Characteristics of the Antarctic surface mass balance (1958-2002) using a Regional Atmospheric Climate Model

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Abstract

Temporal and spatial characteristics of the Antarctic Specific Surface Mass Balance (SSMB) are presented, including its components solid precipitation, sublimation/deposition and melt. For this purpose we use output of a regional atmospheric climate model (RACMO2/ANT, horizontal resolution of ~55 km) for the period 1958 to 2002. RACMO2/ANT uses ERA-40 fields as forcing at the lateral boundaries.

RACMO2/ANT underestimates SSMB in the high interior of East and West Antarctica and overestimates SSMB on the steep coastal slopes. However, the modelled spatial pattern of SSMB otherwise agrees qualitatively very well when compared to recent compilations of in situ observations. Large-scale patterns, like the precipitation shadow effect of the Antarctic Peninsula are well reproduced. Meso-scale SSMB patterns, such as the strong precipitation gradients on Law Dome are also well represented in the model.

The integrated SSMB over the grounded ice sheet is 153 mm water equivalent year^{-1} for the period 1958-2002, which agrees within 5% with the latest compilations of measurements. Sublimation and melt remove 7 and <1% of the solid precipitation. We found a significant seasonality of solid precipitation, with a maximum in autumn and a minimum in summer. No meaningful trend could be identified for the SSMB, because the time series of solid precipitation and SSMB are affected by an inhomogeneity in 1980 within the ERA-40 fields that drives RACMO2/ANT. Sublimation, melt and liquid precipitation increase in time, which is related to a modelled increase in 2 m. temperature.

1 Introduction

In recent decades, compilations of the surface mass balance of the Antarctic ice sheet have improved in quality (Vaughan *and others*, 1999; Giovinetto and Zwally, 2000) but are still compromised by the sparsity of data (Genthon and Krinner, 2001). At the same time, the quality of global atmospherical models has improved significantly; horizontal and vertical resolution have increased because of increased computer power, and parameterisations of physical processes like precipitation, turbulent and radiative budgets produce more accurate results. Another advance has been made in the assimilation of measurements into the models. The European Centre for Medium-Range

Weather Forecasts (ECMWF) recently completed a 40-year re-analysis project (ERA-40), in which all these improvements are cumulated. ERA-40 aims to give an as good and consistent as possible analysis of the global weather of the time period from September 1957 until August 2002.

Over Antarctica, ERA-40 nevertheless shows biases (Genthon, 2002; Reijmer *and others*, 2004). The surface temperature is overestimated by typically 3 °K, for example due to a too low snow albedo; katabatic winds over the slopes of the ice sheet are underestimated, a result of limited model resolution (≈120 km) resulting in flattened model topography and too high effective surface roughness lengths. Finally, ERA-40 underestimates accumulation in the interior of Antarctica, a common problem of numerical models (Genthon and Krinner, 2001; van Lipzig *and others*, 2002).

Compared to a global climate model, a regional atmospheric climate model, forced at the lateral boundaries with output from a general circulation model or a re-analysis, is expected to generate a better climatology for Antarctica, primarily because much higher resolutions are feasible and parameterisations can be adapted to the specific Antarctic situation. The added value of such an approach was shown by e.g. van Lipzig and van den Broeke (2002); van den Broeke and van Lipzig (2003), who presented results of a regional atmospheric climate model, run over Antarctica (RACMO1/ANT). This run used the 15-year re-analysis data of ERA-15 as lateral boundary forcing.

Here, we present results of an integration with a new model (RACMO2/ANT[)], which was driven at the lateral boundaries by output from ERA-40, with a focus on the surface mass balance. The Specific – i.e. valid for one location and a certain time period – Surface Mass Balance (SSMB) is defined as the sum of all mass fluxes towards the surface, integrated over a year:

$$SSMB = \int_{\text{year}} dt \left(P_s + SU + M + ER_{ds} + SU_{ds} \right), \tag{1}$$

where P_s denotes solid precipitation, SU denotes sublimation and M is melt. The term ER_{ds} signifies erosion as a result of divergence in the horizontal snowdrift transport and SU_{ds} is sublimation of drifting snow particles. All values are expressed in mm water equivalent (w.e.) year^{-1}, and contributions are positive when directed towards the surface. Note that SU, M, ER_{ds} and SU_{ds} are negative numbers in equation (1), because they remove mass from the surface. Snowdrift processes are not included in RACMO2/ANT, therefore ER_{ds} and SU_{ds} are not considered in this study. In Antarctica, most (melt-)water will refreeze at some depth in the snow-pack, where temperatures are still below freezing. As this process ('internal accumulation') is not incorporated in RACMO2/ANT physics, it is not considered further either.

After a short model description in section 2, we present results in section 3, starting off with the spatial distribution of the annual mean mass balance components: solid precipitation, sublimation and melt. The modelled SSMB is compared with a compilation of measurements by Vaughan *and others* (1999). Next, we discuss the seasonality of the various SSMB components, averaged for the grounded ice sheet. Also in section 3, time-series of ice sheet integrated SSMB are compared with those derived from ERA-40. Finally, section 4 discusses some possible shortcomings of model and observations and a summary is given in section 5.

2 Model description

RACMO2/ANT uses the atmospheric dynamics of the High Resolution Limited Area Model (HIRLAM, version 5.0.6, Undén *and others* (2002)), which uses a semi-Lagrangian discretisation scheme. The description of physical processes is equal to that of the European Center for Medium-Range Weather Forecasts (ECMWF) atmospheric model employed in the ERA-40 reanalysis (cycle CY23R4, White (2001)). RACMO2/ANT differs fundamentally from RACMO1/ANT which was used by van Lipzig *and others*. RACMO1/ANT uses the dynamics of an older version of HIRLAM which had an Eulerian discretisation scheme, and ECHAM4 physics.

The horizontal resolution of RACMO2/ANT is ~55 km. The model has 40 hybrid-levels in the vertical, of which the lowest is at ~10 m above the surface. Hybrid-levels follow the topography close to the surface and pressure levels at higher altitudes. ERA-40 fields force the model at the lateral boundaries, while the interior of the domain is allowed to evolve freely. The model integration over 2002 is completed using ECMWF operational analysis. Sea surface temperature is prescribed from ERA-40, sea ice is determined using sea surface temperature. If sea ice is prescribed, a sea ice thickness of 1.5 meter is assumed. The model treats ice shelves as grounded ice. Reijmer *and others* (2004) present a more detailed description of RACMO2/ANT and the associated improvements compared to ERA-40. Below, we restrict ourselves to a summary of the most important model adjustments that were made to better represent Antarctic conditions and the post-process correction on the liquid and solid precipitation that was applied.

2.1 Snow albedo

The ECMWF description of snow albedo uses the method described by Douville *and others* (1995), in which the snow albedo decreases linearly from 0.85 immediately after an accumulation event to 0.75 in 12.5 days for temperatures below freezing. The method underestimates snow albedo in Antarctica, where temperatures are well below zero and the albedo changes very slowly.

The snow albedo scheme of van den Hurk and Viterbo (2003) was therefore implemented in RACMO2/ANT. This method accounts for the effect of temperature on albedo changes and assumes a negligible decrease of albedo when temperatures are below −10 °C. Furthermore, we increased the lower limit of albedo to 0.80 and lowered the threshold value of a snow event affecting the albedo to 0.3 mm/hr. In the original formulation, the sea ice albedo consisted of a climatological value with a fixed seasonal cycle. In the formulation of RACMO2/ANT, the sea ice albedo was calculated using the snow albedo scheme, but the minimum albedo for sea ice was set to 0.6.

2.2 Surface roughness lengths

The surface roughness length for momentum (z_0) was initially calculated with the method described by White (2001). This method, however, leads to an overestimation of the roughness length in Antarctica with values up to 100 m. Therefore, z_0 was scaled down to a basic value of 10^{-3} m for the ice sheet and allowed to increase to up to 1 m for mountainous areas like the Trans Antarctic Mountains, to account for sub-grid orography. The ECMWF physics uses the method of White (2001) for the calculation of the roughness lengths for heat and moisture (z_h, z_q). We replaced this by Andreas's theoretical model (1987), which was developed especially for snow and ice surfaces. The model expresses z_h as a function of z_0 and the surface friction velocity u_*. Typical new values of z_h are $3 \cdot 10^{-4}$ m for the quiet upper parts of the interior decreasing to $6 \cdot 10^{-6}$ m for the mountain regions. We assume z_q to be equal to z_h.

2.3 Snow model

The original ECMWF physics treats the surface of the ice sheets as a seasonal snow cover, i.e. as a single snow layer of 10 m w.e. thickness on top of soil, while all calculations of snow temperature use a snow layer of 1 m w.e. thickness. A infinite thin skin layer is used to derive the surface energy fluxes and the surface temperature.

In RACMO2/ANT, a four layer snow model was added between the snow layer already present and the soil. The thickness of the snow layers is fixed and increases with depth from 0.1 to 6 m. With this model, daily and seasonal variations of snow temperature are better represented. The representation of melt and runoff was not changed. Melt-water is assumed to run off immediately, and not to refreeze in the deeper snow layers. Due to the low temperatures in Antarctica, melt seldom occurs in the interior, but quite frequently in the coastal zone (Schneider and Steig, 2002).

2.4 Correction of the liquid and solid precipitation

It was found that RACMO2/ANT overestimates the liquid precipitation over Antarctica at the expense of solid precipitation, because of an inadequate parameterisation of precipitation formation in mixed-phase clouds at temperatures between -20 and 0 °C. In this temperature range, the parameterisation utilised in the ECMWF physics (White, 2001) assumes a direct conversion of cloud water and cloud ice into liquid and solid precipitation, respectively. However, if cloud ice exists at the level where precipitation is formed, the precipitation will develop as solid only (Rogers and Yau, 1989). We have corrected the liquid and solid precipitation output of RACMO2/ANT by analysing the daily vertical profiles of temperature and precipitative fluxes, assuming that the precipitation develops as solid if the vertical layers, in which the precipitation is formed, are partly colder than -10 °C, leaving the total precipitation sum unchanged. More detail about this correction will be given in a following paper.

3 Results

In the next sections, we will discuss the spatial and temporal variability of the modelled SSMB components over Antarctica. Figure 1 shows a map of Antarctic topography and the topographical features that are mentioned in the text.

3.1 Solid precipitation

Figure 2 shows the corrected annual mean solid precipitation (P_s), averaged for 1958-2002. The Antarctic interior is dry, the coastal slopes receive most precipitation, in particular Marie Byrd Land the Antarctic Peninsula. Note the very strong upwind/downwind effects on P_s in coastal East Antarctica, where topographic promontories block the circumpolar easterlies. The spatial pattern of P_s over Law Dome is shown as an example in the inset. The model grid (the crosses in the inset of Figure 2) causes the P_s pattern over Law Dome to be very simplified. Nevertheless, the modelled upwind/downwind effect is a realistic phenomenon, considering the observed strong east-west accumulation gradients on Law Dome (van Ommen *and others*, 2004). Strong precipitation shadow effects are also visible east of the Antarctic Peninsula and over the Ross Ice Shelf.

After the correction described in section 2.4, the frequency of rain events (not shown) agrees with the sparse information available (King and Turner, 1997; Turner *and others*, 1995). Only the coasts receive some rain, but less than 10 mm year^{-1}, except for the Antarctic Peninsula. Towards the northern edge of the Antarctic Peninsula, the amount of rain quickly increases up to 100 mm year^{-1}, which is still a small amount compared to the solid precipitation (Figure 2).

3.2 Sublimation

Sublimation is largely controlled by temperature, which depends strongly on elevation, and regionally by the katabatic wind. The largest values of absolute net sublimation (not shown) are found in Dronning Maud Land and the Transantarctic Mountains with values up to 200 mm w.e. year^{-1}. Net deposition is largest on the plateau of West Antarctica where it reaches values up to 25 mm w.e. year^{-1}. The sublimation on the slopes of Antarctica is similar to earlier model-based estimates (van den Broeke, 1997, and references therein), but the interior deposition seems to be slightly overestimated locally when compared to calculations based on automatic weather station observations (van den Broeke *and others*, 2004).

The sublimation as a fraction of the solid precipitation (SU/P_s) is shown in Figure 3. The areas in Dronning Maud Land, the Lambert Glacier valley and at the foot of the Trans Antarctic Mountains where sublimation exceeds solid precipitation are drawn grey. These areas have high sublimation rates, while the solid precipitation is relatively small. These areas could be sensitive to formation of blue ice, see section 3.4. Over large parts of the dry East Antarctic plateau, deposition constitutes about 10% of the amount of solid precipitation, although the absolute amount is less than 3 mm w.e. year^{-1}.

3.3 Melt

Annual surface melt is shown as fraction of the solid precipitation in Figure 4. As can be seen, all ice shelves experience melting. Large melt fractions (> 50%) are found on the western side of the Antarctic Peninsula (Wilkins Ice Shelf and George VI Ice Shelf) and up to 25% on the Abott Ice Shelf in West Antarctica. Melt exceeds solid precipitation on the former Larsen-A,B Ice Shelves at the eastern side of the Antarctic Peninsula. The absolute annual melt flux (not shown) reaches a maximum of 0.5 m w.e. year^{-1} at the northern edge of the Larsen Ice Shelf. The value for this location is probably still an underestimation, since the lower limit of the albedo was set on 0.8. In case of large melt events, a much lower albedo is likely. For example, meltwater ponds have been observed over the Larsen-A,B Ice Shelf and Wilkins Ice Shelf during summer months (Scambos *and others*, 2000), and melt ponds reduce significantly the surface albedo. The modelled strong melt can not be compared to observations since the surface mass balance has not been measured on the northern part of the Larsen Ice Shelf. The largest melt is nevertheless expected at sea level on the Western side of the Antarctic Peninsula, where the temperatures are significantly higher than on the eastern side. However, at the employed resolution of 55 km the model does not contain continental-gridpoints with a elevation less than 200 m in this area, therefore this maximum is not well represented.

3.4 Specific surface mass balance (SSMB)

Figure 5(a) shows the specific surface mass balance, i.e. the sum of solid precipitation, sublimation/deposition and melt as modelled in RACMO2/ANT. As expected, the SSMB largely reflects the distribution of solid precipitation (Figure 2), but sublimation and melt do have important impacts regionally. For instance, sublimation removes an important part of the precipitated snow in Dronning Maud Land, over the Lambert Glacier basin and at the foot of the Trans Antarctic Mountains, leading locally to areas with a negative SSMB (grey areas in Figure 5(a)). Note that a negative SSMB only occurs in areas with high sublimation together with low solid precipitation.

For comparison, the absolute differences between the modelled SSMB and the SSMB compilation of Vaughan *and others* (1999), based on *in situ* measurements, are shown in Figure 5(b). Although a lot of deviations are visible in this figure, both fields agree in a qualitative sense overall well. Areas with known higher accumulation compared to other coastal zones, i.e. the Western part of the Antarctic Peninsula and Ellsworth Land, receive also more than other coastal regions in the modelled SSMB. The extent of the dry interior, where the accumulation is typically less than 100 mm, is reproduced well. The distribution and extent of areas with a negative SSMB in RACMO2/ANT compares well with reported blue ice areas (Winther *and others*, 2001). However, RACMO2/ANT predicts blue ice areas of Dronning Maud Land and at the foot of the Trans Antarctic Mountains at somewhat lower elevations than reported.

However, systematic differences are also noticed. The SSMB in the Vaughan *and others* (1999) compilation in the interior exceeds the modelled SSMB by about 30 mm per year, about a factor of 2. Modelled SSMB's over the coastal slopes are systematically greater than those reported by Vaughan *and others* (1999). Especially remarkable is the large modelled SSMB on the coast of Marie Byrd Land, which is much greater than compiled values in Figure 5(b).

The resemblance of modelled and observed SSMB in the Antarctic Peninsula (as compiled by Turner *and others* (2002)) is very strong (not shown). The spatial pattern and absolute values agree. Remarkable is the negative SSMB modelled on the Larsen and Wilkins Ice Shelves, caused by a combination of low solid precipitation (Figure 2) due to the rain shadow effect of the Antarctic Peninsula for the Larsen Ice Shelf and Alexander Island for the Wilkins Ice Shelf, and large melting values (Figure 4). It is well known that ice shelves in these regions have shown a significant retreat in recent decades, which has so far been primarily ascribed to an increase in melt (Vaughan and Doake, 1996; Scambos *and others*, 2000).

The SSMB as modelled by RACMO2/ANT is improved on several points compared with the results of RACMO1/ANT (van Lipzig *and others*, 2002, Figure 6b). The spatial resolution has increased, because smoothing of the model fields is no longer required. The latter is caused by the improved discretisation scheme. Sublimation has decreased to more realistic values, due to improved estimates of the surface roughness lengths and melt has been added. However, the underestimation of the SSMB over the interior has increased, and much higher SSMB's are modelled in the coastal zone, which is not necessarily an improvement.

Using the grounding line definitions of Vaughan *and others* (1999), 45 year means of modelled solid precipitation, sublimation, melt and rain, averaged over the grounded ice sheet, are 164, -11, -1 and <1 mm w.e. year^{-1}, respectively. The modelled SSMB over the grounded ice sheet is 153 mm w.e. year^{-1}. If the ice shelves and ice rises are included, the SSMB increases to 165 w.e. year^{-1}. If all meltwater and liquid precipitation is added, the numbers would increase by 1.5 and 4 mm w.e. year^{-1}, respectively.

Table 1 shows that the modelled SSMB, averaged over 1958 to 2002, compares well with estimates based on measurements of Vaughan *and others* (1999) and Giovinetto and Zwally (2000). The modelled SSMB for the satellite era only, beginning at 1980, is somewhat higher than the latter estimates. The RACMO2/ANT modelled SSMB also compares well with model results of van Lipzig *and others* (2002) and Krinner *and others* (1997), but note the different time periods. The model results of Bromwich *and others* (2004) are slightly higher (Table 1).

3.5 Seasonality of the mass balance

Figure 6 shows the modelled seasonality of the various SSMB components (average 1958-2002). All components of the SSMB show a seasonality that exceeds the uncertainty due to year-to-year variability. Solid precipitation (P_s) is smallest during summer and peaks in autumn. A similar pattern was found for the precipitation by van Lipzig *and others* (2002), but in that study the amplitude was not significant as a result of the shorter period. Sublimation (SU) and melt (M) peak during summer and nearly vanish in the other months. In the summer months December and January, sublimation becomes a significant sink term in the SSMB, removing 25-30% of the solid precipitation from the surface. Averaged over the year and across the grounded ice sheet, sublimation removes 7% of the solid precipitation. This is less than the General Circulation Model based estimate of van den Broeke (1997) (10-15%), but compares well with sublimation calculations from automatic weather stations (van den Broeke *and others*, 2004).

Figure 7 shows the seasonality of the solid precipitation per region. The solid precipitation is shown, instead of the SSMB, to avoid a bias associated with sublimation and melt, both summer phenomena. The Filchner-Ronne Ice Shelf and large coastal areas have dry summers (horizontal red lines). The solid precipitation is largest during autumn over large parts of Antarctica. Wilkes Land, however, receives most solid precipitation during winter. This figure compares well with results of van Lipzig *and others* (2002) and Genthon *and others* (1998). The solid precipitation minima and maxima over the ocean are a result of the seasonal cycle of temperature and the associated solid fraction of the precipitation, i.e. less snowfall in summer and more in winter.

3.6 Interannual variability and trends

Figure 8 shows year-to-year variations in the various terms of the SSMB integrated over the grounded ice sheet. We also included the SSMB of ERA-40, calculated by including rain and neglecting melt. We had to do so to obtain realistic numbers, because in ERA-40, rain is strongly overestimated and melt is unrealistically large probably due to underestimated snow albedo. In absolute sense, all components show an increase in time (Table 2). Nevertheless, the time series of solid precipitation and SSMB show an inhomogeneity around 1980, which is most outspoken in the ERA-40 SSMB. The method of Easterling and Peterson (1995) was used for all time series to trace inhomogeneities. Linear trends in the solid precipitation and SSMB over the split periods (pre and post 1980) are not significant.

The time series of sublimation, melt and rain (P_l) do not show an inhomogeneity around 1980. Sublimation, melt and liquid precipitation are controlled most by near surface meteorological conditions, contrary to solid precipitation, which is strongly dependent on the large scale circulation. Near surface conditions are less sensitive to changes in general circulation forcing from ERA-40 at the lateral boundaries than the large scale circulation itself. Therefore, an absence of an inhomogeneity is possible. Linear trend fits to the data are summarised in Table 2. The trends in sublimation, melt and liquid precipitation for the period 1958 to 2002 are much larger than the uncertainty due to interannual variability. But note that 2 metre temperature trends are overestimated in RACMO2/ANT. Trend analysis on the split periods give similar numbers, except for the sublimation. Sublimation seems to be affected by multi-annual variations, which vanish the possible trend if the split times series are considered.

Figure 8 shows that the solid precipitation varies strongly from year to year. This variability is even larger regionally (not shown). The standard deviation of P_s reaches up to 50% of the annual sum in Victoria Land, the Lambert Glacier, the inland part of Marie Byrd Land and the southern and eastern part of the Filchner-Ronne Ice Shelf.

4 Discussion

4.1 The spatial distribution of measured and modelled SSMB

When a comparison is made with a recent compilation of Antarctic SSMB, RACMO2/ANT appears to underestimate accumulation on the plateau of East and West Antarctica and to overestimate the accumulation on the steep coastal slopes. For instance, modelled accumulation on the slopes of Marie Byrd Land is twice the values presented by Vaughan *and others* (1999).

The high modelled accumulation over the slopes of the ice sheet could have been caused by artificial diffusion of moisture along model levels. This diffusion, implemented to stabilise the model, generates an artificial uphill moisture transport. Diffusion enhanced moisture transport is a common problem of atmospherical models in regions of steep topography, see Connolley and King (1996); van Lipzig and van den Broeke (2002); Lenderink *and others* (2003). A one month test with the horizontal diffusion of moisture switched off shows a reduction in accumulation of about 10% on the steepest slopes (not shown). This modest change puts into question the assumption of horizontal diffusion being the culprit.

Other reasons for the differences between modelled and compiled SSMB could be snowdrift transport and snowdrift sublimation, which are not included in RACMO2/ANT. Snowdrift sublimation and erosion is strongest in areas with the strongest wind, which is closely related to the topographic slope. RACMO2/ANT especially seems to overestimate solid precipitation in regions with a large surface slope, therefore including snowdrift associated processes might bring the model results closer to the observations.

The modelled SSMB is more than twice that presented by Vaughan *and others* (1999) on the slopes of Marie Byrd Land, but it compares well with results of other models, e.g. RACMO-/ANT1 (van Lipzig *and others*, 2002), other General Circulation Models and ERA-15 (Genthon and Krinner, 2001) in this region. Such a common bias may be caused by neglecting snowdrift, but it is difficult to explain why snowdrift would affect strongly the accumulation on the slopes of Marie Byrd Land only. Therefore, the sparsity of measurements in this region could also be partly responsible for the difference.

The underestimation of SSMB on the Antarctic plateau appears to be a shortcoming of many numerical atmospheric models (see van Lipzig *and others* (2002); Genthon and Krinner (2001)). A reason could be the neglect of diamond dust, of which the physical mechanism is yet not fully understood. Diamond dust can constitute a substantial component of the SSMB in the Antarctic interior, e.g. up to $\sim$75% at Vostok (Ekaykin, 2003). The artificial diffusion of moisture is not the source for the possible underestimation of the SSMB in the interior. The test without horizontal diffusion did not show any significant increase of SSMB in this part of Antarctica.

The sparsity and temporal inhomogeneity of accumulation measurements could also partly explain the differences. The reliability of observation compilations depends strongly on the quality of the interpolation, in particular over the coastal slopes where accumulation gradients are large. Furthermore, the observations have not been corrected to cover a common time period. A detailed evaluation of the differences between measured and modelled SSMB will be made in a forthcoming paper.

4.2 The integrated SSMB

The problems listed above also affect the integrated SSMB values, but because they partly compensate, the differences between integrated values are small (Table 1). The divergence in wind-driven transport of snow is assumed to be an order of magnitude or more smaller than the other moisture fluxes in the Antarctic SSMB (Déry and Yau, 2002). The contribution of diamond dust to the SSMB is probably significant in the very dry interior, but becomes small if the integrated SSMB is considered. Refreezing of liquid precipitation adds an uncertainty of only 1 mm w.e. year^{-1}. Finally, the long integration period reduces the uncertainty in the mean SSMB due to year-to-year variability to only $\sim$3 mm w.e. year^{-1}. Finally, the temporal inhomogeneity in the SSMB adds uncertainty to the time integrated sums. Since ERA-40 might be of lesser quality before 1980, the inhomogeneity observed for 1980 might indicate that the modelled SSMB before 1980 is slightly underestimated. Despite of the latter uncertainties, the integrated SSMB compares well with measurement estimates.

4.3 Interannual variability and trends

Contrary to what was argued by Bromwich (1988), we found a relatively large year-to-year variation of the Antarctic SSMB. A significant inhomogeneity was found in the times series of solid precipitation and SSMB of RACMO2/ANT, which is even larger in ERA-40. This inhomogeneity nearly coincides with the start of the data assimilation of modern satellite measurements, e.g. TIROS Operational Vertical Sounder (TOVS), into the re-analysis in 1979 (see www.ecmwf.int). This inhomogeneity in the input data is probably the main cause of the jump. Any trend analysis on the time series of solid precipitation and SSMB therefore would require an accurate estimate of the magnitude of this inhomogeneity.

The linear trends of the sublimation (SU) and Melt (M) for 1958 to 2002 in Table 2 are significant up to 99%. We found no indications that these time series were affected by inhomogeneities. But, the integrated sublimation correlates well with the averaged 2 metre temperature ($r = 0.69$, de-trended). A smooth, continent-wide increasing trend is modelled by RACMO2/ANT in the 2 metre temperature. The temperature records of Admundsen-Scott and Vostok Station and the satellite observations from 1979 to 1998 (Comiso, 2000) show a cooling trend. The modelled temperature and sublimation trends are likely erroneous. Satellite observations of melt suggest a decreasing trend averaged over Antarctica (Torinesi *and others*, 2003). A strong increase in rain is observed on the Antarctic Peninsula (Turner *and others*, 1997). Regarding the uncertainties, a final conclusion about trends based on model results is too early.

5 Conclusions

We present characteristics of the specific surface mass balance (SSMB) of Antarctica, using a regional atmospheric climate model (RACMO2/ANT[)], driven at the lateral boundaries by ERA-40 data. This model has a favourable combination of high horizontal (∼55 km) and vertical resolution (40 layers) and a long integration period (1958-2002). The modelled Antarctic SSMB, integrated over the grounded ice sheet, agrees well with earlier estimates from models and observations. The modelled spatial SSMB distribution is qualitatively in good agreement with the most recent compilations of measurements. However, the model seems to underestimate the SSMB in the interior of Antarctica whereas it overestimates the SSMB on the steep coastal slopes. No direct explanation of these differences can be given. The effect of artificial moisture diffusion appears to be small. Other possible reasons are the neglect of snowdrift transport, snowdrift sublimation and diamond dust in RACMO2/ANT. However, the sparsity and temporal mismatch of accumulation observations and shortcomings in the interpolation procedure should neither be ruled out.

The integrated solid precipitation peaks in autumn, but the seasonality of the solid precipitation differs regionally. Sublimation and melt are only significant in summer. Where modelled sublimation exceeds solid precipitation, we find blue ice areas or dry valleys in qualitative agreement with their present position. Melt only affects ice shelves, especially the former Larsen-A,B Ice Shelves in the northern Antarctic Peninsula: here, melt exceeds solid precipitation and causes the SSMB to become significantly negative.

The modelled time series of SSMB and solid precipitation are dominated by an inhomogeneity in 1980, which is found even more prominent in the ERA-40 record. Given that the inhomogeneity coincides with the start of extensive satellite data assimilation into ERA-40, we suspect that this increase is of numerical origin rather than a climatological shift. However, sublimation and melt increase significantly within the full time span of the RACMO2/ANT integration.

In the light of the good quality of this new data-set as described above, we conclude that this data-set offers a range of possibilities not only for the study of the Antarctic SSMB, but also for research of regional climate change, energy balance and circulation patterns.

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Table 1: Integrated specific surface mass balance ($SSMB$) from RACMO2/ANT compared to several compilations. Antartica* is Antarctica except Graham Land, the former Larsen Ice Shelf and eastern Palmer Land.

	period	grounded ice sheet mm w.e. yr^{-1}	Antarctica mm w.e. yr^{-1}	Antarctica* mm w.e. yr^{-1}
RACMO2/ANT	1958-2002	153	165	154
RACMO2/ANT	1958-1979	139	152	141
RACMO2/ANT	1980-2002	166	178	166
Vaughan *and others* (1999)	variable	149	166	
Giovinetto and Zwally (2000)	variable			149 ± 14
van Lipzig *and others* (2002)	1979-1993	156		
Krinner *and others* (1997)	5 years		162	
Bromwich *and others* (2004)	7/96-6/99		186 ± 16	

Table 2: Results of linear trend analysis of SSMB components averaged over the grounded ice sheet. The method described by Easterling and Peterson (1995) has been used to determine the position of the inhomogeneity in the P_s time series. Mean values are in mm w.e. $year^{-1}$ and trends in mm w.e. $year^{-2}$. Error margins in trends are one standard deviation.

	1958-2002		1958-1979		1980-2002	
RACMO2/ANT	mean	trend	mean	trend	mean	trend
$SSMB$	153	-	139	-0.49 ± 0.40	166	0.15 ± 0.28
P_s	164	-	150	-0.45 ± 0.39	178	0.17 ± 0.27
SU	-10.8	-0.035 ± 0.010	-10.3	-0.007 ± 0.03	-11.3	-0.009 ± 0.03
M	-1.0	-0.029 ± 0.005	-0.7	-0.04 ± 0.010	-1.4	-0.013 ± 0.15
P_l	0.5	0.006 ± 0.001	0.4	0.007 ± 0.004	0.5	0.005 ± 0.004

	1958-2001		1958-1979		1980-2001	
ERA-40	mean	trend	mean	trend	mean	trend
$SSMB$	98	-	78	0.03 ± 0.32	119	-0.50 ± 0.22
P	120	-	97	0.18 ± 0.34	142	-0.42 ± 0.24

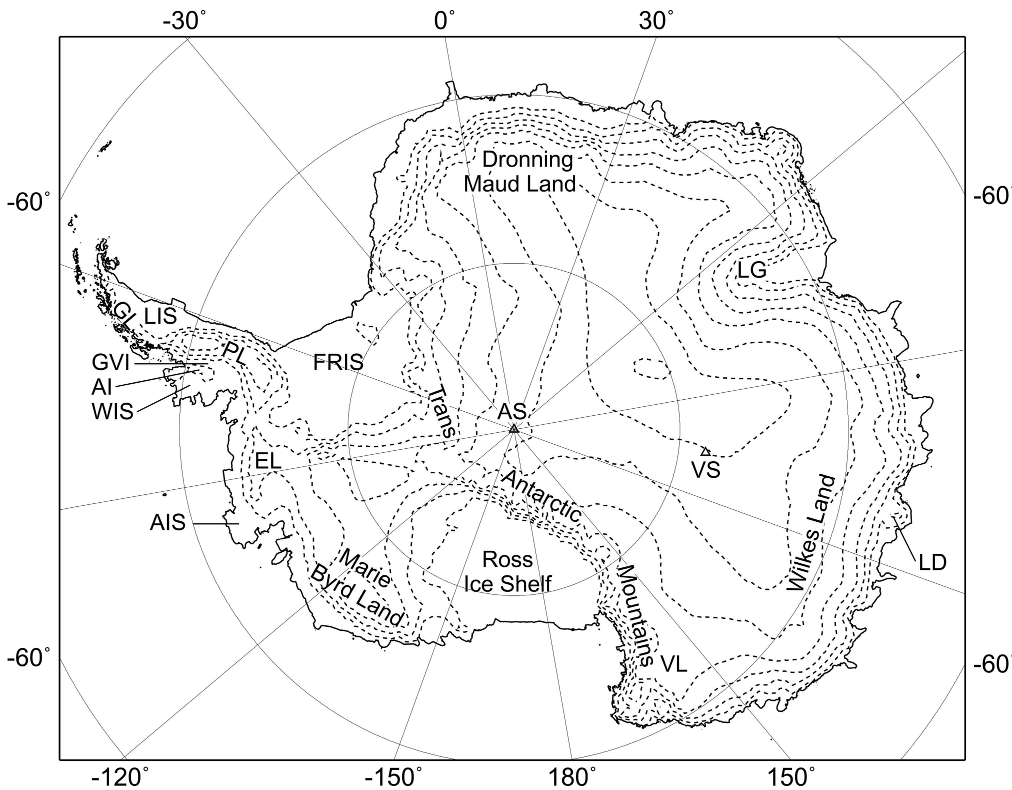


Figure 1: Map of Antarctica with the elevation contours with a 500 m interval. Locations marked are the Larsen Ice Shelf (LIS), Palmer Land (PL), Graham Land (GL), George VI ICe Shelf (GVI), Alexander Island (AI), Wilkins Ice Shelf (WIS), Filchner-Ronne Ice Shelf (FRIS), Ellsworth Land (EL), Abott Ice Shelf (AIS), Lambert Glacier (LG), Law Dome (LD), Victoria Land (VL), Admundsen-Scott Station (AS) and Vostok Station (VS).

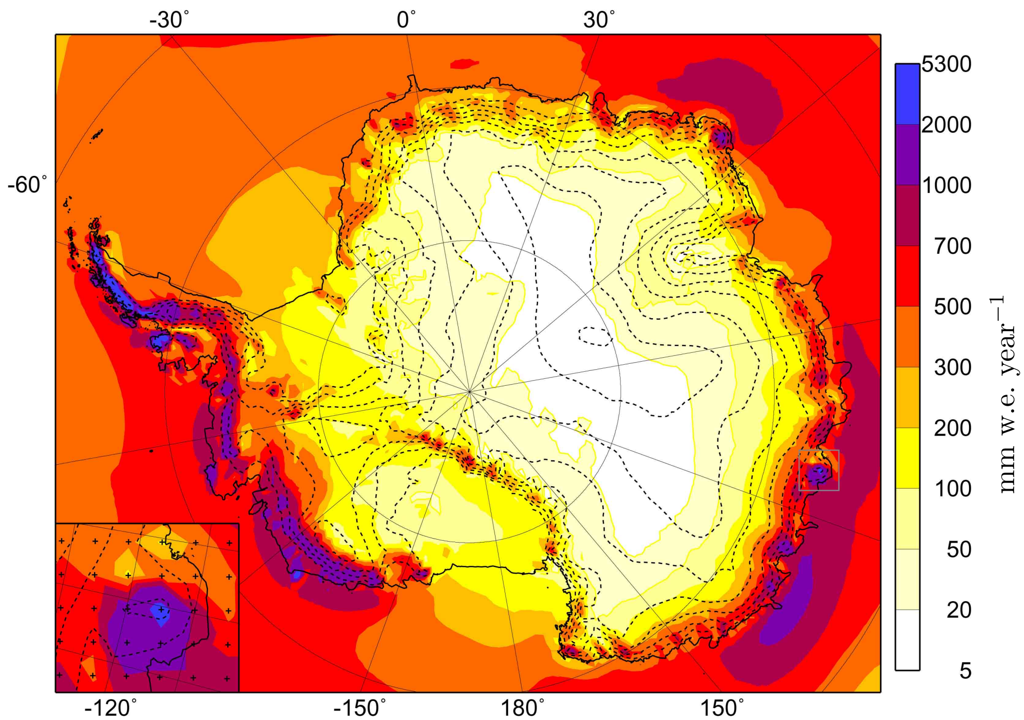


Figure 2: Modelled annual solid precipitation (P_s) averaged for the period 1958-2002. The inset shows is an enlargement of the pattern over Law Dome (grey square). Crosses in this inset mark the location of the model grid points.

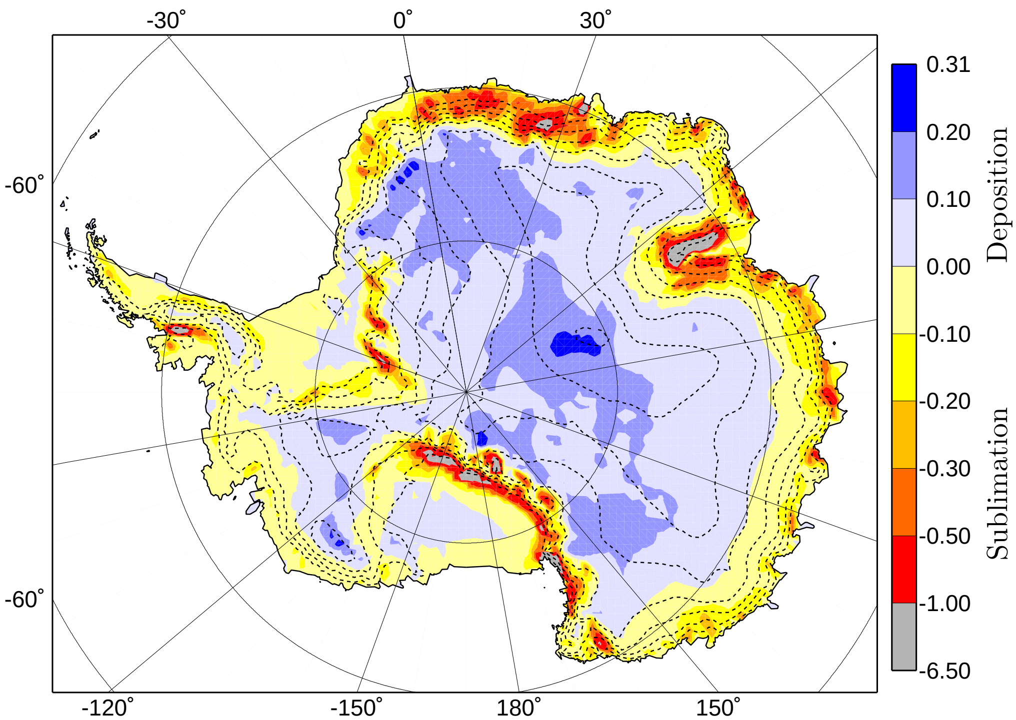


Figure 3: Modelled sublimation/deposition, expressed as a fraction of the solid precipitation, i.e. SU/P_s, averaged for the period 1958-2002. Values below -1 (grey areas) indicate that sublimation exceeds precipitation.

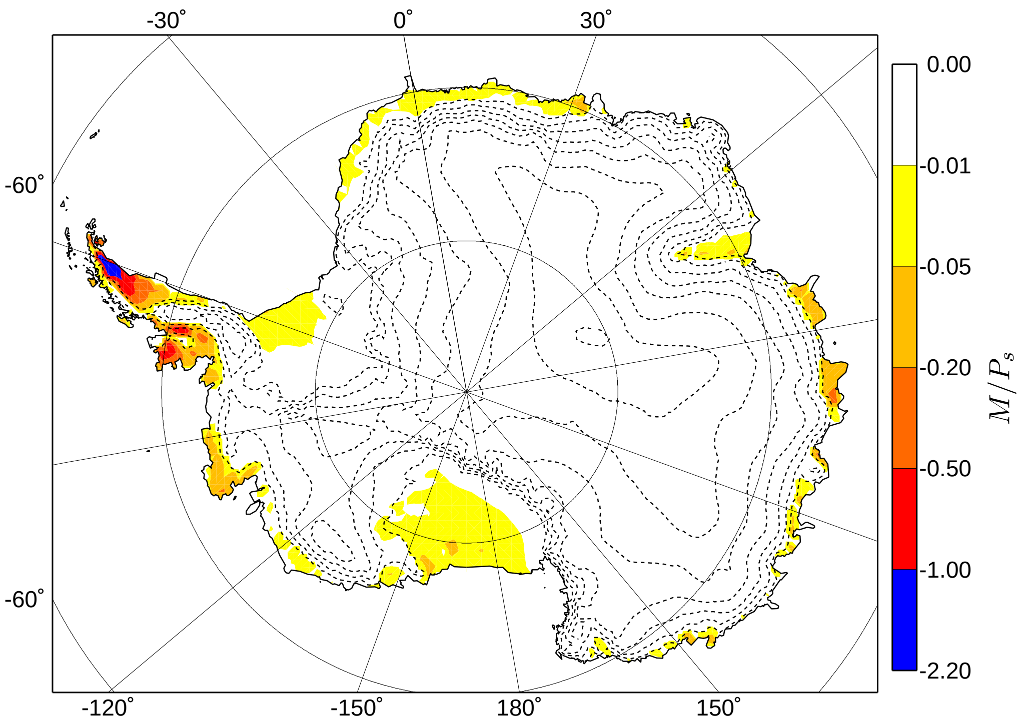
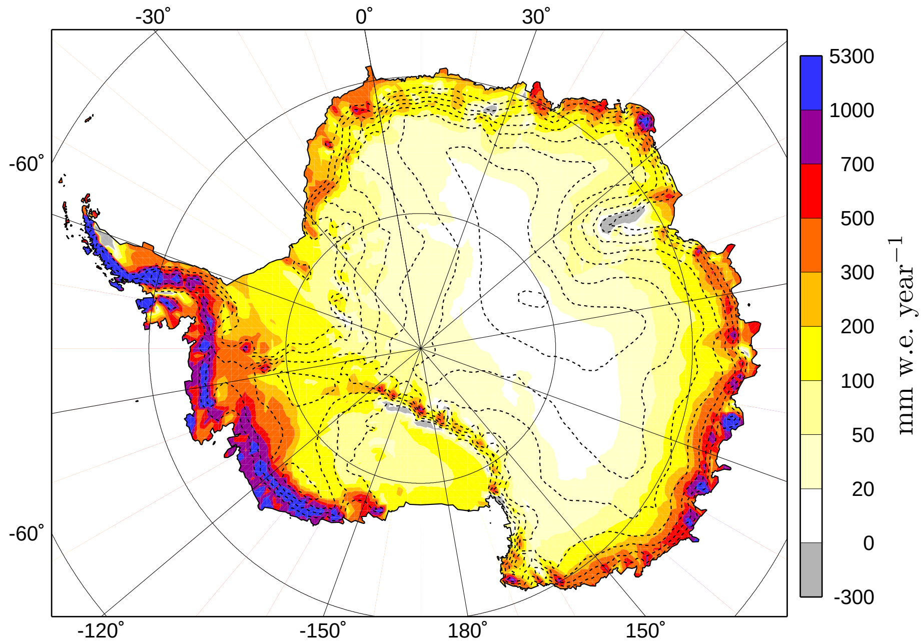
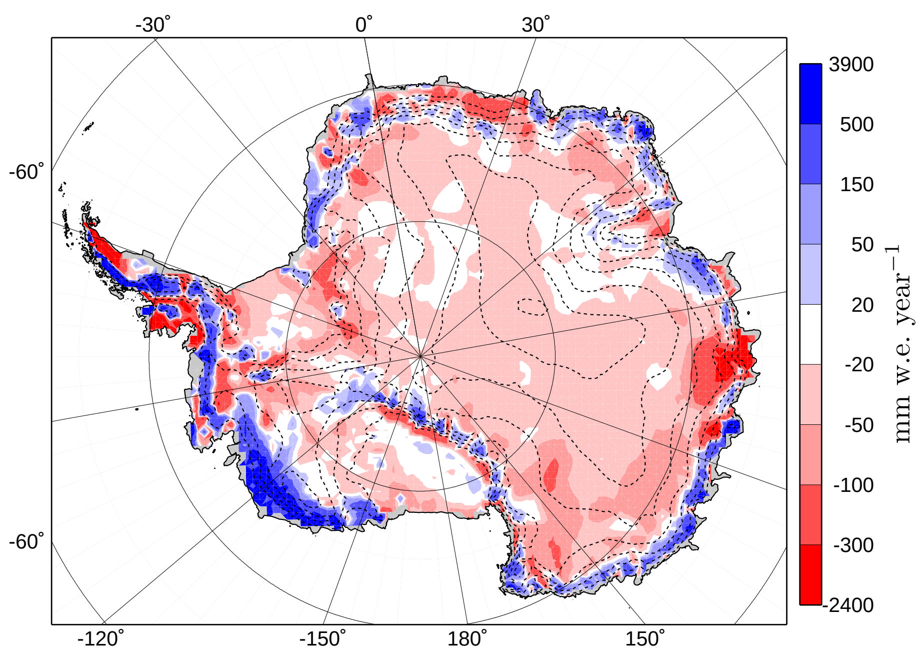


Figure 4: Annual melt flux, expressed as fraction of the solid precipitation (M/P_s), averaged for the period 1958-2002. When this value is less than -1 (blue areas), more snow is removed by melt than is added by snowfall.



(a)



(b)

Figure 5: (a) Modelled specific surface mass balance (SSMB, mm w.e. year^{-1}), averaged for the period 1958-2002. (b) Difference map with the compilation of the surface mass balance (mm w.e. year^{-1}), based on *in situ* observations (Vaughan *and others*, 1999). Positive values implies that the modelled SSMB exceeds the compilation. Grid points for which the compilation is not determined are drawn grey.

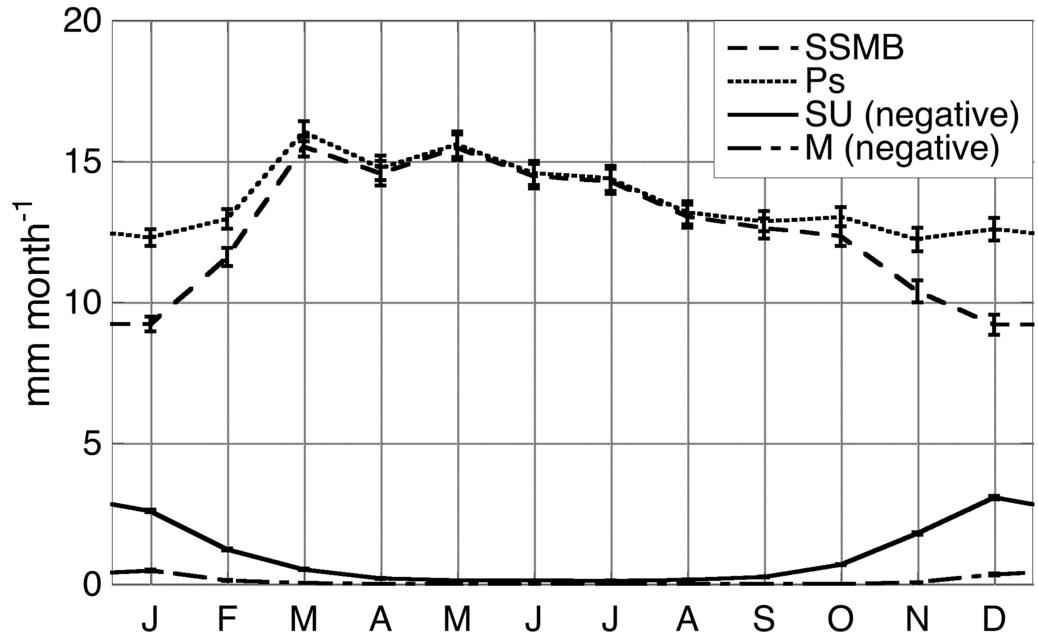


Figure 6: Modelled seasonality of the specific surface mass balance ($SSMB$) and its components over the grounded ice sheet (1958-2002). P_s, SU and M denote solid precipitation, sublimation and melt, respectively. Error bars denote the uncertainty due to year-to-year variability.

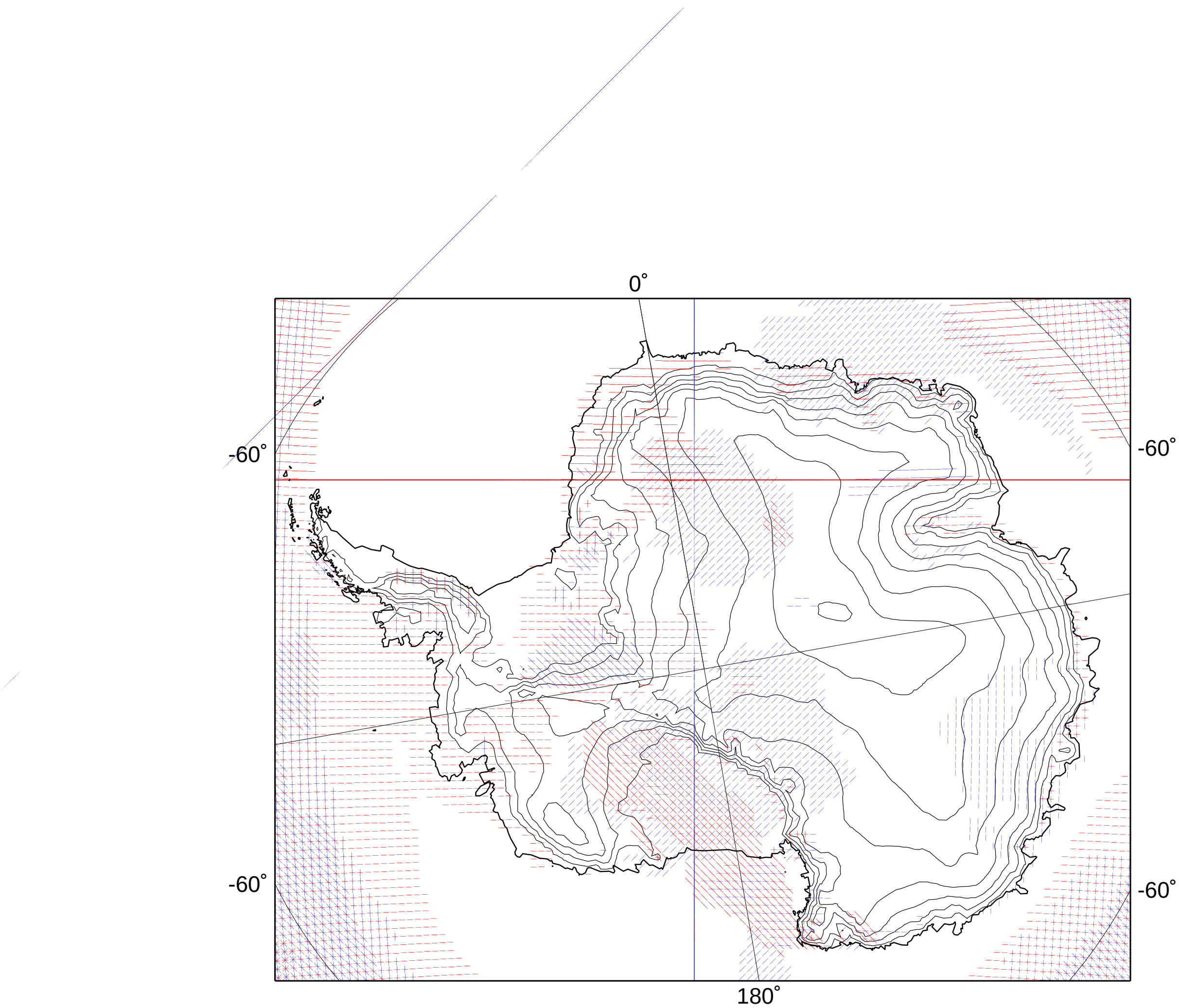


Figure 7: Seasonality of solid precipitation (1958-2002). Blue lines mark areas in which a season is 33% wetter than the annual mean, red lines mark 33% dryer than the annual mean. Deviations were derived by comparing mean daily solid precipitation. Summer is marked by horizontal lines (−), autumn by ╱, winter by | and spring by ╲.

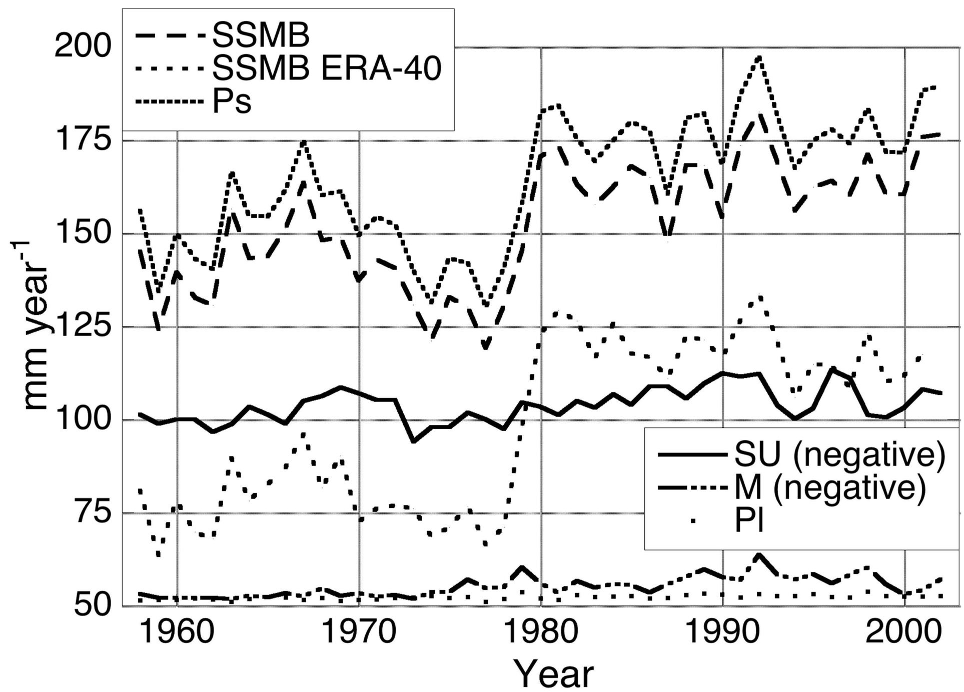


Figure 8: Time series of the components of the specific surface mass balance ($SSMB$), averaged for the grounded ice sheet as found by RACMO2/ANT. The left axis displays the values of $SSMB$, the $SSMB$ determined by ERA-40 and solid precipitation (P_s), the right axis the values for the sublimation (SU) and melt (M).