7 ± 0.7	$0.1 \pm$?	$0.7 \pm$?	0.3 ± 1.0	$0.3 \pm$?	$0.73 \pm$?

Selected data (last column) span 1993–2009 for the observed rise and 2002–2008 for the contributions (see notes [a, b, c, d] below), yielding a large unassigned residual

[a] Compilation of estimates: 1961–2003a, 1993–2003a, by Bindoff et al. (2007); 1961–2003b, by Domingues et al. (2008); 1961–2003c, 1993–2003b, 2003–2007, by Milly et al. (2010)

[b] Observed sea level rise 1993–2009; Ablain et al. (2009)

[c] Thermosteric 2003–2007; Domingues et al. (2008) updated in Church et al. (2010)

[d] Estimates derived from GRACE Antarctic data for 2002–2008 (Wu et al. 2010) and from ICESat Greenland data for 2003–2007 (Zwally et al. 2011) using 357 Gt/mm SLE (Sea Level Equivalent) for comparison with the other cited studies. Elsewhere in this study we use 362 Gt/mm SLE to account for the area of estuaries and tidal marshes over the commonly used 360 Gt/mm SLE

Fig. 1 **a** dI/dt map for Antarctica from Zwally et al. (2005) showing the distribution of mass losses or gains ▶ in combinations of drainage systems (DS) around the continent for 1992–2001. The largest mass loss is in the region of Pine Island, Thwaites, and Smith glaciers in DS 21 and DS 22 in West Antarctica. **b** dI/dt map for Greenland from Zwally et al. (2011) showing the distribution of mass losses or gains in eight major drainage systems for 2003–2007 with the values in parenthesis for 1992–2002 from Zwally et al. (2005). Note that the negative scale is 5 times as large as the negative scale for Antarctica. Large increases in mass loss occurred in DS 3 and DS 4 in the southeast and DS 7 and DS 8 in the west, and small increases in mass gain occurred in the northern DS 1 and DS 2. These changes occurred during a period of significant increases in temperature and acceleration of some outlet glaciers in Greenland as discussed in Zwally et al. (2011). dI/dt is an approximation to the change in thickness of the ice column defined by dI/dt = dH/dt− dC_T/dt−dB/dt, where dH/dt is the measured surface elevation change, dC_T/dt is the change in the rate of firn compaction induced by temperature changes, and dB/dt is the vertical motion of the underlying bedrock
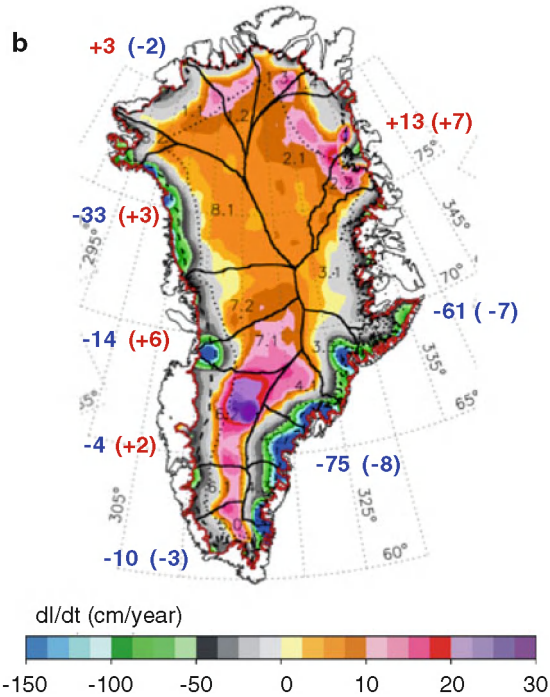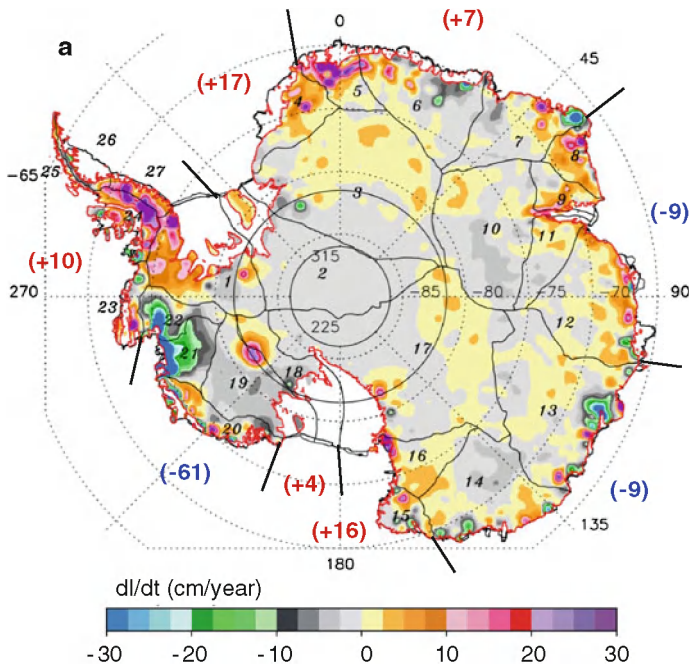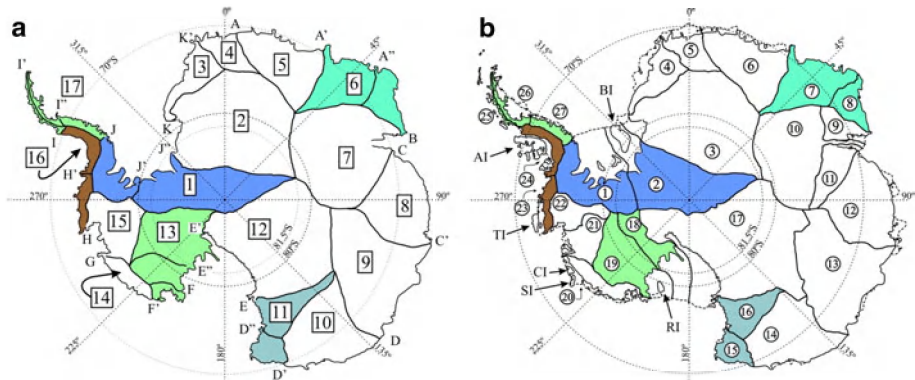
Fig. 2 Drainage entities (basins, sectors, systems, regions) of Antarctic grounded ice as identified in four sources cited in the text. **a** Drainage divides delineate twenty-five systems of the coterminous ice sheet with approximately the same pattern and sharing the same capital-letter designation of points at the coast or grounding line in three sources: Wingham et al. (2006) split the whole set in twenty-one basins, Rignot et al. (2008) in nineteen sectors, and Vaughan et al. (1999) in twenty-four basins. These entities are combined for comparison in seventeen regions (numbers shown in rectangles). The colored areas show where entities have been combined (regions 1, 6, 11, 13, 16, and 17). The drainage divides pattern shown, broadly similar in the three sources, is from Wingham et al. (2006).The boundary between East Antarctica and West Antarctica extends along the Trans-Antarctic Mountains, roughly from E to K. **b** Drainage divides in Zwally et al. (2005) delineate twenty-seven drainage systems (system numbers shown in circles). The budget estimates include all grounded ice (ice rises and on islands attached by ice, notably Berkner I. (BI) in 2, Roosevelt I. (RI) in 19, Siple I. (SI) and Carsey I. (CI) in 20, Thurston I. (TI) in 23, and Alexander I. (AI) in 24). The divides between systems 1, 2 and 17, 18 are drawn on the basis of ice provenance from either East or West Antarctica. The colored areas identify the regions as shown in **a** except for region 7 which includes systems 9–11. Applicable to **a** and **b**: (i) Large non-conformities between systems 1,2 and basins JJ′,J′J″ as well as between system 20 and basins FF′,F′G do not significantly affect the various area-normalized rate comparisons discussed in the text. (ii) Features and place names mentioned in the text: Antarctic Peninsula, roughly systems 24–27 (H′J); Graham Land, systems 25, 26 (II′,I′I″); western and eastern Palmer Land, system 24 (H′I) and 27 (I″J), respectively; northern Marie Byrd Land, broadly the northern zone of system 19 and southern zone of system 20, which overlap some parts of basins and sectors E″-G. (iii) The 81.5°S parallel shows the limit of ERS −1 and −2 radar altimeter coverage

The IPCC07 assessment of the Antarctic ice sheet (AIS) mass balance indicated a range between +50 and −200 Gt/year for the 1992–2003 period. Within the range assessed in IPCC07, the balance estimates closer to zero and either positive or negative are based on satellite radar altimetry from the European Remote-sensing Satellites (ERS). Estimates supporting the middle and lower half of the range are based on the Gravity Recovery and Climate Experiment (GRACE) data as well as on the Input-minus-Output Method (IOM). The ERS method is based on measurement of changes in ice thickness converted to changes in ice mass, the GRACE method is based on measurement of changes in gravity converted to changes in ice mass, and the IOM is based on the difference between surface balance and ice discharge at the grounding line. Generally, the range of estimates in IPCC07 encompassed the errors listed in the studies, but as noted in the report, a mid-range value does not indicate a more reliable estimate, and the composite errors listed in each study do not define confidence limits because important components lack formal statistical derivation. This caution on the error estimates applies to all studies regardless of methods of data collection and analyses.

The focus of this paper is a critical assessment of estimates of the AIS mass balance in IPCC07, along with more recent estimates as listed in Table 2. Our purposes are to find

Table 2 Antarctica. Mass budget estimates for grounded ice (values in parenthesis produced for this study)

Reference/modification	Database type	Period/year of application	Area (×10⁶ km²)		Original budget estimate				Adj. Estimate[a]
			Original[a]	Adjusted[a]	Bulk (Gt/year)		SFE(kg/m²/year)		(Gt/year)
a	b	c	d	e	f	g	h	i	j
Velicogna and Wahr (2006)	GRACE[b]a	2004/2005–2007/2005		12.183	−139	±73	−11.4	±6.0	−139
Raimillen et al. (2006)	GRACE[b]b	2007/2004–2003/2005		12.183	−40	±36	−3.3	±3.0	−40
Velicogna (2009)	GRACE[b]a	2004/2004–2002/2009		12.183	−143	±73	−11.7	±6.0	−143
		2002–2006		12.183	−104		−8.5		
		2006–2009		12.183	−246		−20.2		
Chen et al. (2009)	GRACE[b]b	2004/2002–2001/2009		12.183	−190	±77	−15.6	±6.3	−190
" " " " : Supplementary Information		2002–2006		12.183	−144	±58	−11.8	±4.7	
" " " " : Supplementary Information		2006–2009		12.183	−220	±89	−18.1	±7.3	
" " " " : West Ant. and Ant. Pen.	GRACE[b]b	2004/2002–2001/2009		2.736	−132	±26	−48.2	±9.5	
" " " " : (East Antarctica)		2004/2002–2001/2009		9.447	(−58)	(±72)	−6.1	±7.6	
Wu et al. (2010)/East Ant.	GRACE[b]a	2004/2002–2012/2008		9.447	−23	±29	−2.4	±3.1	
Wu et al. (2010)/West Ant.	GRACE[b]a	2004/2002–2012/2008		2.736	−64	±32	−23.4	±11.7	
(East, West and Ant. Peninsula)		2004/2002–2012/2008		12.183	(−87)	(±43)	−7.1	±12.1	(−87)
Rignot et al. (2008) (R08)	IOM	2000 (?)[c]	12.183	12.183	−136	±92			
Modified Outflow only (T.3, col. r)	IOM_Md	(1996,1997)[c]	12.183	12.183	(+146)				
Modified Outflow and Input (T.3, col. t)	IOM_Md	(?)[c]	12.183	12.183	(−13.2)		−1.1		(−13.2)
Zwally et al. (2005) (Z05f)[d]	ERS	1904/1992–2004/2001	12.193	12.053	−13.6	±5.4	−1.1	±0.4	(−13.4)
Zwally et al. (2005) (Z05i)[d]		1904/1992–2004/2001	12.193	12.053	−30.3	±12.1	−2.5	±1.0	(−30.0)

Table 2 continued

Reference/modification	Database type	Period/year of application	Area (×10⁶ km²)		Original budget estimate		SFE (kg/m²/year)		Adj. Estimate[a] (Gt/year)
			Original[a]	Adjusted[a]	Bulk (Gt/year)				
a	b	c	d	e	f	g	h	i	j
Wingham et al. (2006) (W06)[e] a	ERS	1910/1992–2002/2003	8.49	12.183	+27	±29	+3.2	±3.4	
Wingham et al. (2006) (W06)[e] b	ERS	1910/1992–2002/2003	11.71	12.183	+27	(±40)	+2.3	(±3.4)	(+28.0)
Wingham et al. (2006) (W06)[e] c	ERS	1910/1992–2002/2003	(11.9)	12.183	+37	(±40)	+3.1	(±3.4)	(+37.8)

[a] Area listed in the 'Original' reference used to derive the Surface Flux Equivalent (SFE), and 'Adjusted' to match the compilation in R08. 'Adj. estimate' is the SFE reintegrated for the Adjusted Area

[b] GRACE-based estimates used surface mass trend and GIA models I105 (b) or combinations of it and ICE5G-VM2 (a)

[c] The estimate in R08 is based on discharge (Output) data listed only once per basin and for a single year between 1992 and 2004; it cannot be assigned to 2000 or used to determine trend either from 1996 or to 2006. The surface balance estimate (Input), held constant, is the mean of atmospheric model products for 1980–2004

[d] Area of systems 25–27 (Graham Land and eastern Palmer Land) is excluded from Z05; the estimate includes the area of ice rises and grounded ice on islands attached by ice

[e] a The "best estimate" of +27 ± 29 Gt/year listed in W06 was for the observed area of 8.49 × 10⁶ km²

[e] b Following W06 p. 1633 (i.e. "*Our estimate of the mass gain of the unsurveyed Antarctic interior is comparable to our estimate of the mass loss of the unsurveyed coast*"), we take their best estimate to apply to the sum of basin area values listed in their Table 1 (11.71 × 10⁶ km²) and increase the error estimate in proportion to the respective areas

[e] c Alternatively, we apply +20 Gt/year for the interior following W06 p. 1633 (i.e. "*applying the average elevation rate (9 mm yr⁻¹) for the southernmost degree in latitude provides an estimated growth rate of 22 km³/year for the omitted region*") and apply −10 Gt/year for the unsurveyed coastal areas following W06 p. 1633 (i.e. "*applying the average elevation rate for the coastal 200 km of the surveyed ice sheet (−14 mm yr⁻¹) to the unsurveyed coastal sector... provides an estimated 10 Gt/year source of ocean mass (assuming the change were to occur at the density of ice*")) and use their respective unobserved areas given on p. 1628 (interior 2.6 × 10⁶ km² and coastal 0.8 × 10⁶ km²) for a total of 11.9 × 10⁶ km²

areas of agreement among the methods, to identify outliers, and to provide a rationale for a narrowed range of estimates and a preferred estimate. Table 2 includes two GRACE-based mass loss estimates of 104 Gt/year (Velicogna 2009) and 144 Gt/year (Chen et al. 2009) for the period 2002–2006 and two estimates of 246 Gt/year (Velicogna 2009) and of 220 Gt/year (Chen et al. 2009) for the period 2006–2009. These new GRACE estimates extend the IPCC07 range of AIS mass loss downward, and both papers cite results from the latest IOM estimate (Rignot et al. 2008; R08) in support of their findings, specifically the −136 Gt/year IOM estimate for 2000 and an increasingly negative balance toward 2006. In our evaluation of the IOM estimate of R08, we identify some issues regarding their methodology, and provide a modified IOM estimate. We compare two ERS estimates and our modified IOM estimate on a regional basis and find significant agreement over approximately one half of the AIS area.

Although this paper mainly addresses the AIS, we note results in a recent paper on the mass balance of the Greenland ice sheet for 2003–2007 and 1992–2002 (Zwally et al. 2011). The results for 2003–2007 are from Ice, Cloud, and land Elevation Satellite (ICESat) laser altimetry and the results for 1992–2002 are from a re-analyses of previous results from ERS radar altimetry complemented by airborne laser altimetry on outlet glaciers (Zwally et al. 2005; Z05). Particular relevant aspects include: (1) an improved treatment of firn compaction that enables separation of the elevation changes driven by accumulation changes from those driven by ablation and/or dynamic changes, (2) the calculation of appropriate firn/ice densities for those two elevation change components, and (3) the close agreement between the 171 Gt/year mass loss for the 2003–2007 period and two GRACE-based estimates (Wouters et al. 2008; Luthcke et al. 2009) for about the same time period. Those improved methods are being applied to new analyses of ICESat data over Antarctica for the period 2003–2009 and will be compared with other recent comparisons of ICESat and GRACE analyses (e.g. Gunter et al. 2009).

2 Assessment of Mass Balance Estimates from ERS Altimetry

One estimate (Z05) of AIS mass balance from ERS altimetry in IPCC07 gave a preferred estimate for 1992–2001 of −47 ± 4 Gt/year for West Antarctica (WA), + 16 ± 11 Gt/year for East Antarctica (EA), and −31 ± 12 Gt/year overall, not including Graham Land and eastern Palmer Land (1.07% of the AIS area) in the Antarctic Peninsula (AP). (In this and other references to relative area within the coterminous ice sheet, we use $100\% = 12.183 \times 10^6$ km^2 as compiled in R08.) Another estimate (Davis et al. 2005) gave + 45 Gt/year for EA for 1992–2003. A subsequent report (Wingham et al. 2006; W06) gave a preferred estimate of +27 ± 29 Gt/year for AIS overall for 1992–2003. Direct comparison among these ERS-based estimates is affected by different interpolation/extrapolation procedures (IEP) to attain full area coverage for the area south of 81.5°S, differences in coverage over the relatively narrow zone of steep outer slopes at the ice sheet margin, and differences in analyses for the southwestern region of the AP. In addition, different approaches were used to estimate the appropriate firn/ice density (ρ_i) in the conversion of elevation changes (dH/dt) to mass changes (dM/dt), according to dM/dt = ρ_i dH/dt. Also, only one estimate (Z05) included a correction for variations in the rate of firn compaction caused by changes in surface temperature that do not involve changes in mass.

Regarding the choice of ρ_i, in their estimate for EA, Davis et al. (2005) used 350 kg/m^3, which is characteristic of near-surface firn and is appropriate if the dH/dt were caused

by very recent changes in precipitation and accumulation rate. In contrast, using $\rho_i = 900$ kg/m^3 would have increased their estimate of 45 Gt/year mass gain for EA to 115 Gt/year, which would be appropriate if the changes were caused by a long-term imbalance between accumulation and ice dynamics. The W06 analyses for October 1992–February 2003 lists a preferred estimate of $+27 \pm 29$ Gt/year for AIS overall, with particular approaches showing results between -5 and $+85$ Gt/year. The W06 range includes the difference between restricting the change in elevation to the upper firn layers or attributing it to the whole firn/ice column, and incorporates corrections for accumulation anomalies in 1992–2001 determined from atmospheric modeling of Precipitation minus Evaporation (P-E) ("Appendix", Mass Balance Estimates of Wingham et al. (2006) (W06)). We believe arguments to attribute elevation change to changes in firn thickness on the basis of short-term trends in surface balance (e.g. on basins JJ′ and H-J; W06) might have regional relevance, but overall there is no statistically significant trend for Antarctica as a whole either in the P-E products covering 1958–2002 (van de Berg et al. 2005) or in the field data collated for large areas since the 1950s (Monaghan et al. 2006a).

The preferred estimate given in Z05 was based on use of $\rho_i = 900$ kg/m^3 (Z05i) for the firn and ice column and arguments that the bulk of the changes were caused by a long-term (multi-decadal scale) imbalance given previously mentioned lack of evidence for recent overall trends in Antarctic precipitation and accumulation rate. For comparison purposes, Z05 also gave estimates using $\rho_i = 400$ kg/m^3 (Z05f) for the multi-annual upper firn layers that would reduce the overall AIS mass balance to -14 Gt/year. The dH/dt values from ERS data were also adjusted for changes in the rate of firn compaction (dC/dt) driven by changes in firn temperature. dI/dt = dH/dt−dC/dt−dB/dt was then used to calculate dM/dt using ρ_i dI/dt, where dB/dt is the bedrock motion. For WA, where a regional warming trend caused an increased rate of firn compaction and a surface lowering that did not involve a mass change, the average dC/dt on the grounded ice was -1.58 cm/year (28.4 Gt/year equivalent). In EA, the average dC/dt on the grounded ice was $+0.21$ cm/year (-19.3 Gt/year equivalent). The derived dH/dt data over 77.1% of the AIS were used applying the optimal-interpolation method (krig procedure) to provide nearly complete spatial coverage (99%) of the AIS including the area of grounded ice south of 81.5°S.

For Z05i, the average interpolated dH/dt south of 81.5° S was $+1.6$ cm/year, and the calculated average ice thickness and mass changes were relatively small (dI/dt = $+0.64$ cm/year and dM/dt = $+14$ Gt/year). Overall, their interpolation including the coastal areas lowered the dM/dt from near zero to -31 Gt/year, indicating that about 45 Gt/year of mass loss from grounded ice in the coastal areas (ice sheet periphery, ice rises, and islands) was included by their interpolation. The survey in W06 that provided a "*best estimate of the overall mass trend… of +27 ± 29 Gt/year*" included "*72% of the grounded ice sheet…, omitting just 6% of coastal sectors… where data are lost due to steep slopes, and 22% of the interior…, which lies beyond the latitudinal limit… of the satellite ground track*". Although W06 also estimated a growth rate of $+22$ km^3/year (20 Gt/year) in the area south of 81.5°S and a loss of 10 Gt/year in their unsurveyed coastal area, they stated that the respective gain and loss were comparable (as noted in Table 2) and retained $+27 \pm 29$ Gt/year as their overall estimate. In contrast, Davis et al. (2005) did not interpolate/extrapolate to areas not included in their ERS analyses.

Comparison of ERS-based estimates is also affected by selective use of Glacial Isostatic Adjustment (GIA) estimates, which are implemented singly or in combined values from GIA models in the range between $+1.7$ mm/year average over Antarctica in W06 and $+5.4$ mm/year average in Z05. Using the ice density of 900 kg/m^3, the corresponding GIA corrections are -19 Gt/year for W06 and 59 Gt/year for Z05i. Consideration of GIA in

ERS-based studies leads to smaller mass corrections than in GRACE-based studies (discussed in a following section), because the applicable densities of rock are at least three times larger.

3 Assessment of Mass Balance Estimates from IOM

The IOM essentially consists of calculating the difference between mass input values, obtained from estimates of accumulation rates, and outflow values, obtained from measurements of discharge velocities combined with estimates of ice thickness at the grounding line. The IOM study of R08 presents the most complete survey of discharge at the periphery to date and one of the latest combinations of atmospheric model products to estimate of surface balance. Although accumulation estimates are available for the entire area of grounded ice, discharge estimates have only been made for segments of the periphery. In Rignot and Thomas (2002), balance results were presented for 60% of the ice sheet area and in R08 for 85% of the periphery, which was also taken as 85% of the area. Therefore, a critical aspect of the IOM is the IEP used to derive estimates of the outflow for the non-observed (NOBS) parts of the ice sheet from the values obtained for the observed (OBS) parts.

The data for nineteen drainage sectors as published in R08 and combined into the three ice sheet entities (EA, WA, and AP) are reproduced in Table 3 (columns a to g). We abbreviate their notation of Input+, Net+, and Area+ for the total of OBS and NOBS values to I+, N+, and A+, and use O+ for the total outflow. We also abbreviate their notation of Input, Outflow, Net, and Area for OBS values to I_{ob}, O_{ob}, N_{ob}, and A_{ob}, and use I_{nob}, O_{nob}, N_{nob}, and A_{nob} for the corresponding NOBS values that are not listed in R08. We calculate I_{nob} = I+ $-I_{ob}$, A_{nob} (%) = (A+ $-A_{ob}$)/A+, total discharge O+ = N+ $-$I+, and O_{nob} = O+ $-O_{ob}$ from their values, as listed in columns i to n. Some sums for WA, EA, and AP in Table 3 show differences of ±1 Gt/year from the round-off values listed in R08, and the sum of N+ for EA is −2 Gt/year vs. −4 Gt/year in R08. We carry this difference to N+ for all of the AIS and use −136 Gt/year versus −138 Gt/year, and a total discharge of 2191 Gt/year versus 2193 Gt/year.

Four major issues arise from the R08 IOM analyses. The first issue is the implicit assumption equating the fractions of OBS drainage area to the fractions of OBS drainage-periphery length (i.e. "*we use satellite interferometric synthetic-aperture radar observations from 1992 to 2006 covering 85% of Antarctica's coastline to estimate the total mass flux into the ocean.*" (R08, page 106). Their values of A_{ob} = 10.366 × 10^6 km^2 and A+ = 12.183 × 10^6 km^2 show that their A_{ob} (%) for AIS is also 85%. Although equivalence of NOBS periphery and NOBS area is unlikely to be valid for most of the nineteen sectors, it is accepted here for the purpose of this assessment. However, it remains as a concern in the use of either the IOM results from R08 or our modified IOM results (IOM$_{MD}$). Since the fractions of perimeter with outflow measurements is known, a more appropriate assignment of the corresponding OBS areas could be made by inland mapping of flowlines from the OBS portions of the perimeter. As discussed below, however, the I_{ob} and I_{nob} may have been apportioned by inland mapping and calculation of input over the OBS and NOBS areas.

The second and most important issue is the IEP used in R08 to estimate the discharge from the NOBS periphery or from the NOBS area in each sector. Their IEP is described as "*To include non-surveyed areas, we apply a scaling factor on the mass fluxes of each large basin A-K*" *based on the percentage surveyed area versus total area to cover 100% of*

Table 3 IOM mass balance estimates from R08 for 2000 and modified estimate

	Values for 2000 from Table 1 in R08							Calculated from R08 values						
	Area A_{ob} 10^3 km^2	Input I_{ob} Gt/yr	Outflow O_{ob} Gt/yr	NET N_{ob} Gt/yr	NET+ $N+$ Gt/yr	Area+ $A+$ 10^3 km^2	Input+ $I+$ Gt/yr	$N +_{AS} = N_{ob} \cdot A +/A_{ob}$ Gt/yr	A_{nob} %	$I_{nob} = I+ - I_{ob}$ Gt/yr	%	$O += I + -N +$ Gt/yr	O_{nob} Gt/yr	%
Column	a	b	c	d	e	f	g	h	i	j	k	l	m	n
Col. calc.								d(f/a)	(f−a)/f	g−b	j/g	g−e	1−c	m/l
East ant														
J″K	1698	93	75	18	19	1780	100	19	5	7	7	81	6	7
KK′	218	42	45	−3	−3	246	50	−3	11	8	16	53	8	15
K′A	159	26	28	−1	−1	178	32	−1	11	6	19	33	5	15
AA′	615	60	60	0	0	622	62	0	1	2	3	62	2	3
A′B	354	39	40	−1	−1	645	115	−2	45	76	66	116	76	66
BC	1197	73	77	−4	−4	1332	87	−4	10	14	16	91	14	15
CC′	434	81	87	−7	−11	702	137	−11	38	56	41	148	61	41
C′D	1053	198	207	−8	−9	1162	261	−9	9	63	24	270	63	23
DD′	563	92	94	−2	−2	691	136	−2	19	44	32	138	44	32
D′E	267	20	22	−2	−3	450	62	−3	41	42	68	65	43	66
EE′	1441	61	49	11	13	1639	89	13	12	28	31	76	27	36
Sum	7999	785	784	1	−2	9447	1131	−5	15	346	31	1133	349	31
R08 sum	7998	786	785	1	−4	9447	1131	–	–	–	–	–	–	–
West ant														
E′F′	751	110	80	31	34	845	130	35	11	20	15	96	16	17
F′G	119	108	128	−19	−23	140	128	−22	15	20	16	151	23	15
GH	393	177	237	−61	−64	417	196	−65	6	19	10	260	23	9
HH′	55	51	86	−35	−49	78	71	−50	29	20	28	120	34	28
JJ″	933	142	145	−4	−4	1028	165	−4	9	23	14	169	24	14
Sum	2251	588	676	−88	−106	2508	690	−106	10	102	15	796	120	15

Table 3 continued

	Values for 2000 from Table 1 in R08							Calculated from R08 values						
	Area A_{ob} 10^3 km²	Input I_{ob} Gt/yr	Outflow O_{ob} Gt/yr	NET N_{ob} Gt/yr	NET+ N+ Gt/yr	Area+ A+ 10^3 km²	Input+ I+ Gt/yr	N +$_{AS}$ = N$_{ob}$·A +/A$_{ob}$ Gt/yr	A$_{nob}$ %	I$_{nob}$ = I+·- I$_{ob}$ Gt/yr	I$_{nob}$ %	O +=I + -N + Gt/yr	O$_{nob}$ Gt/yr	O$_{nob}$ %
R08 sum	2251	588	676	-88	-106	2508	690	–	–	–	–	–	–	–
Ant pen														
H′I	92	71	78	-7	-7	98	77	-7	6	6	8	84	6	7
I″	13	15	20	-5	-15	78	125	-30	83	110	88	140	120	86
I″J	11	8	9	-1	-6	52	32	-5	79	24	75	38	29	76
Sum	116	94	107	-13	-28	228	234	-42	49	140	60	262	155	59
R08 sum	116	94	107	-13	-28	228	234	–	–	–	–	–	–	–
AIS														
Sum	10366	1467	1567	-100	-136	12183	2055	-154	15	588	29	2191	624	28
R08 sum	10365	1468	1568	-100	-138	12183	2055	–	–	–	–	–	–	–

	Modified O$_{nob}$ and modified I+					R08 values		AS	Md
OnobAS (area scaled)	O$_{nobMd}$ Gt/yr	O+$_{Md}$ Gt/yr	N+$_{MdO}$=I+-O+$_{Md}$ Gt/yr	I+$_{Mod}$ Gt/yr	N+$_{Md}$=I+$_{Md}$ -O+$_{Md}$ Gt/yr	O$_{ob}$ SFE kg/m²/yr	O$_{nob}$	O$_{nobAS}$	O$_{nobMd}$
Column	p	q	r	s	t	u	v	w	x
Col. calc.	0.7 o	c+p	g-q	s-q	s-q	c/a	m/(f-a)	o/(f-a)	p/(f-a)
East ant									
J″K	3	78	22	100	22	44	73	44	31
KK′	4	49	1	50	1	206	286	206	144
K′A	2	30	2	32	2	176	263	176	123
AA′	0	60	2	62	2	98	286	98	68

Column o: OnobAS (area scaled), Col. calc. c(f-a)/a — values: J″K 4, KK′ 6, K′A 3, AA′ 1

Table 3 continued

	OnobAS (area scaled)	Modified O_{nob} and modified I+					R08 values		AS	Md
		O_{nobMd}	$O+_{Md}$	$N+_{MdO}=I+-O+_{Md}$	$I+_{Mod}$	$N+_{Md}=I+_{Md}-O+_{Md}$	O_{ob} SFE	O_{nob}	O_{nobAS}	O_{nobMd}
	Gt/yr	Gt/yr	Gt/yr	Gt/yr	Gt/yr	Gt/yr	kg/m²/yr			
A'B	33	23	63	52	115	52	113	261	113	79
BC	9	6	83	4	87	4	64	104	64	45
CC'	54	38	125	12	137	12	200	228	200	140
C'D	21	15	222	39	261	39	197	578	197	138
DD'	21	15	109	27	136	27	167	344	167	117
D'E	15	11	33	29	62	29	82	235	82	58
EE'	7	5	54	35	89	35	34	136	34	24
Sum	173	121	905	226	1131	226	98	241	120	84
West ant										
E'F'	10	7	87	43	130	43	107	170	107	75
F'G	23	16	144	-16	44	-100	1076	1095	1076	753
GH	14	10	247	-51	159	-88	603	958	603	422
HH'	36	25	111	-40	53	-58	1564	1478	1564	1095
JJ"	15	10	155	10	165	10	155	253	155	109
Sum	98	68	744	-54	551	-194	300	467	381	266
Ant pen										
H'I	5	4	82	-5	57	-24	848	1000	848	593
II"	100	120	140	-15	125	-15	1538	1846	1538	1846
I"J	34	29	38	-6	32	-6	818	707	818	707
Sum	139	153	260	-26	214	-45	922	1384	1238	1362
AIS										
Sum	410	342	1909	146	1896	-13	151	343	226	188

Antarctica (Table 1)" (R08, page 107), and in their Table 1 as "*Net+: mass balance scaled on the basis of total area (Area+) versus surveyed (Area),...*". The first statement implies a scaling of both the input and output fluxes by the ratio of total area to OBS area (i.e. $A+/A_{ob}$) and the second statement indicates a scaling of the net flux by the same ratio. These scalings should be mathematically equivalent because the three terms are linearly related in a summation. According to the second statement, our calculation of net mass balance values as $N+ = N_{ob} \cdot A+/A_{ob}$ in column h agrees with the NET+ of R08 (column e), except for sector II″ (-30 versus -15 Gt/year) and roundoff differences in the other sectors. However, in contrast to the implication of the first statement, the input and outflow terms (I_{ob}, I_{nob}, O_{ob}, and O_{nob}) of the mass balance from R08 values in Table 3 are not separately consistent with this area scaling, as shown by comparisons of $I_{nob}(\%)$ and O_{nob} (%) in columns k and n with A_{nob} (%) in column i. A more explicit comparison is made below using the surface-flux equivalent (SFE) for each of the mass rate terms. The SFE (kg/m²/year) is the ratio of bulk mass rate (Gt/year) to area (10^6 km²), which normalizes the terms by their respective areas (Fig. 3a).

The inconsistency in scaling is illustrated by examination, for example, of the values for sector EE′ in Table 3 where a N+ of 13 Gt/year (column h) is obtained by scaling by $A+/A_{ob} = 1.137$, in agreement with the R08 N+ of 13 Gt/year (column e). However, separate scaling of the input and output terms by the same factor gives $I+_{AS} = 69.4$ Gt/year and $O+_{AS} = 55.7$ Gt/year, which are very different from respective R08 fluxes of $I+ = 89$ Gt/year (column g) and $O+ = 76$ Gt/year (column l). Since the input, output, and net terms are linearly related in a summation, and are not all scaled by the same factor, the input and output scaling factors must be somewhat different in a compensating manner. In fact, the values for sector EE′ show that input scaling (i.e. $I+/I_{ob} = 89/61 = 1.459$) used by R08 was slightly different from the scaling factor applied to the output flux (i.e. $O+/O_{ob} = 76/49 = 1.551$). Because a smaller scaling factor of 1.459 was applied to a larger OBS input flux of 61Gt/year, compared to a larger scaling factor of 1.551 that was applied to a smaller OBS output flux of 49 Gt/year, the differences compensated to give N+ of 13 Gt/year (i.e. 89–76) that is equal to the NET+ of R08.

The values of I_{nob} (%) (column k) calculated from R08 data range from a low of 3% in sector AA′ in EA to a high of 88% in sector II″ in the AP. For the AIS overall, the $I_{nob}(\%)$ value of 29% is almost twice as large as the A_{nob} (%) of 15%. Therefore, the R08 contributions to input per unit area from NOBS areas are significantly larger than those from the OBS areas, which is shown more clearly by the SFE of the respective mass terms (Fig. 3a). Using the values in Table 3, the I_{nobs} (SFE) is 324 kg/m²/year for the overall AIS and the corresponding I_{ob} (SFE) is 142 kg/m²/year, which are in a ratio of 2.3 to 1. A larger I_{nob} (SFE) than I_{ob} (SFE) seems appropriate, because the drainage areas corresponding to the periphery with the NOBS outflow tend to be more restricted to coastal areas (c.f. next paragraph) where the accumulation rates are generally larger, whereas the faster flowing OBS parts drain more of the interior where the accumulation rates are lower. Although the R08 method of apportionment is not stated, both I_{ob} and I_{nob} may have been calculated from their accumulation input maps, which cover the entire ice sheet, possibly using a tracing of the respective drainage areas inland from the periphery.

In contrast to the input, the outflow (O_{nob}) requires extrapolation, because it is not observed everywhere. However for the AIS overall, the $O_{nob}(\%)$ is 28%, or about twice the A_{nob} (%) of 15%. The values of $O_{nob}(\%)$ by sector in column n are closer to the values of $I_{nob}(\%)$ in column k than to the area ratio A_{nob} (%) in column I, but there are significant compensating differences as discussed above. Table 3 shows that the R08 value for O_{nob} (SFE) for the overall AIS is 343 kg/m²/year (column v) and the corresponding O_{obs} (SFE)
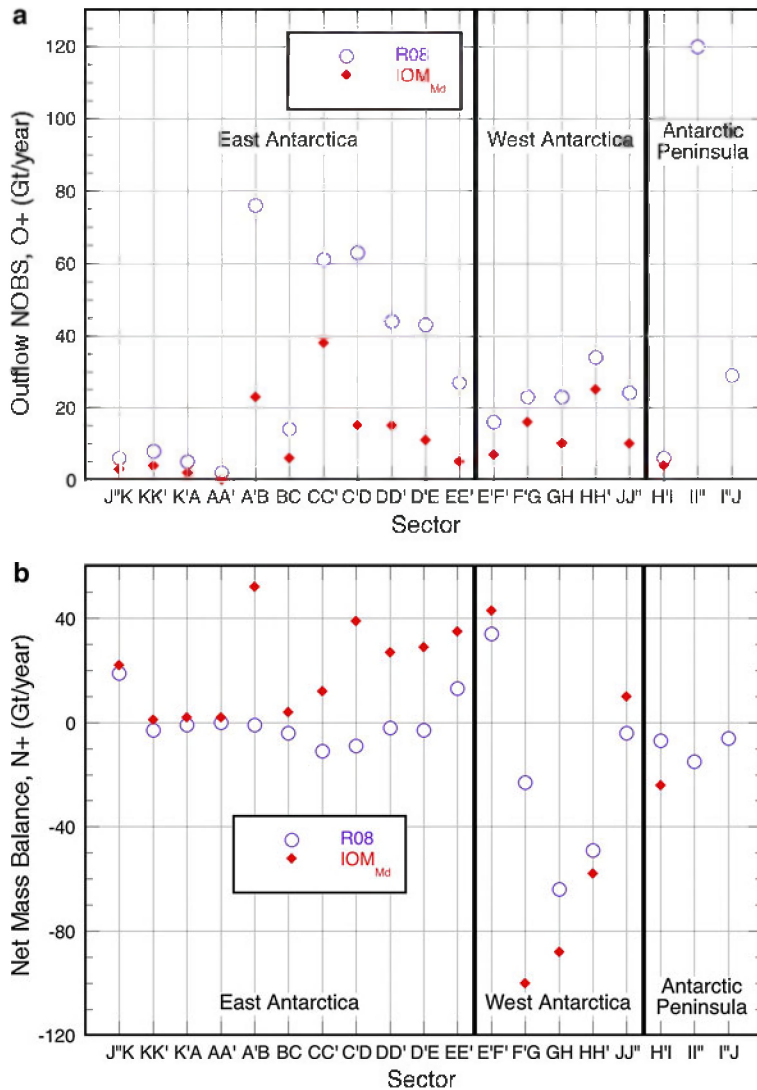
Fig. 3 a Difference in outflow from the non-observed (NOBS) area in each of the nineteen sectors in Rignot et al. 2008 (R08) and the modified estimate (IOM$_{Md}$) using alternate interpolation/extrapolation procedures (IEP). **b** Difference in Net+ for each of the nineteen sectors in R08 introduced by application of the alternate IEP to obtain Outflow from the NOBS area as shown in (a), and substitution of surface balance in sectors F′G, GH, HH′ and H′I from the compilation of Vaughan et al. (1999). There is no modification of Outflow from the NOBS area or of the Net+ statistics for sectors II″ and I″J, Graham Land and eastern Palmer Land, respectively, as cited in R08 from Rignot et al. (2005) and Pritchard and Vaughan (2007)

is 151 kg/m²/year (column u), which are also in a ratio of 2.3 to 1. By sector, the R08 values of O$_{nob}$ (SFE) are all greater than O$_{obs}$ (SFE), except for sectors HH′ and I″J that together account for 1.07% of the AIS area. A larger SFE in the NOBS parts is not consistent with the fact that measured ice velocities used in the outflow calculations tend to be through the faster moving outlet glaciers and not through the slower moving parts of the

ice sheet periphery. Specifically, R08 noted that selection of OBS periphery *"covers all major outlet glaciers, ice streams and tributaries of importance for mass flux calculation"* (R08, page 106). This implies that the NOBS periphery should have a smaller rate of mass discharge per unit length than the OBS periphery, regardless of variable thickness at the grounding line, and that the corresponding O_{nob} (SFE) should be smaller than O_{ob} (SFE), not larger. Therefore, we believe the R08 scaling significantly overestimates the outflow (i.e. 28% of the total outflow from only 15% of the periphery that are the slower portions). For comparison, in columns o, p, and q of Table 3, we calculate the values of O_{nobAS} (column o) using a proportional area scaling of outflow, which gives equal O_{nob} (SFE) and O_{ob} (SFE) outflows (columns u and w). Compared to R08, area scaling reduces the NOBS outflow from 624 Gt/year to 410 Gt/year (columns m and o) and the total outflow (O+) by about 10% from 2191 Gt/year to 1977 Gt/year, which would change the net mass balance from a loss of 136 Gt/year of R08 to a gain of 78 Gt/year.

We present a modified IEP based on the assumption that the contributions to outflow per unit area in the NOBS areas are between 0.5 and 0.9 of that in the OBS areas. We apply a midpoint factor of 0.7 to the O_{ob} (SFE) (column u) to obtain O_{nobMd} (SFE) (column x), which is then multiplied by A_{nob} to obtain O_{nobMd} (Gt/year) (column p). Although applying a common factor is simplistic, a more elaborate IEP would require information such as periphery length, ice thickness at the grounding line, and velocities. In small sectors such as II″ and I″J, applying a common factor seems to introduce biases that would require a more detailed approach beyond the scope of this paper. Therefore for sectors (II″ and I″J), we use the Net+ values cited (Rignot et al. 2005; Pritchard and Vaughan 2007) and used by R08. The resulting modified values of O_{nobMd}, $O+_{Md}$, and $N+_{MdO}$ are in columns p, q, and r. For EA, the O_{nobMd} is reduced to 121 Gt/year (column p) from the 349 Gt/year of R08 (column m) and the corresponding O_{nobMd} (SFE) is reduced to 84 kg/m^2/year (column x) from 241 kg/m^2/year (column v), appropriately reducing the O_{nobMd} (SFE) to a value smaller than the O_{ob} (SFE) of 98 kg/m^2/year (column u). For WA, the O_{nobMd} is reduced to 68 Gt/year (column p) from the 120 Gt/year of R08 (column m) and the corresponding O_{nobMd} (SFE) is reduced to 266 kg/m^2/year (column x) from the 467 kg/m^2/year of R08 (column v), also appropriately reducing the O_{nobMd} (SFE) to a value smaller than the O_{ob} (SFE) of 300 kg/m^2/year (column u). For the seventeen sectors of WA, EA, and sector H′I in the AP, the O_{nobMd} is reduced by 282 Gt/year from the 475 Gt/year of R08 (column m) to 193 Gt/year (column p). Overall, our modification of the NOBS outflow would bring the overall $N+_{MdO}$ for Antarctica up to a mass gain 146 Gt/year (column r), if the input of R08 were used.

The third issue concerns the atmospheric model products used to obtain the surface balance input, generally referred to as P-E ("Appendix", Surface Balance Estimates in Rignot et al. (2008) (R08)). Among various surface balance inputs available, the P-E results used in R08 give the largest estimate of surface balance for most of northern WA and the AP. In these regions, the composite sector F′-H′ (5.2% of the area) includes three sectors in northwestern WA listing increases between 23 and 192% relative to the field data compilation of Vaughan et al. (1999; V99), which has been used as the benchmark for model products in van de Berg et al. (2006) and W06. One other composite sector H′-J (1.9% of the area) includes northeastern WA and the AP, for which the increases relative to the V'99 compilation range between 24 and 177%. These increases are well in excess of the overall increase in the surface balance of the AIS of *"up to 15%"* reported in van de Berg et al. (2006) where it is noted that it would require new field data to corroborate (c.f. van den Broeke et al. 2006b). Regardless of the soundness of the atmospheric models, product verification in sector F′-J is unconvincing. For example, in R08 disagreement between model product and field data sets led to their dismissal of reliable sets in

northeastern WA listed elsewhere (e.g. Turner et al. 2002) rather than to model-recali-bration. Whereas some unreliable data sets are best ignored in the drawing of isopleths in compilations of field data (e.g. Giovinetto et al. 1989), the dismissal in R08 by claiming a bias toward reporting small accumulation rates in central-northern WA on the basis that field observations were made in shallow pits is not justified. Moreover, after acknowl-edging in earlier discussions of atmospheric model product that there are practically no data from the zone between the coast and an elevation of approximately 1200 m where most of the increase in precipitation is allocated (e.g. van de Berg et al. 2006), the citation in R08 of precipitation gauge data from Russkaya to support the model product in northwestern West Antarctica is questionable. Practically all gauge data everywhere in polar regions are grossly unreliable at wind speeds >10 m/s, particularly where there is ample supply of dry snow nearby, as is the case for Russkaya during at least nine months of the year. The Russkaya station (74°46'S, 136°52'W) lists wind speed >15 m/s for 264 days/year and >30 m/s for 136 day/year).

Substitution of the area adjusted V99 estimates of surface balance for the six sectors would reduce the I+ estimate for the whole ice sheet from 2055 to 1810 Gt/year. However, as mentioned in a preceding section the data cited in R08 for sectors II″ and I″J were from Rignot et al. (2005) and Pritchard and Vaughan (2007) and we retain those values. Therefore, we limit our surface balance substitution to four sectors from F′ to I (a combined 6.02% of the area) (Table 3). This substitution reduces the surface balance for the four sectors by 159 Gt/year from 472 to 313 Gt/year and reduces the R08 estimate of I+ from 2055 Gt/year (column g) to I+$_{Md}$ value of 1896 Gt/year (column s). This reduction of the I+, combined with the reduction of output from the 2191 Gt/year (column l) of R08 to the O+$_{Md}$ value of 1909 Gt/year (column q) brings the N+$_{Md}$ (column t) to a small overall loss of 13 Gt/year. The distribution of the differences between the NOBS outflow and the net mass balance from R08 and our IOM$_{Md}$ are shown in Fig. 3b. The largest reductions in the NOBS outflow are in six of the seven sectors from A′B to EE′ of East Antarctica (Fig. 3a), resulting in more positive net balances (Fig. 3b). Two of the five sectors in WA also have more positive net balances in the IOM$_{Md}$ as a result of the reduction in NOBS outflow, and the other three have a more negative balance as a result of our reduction in I+$_{Mod}$ in those sectors.

The fourth issue arises from the reported trend in the mass budget of Antarctica and particular regions and basins centered on the years 1996, 2000, and 2006 (Tables 1 and 2 in R08). An examination of Table S1 in the Supplementary Material of R08 shows estimates of discharge for each of the 66 basins comprising 85.10% of the area, but the estimate for each basin is based on a velocity measurement for only a single year distributed between 1992 and 2004. The number of basins and the fraction of OBS periphery (total observed area of 10.368 × 10^6 km^2) are: for single observations distributed between 1992 and 1997, 46 basins for 79.77% of the area; for single observations during 2000, 19 basins for 20.17% of the area; and for single observations during 2004, 1 basin for 0.05% of the area. There seem to be no acceptable assumptions that could be made to obtain discrete estimate values for 1996, 2000, and 2006 from these data, be it for all of Antarctica or for any region or basin. Therefore, additional measurements of discharge not listed in Table S1 in the Supplementary Material of R08 would be required for calculation of changes or trends in discharge during 1996–2006. Also, rather than assigning the finding in Table 1 of R08 to the single datum year of 2000, it seems that a more appropriate assignment would be 1996–1997, because the ice discharge data were compiled for 77.42% of the OBS periphery using observations made for 23 basins in 1996 for 33.23% of the periphery and 16 basins in 1997 for an additional 44.19% of the periphery.

The above four issues also affect the IOM results in Rignot et al. 2011 (R11) in a similar manner, both in regard to the magnitude of their estimates of I+, O+, and N+ and in regard to their conclusions about accelerations in these terms during 1992 through 2009. Using the trend lines (fitted through the illustrated interannual variability) for input (surface mass balance) and output (D*) in Fig. 1b of R11, the respective values I+, O+, and N+ are 2130, 2157, and −27 Gt/year for January 1992 and 2053, 2265, and −212 Gt/year for January 2006. For comparison, the respective IOM_{MdO} values from Table 3 are 1896, 1909, and −13 Gt/year. The R11 estimated accelerations in I+, O+, and N+ are respectively $I'+ = -5.5 \pm 2$ Gt/year^2, $O'+ = +9.0 \pm 1$ Gt/year^2, and $N'+ = -14.5 \pm 2$ Gt/year^2. Although the R11 discharge estimate includes corrections for grounding line retreat and thinning at the grounding line for two glaciers (Thwaites and Pine Island) in WA, the methodology otherwise appears to be that of R08 and subject to both the overestimate of discharge from the NOBS areas, as well as insufficient information on the time series of discharge velocities used to justify the estimated acceleration of O+.

In regard to the R11 estimate of a deceleration in I+ from 1992 through 2009, we again note that any conclusions regarding possible trends in precipitation, and therefore surface mass balance in Antarctica, are highly dependent on the model used and the time period (Bromwich et al. 2011; Nicolas and Bromwich 2011). The R11 estimated deceleration of 5.5 ± 2 Gt/year^2 for 1992 through 2009 is strongly influenced by the positive anomaly in 1992 to mid 1993. The corresponding linear trend for 1994 through 2009 following the anomaly is a statistically insignificant acceleration of 0.8 ± 2 Gt/year^2. Similarly, for a period beginning before the 1992 anomaly, the ERA-Interim reanalyses data set, considered to provide "*the most realistic depiction of precipitation changes in high southern latitudes during 1989 to 2009*", showed an insignificant change of 0.5 ± 2.7 mm/year/decade and four other reanalyses data sets showed positive trends in P-E (Bromwich et al. 2011). For a longer period, Monaghan et al. (2006b) found "*there has been no statistically significant change in snowfall since the 1950s,…*". Therefore, we believe there is insufficient evidence in the IOM results for either an acceleration or deceleration.

4 Comparison of Regional Distributions of Mass Balance Estimates from IOM and ERS

To assess the impact and distribution of balance estimates for particular drainage entities, we use seventeen regions (Fig. 2) approximately matching the twenty-one "basins" in W06, the nineteen "sectors" in R08, and the twenty-seven drainage "systems" in Z05 as combined in Table 4. These combinations aim to minimize boundary disparities, but several combinations require qualification. To match the sector E'F' in R08 the basins E'E'', E''F, and FF' from W06 are combined, but the area of FF' common to both studies remains incorporated in system 20 of Z05; also, in Z05 the study includes grounded ice areas outside the coterminous ice sheet. However, no adjustments are made for these qualifications, because they do not alter the findings in a significant way.

Comparison of net SFE estimates in Table 4 (columns l–0) and re-integrated bulk estimates for the seventeen regions (columns p-r) show there is close agreement over most of the AIS between the ERS-based estimates of W06 and the two estimates in Z05 (as stated previously, Z05f used a density of 400 kg/m^3 and, for their preferred estimate, Z05i used a density of 900 kg/m^3). For comparison here, we use Z05i as the preferred estimate. Comparison of the estimates by region (Fig. 4a and Table 4), shows that the IOM_{Md} values are mostly the outliers (as it would be the case with the unmodified R08 values), even

Table 4 Antarctica. Comparison of net balance estimates for grounded ice compiled in seventeen regions

Region	Sector	Basin	System	Area (10^6 km² and (%) of total)			Net balance for original area (Gt/year)				Surface flux equivalent (kg/m²/year)				Area adjusted net balance (Gt/year)		
Fig. 1 a[a]	R08 b	W06 c	Z05 d	R08 (%) e	W06 f	Z05 g	IOM^b_{Md} h	W06 i	Z05f j	Z05i k	IOM^b_{Md} l	W06 m	Z05f n	Z05i o	W06 p	Z05f q	Z05i r
1	JI″	JI′JI″	1, 2	1.028 (8.44)	1.04	1.3676	9.67	3.02	2.98	6.73	9.41	2.90	2.18	4.92	2.99	2.24	5.06
2	J″K	J″K	3	1.780 (14.61)	1.59	1.5181	22.47	5.72	5.00	11.25	12.62	3.60	3.29	7.41	6.40	5.86	13.19
3	KK′	KK′	4	0.246 (2.02)	0.24	0.2563	0.95	8.86	2.98	6.70	3.86	36.92	11.63	26.14	9.08	2.86	6.43
4	K′A	K′A	5	0.178 (1.46)	0.19	0.2065	1.66	10.26	6.12	13.78	9.33	54.00	29.64	66.73	9.61	5.28	11.88
5	AA′	AA′	6	0.622 (5.11)	0.59	0.6038	1.52	−1.59	−0.77	−1.73	2.44	−2.70	−1.28	−2.87	−1.68	−0.79	−1.78
6	A′B	A′A″,A″B	7, 8	0.645 (5.29)	0.64	0.6178	51.98	−7.02	−11.21	−25.24	80.59	−10.97	−18.15	−40.86	−7.08	−11.70	−26.35
7	BC	BC	9–11	1.332 (10.93)	1.29	1.3321	3.92	15.09	0.00	0.00	2.94	11.70	0.00	0.00	15.58	0.00	0.00
8	CC′	CC′	12	0.702 (5.76)	0.70	0.7163	12.39	19.53	4.82	10.86	17.65	27.90	6.73	15.16	19.59	4.72	19.64
9	C′D	C′D	13	1.162 (9.54)	1.15	1.1114	39.00	−34.16	−6.15	−13.85	33.56	−29.70	−5.53	−12.46	−34.52	−6.43	−14.48
10	DD′	DD′	14	0.691 (5.67)	0.74	0.6910	27.04	−9.99	−0.07	−0.15	39.13	−13.50	−0.10	−0.22	−9.33	−0.07	−0.15
11	D′E	D′D″,D″E	15, 16	0.450 (3.69)	0.41	0.4024	29.45	3.96	0.38	0.84	65.44	9.66	0.94	2.09	4.35	0.425	0.94
12	EE′	EE′	17	1.639 (13.45)	1.55	1.8481	35.29	2.79	6.56	14.77	21.53	1.80	3.55	7.99	2.95	5.82	13.10
13	E′F′	E′F*,E*F,FF′	18, 19	0.845 (6.94)	0.74	0.6414	42.99	4.15	1.91	4.30	50.88	5.61	2.98	6.70	4.74	2.52	5.67
14	F′G	F′G	20	0.140 (1.15)	0.13	0.2015	−100.01	7.61	1.00	2.25	−714.36	58.54	4.96	11.17	8.20	0.695	1.56
15	GH	GH	21, 22	0.417 (3.42)	0.43	0.4179	−88.03	−33.67	−27.86	−62.76	−211.10	−78.30	−66.67	−150.18	−32.65	−27.80	−62.63
16 (↓)[c]	HI (↓)	HI (below)	23–24(↓)	0.176 (1.44)	0.28	0.2608	−82.44	32.76	0.85	1.91	−468.41	117.00	2.15	4.83	35.80	0.66	1.48
16.1	HH′	HH′[d]	23	0.078 (0.64)	0.28	0.0892	−58.18		−1.18	−2.67	−745.90		−13.23	−29.93		−1.03	−2.34

Table 4 continued

Region	Sector	Basin	System	Area (10^6 km² and (%) of total)			Net balance for original area (Gt/year)				Surface flux equivalent (kg/m²/year)				Area adjusted net balance (Gt/year)		
Fig. 1[a]	R08	W06	Z05	R08 (%)	W06	Z05	IOM$_{Md}$[b]	W06	Z05f	Z05i	IOM$_{Md}$[b]	W06	Z05f	Z05i	W06	Z05f	Z05i
a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r
16.2	H'I	H'I'[d]	24	0.098 (0.80)		0.1716	−24.26		2.03	4.58	−247.55		11.83	26.69		1.16	2.62
17	I'I'', I''J''[d]	I''J''[d]	25–27	0.130 (1.07)		0.1350	−21.00				−161.54						
1–16	All	All	1–24	12.183 (100)	11.71	12.328	−13.15	27.32	−13.46	−30.34	−1.08	2.333	−1.092	−2.461	34.03[e]	−15.72[e]	−35.44[e]

[a] 1-Southwestern Filchner-Ronne I.S., 2-Eastern Filchner-Ronne I.S., 3-Coats Land/Risser-Larsen I.S., 4-Central-Western Fimbul I.S., 5-P. Astrid and P. Ragnhild Coasts, 6-Enderby Land., 7-Amery I.S., 8-Ingrid Christensen Coast/West and Shackleton I.S., 9-Wilkes Land, 10-George V and Adélie Coasts, 11-Rennick Gl./Victoria Land, 12-Southwestern Ross I.S., 13-Eastern Ross I.S., 14-Ruppert Coast/Getz I.S., 15-Walgreen Coast., 16-Abbot I.S./Western Palmer Land, 17-Graham Land/Eastern Palmer Land

[b] Values for IOM$_{Md}$ obtained from Table 3 after modifications of the IEP used to estimate discharge from the non-surveyed periphery in all sectors except II''(Region 17), and of the surface balance for sectors F'-H (Regions 14, 15) and sectors H-I (Region 16)

[c] Statistics for Region 16 are split to highlight the contrasts between 16.1 and 16.2 in net budget estimates and SFE

[d] No separate data are provided for these basins

[e] The sums of reintegrated values based on the generalization imposed by grouping sectors, basins, and systems are listed only to illustrate the numerical effects of the procedure and not as substitutes. The largest distortion affects the adjusted estimate of W06, from 28 to 34 Gt/year in the sum, mainly contributed to by change for basin HJ, from 33 to 36 Gt/year
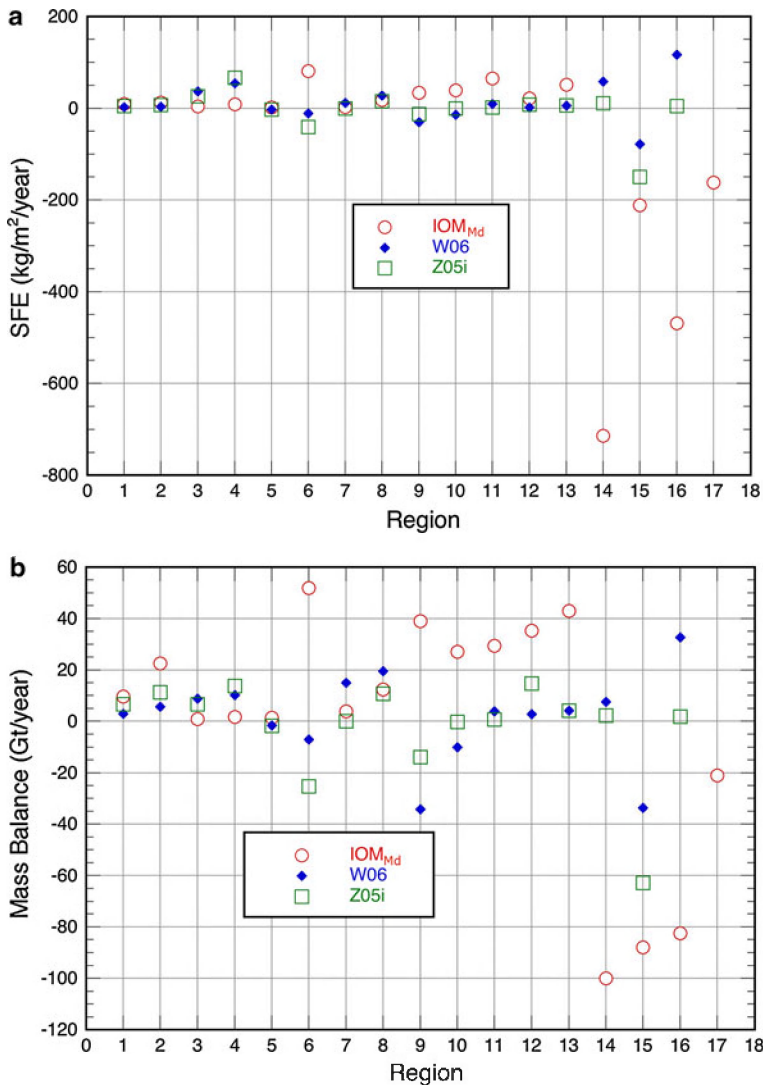
Fig. 4 Comparison of net budget estimates based on ERS radar altimetry data and the Input–Output Method (IOM) compiled for seventeen regions (Fig. 2, Table 4). ERS-based: Zwally et al. 2005 (Z05i), Wingham et al. 2006 (W06). IOM-based: Rignot et al. 2008 (R08) and the modified IOM (IOM$_{Md}$) presented in this study. **a** Comparison of surface flux equivalent (SFE) estimates in kg/m^2/year. **b** Comparison of bulk estimates in Gt/year

though the SFE for all regions for the IOM$_{Md}$ and the ERS-based estimates are in closer agreement. The largest SFE difference (749 kg/m^2/year) is observed in region 14 (F′G, system 20; 1.15% of the AIS area) between the mean of the ERS-based estimates of W06 and Z05i (+35 kg/m^2/year) and the IOM$_{Md}$ estimate (−714 kg/m^2/year). The second largest difference (529 kg/m^2/year) is observed in region 16 (HI in R08, HJ in W06, systems 23,24; 1.44% of the AIS area) between the mean of ERS-based estimates (+61 kg/m^2/year) and the modified IOM estimate (−468 kg/m^2/year). It should be noted that sector

HH′ (0.64% of the area) in the AP with an SFE of −746 kg/m²/year is a principal con-
tributor to the large mass loss in both IOM estimates, but not in ERS-based estimate.
Elsewhere relatively small differences of approximately 100 kg/m²/year are observed in
regions 6 (A′B, systems 7,8; 5.29% of the AIS area: ERS mean of −26 kg/m²/year c.f. the
IOM$_{Md}$ estimate of +81 kg/m²/year) and region 15 (GH, systems 21,22; 3.42% of the area:
ERS mean of −114 kg/m²/year c.f. the IOM$_{Md}$ estimate of −211 kg/m²/year). All other
SFE differences between the mean of the ERS estimates and the IOM$_{Md}$ estimate are of
approximately 50 kg/m²/year or less over 88.63% of the area. Thus, our comparison covers
most of the area (98.93%), except for sector IJ.

    It follows that the re-integration of SFE values over the areas from the R08 compilation
to obtain bulk net mass balance estimates would show a generally similar distribution of
differences between the mean of the two ERS-based estimates (W06 and Z05i) and the
IOM$_{Md}$, albeit enhanced in some regions of relative large area (Fig. 4b). The largest
difference in net balance is observed in region 14 (105 Gt/year; ERS mean of +5 Gt/year
c.f. IOM$_{Md}$ estimate of −100 Gt/year). The second largest difference (101 Gt/year) is
observed in region 16 between the ERS mean of +19 Gt/year and the IOM$_{Md}$ estimate of
−82 Gt/year. Three other relative large differences are observed in region 6 (69 Gt/year;
ERS mean of −17 Gt/year cf. +52 Gt/year for the IOM$_{Md}$ estimate), region 9 (C′D, system
13; 9.54% of the area: 63.5 Gt/year; ERS mean of −24.5 Gt/year cf. +39.0 Gt/year for the
IOM$_{Md}$ estimate), and region15 (40 Gt/year; ERS mean of −48 Gt/year cf. −88 Gt/year for
the IOM$_{Md}$ estimate). Smaller differences are noted in regions 10–13 (D-F′, systems
14–19; 29.75% of the area), where the IOM$_{Md}$ estimates list values of approximately +40
Gt/year and the ERS mean values are in the range between −10 and +10 Gt/year. All other
regions show differences smaller than 25 Gt/year over 48.34% of the area. Again, our
comparison covers 98.93% of the area.

5 Overview of recent GRACE-based budget estimates

The GRACE-based estimates included in the IPCC07 report indicate −139 ± 73 Gt/year
for April 2002–July 2005 (Velicogna and Wahr 2006) and −40 ± 36 Gt/year for July 2002
and March 2005 (Ramillien et al. 2006). More recently estimates based on longer series
indicate an increase in the rate of mass loss. Based on April 2002–February 2009 data
estimated at −143 ± 73 (Velicogna 2009) and on April 2002–January 2009 data at
−190 ± 77 Gt/year (Chen et al. 2009). However, the latest estimate based on April 2002–
December 2008 data list a mean of −87 Gt/year split at −64 ± 32 Gt/year for WA and
−23 ± 29 Gt/year for EA (Table 2). These studies show improvement in the discussion of
the composite error values assigned to the surface mass trend derived from geodynamic
modeling and GIA that is highly dependent on ice sheet evolution (e.g. Gunter et al. 2009).
Model selection denoted in Table 2 is important because the estimate introduced using
either the IJ05 or ICE5G models can yield, e.g. either −190 or −250 Gt/year, respectively
(Chen et al. 2009).

    Implementation of particular GIA models produce mean postglacial rebound values for
the AIS area between approximately 1.5 and 9 mm/year with a density of at least 2700 kg/
m³ implying adjustments ≥60 Gt/year, those actually applied being much larger by a factor
of 3 (e.g. Velicogna and Wahr 2006; Velicogna 2009; Chen et al. 2009). The GIA is
assumed to be constant for the period of analyses and GRACE series extending beyond
2005 allow observation of trend in changes of ice mass regardless of the large uncertainty
in the mean value (e.g. Bromwich and Nicolas 2010). The studies by Velicogna (2009) and

Chen et al. (2009) identify 2006 as the year in which there is an acceleration of mass loss (from −104 Gt/year in 2002–2006 to −246 Gt/year in 2006–2009 or an increase of 137%, and from approximately −160 Gt/year in 2002–2006 to −220 Gt/year or an increase of 19%, respectively) and both cite the IOM results of R08 as part of the support for their findings. However, as discussed in a previous section the suggestion of an increasing rate of loss from IOM in R08 appears to be based on sets of single observations of discharge in particular years on part of the AIS, rather than a set of repeat observations that would support the identification of a trend in the mass loss.

The wide range of GRACE values reported for similar time periods indicates at least some of the GRACE values must be outliers. The issues affecting the derivation of ice mass changes from GRACE data include: uncertainties in the GIA correction from model and density errors, uncertainties in the various terms in the spherical-harmonic expression of the Earth's gravity field, uncertainties in the corrections for variations in the atmospheric mass, errors in the calculations of the scaling factor ("kernel") to account for the effective size of the measurement region or limited spatial resolution of GRACE satellites, and "leakage" of signals from mass changes outside the measurement region. These issues are being addressed by various investigators and reported in the literature (e.g. Gunther et al. 2009). Also, the mass-concentration gravity solutions (Luthcke et al. 2006, 2008), which use the GRACE observations more directly and utilize the full inherent resolution of the gravity signal sensed by GRACE, have been providing higher-resolution results that avoid some of the limitations of the methods using the spherical-harmonic solutions of the gravity field. Also, as noted in Gunther et al. (2009) and elsewhere, comparing or jointly analyzing GRACE and ICESat derived mass changes for the same time period will, for example, enable the selection of an improved GIA correction for both data sets as well as help validate other corrections.

6 Conclusions

Additional estimates of mass balance reported after completion of the IPCC07 increased the range from +50 to −200 Gt/year for the period 1992–2003 to +50 to −250 Gt/year for the period 1992–2009. Some recent reports also suggested an increase in the rate of mass loss in recent years. A range of 300 Gt/year is approximately 15% of the annual mass input and 0.8 mm/year SLE. Our assessment reviews and evaluates those estimates, which are from three essentially different and mostly independent methods: (1) the volumetric method based on measurement of elevation changes by ERS radar altimetry, (2) the IOM that gives the difference between input and output mass fluxes using various measurements and calculations, and (3) the gravimetric method based on measurement of gravity changes by the GRACE satellites.

Assessment of the IOM estimate for overall AIS of −138 ± 92 Gt/year in R08 showed their extrapolation overestimated the discharge from the NOBS areas which are 15% of the total ice sheet area. We provide a modified IOM estimate (IOM_{Md}) that first reduces the outflow SFE for the NOBS areas to 0.7 of the SFE for the OBS areas, which would give a positive overall mass balance of 146 Gt/year. However, the IOM_{Md} estimate also substitutes lower mass input values from a compilation of accumulation data interpolated on the basis of microwave firn emissivity (V99) in place of the modeled P-E estimates in three sectors of WA and one in the AP (total of 6% of the AIS area). Our modification of the outflow changes the balance estimate by +282 Gt/year (15% of the annual output) and modification of the IOM input value changes the balance estimate by −159 Gt/year (8% of

the annual input), which together bring the net balance for overall AIS to a loss of 13 Gt/year.

Comparison between two ERS-based estimates shows that the difference between the preferred estimate for overall AIS of −31 ± 12 Gt/year for 1992 to 2001 given in Z05 and the preferred estimate of +27 ± 29 Gt/year for 1992 to 2003 given in W06 are mainly due to different treatments of firn/ice density, corrections for the rate of upper firn compaction, differences in areal coverage, and IEP. The methodology in Z05 included an important correction for elevation changes caused by changes in the rate of firn compaction driven by changes in surface temperature, covered more AIS area with crossover analyses, and estimated the uncovered areas with optimal interpolation compared to the other analyses. Nevertheless, the difference between the two ERS estimates is only 3% of the annual mass input.

For all of the AIS, the IOM_{Md} estimate lies within the range of the two ERS estimates, which along with the GRACE-based estimate of Raimillen et al. (2006) gives a narrowed range of + 29 to −40 Gt/year that is only about 3.5% of the annual mass input. Our preferred estimate for 1992–2001 is −47 Gt/year for WA, + 16 Gt/year for EA, and −31 Gt/year overall (+0.1 mm/year SLE), not including part of the AP (1.07% of the AIS area) as taken from Z05. However, this narrowed range of estimates leaves the more negative GRACE-based estimates as outliers. Regarding the trend toward an increasing mass loss in some GRACE estimates, we also find that the evidence presented in R08, supporting an increase in mass loss from the IOM analyses, is insufficient as published.

A change of approximately 5% of the annual mass input or output to the AIS is approximately 100 Gt/year, which is 0.3 mm/year SLE and 10% of current sea level rise. Therefore, for the purpose of closing the sea level change budget to 10% or better, obtaining estimates of the AIS mass balance to an accuracy of several percent is required. Considering the state-of-art for determining the input and output fluxes, it is difficult to see how the IOM can achieve the required accuracy even for a snapshot in time. Furthermore, the problems with the IOM are even more difficult for determining trends.

Although the published GRACE estimates of mass change have a wide range and relatively large estimates of error, the methodology for deriving mass changes from GRACE data and correcting errors is improving significantly with time. The convergence of results from ICESat and GRACE within estimated errors for the recent mass loss from Greenland is a significant advance. However, the GIA is significantly larger in the Antarctic and the uncertainty of the modeled GIA is also larger, mainly because of uncertainty in the history of the glacial unloading and the sparsity of data for model calibration. The expansion of Global Positioning System (GPS) measurements of crustal motion in the Antarctic in recent years is providing new data that are being used for improving the modeled GIA estimates (e.g. King et al. 2010). Applying these improvements to GRACE data analyses, the recent improvements applied to the ICES at data analyses for Greenland, and the joint analyses of GRACE and ICESat data for the same time periods should significantly improve not only the estimates of the current mass balance of Antarctica, but also of its changes over time.

Appendix

Mass Balance Estimates of Wingham et al. (2006) (W06)

The study of W06 collated ERS data in a 10 km grid format. Surface elevation change and accumulation anomaly values were given in mm/year (ice), and the accumulation mean for 1979–2001 was given in mm/year (snow). The P-E series were a product of the European Center for Medium-range Weather Forecasts model using boundary and initial conditions based on a 40 year re-analyses (ECMWF_ERA-40), which has a resolution of approximately 55 km. The study discussed the attribution of the observed change and of inter-polated/extrapolated volume changes to either the upper firn layers with a density of 350 kg/m^3 or to the glacial column with a density of 917 kg/m^3. However, the area integration of their summarized surface elevation change and accumulation anomalies match the stated best balance estimate (a round off value of 27 Gt/year) using a density of 900 kg/m^3, which is actually closer to the mean density of firn and glacial ice columns than the often listed value of 917 kg/m^3. The mean snow accumulation values listed were factored by 0.35.

Surface Balance Estimates in Rignot et al. (2008) (R08)

The study of R08 compiles… *"the arithmetic average of the values given"*… by two atmospheric model products (van de Berg et al. 2006; van den Broeke et al. 2006a) to estimate surface balance for 1980–2004, obtained from a regional atmospheric climate model referred to as RAMCO2/ANT_E40 supplemented by the ECMWF_ERA-40 fields (E40 and ERA-40 refer to the same initial and boundary conditions). Surface balance estimates in studies using the IOM, from the least time-constrained field data compilations (e.g. V99), to the P-E obtained from atmospheric modeling products complemented with modeled melt losses (e.g. van de Berg et al. 2006; van den Broeke et al. 2006a) vary from study to study. In those using field data compilations mostly based on strata accumulated since ca. 1940, the difference in surface balance can be as large as 270 Gt/year, in approximately equal parts due to differences in the IEP and in the implementation of a deflation/ablation adjustment that is independent of the IEP (e.g. V99; Giovinetto and Zwally 2000; Z05). In studies using model products to estimate P-E in series generally starting ca. 1980, the difference in surface balance can be in excess of 600 Gt/year (discussed below) mainly due to different selection of initial and boundary conditions (e.g. Monaghan et al. 2006b; W06). There is no significant trend in the P-E statistic, in part due to the short series used (van den Berg et al. 2005). Clearly, in budget estimates based on the IOM the choice of model product determining the input is the principal consideration determining the result. A cursory review of the literature, ignoring the outlier estimates produced in many studies as part of the discussion of alternate initial and boundary conditions, and selecting the preferred results identified in each study, shows P-E estimates range between $130 \pm (7)$ and 180 ± 8 kg/m^2/year (W06, Monaghan et al. (2006b), respectively); the "$\pm(7)$" entry is assigned in this overview and it is an approximation based on similar estimates. Integrated for the area of 12.183×10^6 km^2 (from the latest compilation as reported in R08) the range is between 1584 and 2193 Gt/year, i.e. a difference of 609 Gt/year that could be deemed larger if the errors are considered. Ignoring the error, one half of the range between estimates implies that depending on the choice of model product, a difference of approximately 300 Gt/year (equivalent to 0.8 mm/year in sea level) could be introduced in practically any result obtained using the IOM. This half-

range difference is at least twice as large as that which could be introduced by selecting between different field data compilations each using a different IEP (say 135 Gt/year neglecting the optional use of the deflation/ablation adjustment), and is an order of magnitude larger than that which would result from choices such as attributing the observed change in surface elevation to either snow or ice.

References

Ablain M et al (2009) Ocean Sci 5:193
Bindoff NL et al (2007) Observations: oceanic climate change and sea level. In: Solomon S et al. (ed) Climate change 2007: the physical science basis. Fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge UK, New York, USA
Bromwich DH, Nicolas JP (2010) Ice-sheet uncertainty. Nat Geosci 3:596–597
Bromwich DH, Nicolas JP, Monaghan AJ (2011) An assessment of precipitation changes over Antarctica and the southern ocean since 1989 in contemporary global reanalyses. J Clim (in press)
Chen JL et al (2009) Accelerated Antarctic ice loss from satellite gravity measurements. Nat Geosci 2:859. doi:10.1038/NGEO694
Church JA et al (2010) Ocean temperature and salinity contributions to global and regional sea-level change. In: Church JA et al (eds) Understanding sea-level rise and variability. Wiley-Blackwell, USA, pp 143–176
Davis CH et al (2005) Snowfall-driven growth in east Antarctic ice sheet mitigates recent sea-level rise. Science 308(5730):1898–1901
Domingues CM et al (2008) Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 453:1090–1093
Giovinetto MB, Zwally HJ (2000) Spatial distribution of net surface accumulation on the Antarctic ice sheet. Ann Glaciol 31:171–178
Giovinetto MB, Bentley CR, Bull CB (1989) Choosing between incompatible regional surface-mass-balance data sets in Antarctica. Antarct J US XXIV(1):7–13
Gunter B et al (2009) A comparison of coincident GRACE and ICESat data over Antarctica. J Geod 83:1051–1060
King MA et al (2010) Improved constraints on models of glacial isostatic adjustment: a review of the contribution of ground-based geodetic observations. Surv Geophys 31:465–507. doi:10.1007/s10712-010-9100-4
Lemke P et al (2007) Observations: changes in snow, ice and frozen ground. In: Solomon S et al (eds) Climate change 2007: the physical science basis. Fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK, New York, USA
Lutchke SB et al (2006) Recent greenland ice mass loss by drainage system from satellite gravity observations. Science 314:1286. doi:10.1126/science.1130776
Lutchke SB et al (2008) Recent glacier mass changes in the Gulf of Alaska region from GRACE mascon solutions. J Glaciol 54:188
Lutchke SB et al. (2009) Recent Changes of the earth's land ice from GRACE. Eos Trans AGU 90:52. Fall Meet. Suppl, Abstract H13G-02
Milly PCD et al (2010) Terrestrial water-storage contributions to sea-level rise and variability. In: Church JA et al (eds) Understanding sea-level rise and variability. Wiley-Blackwell, USA, pp 226–255
Monaghan AJ et al (2006a) Recent trends in Antarctic snow accumulation from Polar MM5 simulations. Philos Trans R Soc A364:1683–1708
Monaghan AJ et al (2006b) Insignificant change in Antarctic snowfall since the international geophysical year. Science 313(5788):827–831
Nicolas JP, Bromwich DH (2011) Precipitation changes in high southern latitudes from global reanalyses: a cautionary tale. Surv Geophys. In press (this issue)
Pritchard H, Vaughan D (2007) Widespread acceleration of tidewater glaciers on the Antarctic Peninsula. J Geophys Res 112: F03S29. doi:10.1029/2006JF000597
Ramillien G et al (2006) Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. Glob Planet Change 53:198–208
Rignot E, Thomas RH (2002) Mass balance of polar ice sheets. Science 297(5586):1502–1506
Rignot E et al. (2005) Recent ice loss from the fleming and other glaciers, Wordie Bay, West Antarctic Peninsula. Geophys Res Lett 32:L07502

Rignot E et al (2008) Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. Nat Geosci 1:106–110

Rignot E et al (2011) Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. Geophys Res Lett L05503. doi:10.1029/2011GL046583

Turner J et al (2002) Spatial variability of Antarctic Peninsula net surface mass balance. J Geophys Res 107(D13):4173–4190

van de Berg WJ et al (2005) Characteristics of the Antarctic surface mass balance (1958–2002) using a regional atmospheric climate model. Ann Glaciol 41:97–104

van de Berg WJ et al (2006) Reassessment of the Antarcitc surface mass balance using calibrated output of a regional atmospheric climate model. J Geophys Res 111:D11104–D11118

van den Broeke M et al (2006a) Identification of Antarctic ablation areas using a regional atmospheric climate model. J Geophys Res 111:D18110–D18123

van den Broeke M et al (2006b) Snowfall in coastal West Antarctica much greater than previously assumed. Geophys Res Lett 33:L02505–L02508

Vaughan DG et al (1999) Reassessment of net surface mass balance in Antarctica. J Clim 12:123–130

Velicogna I (2009) Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. Geophys Res Lett 36:L19503. doi:10.1029/2009GL040222

Velicogna I, Wahr J (2006) Measurements of time-variable gravity show mass loss in Antarctica. Science 311:1754–1756

Wingham DJ et al (2006) Mass balance of the Antarctic ice sheet. Phil Trans R Soc A364:1627–1635

Wouters B et al. (2008) GRACE observes small-scale mass loss in Greenland. Geophys Res Lett 35: L20501. doi:10.1029/2008GL034816

Wu Xiaoping et al (2010) Simultaneous estimation of global present-day water transport and glacial isostatic adjustment. Nat Geosci 3:642–646

Zwally HJ et al (2005) Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002. J Glaciol 51(175):509–527

Zwally HJ et al (2011) Greenland ice sheet mass balance: distribution of increased mass loss with climate warming. J Glaciol 57(201):88–102