Snowfall in coastal West Antarctica much greater than previously assumed

Michiel van den Broeke,[1] Willem Jan van de Berg,[1] and Erik van Meijgaard[2]

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[1] A new Antarctic accumulation distribution, based on regional model output calibrated with 1900 in-situ observations, is used to re-assess accumulation in 24 Antarctic ice drainage basins. When compared to the previous compilation, good agreement is found for 19 of the 24 basins, representing 93% of the ice sheet that is reasonably well covered with observations. In contrast, the Amundsen Sea sector of West Antarctica and the western Antarctic Peninsula, both data sparse regions, are found to receive 80–96% more accumulation than previously assumed. For the Pine Island and Thwaites Glaciers (West Antarctica), which have recently undergone rapid acceleration and thinning, this means a downward adjustment of their contribution to global sea level rise from 0.24 to 0.14 mm per year. Model time series do not show a significant change in Antarctic accumulation over the period 1980–2004. **Citation:** van den Broeke, M., W. J. van de Berg, and E. van Meijgaard (2006), Snowfall in coastal West Antarctica much greater than previously assumed, *Geophys. Res. Lett.*, *33*, L02505, doi:10.1029/2005GL025239.

1. Introduction

[2] The Antarctic ice sheet holds sufficient water to raise global sea level by 61 m [*Huybrechts and De Wolde*, 1999]. Mass changes in the ice sheet and associated changes in sea level result from an imbalance between surface accumulation and export of solid ice across the grounding line. In 2001, the Intergovernmental Panel on Climate Change estimated the contribution of the Antarctic ice sheet to global sea level rise during the past century to be slightly negative (−0.1 ± 0.1 mm per year) [*Intergovernmental Panel on Climate Change*, 2001], suggesting that the ice sheet is nearly in balance with the present climate. However, recent research shows various Antarctic ice drainage basins to be strongly out of balance. Pine Island and Thwaites glaciers in West Antarctica are accelerating and thinning, leading to an estimated rise in global sea level of 0.24 mm per year [*Thomas et al.*, 2004]. In the eastern and western Antarctic Peninsula (AP), grounded tributary glaciers have also undergone significant acceleration and thinning, following the retreat of the northernmost ice shelves since 1986 [*Vaughan and Doake*, 1996; *Rott et al.*, 2002; *De Angelis and Skvarça*, 2003; *Scambos et al.*, 2003]. Over the past 61 years, most of the marine glacier fronts in the Antarctic Peninsula have retreated [*Cook et al.*, 2005]. In contrast, satellite radar altimetry suggests that the East Antarctic ice sheet has thickened between 1992 and 2003, mitigating sea level rise by 0.12 mm per year [*Davis et al.*, 2005].

[3] The reliability of these projections suffers from a lack of in-situ accumulation observations. To obtain full spatial coverage, the sparsely available accumulation observations are usually interpolated using background fields of accumulation-related parameters such as temperature, surface elevation and slope [*Giovinetto et al.*, 1990; *Fortuin and Oerlemans*, 1990] or passive microwave data from satellites [*Zwally and Giovinetto*, 1995; *Vaughan et al.*, 1999]. A different approach is to calibrate output of a high-resolution regional atmospheric climate model to optimally match in-situ observations. Here we show that the latter approach provides important new insights into the surface mass (im-)balance of Antarctic ice drainage basins.

2. Methods

2.1. Model Description

[4] The Regional Atmospheric Climate Model v.2 (RACMO2) was run over Antarctica for the period 1957–2004 with a horizontal resolution of 55 km and 40 vertical layers, forced at the lateral boundaries by ERA40, the 40-year re-analysis of the European Centre for Medium range Weather Forecasts (ECMWF Re-Analysis, January 1957–September 2002) and ECMWF operational analysis (October 2002 to December 2004). Sea surface temperature and sea ice cover are also prescribed from ERA40. Surface accumulation (kg m^{-2} yr^{-1}) is obtained by subtracting sublimation and melt from solid precipitation. Snowdrift related processes are not taken into account, because no observational evidence exists that this significantly influences basin-wide accumulation [*Déry and Yau*, 2002]. Only the period 1980–2004, for which ERA40 is known to perform well in the southern hemisphere, is used [*Van de Berg et al.,* 2004, *Bromwich and Fogt*, 2004].

2.2. Model Performance and Calibration Procedure

[5] RACMO2 produces a very realistic Antarctic accumulation field: a direct linear regression with 1900 spatially-weighted quality-controlled in-situ observations yields a correlation coefficient of 0.82 and a regression slope of 1.21 [*Van de Berg et al.*, 2006]. This result is remarkable given that model and observations mostly cover different time periods and that observations are known to suffer from post-depositional noise. To force the regression slope toward one, model output was calibrated using linear regressions in 500 m elevation bins [*Van de Berg et al.*, 2006]. The resulting accumulation distribution is given in Figure 1a.

[1]Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, Netherlands.
[2]Royal Netherlands Meteorological Institute, De Bilt, Netherlands.

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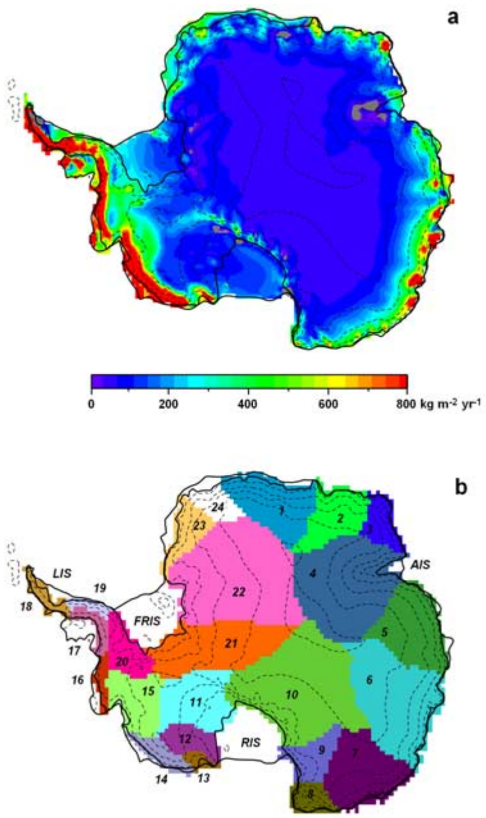

Figure 1. (a) Re-assessment of accumulation in Antarctica (1980–2004) [*Van de Berg et al.*, 2006]. Grey areas denote ablation, contours denote 500 m elevation intervals (starting at 150 m asl). (b) Colored delineations of Antarctic ice drainage basins and topographic features mentioned in the text. RIS = Ross Ice Shelf; FRIS = Filchner-Ronne Ice Shelf; LIS = Larsen Ice Shelf; AIS = Amery Ice Shelf.

2.3. Drainage Basin Delineation

[6] Throughout this paper we compare our results to the most recent compilation of Antarctic accumulation by *Vaughan et al.* [1999] (hereinafter referred to as V99), which is based on spatial interpolation of observations using passive microwave data. Delineations of Antarctic ice drainage basins (Figure 1b) were derived from model topography and 24 predefined coastal ice flux gates [*Giovinetto and Bentley*, 1985]. To make the basins compatible with V99, we used his definition of the ice sheet grounding line with several manual amendments, notably to basins 9 and 21. Figure 2a shows that the surface area of individual ice drainage basins agrees well with V99 (see also Table S1).[1] The total area of grounded ice sheet in the model is 12,135,900 km^2, 0.3 % more than V99.

2.4. Estimate of Uncertainties

[7] Two types of uncertainties in basin accumulation can be distinguished: one associated with model errors, which has been minimized using the calibration procedure outlined in section 2.2. The second uncertainty derives from the calibration procedure itself, and was quantified by repeating the calibration procedure 10,000 times using an arbitrarily selected one-third of the observations. The resulting (accumulated) standard deviation is used in Figures 2b–2d and in the auxiliary figure/table.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL025239.

3. Results

3.1. Spatial Distribution of Accumulation

[8] Apart from the well-known accumulation decrease from the coast to the interior ice sheet (Figure 1a), the new accumulation map shows pronounced longitudinal gradients in coastal East Antarctica in association with topographic disturbances that interact with the predominantly easterly coastal circulation. Due to persistent onshore flow in combination with steep coastal topography, accumulation exceeds 800 kg m^{-2} yr^{-1} on eastward facing slopes in coastal East Antarctica, in the Amundsen Sea coast of West Antarctica and the west coast of the Antarctic Peninsula. These high-accumulation areas correspond well with passive microwave data [*Zwally and Giovinetto*, 1995]. Ablation areas (grey areas in Figure 1a) are also accurately

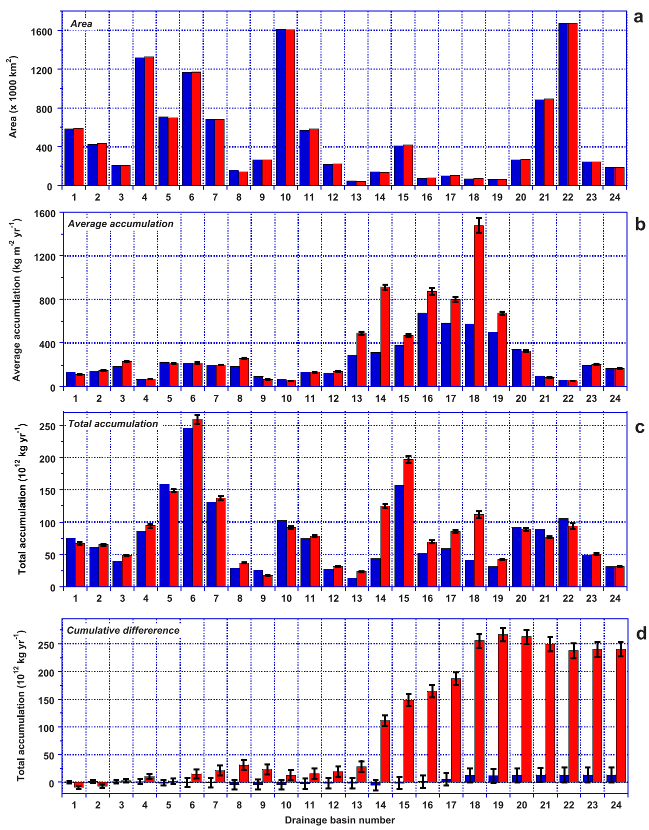

Figure 2. (a) Area of ice drainage basins, from V99 (blue bars) and this study (red bars); (b) basin average accumulation from V99 (blue bars) and this study (1980–2004, red bars); (c) basin total accumulation [area times average accumulation) from V99 (blue bars) and this study (1980–2004, red bars); (d) cumulative difference in total accumulation, resulting from accumulation differences (red bars) and differences in basin area (blue bars). Error bars in Figures 2b–2d denote uncertainty in calibration procedure (see text). A tabulated version of Figures 2a, 2b and 2c is available as auxiliary material.

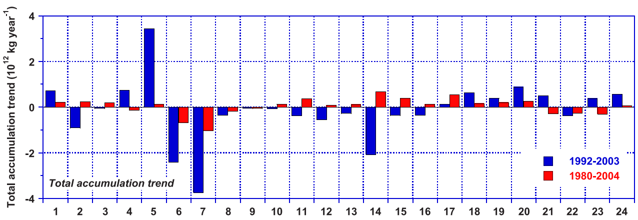

Figure 3. Trends in basin total accumulation, for the period 1992–2003 (blue bars) and 1980–2004 (red bars).

represented, including the northern Larsen ice shelf, which recently disintegrated [*Scambos et al.*, 2003], and the Dry Valleys northwest of the Ross Ice Shelf.

3.2. Drainage Basin Accumulation

[9] Figure 2 compares basin-mean (Figure 2b) and total accumulation (area times average accumulation; Figure 2c) to V99. For basin numbers 1–13 and 19–24, representing more than 93% of the grounded ice sheet surface, the two compilations are highly correlated (R = 0.99, regression slope 0.99; see Figure S1). In contrast, the new compilation is much wetter in basins 14 to 18, covering the Amundsen Sea coast of West Antarctica and the Antarctic Peninsula, both data-sparse regions.

[10] Figure 2d shows the cumulative difference in total accumulation, subdivided in contributions made by accumulation differences (red bars) and by biases in basin area (blue bars). The area bias effect is small compared to the total effect. The accumulation difference integrated over the grounded ice sheet is 251 10^{12} kg yr^{-1}, representing a 14% increase compared to V99. This is a significant amount considering that it stems from less than 7% of the grounded ice sheet area.

[11] An accumulation increase of 97 10^{12} kg yr^{-1} (+96%) is found for the western Antarctic Peninsula (basins 17 and 18). The relative increase is especially large for basin 18 (+173%; Figure 2c), but this result must be treated with care: accumulation on the narrow spine of the Antarctic Peninsula may be sensitive to snowdrift related processes [*Van Lipzig et al.*, 2004; *Turner et al.*, 2002]. For the Amundsen Sea coast of West Antarctica (basins 14 to 16) the accumulation increase is 140 10^{12} kg yr^{-1} (+80%). For the catchment area of Pine Island and Thwaites Glaciers (basin 15), the updated total accumulation is 197 10^{12} kg yr^{-1} (+26%). This is 21% less than the estimated solid ice flux over the grounding line (250 10^{12} kg yr^{-1}) [*Thomas et al.*, 2004]. Compared to previous estimates [*Rignot et al.*, 2004], this means a downward adjustment of their contribution to global sea level rise from 0.24 to 0.14 mm per year.

3.3. Accumulation Trends

[12] Linear trends were calculated using regressions on (uncalibrated) annual mean accumulation values. *Davis et al.* [2005] reported a snowfall-driven growth of the East Antarctic ice sheet over the period 1992–2003. RACMO2 1992–2003 solid precipitation trends (blue bars in Figure 3) compare qualitatively well with those reported by *Davis et al.* [2005], with alternating areas of increasing (basins 4, 5) and decreasing (basin 6, 7) accumulation in East Antarctica, and generally decreasing accumulation in coastal West Antarctica, especially in basin 14, but an increase in basins 17–20. If basin accumulation trends are calculated over the full available period (1980–2004; red bars in Figure 3), the magnitudes are strongly reduced, indicating that the 1992–2003 trends are not part of a long-term change that started before 1992. For both periods, no significant trend is found for accumulation integrated over the grounded ice sheet. Note that, due to the brevity of the time series, none of the trends in Figure 3 is statistically significant.

[13] For the period 1980–2004, the standard deviation of annual accumulation over the grounded ice sheet is less than 5% of the mean value. This is a modest value, but still about sixty times larger than the annual accumulation increase. This means that interannual variability has overwhelmed any potential increase in Antarctic accumulation during the past 25 years. It remains a matter of debate what caused the overall ice sheet thickening in East Antarctica over 1992–2003 as reported by *Davis et al.* [2005]. A possible candidate is a lower density of newly fallen snow owing to weaker near-surface winds and lower temperatures in East Antarctica, following an increase in the strength of the polar vortex [*Thompson and Solomon*, 2002; *Marshall*, 2003; *Van den Broeke and van Lipzig*, 2003].

4. Conclusions

[14] The surface mass balance of Antarctic ice drainage basins is re-assessed using a new Antarctic accumulation distribution. For 93% of the grounded ice sheet area, accumulation is in good agreement with previous estimates by *Vaughan et al.* [1999]. However, significantly higher accumulation values (+80 to +96%) are found for the data sparse regions in the Amundsen Sea sector of West Antarctica and the western Antarctic Peninsula, revising downward its contribution to global sea level rise. Model accumulation does not show a significant change in Antarctic accumulation over the period 1980–2004.

[15] Estimates of Antarctic accumulation have been regularly adjusted upward since the 1970s, because improved prediction fields have become available that better capture the data sparse and narrow high-accumulation zones in coastal Antarctica. To further constrain Antarctic mass (im-)balance and associated changes in global sea level, new observations from high-accumulation areas, especially from coastal West Antarctica and the western Antarctic Peninsula, are urgently needed. This is a major challenge for the upcoming International Polar Year (2007–2009).

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W. van de Berg and M. van den Broeke, Institute for Marine and Atmospheric Research, Utrecht University, P.O. Box 80005, NL-3508 TA Utrecht, Netherlands. (broeke@phys.uu.nl)

E. van Meijgaard, Royal Netherlands Meteorological Institute, Postbus 201, NL-3730 AE De Bilt, Netherlands.