

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

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**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

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## 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 <sup>a</sup> | 1961–2003b <sup>a</sup> | 1961–2003c <sup>a</sup> | 1993–2003a <sup>a</sup> | 1993–2003b <sup>a</sup> | 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 <sup>b</sup>   |
| 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 <sup>c</sup>  |
| 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 <sup>a</sup>  |
| Ice sheets:           | –                       | –                       | 0.2 ± 0.2               | –                       | 0.4 ± 0.2               | 0.72 ± ? <sup>d</sup>    |
| Antarctica            | 0.14 ± 0.41             | 0.2 ± 0.4               | –                       | 0.21 ± 0.35             | –                       | 0.24 ± 0.12 <sup>d</sup> |
| Greenland             | 0.05 ± 0.12             | 0.1 ± 0.1               | –                       | 0.21 ± 0.07             | –                       | 0.48 ± 0.01 <sup>d</sup> |
| Unassigned            | 0.7 ± 0.7               | 0.1 ± ?                 | 0.7 ± ?                 | 0.3 ± 1.0               | 0.3 ± ?                 | 0.73 ± ?                 |

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

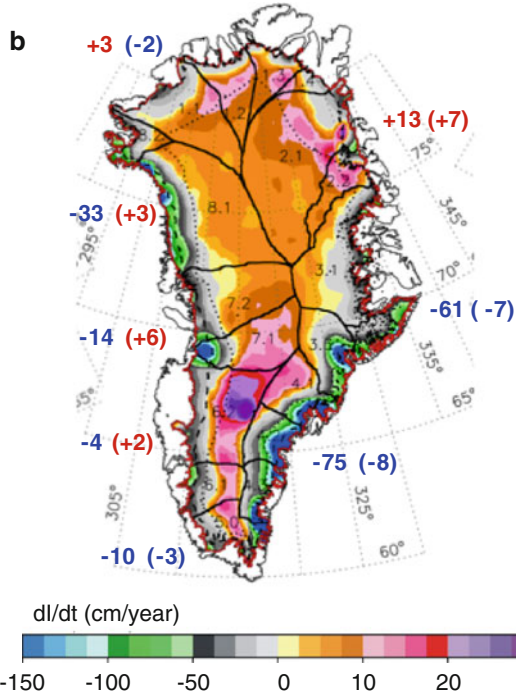
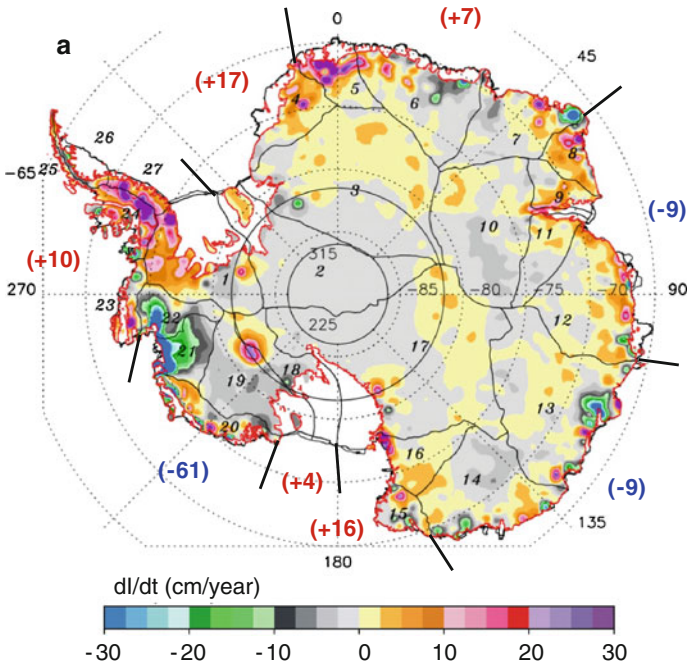
<sup>a</sup> Compilation of estimates: 1961–2003a, 1993–2003a, by Bindoff et al. (2007); 1961–2003b, by Domingues et al. (2008); 1961–2003c, 1993–2003b, 2003–2007, by Milly et al. (2010)

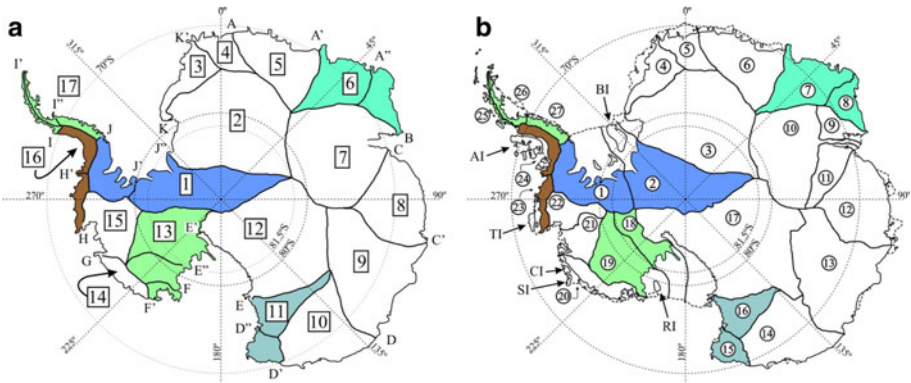
<sup>b</sup> Observed sea level rise 1993–2009; Ablain et al. (2009)

<sup>c</sup> Thermosteric 2003–2007; Domingues et al. (2008) updated in Church et al. (2010)

<sup>d</sup> 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 ( $\times 10^6$ km <sup>2</sup> ) |                       | Original budget estimate |            |       |                              |         |  | Adj. Estimate <sup>a</sup><br>(Gt/year) |
|--|---------------------------------|----------------------------|--|-----------------------|--------------------------|------------|-------|------------------------------|---------|--|---|
|  |                                 |                            | Original <sup>a</sup>                  | Adjusted <sup>a</sup> | Bulk (Gt/year)           |            |       | SFE(kg/m <sup>2</sup> /year) |         |  |   |
|  |                                 |                            |  |                       | f                        | g          | h     | i                            | j       |  |   |
| Velicogna and Wahr (2006)                | GRACE <sup>b</sup> <sub>a</sub> | 2004/2005–2007/2005        | 12.183                                 | 12.183                | -139                     | $\pm 73$   | -11.4 | $\pm 6.0$                    | -139    |  |   |
| Raimillen et al. (2006)                  | GRACE <sup>b</sup> <sub>b</sub> | 2007/2004–2003/2005        | 12.183                                 | 12.183                | -40                      | $\pm 36$   | -3.3  | $\pm 3.0$                    | -40     |  |   |
| Velicogna (2009)                         | GRACE <sup>b</sup> <sub>a</sub> | 2004/2004–2002/2009        | 12.183                                 | 12.183                | -143                     | $\pm 73$   | -11.7 | $\pm 6.0$                    | -143    |  |   |
|  |                                 | 2002–2006                  | 12.183                                 | 12.183                | -104                     |            | -8.5  |                              |         |  |   |
|  |                                 | 2006–2009                  | 12.183                                 | 12.183                | -246                     |            | -20.2 |                              |         |  |   |
| Chen et al. (2009)                       | GRACE <sup>b</sup> <sub>b</sub> | 2004/2002–2001/2009        | 12.183                                 | 12.183                | -190                     | $\pm 77$   | -15.6 | $\pm 6.3$                    | -190    |  |   |
| " " " " ; Supplementary Information      |                                 | 2002–2006                  | 12.183                                 | 12.183                | -144                     | $\pm 58$   | -11.8 | $\pm 4.7$                    |         |  |   |
| " " " " ; Supplementary Information      |                                 | 2006–2009                  | 12.183                                 | 12.183                | -220                     | $\pm 89$   | -18.1 | $\pm 7.3$                    |         |  |   |
| " " " " ; West Ant. and Ant. Pen.        |                                 | 2004/2002–2001/2009        | 2.736                                  | 2.736                 | -132                     | $\pm 26$   | -48.2 | $\pm 9.5$                    |         |  |   |
| " " " " ; (East Antarctica)              |                                 | 2004/2002–2001/2009        | 9.447                                  | 9.447                 | (-58)                    | $\pm 72$   | -6.1  | $\pm 7.6$                    |         |  |   |
| Wu et al. (2010)/East Ant.               | GRACE <sup>b</sup> <sub>a</sub> | 2004/2002–2012/2008        | 9.447                                  | 9.447                 | -23                      | $\pm 29$   | -2.4  | $\pm 3.1$                    |         |  |   |
| Wu et al. (2010)/West Ant.               | GRACE <sup>b</sup> <sub>a</sub> | 2004/2002–2012/2008        | 2.736                                  | 2.736                 | -64                      | $\pm 32$   | -23.4 | $\pm 11.7$                   |         |  |   |
| (East, West and Ant. Peninsula)          |                                 | 2004/2002–2012/2008        | 12.183                                 | 12.183                | (-87)                    | $\pm 43$   | -7.1  | $\pm 12.1$                   | (-87)   |  |   |
| Rignot et al. (2008) (R08)               | IOM                             | 2000 (?) <sup>c</sup>      | 12.183                                 | 12.183                | -136                     | $\pm 92$   |       |                              |         |  |   |
| Modified Outflow only (T.3, col. r)      | IOM <sub>Md</sub>               | (1996, 1997) <sup>c</sup>  | 12.183                                 | 12.183                | (+146)                   |            |       |                              |         |  |   |
| Modified Outflow and Input (T.3, col. t) | IOM <sub>Md</sub>               | (?) <sup>c</sup>           | 12.183                                 | 12.183                | (-13.2)                  |            | -1.1  |                              | (-13.2) |  |   |
| Zwally et al. (2005) (Z05f) <sup>d</sup> | ERS                             | 1904/1992–2004/2001        | 12.193                                 | 12.053                | -13.6                    | $\pm 5.4$  | -1.1  | $\pm 0.4$                    | (-13.4) |  |   |
| Zwally et al. (2005) (Z05i) <sup>d</sup> |                                 | 1904/1992–2004/2001        | 12.193                                 | 12.053                | -30.3                    | $\pm 12.1$ | -2.5  | $\pm 1.0$                    | (-30.0) |  |   |

Table 2 continued

| Reference/modification                   | Database type | Period/year of application | Area ( $\times 10^6 \text{ km}^2$ ) |                       | Original budget estimate |                              |      | Adj. Estimate <sup>a</sup><br>(Gt/year) |   |
|--|---------------|----------------------------|-------------------------------------|-----------------------|--------------------------|------------------------------|------|---|---|
|  |               |                            | Original <sup>b</sup>               | Adjusted <sup>a</sup> | Bulk (Gt/year)           | SFE(kg/m <sup>2</sup> /year) |      |   |   |
|  |               |                            |                                     |                       |                          | f                            | g    |   | h |
| Wingham et al. (2006) (W06) <sup>a</sup> | ERS           | 1910/1992–2002/2003        | 8.49                                | 12.183                | +27                      | $\pm 29$                     | +3.2 | $\pm 3.4$                               |   |
| Wingham et al. (2006) (W06) <sup>b</sup> | ERS           | 1910/1992–2002/2003        | 11.71                               | 12.183                | +27                      | ( $\pm 40$ )                 | +2.3 | ( $\pm 3.4$ ) (+28.0)                   |   |
| Wingham et al. (2006) (W06) <sup>c</sup> | ERS           | 1910/1992–2002/2003        | (11.9)                              | 12.183                | +37                      | ( $\pm 40$ )                 | +3.1 | ( $\pm 3.4$ ) (+37.8)                   |   |

<sup>a</sup> 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

<sup>b</sup> GRACE-based estimates used surface mass trend and GIA models I105 (b) or combinations of it and ICESG-VM2 (a)

<sup>c</sup> 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

<sup>d</sup> 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

<sup>e</sup> a The "best estimate" of  $\pm 27 \pm 29 \text{ Gt/year}$  listed in W06 was for the observed area of  $8.49 \times 10^6 \text{ km}^2$

<sup>e</sup> 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 ( $11.71 \times 10^6 \text{ km}^2$ ) and increase the error estimate in proportion to the respective areas

<sup>e</sup> c Alternatively, we apply  $\pm 20 \text{ Gt/year}$  for the interior following W06 p. 1633 (i.e. "applying the average elevation rate ( $9 \text{ mm yr}^{-1}$ ) for the southernmost degree in latitude provides an estimated growth rate of  $22 \text{ km}^3/\text{year}$  for the omitted region") and apply  $-10 \text{ Gt/year}$  for the unsurveyed coastal areas following W06 p. 1633 (i.e. "applying the average elevation rate for the coastal  $200 \text{ km}$  of the surveyed ice sheet ( $-14 \text{ mm yr}^{-1}$ ) to the unsurveyed coastal sector... provides an estimated  $10 \text{ Gt/year}$  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  $2.6 \times 10^6 \text{ km}^2$  and coastal  $0.8 \times 10^6 \text{ km}^2$ ) for a total of  $11.9 \times 10^6 \text{ km}^2$

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  $-47 \pm 4$  Gt/year for West Antarctica (WA),  $+16 \pm 11$  Gt/year for East Antarctica (EA), and  $-31 \pm 12$  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<sup>2</sup> 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  $+27 \pm 29$  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 ( $\rho_i$ ) in the conversion of elevation changes (dH/dt) to mass changes (dM/dt), according to  $dM/dt = \rho_i dH/dt$ . 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  $\rho_i$ , in their estimate for EA, Davis et al. (2005) used 350 kg/m<sup>3</sup>, 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  $\rho_i = 900 \text{ kg/m}^3$  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  $+27 \pm 29 \text{ Gt/year}$  for AIS overall, with particular approaches showing results between  $-5$  and  $+85 \text{ Gt/year}$ . 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; W’06) 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  $\rho_i = 900 \text{ kg/m}^3$  (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  $\rho_i = 400 \text{ kg/m}^3$  (Z05f) for the multi-annual upper firn layers that would reduce the overall AIS mass balance to  $-14 \text{ Gt/year}$ . 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  $\rho_i dI/dt$ , 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  $-1.58 \text{ cm/year}$  (28.4 Gt/year equivalent). In EA, the average  $dC/dt$  on the grounded ice was  $+0.21 \text{ cm/year}$  ( $-19.3 \text{ Gt/year}$  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  $81.5^\circ\text{S}$ .

For Z05i, the average interpolated  $dH/dt$  south of  $81.5^\circ\text{S}$  was  $+1.6 \text{ cm/year}$ , and the calculated average ice thickness and mass changes were relatively small ( $dI/dt = +0.64 \text{ cm/year}$  and  $dM/dt = +14 \text{ Gt/year}$ ). Overall, their interpolation including the coastal areas lowered the  $dM/dt$  from near zero to  $-31 \text{ Gt/year}$ , 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  $+27 \pm 29 \text{ Gt/year}$* ” 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  $+22 \text{ km}^3/\text{year}$  (20 Gt/year) in the area south of  $81.5^\circ\text{S}$  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  $+27 \pm 29 \text{ Gt/year}$  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  $+1.7 \text{ mm/year}$  average over Antarctica in W06 and  $+5.4 \text{ mm/year}$  average in Z05. Using the ice density of  $900 \text{ kg/m}^3$ , the corresponding GIA corrections are  $-19 \text{ Gt/year}$  for W06 and  $59 \text{ Gt/year}$  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  $\pm 1$  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  $A_{ob} = 10.366 \times 10^6$  km<sup>2</sup> and  $A+ = 12.183 \times 10^6$  km<sup>2</sup> 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<sub>MD</sub>). 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                | Input    | Output                              | NET      | NET+  | Area+               | Input+ | $N + A_S = N_{ob} \cdot A + /A_{ob}$ | $A_{nob}$ | $I_{nob} = I + - I_{ob}$ | $O + = I + - N +$ | $O_{nob}$ | Column     | a                   | b                          | c     | d     | e     | f                   | g     | h      | i       | j   | k   | l   | m   | n |   |  |
| $A_{ob}$            | $I_{ob}$ | $O_{ob}$                            | $N_{ob}$ | $N+$  | $10^3 \text{ km}^2$ | $I+$   | Gt/yr                                | %         | Gt/yr                    | Gt/yr             | Gt/yr     | Col. calc. | $10^3 \text{ km}^2$ | Gt/yr                      | Gt/yr | Gt/yr | Gt/yr | $10^3 \text{ km}^2$ | Gt/yr | d(f/a) | (f-a)/f | g-b | j/g | g-e | l-c | m | n |  |
| $10^3 \text{ km}^2$ | Gt/yr    | Gt/yr                               | Gt/yr    | Gt/yr | $10^3 \text{ km}^2$ | Gt/yr  | Gt/yr                                | %         | Gt/yr                    | Gt/yr             | Gt/yr     | East ant   |                     |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 1698     | 93                                  | 75       | 18    | 19                  | 1780   | 100                                  |           | 19                       | 5                 | 7         | 7          | J'/K                |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 218      | 42                                  | 45       | -3    | -3                  | 246    | 50                                   |           | -3                       | 11                | 8         | 16         | KK'                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 159      | 26                                  | 28       | -1    | -1                  | 178    | 32                                   |           | -1                       | 11                | 6         | 19         | K'A                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 615      | 60                                  | 60       | 0     | 0                   | 622    | 62                                   |           | 0                        | 1                 | 2         | 3          | AA'                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 354      | 39                                  | 40       | -1    | -1                  | 645    | 115                                  |           | -2                       | 45                | 76        | 66         | A'B                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 1197     | 73                                  | 77       | -4    | -4                  | 1332   | 87                                   |           | -4                       | 10                | 14        | 16         | BC                  |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 434      | 81                                  | 87       | -7    | -11                 | 702    | 137                                  |           | -11                      | 38                | 56        | 41         | CC'                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 1053     | 198                                 | 207      | -8    | -9                  | 1162   | 261                                  |           | -9                       | 9                 | 63        | 24         | C'D                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 563      | 92                                  | 94       | -2    | -2                  | 691    | 136                                  |           | -2                       | 19                | 44        | 32         | DD'                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 267      | 20                                  | 22       | -2    | -3                  | 450    | 62                                   |           | -3                       | 41                | 42        | 68         | D'E                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 1441     | 61                                  | 49       | 11    | 13                  | 1639   | 89                                   |           | 13                       | 12                | 28        | 31         | EE'                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 7999     | 785                                 | 784      | 1     | -2                  | 9447   | 1131                                 |           | -5                       | 15                | 346       | 31         | Sum                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 7998     | 786                                 | 785      | 1     | -4                  | 9447   | 1131                                 |           | -                        | -                 | -         | -          | R08 sum             |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     |          |                                     |          |       |                     |        |                                      |           |                          |                   |           |            | West ant            |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 751      | 110                                 | 80       | 31    | 34                  | 845    | 130                                  |           | 35                       | 11                | 20        | 15         | E/F'                |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 119      | 108                                 | 128      | -19   | -23                 | 140    | 128                                  |           | -22                      | 15                | 20        | 16         | F'G                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 393      | 177                                 | 237      | -61   | -64                 | 417    | 196                                  |           | -65                      | 6                 | 19        | 10         | GH                  |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 55       | 51                                  | 86       | -35   | -49                 | 78     | 71                                   |           | -50                      | 29                | 20        | 28         | HH'                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 933      | 142                                 | 145      | -4    | -4                  | 1028   | 165                                  |           | -4                       | 9                 | 23        | 14         | JJ'                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |
|                     | 2251     | 588                                 | 676      | -88   | -106                | 2508   | 690                                  |           | -106                     | 10                | 102       | 15         | Sum                 |                            |       |       |       |                     |       |        |         |     |     |     |     |   |   |  |



Table 3 continued

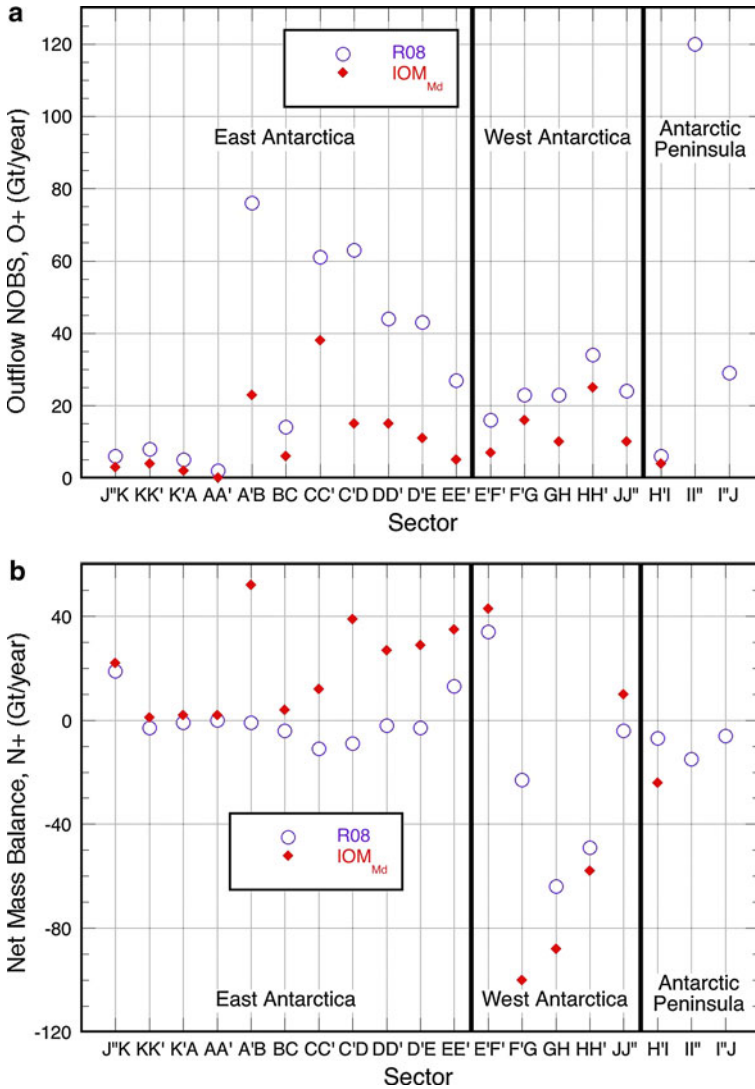
|          | OnobAS (area scaled) | Modified O <sub>nob</sub> and modified I+ |       |                   |       |                    |       | R08 values      |                       | AS   | Md   |                    |                    |
|----------|----------------------|---|-------|-------------------|-------|--------------------|-------|-----------------|-----------------------|------|------|--------------------|--------------------|
|          |                      | O <sub>nobMd</sub>                        |       | O <sub>+</sub> Md |       | I <sub>+</sub> Mod |       | O <sub>ob</sub> | O <sub>nob</sub>      |      |      | O <sub>nobAS</sub> | O <sub>nobMd</sub> |
|          |                      | Gt/yr                                     | Gt/yr | Gt/yr             | Gt/yr | Gt/yr              | Gt/yr | SFE             | kg/m <sup>2</sup> /yr |      |      |                    |                    |
| A/B      | 33                   | 23  | 63    | 52                | 115   | 52                 | 113   | 261             | 113                   | 113  | 79   |                    |                    |
| BC       | 9                    | 6   | 83    | 4                 | 87    | 4                  | 64    | 104             | 64                    | 64   | 45   |                    |                    |
| CC'      | 54                   | 38  | 125   | 12                | 137   | 12                 | 200   | 228             | 200                   | 200  | 140  |                    |                    |
| C'D      | 21                   | 15  | 222   | 39                | 261   | 39                 | 197   | 578             | 197                   | 197  | 138  |                    |                    |
| DD'      | 21                   | 15  | 109   | 27                | 136   | 27                 | 167   | 344             | 167                   | 167  | 117  |                    |                    |
| D'E      | 15                   | 11  | 33    | 29                | 62    | 29                 | 82    | 235             | 82                    | 82   | 58   |                    |                    |
| EE'      | 7                    | 5   | 54    | 35                | 89    | 35                 | 34    | 136             | 34                    | 34   | 24   |                    |                    |
| Sum      | 173                  | 121                                       | 905   | 226               | 1131  | 226                | 98    | 241             | 98                    | 120  | 84   |                    |                    |
| West ant |                      |   |       |                   |       |                    |       |                 |                       |      |      |                    |                    |
| E'F'     | 10                   | 7   | 87    | 43                | 130   | 43                 | 107   | 170             | 107                   | 107  | 75   |                    |                    |
| F'G      | 23                   | 16  | 144   | -16               | 44    | -100               | 1076  | 1095            | 1076                  | 1076 | 753  |                    |                    |
| GH       | 14                   | 10  | 247   | -51               | 159   | -88                | 603   | 958             | 603                   | 603  | 422  |                    |                    |
| HH'      | 36                   | 25  | 111   | -40               | 53    | -58                | 1564  | 1478            | 1564                  | 1564 | 1095 |                    |                    |
| JJ''     | 15                   | 10  | 155   | 10                | 165   | 10                 | 155   | 253             | 155                   | 155  | 109  |                    |                    |
| Sum      | 98                   | 68  | 744   | -54               | 551   | -194               | 300   | 467             | 381                   | 381  | 266  |                    |                    |
| Ant pen  |                      |   |       |                   |       |                    |       |                 |                       |      |      |                    |                    |
| H'I      | 5                    | 4   | 82    | -5                | 57    | -24                | 848   | 1000            | 848                   | 848  | 593  |                    |                    |
| I''      | 100                  | 120                                       | 140   | -15               | 125   | -15                | 1538  | 1846            | 1538                  | 1538 | 1846 |                    |                    |
| I'J      | 34                   | 29  | 38    | -6                | 32    | -6                 | 818   | 707             | 818                   | 818  | 707  |                    |                    |
| Sum      | 139                  | 153                                       | 260   | -26               | 214   | -45                | 922   | 1384            | 1238                  | 1238 | 1362 |                    |                    |
| AIS      |                      |   |       |                   |       |                    |       |                 |                       |      |      |                    |                    |
| Sum      | 410                  | 342                                       | 1909  | 146               | 1896  | -13                | 151   | 343             | 226                   | 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 ( $\text{kg}/\text{m}^2/\text{year}$ ) is the ratio of bulk mass rate (Gt/year) to area ( $10^6 \text{ km}^2$ ), 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 61 Gt/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  $324 \text{ kg}/\text{m}^2/\text{year}$  for the overall AIS and the corresponding  $I_{ob}$  (SFE) is  $142 \text{ kg}/\text{m}^2/\text{year}$ , 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 l, 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  $343 \text{ kg}/\text{m}^2/\text{year}$  (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<sub>Md</sub>) 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  $151 \text{ kg/m}^2/\text{year}$  (column u), which are also in a ratio of 2.3 to 1. By sector, the R08 values of  $O_{\text{nob}}$  (SFE) are all greater than  $O_{\text{obs}}$  (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  $O_{\text{nob}}$  (SFE) should be smaller than  $O_{\text{ob}}$  (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  $O_{\text{nobAS}}$  (column o) using a proportional area scaling of outflow, which gives equal  $O_{\text{nob}}$  (SFE) and  $O_{\text{ob}}$  (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  $O_{\text{ob}}$  (SFE) (column u) to obtain  $O_{\text{nobMd}}$  (SFE) (column x), which is then multiplied by  $A_{\text{nob}}$  to obtain  $O_{\text{nobMd}}$  (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  $O_{\text{nobMd}}$ ,  $O+_{\text{Md}}$ , and  $N+_{\text{MdO}}$  are in columns p, q, and r. For EA, the  $O_{\text{nobMd}}$  is reduced to 121 Gt/year (column p) from the 349 Gt/year of R08 (column m) and the corresponding  $O_{\text{nobMd}}$  (SFE) is reduced to 84 kg/m<sup>2</sup>/year (column x) from 241 kg/m<sup>2</sup>/year (column v), appropriately reducing the  $O_{\text{nobMd}}$  (SFE) to a value smaller than the  $O_{\text{ob}}$  (SFE) of 98 kg/m<sup>2</sup>/year (column u). For WA, the  $O_{\text{nobMd}}$  is reduced to 68 Gt/year (column p) from the 120 Gt/year of R08 (column m) and the corresponding  $O_{\text{nobMd}}$  (SFE) is reduced to 266 kg/m<sup>2</sup>/year (column x) from the 467 kg/m<sup>2</sup>/year of R08 (column v), also appropriately reducing the  $O_{\text{nobMd}}$  (SFE) to a value smaller than the  $O_{\text{ob}}$  (SFE) of 300 kg/m<sup>2</sup>/year (column u). For the seventeen sectors of WA, EA, and sector H'I in the AP, the  $O_{\text{nobMd}}$  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  $N+_{\text{MdO}}$  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-recalibration. 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 acknowledging 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 ( $74^{\circ}46'S$ ,  $136^{\circ}52'W$ ) lists wind speed  $>15$  m/s for 264 days/year and  $>30$  m/s for 136 days/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+<sub>Md</sub> 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+<sub>Md</sub> value of 1909 Gt/year (column q) brings the N+<sub>Md</sub> (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<sub>Md</sub> 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<sub>Md</sub> 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+<sub>Mod</sub> 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  $10.368 \times 10^6$  km<sup>2</sup>) 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<sup>2</sup>,  $O'+ = +9.0 \pm 1$  Gt/year<sup>2</sup>, and  $N'+ = -14.5 \pm 2$  Gt/year<sup>2</sup>. 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  $5.5 \pm 2$  Gt/year<sup>2</sup> 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  $0.8 \pm 2$  Gt/year<sup>2</sup>. 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  $0.5 \pm 2.7$  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–o) 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<sup>3</sup> and, for their preferred estimate, Z05i used a density of  $900$  kg/m<sup>3</sup>). 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 ( $10^6$ km <sup>2</sup> and (%) of total) |         | Net balance for original area (Gt/year) |         |        |        |                                |         | Surface flux equivalent (kg/m <sup>2</sup> /year) |        |         |        |        |        | Area adjusted net balance (Gt/year) |     |      |      |  |  |
|---------------------|--------|------------------|----------|---|---------|---|---------|--------|--------|--------------------------------|---------|---|--------|---------|--------|--------|--------|-------------------------------------|-----|------|------|--|--|
|                     |        |                  |          | Z05   | R08 (%) | W06                                     | Z05     | Z05f   | Z05i   | IOM <sub>Md</sub> <sup>b</sup> | W06     | Z05f  | Z05i   | Z05f    | Z05i   | W06    | Z05f   | Z05i                                | W06 | Z05f | Z05i |  |  |
| 1                   | JJ'    | JJ',JJ''         | 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'E'',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 (J) <sup>c</sup> | HI (L) | HI (L)           | 23-24(L) | 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' <sup>d</sup> | 23       | 0.078 (0.64)                                    |         | 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 ( $10^6$ km <sup>2</sup> and (%) of total) |         |        |        |                                |       | Net balance for original area (Gt/year) |         |                                |       |        |        | Surface flux equivalent (kg/m <sup>2</sup> /year) |                     |                     |      |                                |     | Area adjusted net balance (Gt/year) |      |                                |  |  |  |
|----------------|---------|------------------|--------|---|---------|--------|--------|--------------------------------|-------|---|---------|--------------------------------|-------|--------|--------|---|---------------------|---------------------|------|--------------------------------|-----|-------------------------------------|------|--------------------------------|--|--|--|
|                |         |                  |        | Z05   | R08 (%) | W06    | Z05    | IOM <sub>Md</sub> <sup>h</sup> | W06   | Z05f                                    | Z05i    | IOM <sub>Md</sub> <sup>h</sup> | W06   | Z05f   | Z05i   | IOM <sub>Md</sub> <sup>h</sup>                    | W06                 | Z05f                | Z05i | IOM <sub>Md</sub> <sup>h</sup> | W06 | Z05f                                | Z05i | IOM <sub>Md</sub> <sup>h</sup> |  |  |  |
| a <sup>†</sup> | b       | c                | d      | e   | f       | g      | h      | i                              | j     | k                                       | l       | m                              | n     | o      | p      | q   | r                   | s                   | t    | u                              | v   | w                                   | x    |                                |  |  |  |
| 16.2           | H'I     | H'I <sup>d</sup> | 24     | 0.098 (0.80)                                    |         | 0.1716 | -24.26 |                                | 2.03  | 4.58                                    | -247.55 |                                | 11.83 | 26.69  |        | 1.16  | 2.62                |                     |      |                                |     |                                     |      |                                |  |  |  |
| 17             | II',I'' | I'' <sup>d</sup> | 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 <sup>e</sup>                                | -15.72 <sup>e</sup> | -35.44 <sup>e</sup> |      |                                |     |                                     |      |                                |  |  |  |

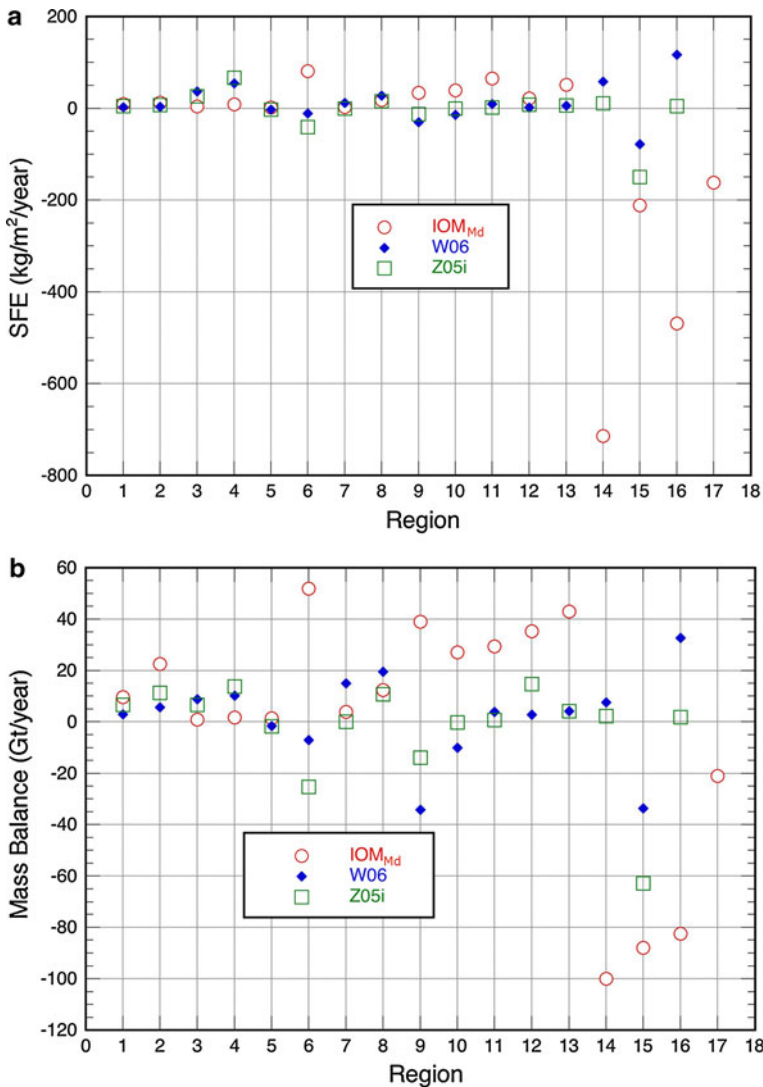
<sup>a</sup> 1-Southwestern Filchner-Ronne I.S., 2-Eastern Filchner-Ronne I.S., 3-Coats Land/Risser-Larsen I.S., 4-Central-Western Fimbul I.S., 5-P. Astrid and P. Ragnhild Coasts, 6-Enderby Land, 7-Amery I.S., 8-Ingriid Christensen Coast/West and Shackleton I.S., 9-Wilkes Land, 10-George V and Adélie Coasts, 11-Rennick Gf/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

<sup>b</sup> Values for IOM<sub>Md</sub> 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)

<sup>c</sup> Statistics for Region 16 are split to highlight the contrasts between 16.1 and 16.2 in net budget estimates and SFE

<sup>d</sup> No separate data are provided for these basins

<sup>e</sup> 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 HI, 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<sub>Md</sub>) presented in this study. **a** Comparison of surface flux equivalent (SFE) estimates in kg/m<sup>2</sup>/year. **b** Comparison of bulk estimates in Gt/year

though the SFE for all regions for the IOM<sub>Md</sub> and the ERS-based estimates are in closer agreement. The largest SFE difference (749 kg/m<sup>2</sup>/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<sup>2</sup>/year) and the IOM<sub>Md</sub> estimate (−714 kg/m<sup>2</sup>/year). The second largest difference (529 kg/m<sup>2</sup>/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<sup>2</sup>/year) and the modified IOM estimate (−468 kg/m<sup>2</sup>/year). It should be noted that sector

HH' (0.64% of the area) in the AP with an SFE of  $-746 \text{ kg/m}^2/\text{year}$  is a principal contributor to the large mass loss in both IOM estimates, but not in ERS-based estimate. Elsewhere relatively small differences of approximately  $100 \text{ kg/m}^2/\text{year}$  are observed in regions 6 (A'B, systems 7,8; 5.29% of the AIS area: ERS mean of  $-26 \text{ kg/m}^2/\text{year}$  c.f. the  $\text{IOM}_{\text{Md}}$  estimate of  $+81 \text{ kg/m}^2/\text{year}$ ) and region 15 (GH, systems 21,22; 3.42% of the area: ERS mean of  $-114 \text{ kg/m}^2/\text{year}$  c.f. the  $\text{IOM}_{\text{Md}}$  estimate of  $-211 \text{ kg/m}^2/\text{year}$ ). All other SFE differences between the mean of the ERS estimates and the  $\text{IOM}_{\text{Md}}$  estimate are of approximately  $50 \text{ kg/m}^2/\text{year}$  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  $\text{IOM}_{\text{Md}}$ , 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  $+5 \text{ Gt/year}$  c.f.  $\text{IOM}_{\text{Md}}$  estimate of  $-100 \text{ Gt/year}$ ). The second largest difference (101 Gt/year) is observed in region 16 between the ERS mean of  $+19 \text{ Gt/year}$  and the  $\text{IOM}_{\text{Md}}$  estimate of  $-82 \text{ Gt/year}$ . Three other relative large differences are observed in region 6 (69 Gt/year; ERS mean of  $-17 \text{ Gt/year}$  cf.  $+52 \text{ Gt/year}$  for the  $\text{IOM}_{\text{Md}}$  estimate), region 9 (C'D, system 13; 9.54% of the area: 63.5 Gt/year; ERS mean of  $-24.5 \text{ Gt/year}$  cf.  $+39.0 \text{ Gt/year}$  for the  $\text{IOM}_{\text{Md}}$  estimate), and region 15 (40 Gt/year; ERS mean of  $-48 \text{ Gt/year}$  cf.  $-88 \text{ Gt/year}$  for the  $\text{IOM}_{\text{Md}}$  estimate). Smaller differences are noted in regions 10–13 (D-F', systems 14–19; 29.75% of the area), where the  $\text{IOM}_{\text{Md}}$  estimates list values of approximately  $+40 \text{ Gt/year}$  and the ERS mean values are in the range between  $-10$  and  $+10 \text{ Gt/year}$ . All other regions show differences smaller than  $25 \text{ Gt/year}$  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  $-139 \pm 73 \text{ Gt/year}$  for April 2002–July 2005 (Velicogna and Wahr 2006) and  $-40 \pm 36 \text{ Gt/year}$  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  $-143 \pm 73$  (Velicogna 2009) and on April 2002–January 2009 data at  $-190 \pm 77 \text{ Gt/year}$  (Chen et al. 2009). However, the latest estimate based on April 2002–December 2008 data list a mean of  $-87 \text{ Gt/year}$  split at  $-64 \pm 32 \text{ Gt/year}$  for WA and  $-23 \pm 29 \text{ Gt/year}$  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  $-250 \text{ Gt/year}$ , 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  $2700 \text{ kg/m}^3$  implying adjustments  $\geq 60 \text{ Gt/year}$ , 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  $-138 \pm 92$  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  $-31 \pm 12$  Gt/year for 1992 to 2001 given in Z05 and the preferred estimate of  $+27 \pm 29$  Gt/year for 1992 to 2003 given in W06 are mainly due to different treatments of firm/ice density, corrections for the rate of upper firm 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 firm 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 ICESat 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.

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## 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 interpolated/extrapolated volume changes to either the upper firn layers with a density of  $350 \text{ kg/m}^3$  or to the glacial column with a density of  $917 \text{ kg/m}^3$ . 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  $900 \text{ kg/m}^3$ , which is actually closer to the mean density of firn and glacial ice columns than the often listed value of  $917 \text{ kg/m}^3$ . 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  $180 \pm 8 \text{ kg/m}^2/\text{year}$  (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  $12.183 \times 10^6 \text{ km}^2$  (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.

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