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Mass balance of the Antarctic ice sheet

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The Antarctic contribution to sea-level rise has long been uncertain. While regional variability in ice dynamics has been revealed, a picture of mass changes throughout the continental ice sheet is lacking. Here, we use satellite radar altimetry to measure the elevation change of 72% of the grounded ice sheet during the period 1992–2003. Depending on the density of the snow giving rise to the observed elevation fluctuations, the ice sheet mass trend falls in the range -5–$+85$ Gt yr^{-1}. We find that data from climate model reanalyses are not able to characterise the contemporary snowfall fluctuation with useful accuracy and our best estimate of the overall mass trend—growth of 27 ± 29 Gt yr^{-1}—is based on an assessment of the expected snowfall variability. Mass gains from accumulating snow, particularly on the Antarctic Peninsula and within East Antarctica, exceed the ice dynamic mass loss from West Antarctica. The result exacerbates the difficulty of explaining twentieth century sea-level rise.

Keywords: Antarctica; sea level; mass balance; altimetry

1. Introduction

During the twentieth century, the rate of mean global sea-level rise was 1.8 mm yr^{-1} (Church & Gregory 2001). Remote satellite platforms offer the only prospect for estimating the sea level contribution due to Antarctica. This may be achieved through measurements of volume change (Wingham *et al.* 1998), of mass discharge (Rignot & Thomas 2002) and of gravitational perturbations (Bentley & Wahr 1998). Today, there are limitations in both the scope and accuracy of each approach. The rate of volume change is known for *ca* 70% of the grounded ice (Wingham *et al.* 1998), but the density at which that fluctuation has occurred is certain over a still smaller region (Shepherd *et al.* 2002; Davis *et al.* 2005). The rate of glacier mass discharge is known for *ca* 60% of the grounded ice (Rignot & Thomas 2002), but the accuracy to which the atmospheric mass supply can be determined is limited by decadal fluctuations in snow accumulation (Wingham *et al.* 1998). The change in gravitational attraction can be resolved for regions occupying *ca* 10% of the grounded

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ice area (Wahr *et al.* 1998), but, while data on Greenland are available (Velicogna *et al.* 2005), a comprehensive survey of perturbations near Antarctica is still lacking. Based on some of these methods, recent estimates of the Antarctic ice sheet mass balance have placed it as a 60 ± 76 Gt yr^{-1} source (Wingham *et al.* 1998), a 26 ± 37 Gt yr^{-1} source (from the mass budget data of Rignot & Thomas (2002)) and (for East Antarctica only) a 45 ± 7 Gt yr^{-1} sink (Davis *et al.* 2005) of ocean mass. Together, these values provide Antarctic sea level contributions in the range -0.12–$+0.17$ mm yr^{-1} and improvement in certainty requires measurements with increased scope or accuracy.

2. Methodology

We analysed 1.2×10^8 European remote sensing (ERS) satellite altimeter echoes to determine the change in volume of the Antarctic ice sheet from 1992 to 2003. By using multiple orbit reference cycles (Zwally *et al.* 2002), we extend an earlier survey (Wingham *et al.* 1998) in space to within, on average, 26 km of the ice sheet margin, and in time to encompass 11 years of continuous measurement. For this study, we used ERS-1 and ERS-2 WAP v. 3 altimeter data with DGME04 delft precise orbits from October 1992 to February 2003. The data were separated into orbit cycles of 35 days. Five ERS-1 orbits repeats and 16 ERS-2 orbit repeats were selected as reference cycles. For each satellite and each reference cycle, dual cycle cross-overs of elevation and power were formed and placed in 100 km^2 bins. The elevation changes were corrected for covariance of trends in power and elevation and the two satellites cross-calibrated following the method of (Wingham *et al.* 1998). We also investigated, separately, the trends of the atmospheric corrections: none of these were significant. To edit the data, individual orbits or repeats with gross errors were removed. We did not use the conventional '3-sigma' edit on the variance of elevation time series, for fear of removing the larger signals. Instead, we used an edit on the magnitude and seasonality of elevation trends; time-series with trends greater than 2 and 4 m yr^{-1} were excluded in East and West Antarctica, respectively, and all time-series with seasonal-cycle amplitudes over 1.2 m were removed. In addition, time-series with fewer than 20% of the possible number of cross-overs in a 100 km^2 bin were also removed. Our survey includes 72% of the grounded ice sheet (8.5×10^6 km^2), omitting just 6% of coastal sectors (0.8×10^6 km^2) where data are lost due to steep slopes, and 22% of the interior (2.6×10^6 km^2), which lies beyond the latitudinal limit (81.6°S) of the satellite ground track.

We fitted a trend and annual cycle to the elevation time series at each 100 km^2 bin to characterize their variance; an interpolation of the trend is shown in figure 1. To determine the rate of elevation change of individual ice drainage basins (table 1) and the trend of the entire region of coverage (figure 2), we averaged the time-series over their respective areas. In determining basin-wide trends, we did not use ERS-1 if its coverage was less than 85% of that of ERS-2 for fear of biasing the result by relatively few ERS-1 observations. This principally affected basin H–J′. To correct for the isostatic rebound of the continent we used a value (Nakada *et al.* 2000) of 1.7 mm yr^{-1}. Our survey covers 85% of the East Antarctic ice sheet and 51% of the West Antarctic ice sheet and includes basins missing from mass budget compilations (Rignot & Thomas 2002).

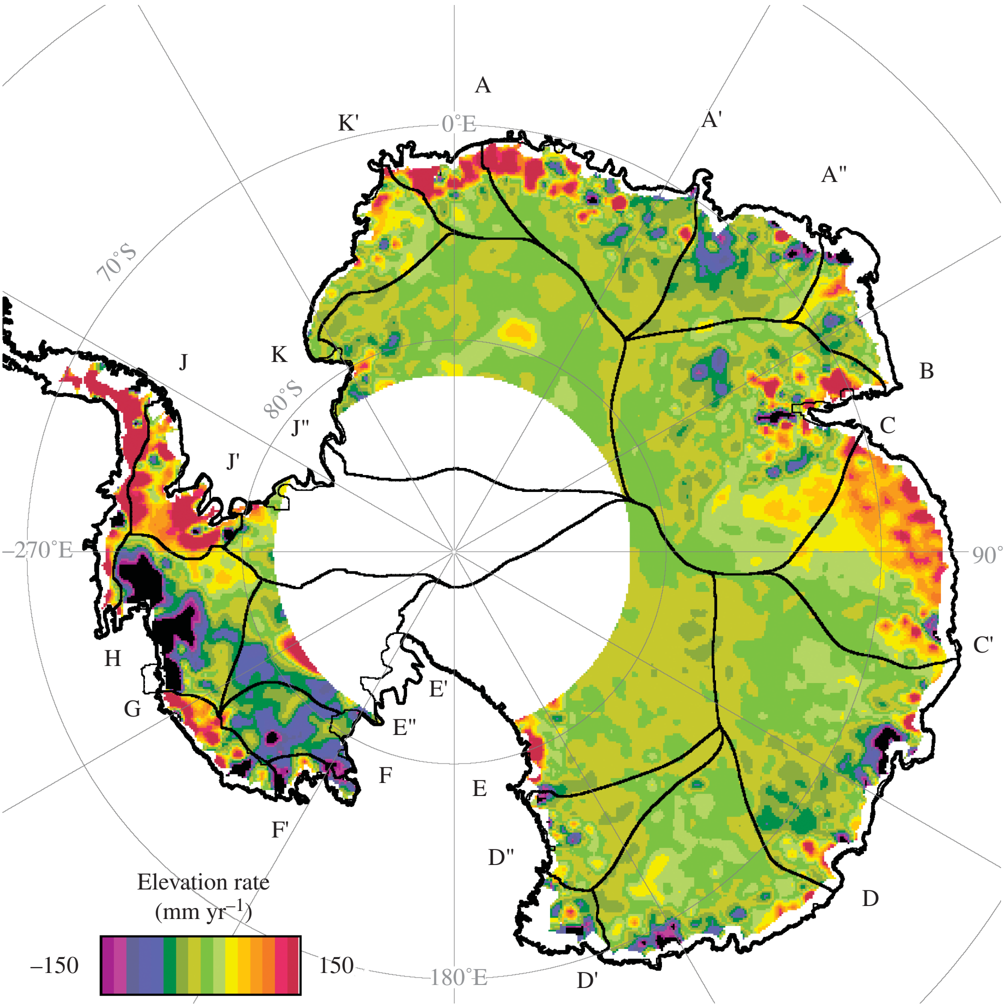

Figure 1. Rate of elevation change of the Antarctic ice sheet, 1992–2003, interpolated using a Gaussian filter of radius 50 km.

3. Results and discussion

Although our altimeter data are derived from the same source as those of Davis *et al.* (2005), our analysis is at a finer resolution and our interpretation of snow accumulation records is altogether different. By making improvements on the spatial and temporal coverage of past surveys (Wingham *et al.* 1998; Davis *et al.* 2005), our survey reveals a clearer picture of changes of the Antarctic ice sheet. In particular, the fine (10 km) spatial resolution is sufficient to distinguish changes associated with distinct glacial systems. The draw down of the Pine island, Thwaites and Smith glaciers in the Amundsen Sea sector (basin G–H) of West Antarctica are prominent, as is the thickening of the Kamb ice stream (basin E′–E″) at the Siple coast. These changes have been previously identified (Anandakrishnan & Alley 1997; Shepherd *et al.* 2002), and their origin is related to known ice dynamic disequilibria. Flow-related thinning in the coastal sections

Table 1. Antarctic drainage basin area, 1992–2003 elevation rate, 1979–2001 mean accumulation rate (MAR) and 1992–2001 accumulation rate anomaly with respect to the MAR.

basin	area (10^6 km^2)	observed area (10^6 km^2)	elevation rate (mm yr^{-1})	mean accumulation rate (mm yr^{-1})	mean accumulation rate anomaly (mm yr^{-1})
K–K′	0.24	0.22	23±3	444	18
J″–K	1.59	0.97	5±1	156	−1
J′–J″	0.8	0.07	24±4	494	−36
J–J′	0.24	0.19	91±4	915	−37
H–J	0.28	0.12	164±8	1481	−34
G–H	0.43	0.4	−68±3	924	−19
F′–G	0.13	0.11	39±6	744	26
F–F′	0.06	0.04	−58±7	669	−19
E″–F	0.19	0.19	−52±3	307	–4
E′–E″	0.49	0.18	−11±3	370	–3
E–E′	1.55	0.8	0±1	150	2
D″–E	0.28	0.26	1±2	210	11
D′–D″	0.13	0.06	−3±5	401	11
D–D′	0.74	0.67	5±2	428	−20
C′–D	1.15	1.08	−1±3	495	−32
C–C′	0.7	0.63	47±4	503	−16
B–C	1.29	1.27	10±1	160	3
A″–B	0.22	0.14	17±4	365	1
A′–A″	0.42	0.37	−11±2	308	−17
A–A′	0.59	0.55	6±1	290	−9
K′–A	0.19	0.16	37±3	375	23
WAIS	4.16	2.09	−7±1	529	−9
EAIS	7.54	6.4	7±1	322	−8
AIS	11.7	8.49	5±1	373	−9

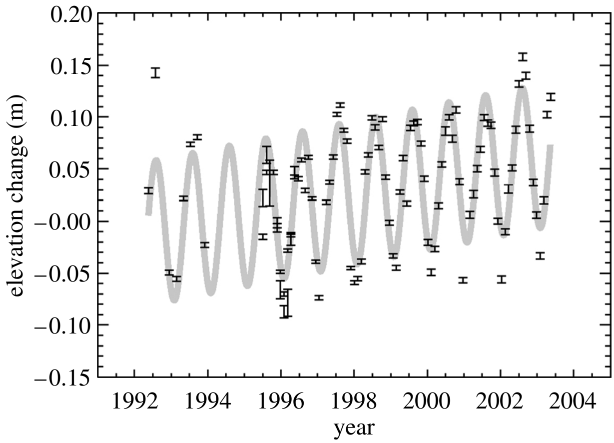

Figure 2. Elevation change of the Antarctic ice sheet, 1992–2003.

of the Cook (basin D–D′) and Totten (basin C′–D) glaciers is also apparent. In addition to these ice dynamic fluctuations, there are regions of thickening whose patterns are correlated with that of mean accumulation (Vaughan *et al.* 1999). The most striking examples include the east–west gradient across the Antarctic Peninsula (basins J–J′ and H–J′), the increase north of the coastal mountains of Dronning Maud Land (basin K′–A′) and the increase coastward in Wilkes Land (C–C′). Because these changes occur over slow-moving ice, we attribute them to a contemporary snowfall fluctuation—accumulation higher than the long-term discharge through flow. Overall, the data, corrected for isostatic rebound, show the ice sheet growing at 5 ± 1 mm yr^{-1}.

To determine the change in mass requires knowledge of the density at which the volume changes (figure 1) have occurred. However, of the 21 Antarctic drainage basins included in our survey, we can confidently attribute the fluctuation to changes in ice or snow at only four: basins G–H and E′–E″ have, predominantly, lost and gained *ice*, respectively, and basins J–J′ and H–J have, predominantly, gained *snow*. These fluctuations are each supported by a range of either glaciological or meteorological observations. Elsewhere, signals of thickening or thinning are correlated with flow, accumulation or neither, both within and across basin boundaries. To convert the volume changes of such basins to changes in mass requires either other data on, for instance, the contemporary snowfall fluctuation, or a method by which the uncertainty may be reasonably bound.

We considered the contemporary fluctuation in snow accumulation. We used a 21 year subset of data from the European Centre for Medium-range Weather Forecasting (ECMWF) climate model reanalyses (ERA-40) to estimate changes in net snow accumulation (precipitation minus evaporation) for the period 1979–2001. Prior to this epoch, the ERA-40 data is known to be less certain (Marshall 2003). From the subset, we calculated the longest-term mean accumulation rate (MAR) across the entire Antarctic ice sheet. As a check, we compared the MAR to a map of net snow accumulation (NSA) computed from an interpolation of *in situ* records (Vaughan *et al.* 1999). The MAR for Antarctica was 373 mm snow yr^{-1} and the root mean square departure of the MAR of the 21 separate drainage basins from the NSA record was 110 mm yr^{-1}of snow . It is important to note that, since the NSA record incorporates data representative of fluctuations over a range of timescales, there is no reason it should match the ERA-40 MAR, directly. Because contemporary fluctuations in accumulation will affect a change in ice sheet volume only if they *depart* from the long-term mean (Van der Veen 1993), we differenced the average ERA-40 accumulation rate over the period of our satellite survey (1992–2001) from the MAR to estimate the component of Antarctic elevation change due to snowfall (figure 3 and table 1). This comparison differs from that of (Davis *et al.* 2005); that survey failed to account for the long-term MAR.

The ERA-40 snowfall departure (figure 3) matches poorly the elevation change recorded over the same period (figure 1). While it is possible that none of the elevation change is due to a contemporary snowfall fluctuation, there is good evidence to suppose that, for instance, growth of Dyer Plateau at the Antarctic Peninsula is through precisely that mechanism (Thompson *et al.* 1994). In fact, the sharp boundary in elevation change across Dyer plateau (figure 1) falls on the drainage divide between the east and west coasts of the peninsula, where

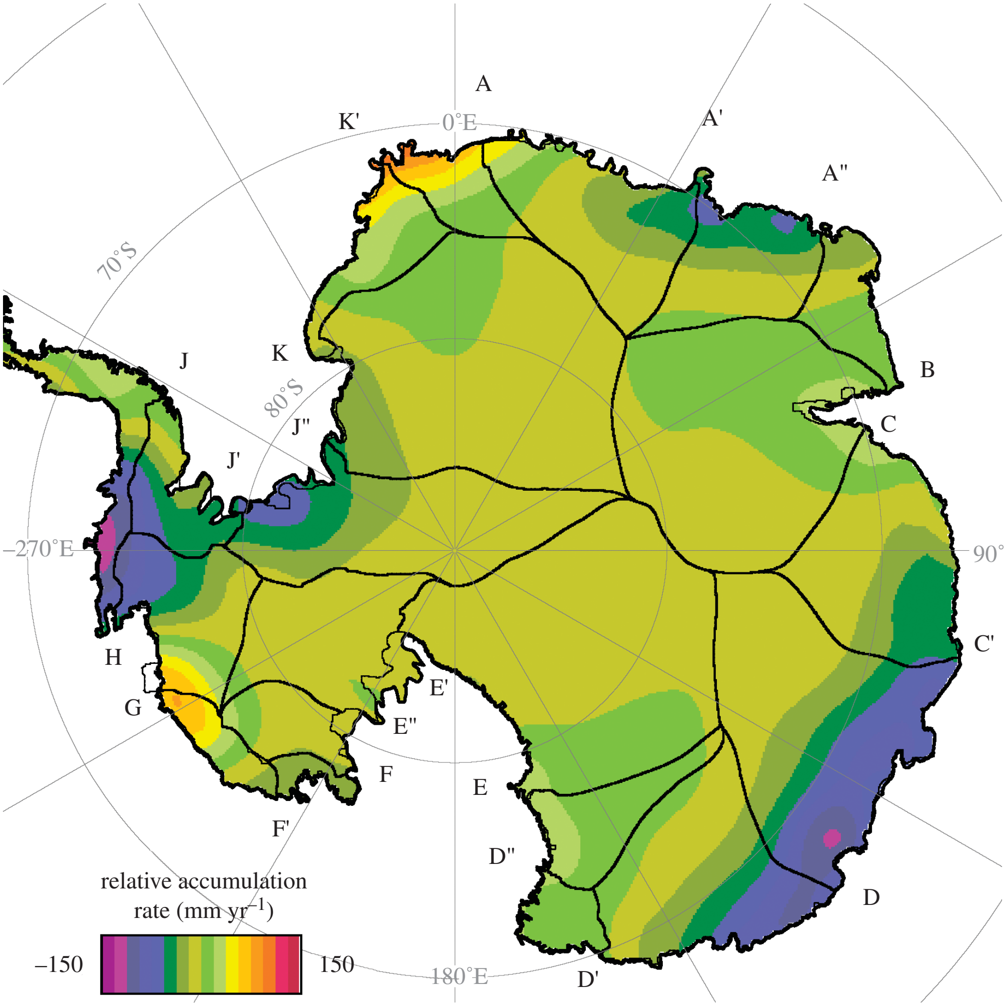

Figure 3. 1992–2001 departure in accumulation rate from the long-term (1979–2001) mean.

precipitation gradients are known to be strong (Turner *et al.* 2002). Elsewhere, the coastal growth of Dronning Maud Land is represented in the ERA-40 data, but the growth of Wilkes Land is not. Making a direct comparison of the snowfall departure and elevation change for all Antarctic basins reveals the scale of dissimilarity (figure 4); there is little, if any, closure between the two data sets. It seems likely that the ERA-40 data are of too short a duration to capture slight departures in accumulation from the long-term mean and, in consequence, the data are of little use in ascribing a density to the elevation fluctuations (figure 1).

Instead, we prescribed density limits to bound the mass fluctuation. In the thickness trend, decadal accumulation fluctuations are exaggerated over longer trends in the ratio of the densities of ice and snow (Wingham 2000), and different durations of accumulation fluctuation (in general, poorly constrained by other data) allow different mass trends. First, we consider two limiting cases; we bound the mass trend by assuming that all thickness gains are decadal fluctuations,

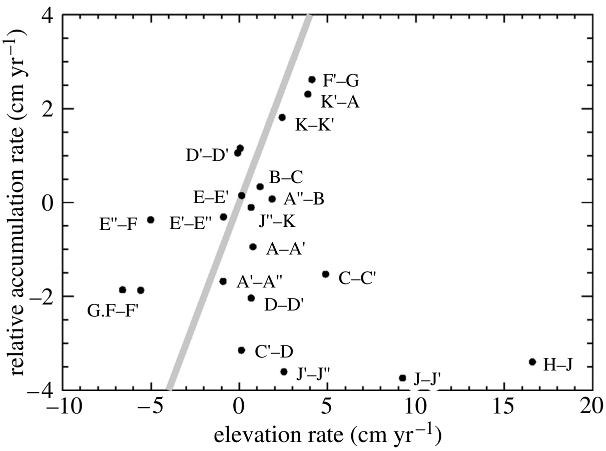

Figure 4. Scatter plot of elevation rate against accumulation rate relative to the long-term (1979–2001) mean for drainage basins of the Antarctic ice sheet.

while all losses are longer term, and vice versa. Multiplying the basin-wide trends (table 1) by either the densities of snow ($350\,\mathrm{kg\,m^{-3}}$) and ice ($917\,\mathrm{kg\,m^{-3}}$) provides a range -5–$+85\,\mathrm{Gt\,yr^{-1}}$. This is almost certainly too generous. The thickening of E′–E″ and the thinning of G–H are ice dynamic fluctuations; the Peninsula (H–J′) thickening matches the pattern of its warming trend (Vaughan *et al.* 2001) and on this basis dates from the 1950s. Assigning these to the longer term and others to recent fluctuation, and treating the measurement error and expected snowfall variability ($0.7\,\mathrm{cm\,yr^{-1}}$ across the entire regions of coverage, from the data of Wingham *et al.* 1998) as equivalent sources of uncertainty, provides an overall trend of $27\pm29\,\mathrm{Gt\,yr^{-1}}$.

Other data are needed to settle this value. In any case, our data excludes 28% of the grounded ice. The change in mass of the interior (80% of the omitted area) is likely to be small. For instance, the mass balances of the least surveyed basins (J′–J and E″–E) are small (Rignot & Thomas 2002) and, applying the average elevation rate ($9\,\mathrm{mm\,yr^{-1}}$) for the southernmost degree in latitude provides an estimated growth rate of $22\,\mathrm{km^3\,yr^{-1}}$ for the omitted region. Assigning such a growth to the short term provides an additional $7\,\mathrm{Gt\,yr^{-1}}$ mass gain. The change in mass of unsurveyed coastal sectors presents the greatest source of uncertainty. While the data themselves suggest that the unsurveyed areas of the Peninsula are sinks of ocean mass, elsewhere ice thinning is correlated with ice flow and, in turn, ice flow rates peak at the ice margin where elevation data are lacking. For the coastal regions omitted from our survey (6% of the grounded ice sheet), a straightforward extrapolation of the elevation data is likely inappropriate, since patterns of ice flow are irregular and, in any case, thinning rates are not everywhere correlated with flow. Nevertheless, applying the average elevation rate for the coastal 200 km of the surveyed ice sheet ($-14\,\mathrm{mm\,yr^{-1}}$) to the unsurveyed coastal sector ($0.8\times10^6\,\mathrm{km^2}$) provides an estimated $10\,\mathrm{Gt\,yr^{-1}}$ source of ocean mass (assuming the change were to occur at the density of ice). Our estimate of the mass gain of the unsurveyed Antarctic interior is comparable to our estimate of the mass loss of the unsurveyed coast.

4. Conclusions

We show that 72% of the Antarctic ice sheet is gaining 27 ± 29 Gt yr^{-1}, a sink of ocean mass sufficient to *lower* global sea levels by 0.08 mm yr^{-1}. The IPCC third assessment (Church & Gregory 2001) partially offset an ongoing sea-level rise due to Antarctic retreat since the last glacial maximum (0.0–0.5 mm yr^{-1}) with a twentieth century fall due to increased snowfall (-0.2–0.0 mm yr^{-1}). But that assessment relied solely on models that neither captured ice streams nor the Peninsula warming, and the data show both have dominated at least the late twentieth century ice sheet. Even allowing a ± 30 Gt yr^{-1} fluctuation in unsurveyed areas, they provide a range of -35–$+115$ Gt yr^{-1}. This range equates to a sea level contribution of -0.3–$+0.1$ mm yr^{-1} and so Antarctica has provided, at most, a negligible component of observed sea-level rise. In consequence, the data places a further burden on accounting (Munk 2003) for the twentieth century rise of 1.5–2 mm yr^{-1}. What is clear, from the data, is that fluctuations in some coastal regions reflect long-term losses of ice mass, whereas fluctuations elsewhere appear to be short-term changes in snowfall. While the latter are bound to fluctuate about the long-term MAR, the former are not, and so the contribution of retreating glaciers will govern the twenty-first century mass balance of the Antarctic ice sheet.

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