A new, high-resolution surface mass balance map of Antarctica (1979–2010) based on regional atmospheric climate modeling

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[1] A new, high resolution (27 km) surface mass balance (SMB) map of the Antarctic ice sheet is presented, based on output of a regional atmospheric climate model that includes snowdrift physics and is forced by the most recent reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF), ERA-Interim (1979–2010). The SMB map confirms high accumulation zones in the western Antarctic Peninsula (>1500 mm y^{-1}) and coastal West Antarctica (>1000 mm y^{-1}), and shows low SMB values in large parts of the interior ice sheet (<25 mm y^{-1}). The location and extent of ablation areas are modeled realistically. The modeled SMB is in good agreement with $\pm$750 in-situ SMB measurements (R = 0.88), without a need for post-calibration. The average ice sheet-integrated SMB (including ice shelves) is estimated at 2418 $\pm$ 181 Gt y^{-1}. Snowfall shows modest interannual variability (σ = 114 Gt y^{-1}), but a pronounced seasonal cycle (σ = 30 Gt mo^{-1}), with a winter maximum. The main ablation process is drifting snow sublimation, which also peaks in winter but with little interannual variability (σ = 9 Gt y^{-1}). **Citation:** Lenaerts, J. T. M., M. R. van den Broeke, W. J. van de Berg, E. van Meijgaard, and P. Kuipers Munneke (2012), A new, high-resolution surface mass balance map of Antarctica (1979–2010) based on regional atmospheric climate modeling, *Geophys. Res. Lett.*, *39*, L04501, doi:10.1029/2011GL050713.

1. Introduction

[2] Improving our knowledge of the surface mass balance (SMB) of the Antarctic Ice Sheet (AIS), which has a volume equivalent to 56.6 m of sea level rise (IPCC AR4), is vital to improve predictions of the future mass balance of the ice sheet and associated changes in global sea level [*Rignot et al.*, 2011]. The SMB [mm w.e. y^{-1}] for a specific location on the ice sheet is defined as:

$$SMB = \int_{year} (P - SU_s - RU - ER_{ds} - SU_{ds})dt \qquad (1)$$

where P represents precipitation (snow and rain), SU_s, is surface sublimation, RU meltwater runoff and ER_{ds} erosion by and SU_{ds} sublimation of drifting snow.

[3] Previous estimates of the SMB of the Antarctic ice sheet (AIS) [*Vaughan et al.*, 1999; *Arthern et al.*, 2006; *Bromwich et al.*, 2004; *van de Berg et al.*, 2005] revealed that precipitation (mainly snowfall) decreases quickly from the coast towards the interior ice sheet, where desert conditions prevail. High-accumulation zones (>1000 mm y^{-1}) were recently identified on the western side of the Antarctic Peninsula (AP) and in coastal West Antarctica [*van den Broeke et al.*, 2006; *Nicolas and Bromwich*, 2011a], with peak values in the AP in excess of 5000 mm y^{-1}, equivalent to $\sim$15 m of snow per year. In these model studies, the processes of drifting and blowing snow (hereafter referred to as drifting snow) have been neglected, necessitating a calibration procedure to match model output with in-situ observations [*van de Berg et al.*, 2006]. As shown by *Lenaerts and van den Broeke* [2012], neglecting snowdrift processes can lead to significant errors in the SMB on a local scale, where drifting snow erosion (ER_{ds}) can become large, as well as a general SMB overestimation in coastal areas, where drifting snow sublimation (SU_{ds}) removes 50–200 mm y^{-1} of the precipitated snow.

[4] In this study, we used the regional atmospheric climate model RACMO2.1/ANT to simulate the SMB of the AIS. This version of the model includes a drifting snow routine. *Lenaerts et al.* [2012] showed that RACMO2.1/ANT is capable of realistically simulating the near-surface temperature and wind climate of the AIS. Moreover, surface snow densities have been fitted, such that modeled drifting snow frequencies agree with available observations. To better resolve the complex topography and its impact on patterns of accumulation, wind and drifting snow, we used a high horizontal resolution of 27 km. We performed a model integration for the period 1979–2010 and forced the model at the lateral boundaries and ocean surface using ERA-Interim fields.

[5] The model and an evaluation of the SMB are presented in section 2, and the SMB and the spatial and temporal variability of its components are discussed in section 3, followed by conclusions.

2. Methods

[6] The regional atmospheric climate model RACMO2.1/ANT [*van Meijgaard et al.*, 2008] combines the dynamics of HIRLAM [*Undén et al.*, 2002] with the physical processes as described in the model of the European Centre for Medium-Range Forecasts (ECMWF) (cycle CY23R4 [*White*, 2001]). To be able to capture the topographic complexity in some parts of the AIS, RACMO2.1/ANT has a horizontal grid spacing of 27 km and 40 vertical levels. It is forced by ERA-Interim at its lateral and ocean boundaries (Jan. 1979–Dec. 2010), but is allowed to evolve freely in the domain interior.

[7] The model has been adapted to simulate conditions on the large ice sheets [*Reijmer et al.*, 2005]. A multilayer

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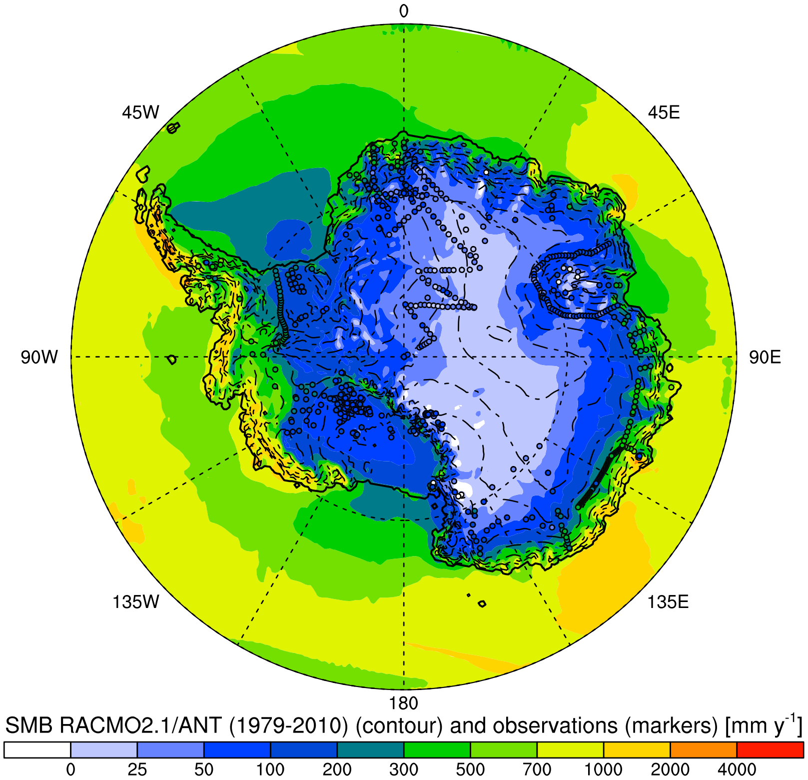

Figure 1. Mean (1979–2010) surface mass balance [mm w.e. y^{-1}] as simulated by RACMO2.1/ANT (contours) and according to observations (markers). Note that on the seasonal sea-ice, SMB equals precipitation (P) minus surface sublimation (SU_s) and on open ocean $SMB = P$.

snow/ice scheme calculates melt, percolation, refreezing and runoff of meltwater [*Ettema et al.*, 2010] and surface albedo, based on a prognostic scheme for snow grain size [*Kuipers Munneke et al.*, 2011]. It also includes a drifting snow routine to simulate the interactions of drifting snow with the surface and the lower atmosphere [*Lenaerts et al.*, 2012]. We refer the reader to *Lenaerts et al.* [2012] for more details on the model and simulation setup.

[8] The model SMB values are compared with in-situ observations from various sources [*van de Berg et al.*, 2006]. In several cases, the quality of observations is doubtful, depending on the method used; we follow the approach of *Genthon et al.* [2009] and remove accumulation observations that are based on snow stratigraphy, natural ^{210}Pb, stable isotope or chemical markers, and all observations for which the method is unknown. Finally, we leave out observations located outside of the ice sheet mask of RACMO2.1/ANT, single-year measurements and measurements for which the elevation difference with the model is larger than 100 m. As a result, we rejected 65% of the original 2128 measurements. We added several recent observations. For instance, the Norwegian-US traverse from Troll to South Pole and back provided accumulation measurements from the extremely dry (SMB < 50 mm y^{-1}) interior of Dronning Maud Land [*Anschütz et al.*, 2009]. This leaves us with 745 reliable in-situ SMB estimates.

[9] To account for the fact that the observations are not equally distributed over the ice sheet, we follow the approach of *van de Berg et al.* [2006]: each observation is compared to RACMO2.1/ANT by calculating a weighted average of the 4 surrounding grid points. Moreover, a weighting factor is assigned to each observation, such that areas with dense observational coverage are not overrepresented in the comparison.

3. Results

3.1. Spatial Variability

[10] Figure 1 shows the spatial distribution of modeled SMB. The large SMB gradient from the interior towards the coast is well captured. Figure 2 confirms that modeled SMB

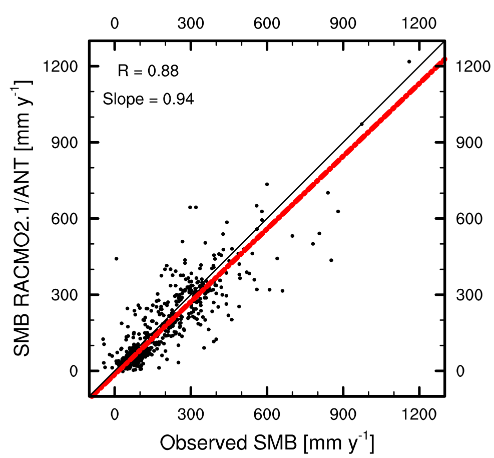

Figure 2. Observed versus modeled SMB [mm w.e. y^{-1}]. The black line represents the 1:1 line, and the red line is the best linear fit determined by the smallest perpendicular distance from each model value to the observation.

Table 1. Ice Sheet-Integrated SMB Values [Gt y^{-1}], and Comparison With Earlier Estimates[a]

	TotIS	GIS
Total Area [10^6 km^2]	13.93	12.33
This study	2418 ± 181	1983 ± 122
van de Berg et al. [2006]	2521 ± 118	2076 ± 108
Arthern et al. [2006]		1768 ± 49[b]
Bromwich et al. [2004]	2572 ± 221	
Vaughan et al. [1999]	2288	1811

[a]TotIS is the total ice sheet (including ice shelves), GIS is the grounded ice sheet. The uncertainty calculation is based on a model-to-data comparison [*Rignot et al.*, 2008]. The SMB uncertainty is larger in this study than in that of *van de Berg et al.* [2006], because we have used fewer observations.
[b]Assuming the same area for the grounded ice sheet as in this study.

agrees well with the in-situ observations. The correlation coefficient equals 0.88, and the slope of the best linear fit equals 0.94. The relatively high horizontal resolution reveals patterns of longitudinal SMB variability along the coast that are related to topographic features (Figure 1), which enhance/limit precipitation on the upwind/downwind side. These features also lead to drifting snow erosion where the near-surface wind pattern diverges, and snow deposition where the flow converges [*Lenaerts and van den Broeke*, 2012]. The presence of high-accumulation regions in the Antarctic Peninsula and coastal West Antarctica confirms results from *van de Berg et al.* [2006] and *van den Broeke et al.* [2006], and recently observed extreme accumulation rates on Bruce Plateau (>1 m of snow per month (T. Scambos, personal communication, 2010)). Using 20 km Polar-MM5 simulations, *Nicolas and Bromwich* [2011a] found similar high accumulation patterns in coastal West Antarctica (>1500 mm y^{-1}). Furthermore, RACMO2.1/ANT simulates very low SMB in the interior, which is also confirmed by the observations. However, the model appears to underestimate SMB in the escarpment zone in Victoria Land and Adélie Land (70–90°S, 135–160°E). A possible explanation is that the contribution of diamond dust to the SMB is not included in the model or that cloud ice precipitates too quickly [*van de Berg et al.*, 2005].

[11] Our results indicate that around 0.5% of the area of the Antarctic ice sheet is subject to ablation (SMB < 0). This estimate is somewhat lower than the satellite-based estimate of *Winther et al.* [2001] (0.8%), but clearly an improvement compared to a model run without drifting snow (<0.1%). This suggests that snowdrift is an important factor in the formation of Antarctic blue-ice (ablation) areas.

[12] Values of ice-sheet integrated SMB are given in Table 1, and compared to earlier studies. Both for the ice sheet including ice shelves and for the grounded ice sheet, our estimate agrees within error bars of that of *van de Berg et al.* [2006] and *Bromwich et al.* [2004]. It is significantly higher than estimates that are based on satellite-guided interpolation of in-situ data [*Vaughan et al.*, 1999; *Arthern et al.*, 2006]. This is mainly due to the higher model accumulation rates in the coastal zones, features that have yet to be fully verified owing to a lack of in-situ SMB observations.

3.2. Interannual Variability

[13] Figure 3 shows the 1979–2010 time series of annual mean SMB and its relevant components, integrated over the full ice sheet. Runoff (not shown) is nearly zero in Antarctica, because most of the meltwater refreezes. Rainfall and melt have been plotted instead. Drifting snow erosion (not shown) is locally important, but small (~4 Gt y^{-1}) when integrated over the ice sheet. Interannual variability in snowfall is significant: the wettest year in this period (1992) had 21% more snowfall than the driest year (2007). The interannual variability in SU_{ds}, is small (σ = 12 Gt y^{-1}). Its magnitude exceeds that of snowmelt, except for 1992, when strong surface melting occurred in the western Antarctic Peninsula and in coastal West Antarctica [*Kuipers Munneke et al.*, 2012]. SU_s, is also clearly smaller than SU_{ds}, which indicates that SU_{ds}, is the largest ablation term in the Antarctic SMB. Rainfall varies between 20 and 60 Gt y^{-1}, but due to low temperatures in the snowpack, most of this refreezes instantly. The surface mass balance variability follows to a great extent the interannual variation of snowfall.

3.3. Seasonal Cycle

[14] Figure 4 presents the average (1979–2010) annual cycle of the SMB components, integrated over the full ice sheet. A significant seasonal cycle is found in all SMB components. On average, snowfall is largest in early winter (May) and smallest in summer. The maximum in winter is

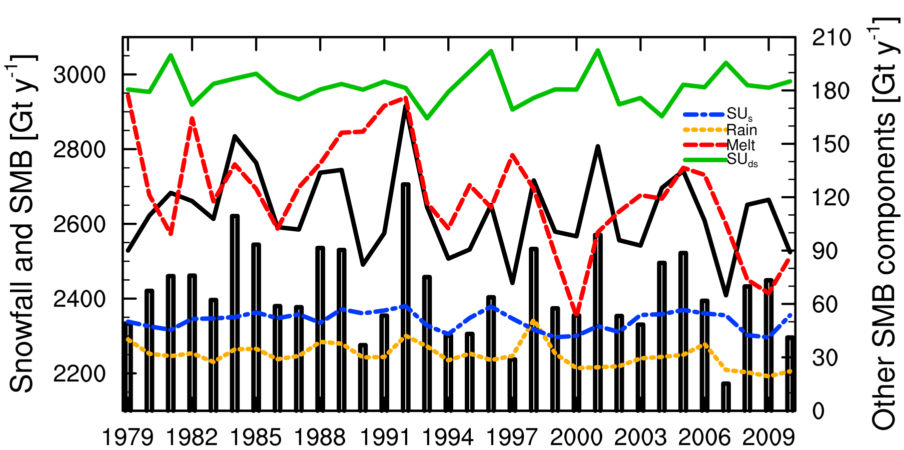

Figure 3. Time series of SMB components, integrated over the ice sheet including ice shelves, for the period 1979–2010 [all in Gt y^{-1}]. Snowfall (black solid line) is shown on the left axis, together with the SMB (bars), the other components are shown on the right axis.

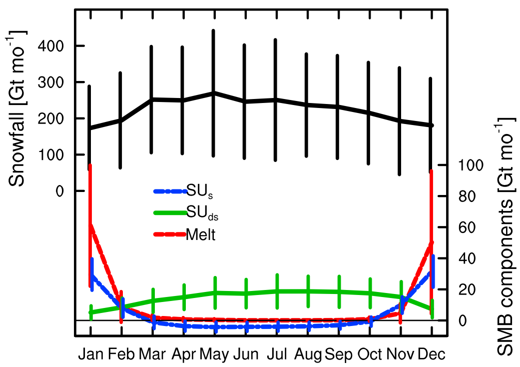

Figure 4. Monthly mean [expressed in Gt per month] SMB components, integrated over the full ice sheet. Snowfall (black solid line) is shown on the left axis, the other components are shown on the right axis. The vertical bars represent ±1 temporal standard deviation based on the period 1979–2010. The horizontal black line represents zero on the right axis.

related to increased cyclonic activity; the weak double maximum in winter may be related to the semi-annual oscillation [*van den Broeke*, 1998], although it is not significant. Interannual snowfall variability is similar for all months. Drifting snow sublimation varies from ∼10 Gt mo^{-1} during the short summer (December and January) to ∼20 Gt mo^{-1} in midwinter. This annual cycle can be explained by the combined effects of larger wind speeds in winter and the occurrence of melt in summer, consolidating the surface snow and reducing the potential for snowdrift to occur [*Lenaerts and van den Broeke*, 2012]. Surface sublimation and melt are strongly determined by surface temperature, and are only significant in summer. The interannual variability for monthly means of SU_{ds}, SU_s and melt is small.

3.4. Trend

[15] We found no significant trend in the 1979–2010 ice sheet integrated SMB components, which confirms the results from *Monaghan et al.* [2006]. The estimated SMB trend, integrated over the ice sheet, equals -3 ± 2 Gt y^{-2}. However, we detect trends on a regional scale. The 32-year (1979–2010) SMB trend is depicted in Figure S1 in the auxiliary material.[1] In coastal Adélie Land, a negative trend occurs (∼−2 to ∼−10 mm y^{-2}), whereas a positive, but insignificant trend is found on the western side of the Atlantic Peninsula and in coastal Dronning Maud Land (∼2 to ∼10 mm y^{-2}). These trends are only locally significant in Adélie Land, where strong interannual and multi-annual variability is also observed [*Agosta et al.*, 2012]. Because ERA-Interim forces our model at its lateral boundaries, SMB trends from ERA-Interim and RACMO2.1/ANT are similar [*Nicolas and Bromwich*, 2011b]. These trends may be assumed to be realistic, since ERA-Interim clearly outperforms other reanalyses concerning Antarctica P-E estimates [*Nicolas and Bromwich*, 2011b].

4. Conclusions

[16] The regional atmospheric climate model RACMO2.1/ANT, with a new snowdrift routine, a horizontal grid spacing of 27 km and forced by ERA-Interim (1979–2010), provides a realistic simulation of the surface mass balance of the Antarctic ice sheet. Without additional calibration, the modeled SMB agrees very well with 750 in-situ SMB observations (R = 0.88). The relatively high horizontal resolution and the inclusion of snowdrift physics provide a realistic pattern of ablation areas on the ice sheet. High accumulation values in the Antarctic Peninsula (>1500 mm y^{-1}) and in coastal West Antarctica (>1000 mm y^{-1}) lead to a relatively high ice sheet integrated surface mass balance, in support of recent studies that also used high-resolution climate modeling [*Bromwich et al.*, 2004; *van de Berg et al.*, 2006]. No significant trend in the ice sheet-integrated SMB is found over the period 1979–2010, and only (insignificant) trends exist regionally. Snowfall is characterized by strong interannual (σ = 114 Gt y^{-1}) and intra-annual variability (σ = 30 Gt mo^{-1}). Snowdrift sublimation is the main ablation process and shows little interannual variability (σ = 9 Gt y^{-1}).

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL050713.

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