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Antarctic surface mass balance and systematic biases in general circulation models

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Abstract. Atmospheric general circulation models (GCMs) simulate two of the main components of the Antarctic surface mass balance (SMB), precipitation and sublimation, which are generally assumed to dominate the SMB. Resemblances between the Antarctic SMB simulated by seven different GCMs run at high (≈ 100 – 200 km) resolution, and differences with a recently produced observation-based map are analyzed. A number of these differences are common to all seven models. They are called systematic model biases and are summarized as a composite of all seven models. It is found unlikely that higher model resolution would significantly affect the systematic biases. All but one of the models studied here use an inaccurate prescribed topography of Antarctica, with errors as large as 1000 m. Although wrong topography does not seem to consistently explain model SMB biases, it is strongly recommended that the Antarctic topography in GCMs be updated. Wind erosion and drifting snow are not simulated in GCMs. Because the processes of wind erosion are complex and nonlinear, evaluation of its possible contribution to systematic model biases is not straightforward. Partial correspondence between regions of strongest winds and model biases suggest that wind erosion may contribute and should be formulated in GCMs. Sublimation is another significant potential negative term in the SMB of Antarctica, but it does not seem to explain any systematic model bias. Finally, it is proposed that some of the systematic differences between models and observation-based maps actually signal errors in the latter rather than in the models. These errors occur in regions devoid of field observation. They may thus be related to the process of interpolation used to build the SMB maps.

1. Introduction

General circulation models (GCMs) simulate a wide range of physical processes which affect global and regional climate on timescales of seconds to millennia. GCMs have a correspondingly wide range of applications, one of which is the prediction of the future climate change and associated impact on the human environment. The atmospheric component of a GCM (also henceforth simply referred to as a GCM, since only atmospheric GCMs are analyzed here) accounts for atmospheric processes, for the exchange of mass and energy between the atmosphere and the surface, and to some extent for processes which are relevant solely to the surface. Precipitation, evaporation and sublimation, phase changes both in the atmosphere and at the surface, and runoff from continental surfaces to the oceans, are processes traditionally simulated by GCMs. These processes largely determine the overall mass balance of

the different kinds of continental cryosphere (glaciers, ice caps, snow cover, and permafrost). For flowing ice with flow termination at the sea, that is, for some polar glaciers and ice caps and parts of the polar ice sheets, an other important term in the mass balance is iceberg calving which is not accounted for in GCMs. The importance for continental ice of snow deflation and transport by wind is still debated. This is also not included in current GCMs.

Altogether, GCMs provide an essential, if incomplete, picture of the mass budget of continental ice. Such models should therefore significantly contribute to evaluating the sensitivity of land ice to climate change, to quantifying ice-related feedbacks, and to predicting continental ice changes and impacts to natural and human environments. Sea level is a serious global concern. Current predictions suggest that over the coming century and in response to climate warming by anthropogenic activities, loss of continental ice can contribute several tens of centimeters of sea level rise. Thermal expansion of the oceans will also largely contribute to sea level rise. However, the largest uncertainty on predictions of sea level change is dependent on the mass

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budget of the major ice sheets. This assessment is valid with respect to both the observation of a 10-25 cm rise of sea level from a century ago to present and the prediction of a 13-94 cm rise by the year 2100 [Warrick *et al.*, 1996]. For instance, a 10% uncertainty on the current surface mass balance (SMB) of Antarctica [Vaughan *et al.*, 1999] is equivalent to ≈ 5 cm/century (or 20 to 50%) of uncertainty on the contribution of Antarctica to recent sea level change.

That some important physical processes are taken into account in GCMs does not guarantee that these processes and their consequences are adequately simulated. Ideally, all modeled processes should be formulated from full fundamental physics and thus should perform equally well in different climate conditions. In practice, many processes are parameterized in GCMs, either because the corresponding physics is not well identified or because the numerical cost of implementing purely fundamental physics is too high. Parameterizations are adjusted, at best to fit fundamental physics, often to fit observations. At worst, parameterizations provide relatively free parameters which can be tuned to optimize climate simulations with respect to selected criteria. Such parameterizations often cannot equally well represent the real processes everywhere in the world. They tend to fail in extreme climates, and the climate of the polar ice sheets is particularly extreme.

As an example, precipitation is a process which involves physics at microscales to mesoscales and which therefore cannot be explicitly resolved by the global GCMs with grid spacings of 100 km or more. Even if large-scale water vapor saturation is explicit, features like the subgrid distribution of water or the fraction of condensed water which remains airborne must be parameterized. While a cloudy sky is an associated feature of precipitation almost everywhere on the globe, clear-sky ice crystal precipitation is usual in the interior of Antarctica. This is one visible hint that Antarctic precipitation is atypical and that parameterizations of the hydrological cycle may perform differently over polar ice sheets and elsewhere. In addition, limited observations due to an inhospitable environment and difficult logistics make it harder than elsewhere to verify and to validate simulated climate over polar ice sheets.

Numerical discretization does not generally involve parameterization, yet fundamental physics can significantly suffer from being discretized. For instance, discrete advection schemes have difficulty with topographic barriers and strong gradients. Even the relatively smooth slopes (1%) that surround much of the Antarctic ice sheet are reasonably resolved by only the finest resolution GCMs. Mountain slopes, for example in the Antarctic Peninsula, are badly smoothed. Topography induces horizontal temperature gradients which in turn, because saturation is an exponential function

of temperature, induce strong horizontal moisture gradients. These gradients are not well resolved by GCMs, with consequences for the net advection of moisture. The momentum equations are formulated with few and well understood approximations in GCMs but they are sensitive to discretization too. The Antarctic circumpolar atmosphere is rough, with most of the moisture import across the ice sheet boundaries made by transient synoptic cyclones [e.g., Genthon and Krinner, 1998]. The pressure trough that surrounds the ice sheet is a signature of these cyclones. The fact that models often fail to simulate the depth, position and/or seasonality of the circumpolar trough indicates that the cyclones themselves are not consistently well reproduced.

Although not yet generalized, a substantial step in the trend toward increasing the horizontal resolution of GCMs has been made in the last few years. Standard resolution is still of the order of 300 km, with grid meshes coarser than 500 km still not uncommon. However, a few simulations spanning 5 to 10 years with a resolution of the order of 100 km have been produced and published. In particular, the HIGH-REsolution Ten-Year Climate Simulations (HIRETYCS) [1998] project was aimed at comparing the general performances of three different GCMs at high (≈ 100 km) and medium (≈ 300 km) resolution. The conclusion was that increasing the resolution alone may not be worth the additional computing cost. In fact, it may be more sensible to use additional computer resource as it becomes available to develop and run more complex physical parameterizations, or to increase vertical resolution, rather than to improve horizontal discretization alone. There is one important exception to this general conclusion: the climate of the polar ice sheets, which definitely benefit from a higher horizontal resolution. This is largely due to a better accounting of topography and more generally of the atmospheric transport of heat and moisture.

In the present paper, the SMB of Antarctica as simulated by several GCMs, including the models that took part in the HIRETYCS project, is analyzed and compared with observation-based maps. The SMB is defined as the difference between annual mean precipitation and evaporation or sublimation (henceforth together summarized as sublimation since liquid water and thus evaporation are infrequent). This is a common definition for Antarctica where melting and runoff, and export as wind-blown snow are generally considered small. However, the mass balance measured on the field does account for all terms. Observations and GCMs are first described (sections 2 and 3, respectively). Possible causes of systematic differences between observations and model results are evaluated on aspects such as horizontal model resolution, prescribed topography, missing terms in the SMB equation, and including possible errors in the observation-based SMB maps (section 4). A summary discussion and conclusions close the paper (section 5).

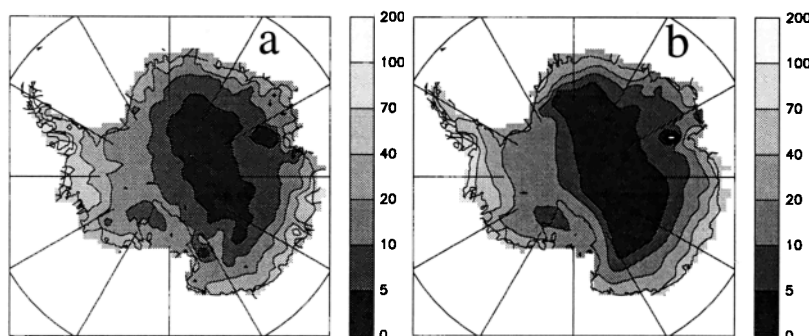


Figure 1. Mean SMB of Antarctica according to (a) *Vaughan et al.* [1999] and (b) *Giovinetto and Bentley* [1985]. Units are cm yr^{-1} .

2. Observed Surface Mass Balance of Antarctica

A number of methods have been used to measure the SMB of Antarctica. *Vaughan et al.* [1999] (henceforth V99) report analyzing 1860 observations obtained from measuring the burial of stakes, counting annual layers using visual, chemical, or isotopic markers, or identifying radioactively marked well-dated horizons (atmospheric bomb tests). Not all methods are equally reliable. In addition, not all data sample the same period while the mass balance of Antarctica is known to fluctuate. This point is further discussed in relation with the periods sampling by models in section 4.1. With these data, and using microwave remote sensing as a semiempirical tool to interpolate between observation sites, V99 produce the latest of a series [*Giovinetto and Bull*, 1987] of published maps of the SMB of Antarctica. Figure 1 shows this map along with that of *Giovinetto and Bentley* [1985] (henceforth GB85) which, over the last few years, was widely used as a reference for climate model verification [e.g., *Tzeng et al.*, 1993; *Genthon*, 1994; *Connolley and Cattle*, 1994; *Krinner et al.*, 1997; *van Lipzig*, 1999]. Both maps show that the SMB of Antarctica decreases from roughly 40 cm yr^{-1} in coastal areas to less than 5 cm yr^{-1} in the remote interior of the ice sheet (all SMB values are given in water equivalent). Coastal mass balance varies largely with longitude from more than 1 m yr^{-1} to less than 20 cm yr^{-1} , due to the direction of the dominant winds, the moisture content of the atmosphere, the frequency of low-pressure systems offshore and the topographic barriers. Although the two maps on Figure 1 differ visibly in the interior of Antarctica, the most recent being significantly wetter, differences are larger but more localized near the coasts as illustrated by Figure 2. The integrated SMB reported by V99 is more than 15% larger than that of GB85. Feeding the grounded Antarctic ice at its surface with 14.9 cm yr^{-1} (the number reported by V99) of water is equivalent to evaporating about 5 mm yr^{-1} at the surface of the global ocean.

Successive reconstructions of the SMB of Antarctica from field observations have yielded different integrated numbers because the number, quality and spatial coverage of the available observations have consistently increased with time, and also because different methods to discriminate between conflicting data and to interpolate across large data-void regions have been used (V99). V99 have selected microwave satellite data to constrain spatial interpolation. The thermal emission of snow in the microwave range is a function of snow temperature to a first order, of snow structure to a second order. SMB and surface temperature are physically related by the fact that the moisture holding capacity of the atmosphere is a function of temperature. As a consequence, the observed snow temperature and mass balance show partially coherent patterns. In addition, the structure of snow (grain size and shape, stratigraphy, etc.) is a result of surface meteorology, including

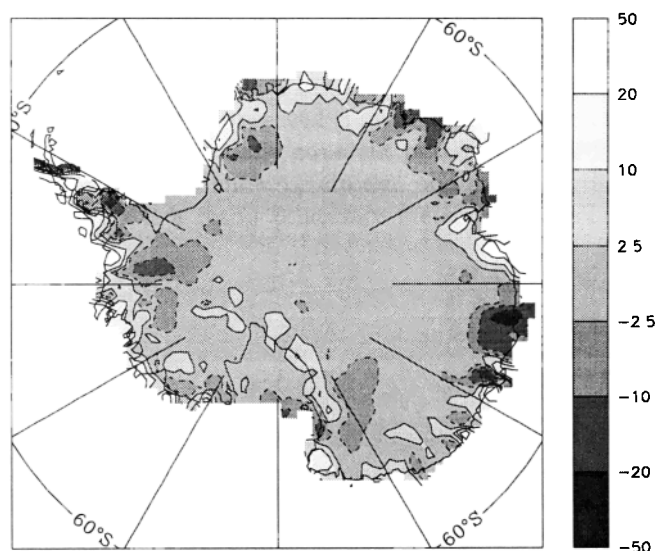


Figure 2. Difference between *Vaughan et al.* [1999] and *Giovinetto and Bentley* [1985] SMB. Negative contours are dashed. Units are cm yr^{-1} .

mean temperature and precipitation, winds, radiation, and the variability of these parameters [e.g., *Genthon et al.*, 2001]. Therefore, there is a potential for microwave data to help provide a full coverage picture of the mass balance of the ice sheets [e.g., *Zwally and Giovinetto*, 1995]. This potential is partially exploited by V99 who use a fit of the SMB observations versus satellite-derived microwave brightness temperature to fill the gaps between available field observations.

V99 have not used climate model results to complement observations, in order that their product be a fully independent information to characterize models. In fact, it may appear strange to suggest that models could be used to complement observations since, if they are deemed fully reliable, the models provide all the information wanted. That would be if modeled SMB were within the observed range at the sites of the observations, and/or if different models fully agreed with each other, which is not the case. On the other hand, consistent disagreement of models of different origin and construction with observations may signal problems with the observations. Alternately, they may signal a problem with one of the common factors in GCMs or in analyzing GCM results. It is thus of interest to search for systematic disagreements between climate model results and observation-based SMB maps.

3. Models

Three GCMs contributed to the HIRETYCS project, the results of which are exploited here. The *Activit e de Recherche Petite Echelle - Grande Echelle* (ARPEGE), European Center/HAMburg (ECHAM) and HADley center Atmospheric Model (HADAM) GCMs are two spectral and one grid point models developed by Centre National de Recherches M t orologiques (M t o-France, Toulouse), the Max-Planck Institute for Meteorology (Hamburg) and the Hadley Centre (U.K. MetOffice, Bracknell), respectively. For the two spectral models, spectral truncation T106 (equivalent grid point resolution for physical processes ≈ 125 km) is available. Spectral truncation T42 (≈ 300 km) from the ARPEGE model is also used here. The grid point model has regular grid with resolution $0.833^\circ \times 1.25^\circ$ or $2.5^\circ \times 3.75^\circ$ (latitude \times longitude). The GCMs were run for 10 years using the Atmospheric Model Intercomparison Project (AMIP) sea surface boundary conditions for the period 1979-1988. Details of the models and of their performances, including some aspects of the moisture budget and SMB of the Greenland and Antarctic ice sheets, can be found in the HIRETYCS project final report [*HIRETYCS*, 1998] and references therein.

In addition to the three HIRETYCS models, results from a previous version (version 0) of the ARPEGE model at relatively fine resolution (truncation T79, that is a resolution of about 170 km) and from the variable-grid grid point Laboratoire de M t orologie Dynamique-Zoom (LMDZ) GCM with a "zoom" over the Antarctic

region (≈ 100 - 200 km resolution over this region) are also used here. One of the main differences between version 0 of ARPEGE and the HIRETYCS version (version 1) is a change in the treatment of clouds and radiation. As a consequence, the HIRETYCS model is warmer over Antarctica; in fact, it is too warm, and it simulates more precipitation. Sublimation is also significantly larger, largely because the model is warm. As a consequence, the SMB is not so different in the version 0 and version 1. The mass balance of version 0 at different truncations was analyzed by *Genthon* [1994] and *Genthon et al.* [1994] and considered quite good at T79. The LMDZ GCM was developed by Laboratoire de M t orologie Dynamique (Centre National de la Recherche Scientifique (CNRS), Paris) and further refined for polar climate applications by Laboratoire de Glaciologie et G ophysique de l'Environnement (CNRS, Grenoble) [*Krinner et al.*, 1997]. An original aspect of this model is that the grid may be compressed and stretched in order to refine horizontal resolution over a region of particular interest. This is obtained at the expense of resolution over the rest of the globe, but computing time is correspondingly lower than for a uniformly fine GCM. A meridional zoom with finer grid over the Antarctic region has allowed high resolution studies of climate and climate change of the Antarctic ice sheet [e.g., *Krinner et al.*, 1997; *Krinner and Genthon*, 1998a; *Krinner and Genthon*, 1998b]. Results of simulations made for these studies are used here. LMDZ runs are 5 years long using the AMIP boundary conditions for 1987-1991.

Finally, hydrologic data from short-term forecasts by the European Centre for Medium-range Weather Forecasts (ECMWF) are also used here. These forecasts are produced by a GCM initialized from meteorological analyses of the continuous observation of the atmosphere and surface by meteorological stations and satellites. The constrain by the observations at the analysis step has not always proved sufficient to limit model biases to the point that the short-term forecasts are consistently better than free climate GCM results. *Genthon and Braun* [1995] show that the ECMWF operational analyses, that is, the analysis performed in near real time for operational weather forecasting, over the period 1985 to 1991, yielded fairly good reconstruction of the SMB of Antarctica and Greenland. To offer a product free of spurious temporal variability due to periodic changes of the numerical tools, the ECMWF has recently produced a global reanalysis for the 15 years 1979-1993 with a frozen version of the GCM and assimilation suite. *Genthon and Krinner* [1998] show that the SMB of central Antarctica is dryer in the reanalysis than in the previously mentioned product and that in fact it is too dry. Both the 1985-1991 operational analyses and the 1979-1993 reanalysis (henceforth EOA and ERA, respectively) are used here since, although the EOA results appear better, the ERA product is widely used and referred to in the literature. In addition, the

Table 1. List and Characteristics of Models

Model / Forecasts	Type	Resolution	Levels	Period	<i>PR</i>	<i>SU</i>
ARPEGE HIRETYCS (version 1)	spectral	T106 / T42	30	1979–1988	20.0	6.8
ECHAM HIRETYCS (ECHAM4)	spectral	T106	19	1979–1988	17.8	2.0
HADAM HIRETYCS (HADHAM2b)	grid point	$0.833^\circ \times 1.25^\circ / 2.5^\circ \times 3.75^\circ$	19	1979–1988	15.2	1.2
ARPEGE version 0	spectral	T79	30	1979–1988	16.0	4.2
LMDZ (version 1), Antarctic zoom	grid point	irregular, $\approx 100\text{--}200$ km over the Antarctic ice sheet	15	1987–1991	17.7	2.4
ECMWF EOA	spectral	T106	19	5/1985–4/1991	13.7	1.6
ECMWF ERA	spectral	T106	19	1979–1993	14.6	1.0

Type is the numerics used to solve the dynamic equations. Resolution is the horizontal resolution or truncation. Levels is the number of layers in the vertical. Period is the period of integration. *PR* and *SU* are the mean precipitation and sublimation, respectively, for the high-resolution models, areally averaged over the grounded Antarctic ice (see section 3 for details of the computation) in cm yr^{-1} . From glaciological observations, *Vaughan et al.* [1999] report a mean accumulation ($PR - EV$) of 14.9 cm yr^{-1} .

SMB in the EOA product shows spurious spatial variability due to the spectral advection of moisture (this will be further discussed in section 4). The ERA product does not. In both cases, the GCM is a spectral model with T106 truncation.

Table 1 summarizes the main characteristics of the different models. The areally averaged modeled precipitation and sublimation at the surface of the grounded ice are also given for the high-resolution versions of the models. To consistently compute these means, the land-ice mask of the ECMWF model is used as a weighting mask for all models. The mask includes the Antarctic Peninsula and the ice rises within the ice shelves

as resolved by the ECMWF model. As pointed in section 1, model SMB is taken as the difference between precipitation and sublimation. For the high-resolution models, the mean Antarctic SMB ranges from 11.8 to 15.8 cm yr^{-1} (precipitation alone ranges from 13.7 to 20 cm yr^{-1} ; see Table 1). To illustrate spatial structure, Figure 3 maps the results by the HADAM high-resolution model (the finest of all models studied here), the ERA forecasts (generally moister at the coasts and dryer inland) and a composite of all models. The composite is an average of the SMB simulated by the finest resolution models, that is, ARPEGE T106 and T79, ECHAM T106, HADAM $0.833^\circ \times 1.25^\circ$, LMDZ, ERA,

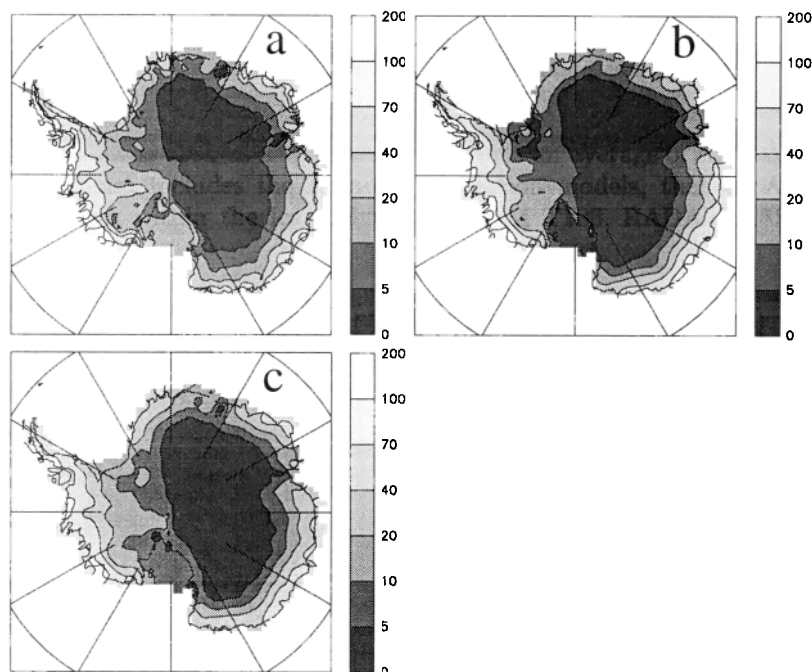


Figure 3. The SMB of Antarctica in (a) the HADAM high-resolution, (b) the ERA forecasts, and (c) the model composite. See section 3 and Table 1 for details on models and composite. Units are cm yr^{-1} .

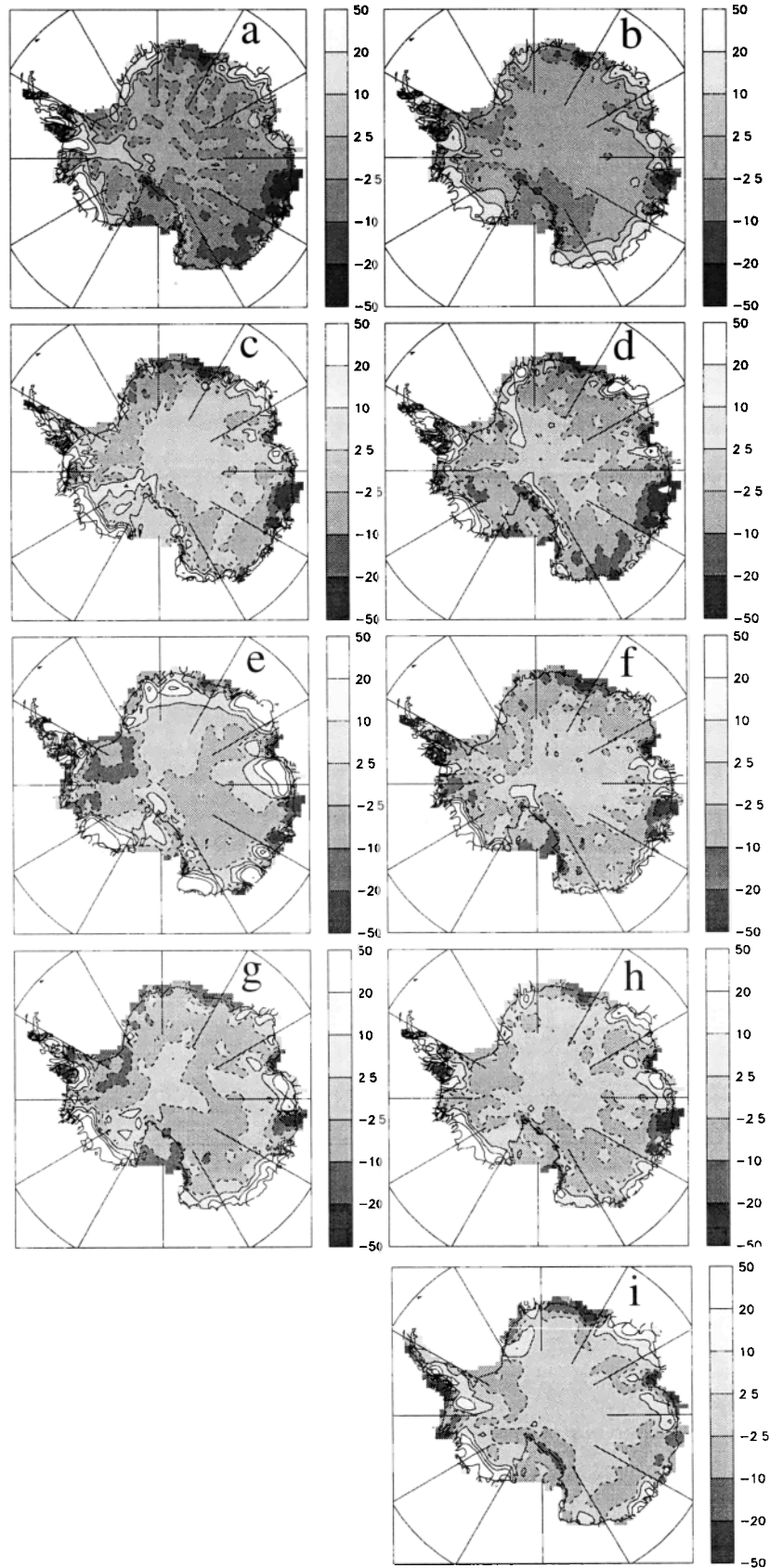


Figure 4. Models SMB biases with respect to observation-based estimates: (a) ARPEGE HIRETYCS, (b) ECHAM HIRETYCS, (c) HADAM HIRETYCS, (d) ARPEGE version 0, (e) LMDZ, (f) ECMWF EOA, (g) ECMWF ERA, (h) and (i) Model composite. All biases are with respect to *Vaughan et al.* [1999] except for Figure 4i, with respect to *Giovinetto and Bentley* [1985]. See section 3 and Table 1 for details on models and composite. Negative contours are dashed. Units are cm yr^{-1} .

and EOA. The spatial pattern is broadly similar to the observations (Figure 1). On average, the models tend to be somewhat dryer in the interior of the ice sheet. Other differences are more localized and are discussed in section 4.

4. Observations Versus Models

4.1. Systematic Biases in Model Results at High and Medium Resolution

Figure 4 shows the difference between the observation-based SMB and the results of each of the seven high-resolution models. For simplicity, the observation-based maps will often be simply referred to as the observations in the following, and the differences between the models and the observations will be referred to as model biases, although it is not excluded that some of these biases might actually pertain to the observations themselves (section 4.4). Figure 4 also shows the SMB biases in the model composite described in section 3. With both V99 and GB85 observations, there is a tendency for the models to be on average too dry in the interior of the ice sheet and too wet in coastal regions with respect to observations. Most areas with significant biases show up similarly with respect to V99 or with GB85, although the extension of these regions and/or the magnitude of the biases vary.

The time periods sampled in the model simulations are relatively short (5 to 15 years) but consistent because boundary conditions of the 1980s (plus or minus a few years) are used for all models. The time periods sampled for the observations used to build SMB maps as in GB85 and V99 are highly variable. Some stakes readings represent only 1 year of accumulation, whereas radioactivity-based measurements average accumulation over decades. Some data are representative of the 1980s but others are three decades older. Interpolating radiometer data in V99 were collected in the 1970s. When comparing model results and observations, time sampling incoherences, both within the observations themselves and between the observations and the models, may be of concern if variability and trends are significant. In spite of common boundary conditions, common interannual variability in the models is

low. Systematic biases on Figure 4 may be associated with lags of at most three decades between the periods of observation and of simulation. However, reported multidecadal trends [e.g., *Mosley-Thomson et al.*, 1999, and references therein] appear too weak to contribute to these biases. A 40-year (1950–1991) GCM simulation by *Smith et al.* [1998] also produces regional trends which are too weak (up to 3 cm yr⁻¹ per century) to contribute to the systematic biases of Figure 4. It may be noted that fully evacuating temporal inconsistencies between simulations and observations of the Antarctic SMB would require considerable work to produce both much longer GCM simulations and systematic sorting of observations by age and period covered.

To compare the impact of spatial resolution in the models, a high and a medium resolutions composite are produced as the average of the SMB simulated by the ARPEGE and HADAM HIRETYCS high (≈ 100 km) and medium (≈ 300 km) resolution models only. Their biases with respect to V99 are shown on Figure 5. The spotty structure corresponds to negative SMB in the ARPEGE model. In this model, as well as in the ECMWF GCM used for the EOA data, advection is treated in the spectral domain. When the moisture spectral field is transformed to the grid point domain for the computation of column physics and parameterizations, negative values result. This is particularly sensitive over the Antarctic ice sheet due to the strong moisture gradients across the coastal slope regions. The negative values are arbitrarily compensated, but this results in near-zero surface moisture which, associated with warm temperatures in this model, induces excessive sublimation. Increasing the spatial resolution clearly improves this aspect as spurious negative values from spectral representation are strongly damped.

The broad structure of the model biases is barely sensitive to resolution (Figure 5). Similar features show up at both resolutions, only they tend to be of finer scale in the high-resolution composite. In particular, some of the strongest biases, besides those related to the spectral representation of moisture, are located in the coastal regions. They are more efficiently confined to regions with steepest slopes in the high resolution composite which better resolves topography. In turn,

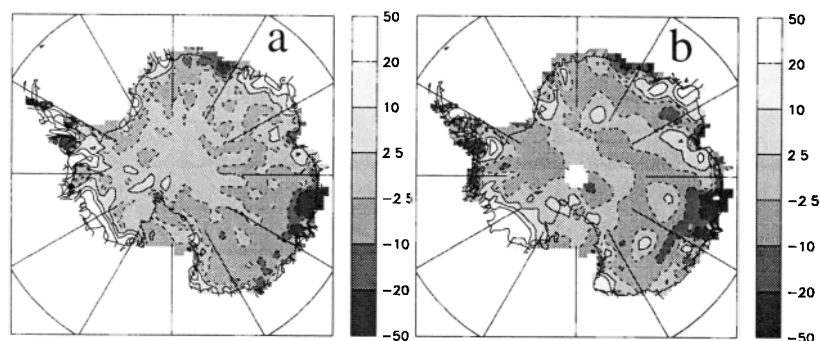


Figure 5. The reduced composite model SMB biases (see section 4.1) at (a) high and (b) low resolution. Negative contours are dashed. Units are cm yr⁻¹.

the broad structure of the biases in the high-resolution two-model (Figure 5) and seven-model (Figure 4) composites is very similar. In fact, many of the features of the model biases prove to be both model and resolution independent: they are robust differences between the models and the observations.

In all high-resolution models, within ≈ 500 km from the coast, the SMB is underestimated with respect to V99 in the following regions, from Greenwich meridian eastward: (1) in the sector 15° – 30° E, extending to 0° in some models; (2) over the Amery ice shelf ($\approx 70^\circ$ E); (3) in the sector 90° – 120° E (Queen Mary and Knox coast), with a striking discontinuity near 110° E; (4) right at the coast, slightly west of the 140° E meridian (George V coast). Five out of seven models simulate a very localized spot of low SMB; (5) along and north of the Mc Murdo Sound ($\approx 165^\circ$ W), extending in some models along the transantarctic mountains and/or along the edge of the Ross ice shelf; (6) south and west of Alexander Island, in the Peninsula.

The SMB is conversely overestimated in the following regions: (1) in the sector 40° – 70° E, reaching significantly over 20 cm yr^{-1} in some models, less in others; (2) east of the Amery ice shelf to 90° E; (3) along much of the sector 120° – 170° E in five models, more localized in two, with variable extension inland; (4) at the coast of Marie Byrd land (along the Executive Range, $\approx 210^\circ$ – 250° W) with values largely exceeding 20 cm yr^{-1} ; (5) in the highlands of the Antarctic Peninsula.

Signal-to-noise-ratio (that is, composite bias over intermodel variability) is particularly high for negative biases 1, 2 and 3, and for positive bias 4. Except for a tendency for the models to be generally too dry, biases are less stable and systematic on the plateau inland than at the coasts. That systematic biases occur in the coastal regions, where surface slopes are stronger, suggests a possible link with topography.

4.2. Role of Topography

Topography obviously plays a determining role in the distribution of SMB. As previously discussed, coastal slopes induce strong precipitation gradients. Also, the

Antarctic land mass distribution is known to contribute to the preferred longitudes of high circumpolar cyclone frequencies. These cyclones have a significant contribution to the transport of moisture to the Antarctic continent. The topographic maps used in all but a few GCMs are notoriously erroneous over Antarctica [Genthon, 1994; Genthon and Braun, 1995]. The ERA and EOA data were both produced with an outdated Antarctic topography. Although they are constrained by observations of the atmospheric circulation, they both show biases similar to the other models. Of the models reported here, only the LMDZ GCM was run with a prescribed topography of Antarctica of relatively recent origin. The fact that the LMDZ model has biases in common with other GCMs suggests either that (1) this newer topography is still incorrect, or that (2) even for fine-grid GCMs, spatial resolution is not sufficient to adequately capture topography and its consequences for Antarctic SMB, or that (3) topography is not involved in the common model biases. The three hypotheses are examined in turn.

In the past few years, satellite-borne altimeters have considerably contributed to determining surface elevation on a global scale. This is particularly true for the oceans and for the remotest continental regions like Antarctica. The digital elevation model of the Antarctic ice sheet derived from ERS-1 data by Bamber [1994] shows significant differences with the previous topographic maps, obtained with more conventional methods and which are still used by most GCMs (except here the LMDZ model). An even more accurate ERS-1 map was very recently produced by Remy *et al.* [1999], which appears to correct some remaining coastal biases in Bamber's. Except for the cap south of 82° S, which was out of reach of the satellite, newer measurements and processing are unlikely to revise Remy *et al.*'s topography to an extent that would significantly affect GCM simulations. Remy *et al.*'s topography is used as a reference to characterize model topography errors below.

Figure 6 displays the Antarctic topography error in the HADAM high-resolution model, the finest of all

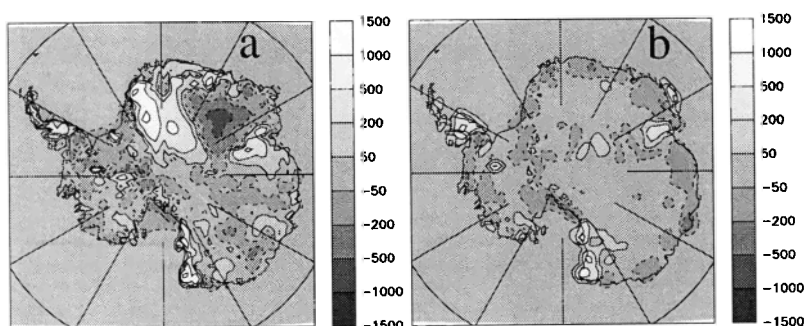


Figure 6. Topography errors in (a) the high-resolution HADAM and (b) the LMDZ models. Some of these errors are due to model resolution, but most are due to errors in the topography reference. Negative contours are dashed. Units in meters.

models discussed here, and that of the LMDZ model. The topography of the HADAM model is very similar to that used by all other GCMs in Table 1, except the LMDZ model which uses Bamber's. Much of the large topography errors of the former model in the interior of the ice sheet are corrected in the latter. On the other hand, many smaller scale errors, reaching up to 500 m, still show up in the coastal and the mountain regions. These errors largely coincide with larger slopes which are more prone to measurement inaccuracies. However, SMB biases do not linearly correlate with topography errors. For instance, large and robust SMB biases along the coast of Marie Byrd Land and Knox and Queen Mary coasts coincide with moderate topography errors, whereas some of the largest topography errors along Mc Murdo Sound and Lambert Glacier are associated with weak SMB bias in the two models. On the other hand, south of Mc Murdo Sound near Oates coast, as well as in the Peninsula, large topography errors are indeed associated with relatively strong SMB biases.

Although topography errors are unlikely to account for the bulk of the systematic coastal SMB biases discussed here, it is recommended that the topography of Antarctica in modern GCMs be updated. This may result in significant overall improvement, including for variables other than the SMB (e.g., for surface temperature), at negligible cost. Finer model resolution is also likely to further refine the simulated SMB, yet it may not significantly improve on the systematic biases (section 4.1). In fact, a high-resolution (55 km) regional model simulation of the Antarctic SMB was recently produced, which still shows many of the systematic biases identified in GCMs [*van Lipzig, 1999, Figure 4.1*]. Examination of recent analyses-based SMB produced by the ECMWF with a similarly fine nominal resolution (not shown) confirm this insensitivity to resolution.

4.3. Wind Erosion and Sublimation

Since melting and runoff to the oceans is widely recognized as negligible, it is not considered a potential contributor to systematic Antarctic SMB biases in GCMs except possibly north of $\approx 65^\circ$ in the Peninsula. There are indications, however, that blowing snow may significantly enhance sublimation, redistribute mass and export solid water across continental margins [e.g. *Gallée, 1998*]. As blowing snow is a function of surface wind speed, and the predominantly katabatic winds are constrained by topography [e.g., *Parish and Bromwich, 1987*], models with reasonably high spatial resolution simulate generally well the surface flow. Figure 7 shows the winter-mean (June-July-August) 10-m wind as analyzed by the ECMWF for 1999 at a spatial resolution of about 60 km. Interannual variability is insignificant for our purpose. Figure 7 is indeed in good agreement with previously published such maps [e.g., *Parish and Bromwich, 1987*]. Neglecting wind erosion and export in GCMs results in an overestimation of the SMB. If erosion is simply related to mean wind intensity, then

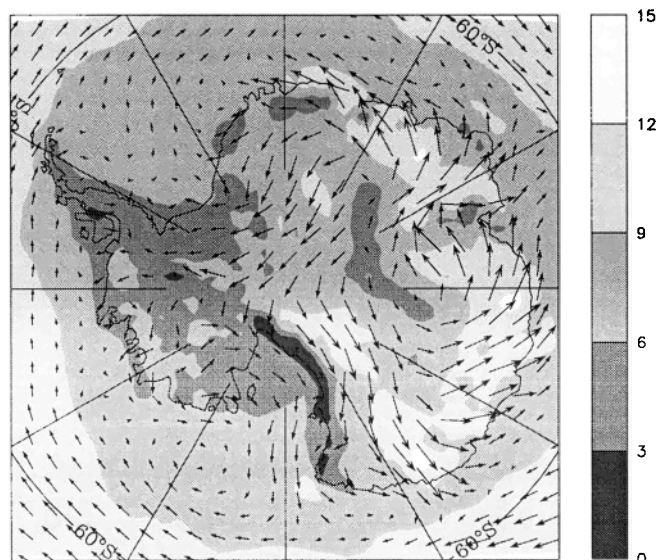


Figure 7. Surface (10-m) wind analyzed by ECMWF for June-July-August 1999. Units are m s^{-1} .

it may contribute to several of the positive systematic biases listed in section 4.1 but not to the biases identified in the sector $30^\circ\text{--}60^\circ\text{E}$ or along Marie Byrd coast. In addition, a well-known region of very strong winds in Adélie Land coincides with a spot of negative bias, and the strong negative bias along Knox and Queen Mary coasts coincides with a region of relatively strong winds.

Mass transfer by blowing snow transport is not linearly related to surface wind speed, and transport is not necessarily effective over long distances. Consequently, a simple analysis of mean surface winds suggests that wind erosion may contribute to systematic biases in GCM SMB, but concluding on this aspect requires that formulations of snow erosion and transport [*Gallée, 1998*] are implemented in the models. Developing and testing such formulations is an urgent necessity.

The importance of sublimation to the SMB of Antarctica is also a debated subject. For instance, *van den Broeke [1997]* finds that in a previous version of the ECHAM model (ECHAM3), 10 to 15% of the annual precipitation of Antarctica is lost through sublimation. The model version used in the HIRETYCS study (ECHAM4) seems to confirm this (11%). However, the HIRETYCS version simulates deposition (inverse sublimation) over much of the central plateau, whereas *van den Broeke [1997]* reports that deposition is marginal. Mean sublimation on the grounded ice ranges from 1.0 to 6.8 cm yr^{-1} in the high-resolution models. The larger value, from the ARPEGE-HIRETYCS (version 1) model, is most likely too large: ARPEGE probably overestimates sublimation for reasons developed in section 4.1, and the other models simulate significantly less. Figure 8 shows a sublimation composite built as the average of sublimation in all high-resolution models except ARPEGE-HIRETYCS. In coastal regions this is similar to the map shown by *van den Broeke [1997, Fig-*

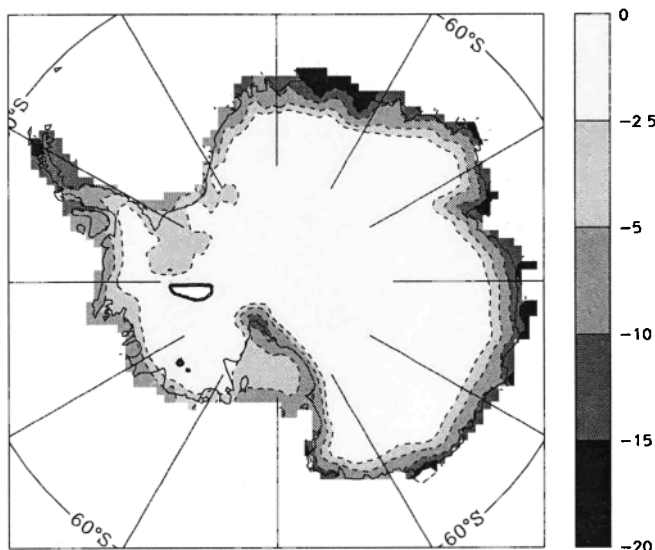


Figure 8. Model composite sublimation (water flux positive downward). Units are cm yr^{-1} .

ure 9]. In particular, the only regions of high sublimation (above 20 cm yr^{-1}) extending significantly inland from the coasts are found in the sector 10° to 30°E . These regions coincide with significant underestimation of the SMB (Figure 4) by as much as 20 cm yr^{-1} . There is no other evidence, except possibly east of the Amery ice shelf, of a systematic underestimation of the SMB which could be associated with a possible overestimation of sublimation. There is no evidence either that systematic overestimation of the SMB is associated with possible underestimation of sublimation: sublimation is not particularly low at any of the regions where the SMB is overestimated by the models. Altogether, if SMB biases reflect common deficiencies in the model physics, then deficiencies in the simulation of precipitation are more likely than deficiencies in the simulation of sublimation.

4.4. Possible Errors in Observation-Based SMB Maps

V99 (their Figure 4) show the distribution of in situ SMB measurements they have used in their study. In several instances, the systematic model SMB biases fall in areas with little or no field observation and where therefore much of the SMB estimation is an extrapolation based on microwave satellite data (section 2). As mentioned by V99, their map shows significantly more spatial variability in the coastal regions than that of GB85. Again, much of this extra variability occurs in regions devoid of field observation, and thus reflects the different approaches to spatial extrapolation in V99 and GB85. The possibility that some of the model SMB biases with respect to V99 are in fact extrapolation SMB biases in V99 map should thus not be overlooked.

In fact, Figure 2 clearly shows that a number of differences between V99 and GB85 maps coincide with model

SMB biases (Figure 4h) in such a way that some of the model biases are reduced or vanish if GB85 is used as a reference rather than V99 (Figure 4i). This is the case, in particular, for the model overestimations east of the Amery ice shelf and east of Oates Coast. The coincidence is striking for the model underestimations in the 100° – 120°E sector. In this case, the coast is largely devoid of field information except for a transect along the Casey-Vostok route. Both the model bias and the difference between V99 and GB85 are minimal along this route and much larger west and east of the route. V99 report that fitting the microwave data to the actual in situ observations results in relatively poor correlation ($r=0.46$) and high residuals (13.1 cm yr^{-1} on average). The local maximum of SMB along the Casey-Vostok route at the coast (Figure 1) most likely reflects a high residual in this area. The microwave-based extrapolation is thus questionable, and a coherent response by several models may be more trustable, particularly if it agrees well with GB85 as is the case here. One might in fact recommend that, in regions where residuals with respect to microwave data are high, data from consistent climate models and/or meteorological analyses should be preferred as interpolant.

V99 report particularly high residuals (more than 20 cm yr^{-1} , negative) along the coast in the sector 105° – 150°W . This is very consistent with one of the strongest (20 cm yr^{-1} and more) and most robust model bias along the coast of Marie Byrd Land. V99 further mention that points that show “infeasibly” large residuals (more than 20 cm yr^{-1} , again) are removed from the database, which probably explains the good agreement between V99 and GB85 in this area. However, the models support that the SMB is quite larger than estimated and that these points may not actually be so “infeasibly” large. If they were taken into account, then the model SMB bias with respect to V99 would have been reduced or would have vanished. Here again, an attention to model results could have changed the judgment of V99.

5. Discussion and Conclusion

There are many reasons why GCMs may not be able to correctly simulate the SMB of Antarctica: limited spatial resolution, wrong topography of Antarctica, inadequate parameterizations or missing formulations of important hydrological processes (e.g., snow erosion by wind), and inappropriate numerics (e.g., spectral advection of moisture). However, when several GCMs of different origin and concept, some being constrained by meteorological observations, run at remarkably high resolution by present-day standard, all display similar biases with respect to observations, one may be tempted to question the observations. In general, systematic biases in GCMs should first be considered the signature of systematic deficiencies with a common origin in the models. Common practice is first to suspect common

boundary conditions (e.g., topography) or common approaches to formulating (or not formulating) physical processes. When these have been evaluated and at least partially rejected, then the observations can be questioned.

Observations are prone to criticism when they are incomplete, must be interpolated, and result from complex field and data analysis work. For these reasons, the SMB of Antarctica is not well known. The latest compilation by V99 (Figure 1) has increased the best previous estimate of the mean SMB by 18%. The remaining uncertainty is hard to estimate. The fact that seven very high resolution GCM simulations and analyses agree to show systematic differences with V99 (Figure 4) might indicate significant remaining problems with the observation-based continental maps. However, as stressed just above, the models should first be questioned.

Spatial resolution is unlikely to contribute in a significant way to the model systematic SMB biases. Much of these biases still show up in models at resolution both coarser and finer than the 100–200 km of the models analyzed here. Inadequately prescribed topography is also unlikely to explain the bulk of the systematic biases, even though all except one of the models considered here use an orography which is regionally in error by as much as 1000 m. Snow erosion and export by wind, which is very poorly known and ignored in all models, is a possible candidate to explain some but clearly not all of the systematic biases. Sublimation at the surface of Antarctica is not well known. It is simulated by all GCMs but possible errors in its simulation seem unlikely to contribute to systematic SMB biases. Biases remain which cannot be explained by any of the above possible model deficiencies.

Comparing V99 and a previous observation-based SMB map by GB85 (Figure 2) shows significant differences in areas where systematic model SMB biases are also large. Furthermore, these are areas with little or no actual field measurement: SMB estimates are thus largely the result of an extrapolation. V99 use satellite microwave data as an interpolant. V99 admit that the microwave interpolant can be considerably in error, in fact by as much as some of the largest systematic model biases. Some of the systematic model differences with V99 are most probably, in fact, remaining errors in V99 due to the microwave interpolation.

We are not yet at a point where one could recommend that, in areas where field estimates of the SMB of Antarctica are not available or particularly questionable, consistent results from different high-resolution GCMs could be systematically used to fill a complete reference map. This is all the more undesirable that such a map would be used, among other application, to validate model results. On the other hand, keeping an eye on model results, for example, composite maps such as Figure 3c, and tracking systematic differences between models and observations-based estimates could

most probably help improve the latter, for example to discriminate between conflicting observations, to validate interpolation between observations, or to detect where additional field observations are most necessary.

Meanwhile, recommendations can be made to improve the ability of GCMs to simulate the SMB of Antarctica. These recommendations may help make the models converge toward estimates such as V99's, except obviously where the estimates are wrong:

1. Higher spatial resolution means better account of topography and of its control on the climate of Antarctica. It also makes it easier to compare model results with local meteorological observations, many of which are made at the coast where steeper topography and land-sea contrast make spatial gradients particularly large. Limited-area models [e.g., *van Lipzig*, 1999] and variable-resolution GCMs [e.g., *Krinner et al.*, 1997] provide high resolution at lower computational cost than globally fine GCMs [e.g., *HIRESYCS*, 1998].

2. High resolution does not help with topography if the underlying topography database is in error. The most recent topography of Antarctica available to date, from satellite radar altimeter, is that of *Remy et al.* [1999]. Further refinements of the topography of Antarctica are unlikely to affect model results.

3. Parameterizations of erosion and export of surface snow by wind should be developed [e.g., *Gallée*, 1998] and implemented in GCMs. There is no guarantee that this will result in a significant alteration of the simulated SMB. However, considering the non linear relations of erosion with wind and with other dynamic aspects of the surface atmospheric circulation, only in-line modeling can reasonably address the question.

This is by no means an exhaustive set of recommendation, and many other aspects of climate models need to be more thoroughly studied. Although not considered a significant potential contributor to systematic model biases, sublimation is still an open question. The fraction of precipitation on the grounded ice which is returned to the atmosphere through sublimation ranges from 6 to 25% in the high-resolution models studied here (excluding ARPEGE-HIRESYCS). Differences in the spatial distributions of sublimation are also striking, with some models simulating inverse sublimation over large regions in the interior of Antarctica and others not. Precipitation itself, the major component of the SMB of Antarctica, has not been discussed here. In spite of common features between the models (Figure 3), the spatial distribution of precipitation differs in a number of respects. The time variability can also be different [e.g., *Genthon et al.*, 1998]. Data on Antarctic precipitation are extremely rare and subject to caution [*Genthon et al.*, 1998], a fact that will continue to strongly limit model validation in this respect. Finally, observations used to build SMB maps span several decades. More coherent data-model comparisons would thus require multi decadal GCM simulations starting in

the 1950s [Smith *et al.*, 1998] and comprehensive sorting of the observations with respect to time, both tasks at considerable additional work.

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