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Spatial and temporal variation of sublimation on Antarctica: Results of a high-resolution general circulation model

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Abstract. In this paper we use output of a high-resolution general circulation model (ECHAM-3 T106, resolution 1.1° × 1.1°) to study the spatial and temporal variation of sublimation on Antarctica. First, we compare model results with available observations of sublimation rates. The yearly cycle, with small latent heat fluxes during the winter, is well reproduced, and the agreement with sparsely available spot observations is fair. The model results suggest that a significant 10–15% of the annual precipitation over Antarctica is lost through sublimation and that sublimation plays an important role in the formation of blue ice areas. A preliminary analysis of the atmospheric boundary layer moisture budget shows that the spatial variation of sublimation in the coastal zone of East Antarctica can be explained by variations of horizontal advection of dry air. Dry air advection, and thus surface sublimation, is enhanced in areas where katabatic winds are strong and have a large downslope component and where the Antarctic topography drops suddenly from the plateau to the coastal zone. In areas where horizontal advection is small, like the plateau and the large ice shelves, special conditions must be met to make significant sublimation at the surface possible.

1. Introduction

The performance of general circulation models (GCMs) over Antarctica has improved considerably during the last decade [*Xu et al.*, 1990; *Simmonds*, 1990; *Chen et al.*, 1995], partly as a result of increased model resolution and partly because physical parameterizations have been improved. For instance, *Tzeng et al.* [1994] and *Bromwich et al.* [1995] report on the Antarctic accumulation distribution of the National Center for Atmospheric Research (NCAR) Community Climate Model, Version 2 (CCM2) which gave much improved results compared to an earlier model version because of improvement of the moisture transport scheme and increased resolution. *Genthon and Braun* [1995] found good agreement between accumulation observations and 5 years of European Centre for Medium Range Weather Forecasts (ECMWF) analyses, but the results did not appear to be superior to those obtained with GCMs in pure climate mode, i.e., which are not constrained by observations [*Connolley and Cattle*, 1994; *Genthon*, 1994].

Not much attention has been given to sublimation of snow over the large ice sheets (sublimation refers to the transition from the solid to the vapor phase; deposition refers to the transition from the vapor to the solid phase). *Loewe* [1962] suggested that sublimation/deposition processes do not contribute significantly to the mass balance of the ice sheet. Although he was probably right as far as the high plateau is concerned, observations performed in the coastal zone show that sublimation can remove a substantial part of the yearly precipitation from the surface, especially in areas where katabatic winds are active.

In the present paper we use output generated by the ECHAM-3 GCM, run in T106 mode (resolution 1.125°, 160 by 320 gridpoints), to compare modeled sublimation rates (and those variables that determine it, like wind and temperature) with observations (section 3). In section 4 we present the spatial and temporal variation of sublimation over Antarctica. In section 5 we discuss the results in terms of the simplified moisture budget of the atmospheric boundary layer (ABL). In the next section we give a short description of the model.

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2. Model and Runs

The ECHAM-3 GCM has been developed at the Max Planck Institute for Meteorology in Hamburg, Germany, and originates from the ECMWF model. The version of the model that was used in this study has a grid spacing of 1.125° × 1.125° (T106, truncation at wavenumber 106). The model equations are solved on 19 vertical levels in the atmosphere, and the heat transfer equation is solved in a five-layer soil model assuming vanishing heat flux at the bottom. Values of 2 m temperature and humidity and 10 m wind speed are obtained by interpolation between the surface and the lowest model layer.

To simulate the present-day climate, the ECHAM-3 GCM has been integrated over 5 1/2 years (model time). Five complete years of T106 simulation were used in the analysis to obtain monthly averaged fields. In this control run, sea surface temperatures and sea ice are updated daily by linear interpolation between monthly mean climatologies from the atmospheric intercomparison project (AMIP) sea surface temperature and sea ice data set [*Gates*, 1992]. The sea ice thickness is prescribed in the model as alternating rows of 1 and 2 m thick but with continuous coverage; that is, leads are not accounted for.

The orography is based on mean terrain heights computed from the high-resolution (10′) U.S. Navy data set. Subgrid processes in the ABL are parameterized according to *Louis*

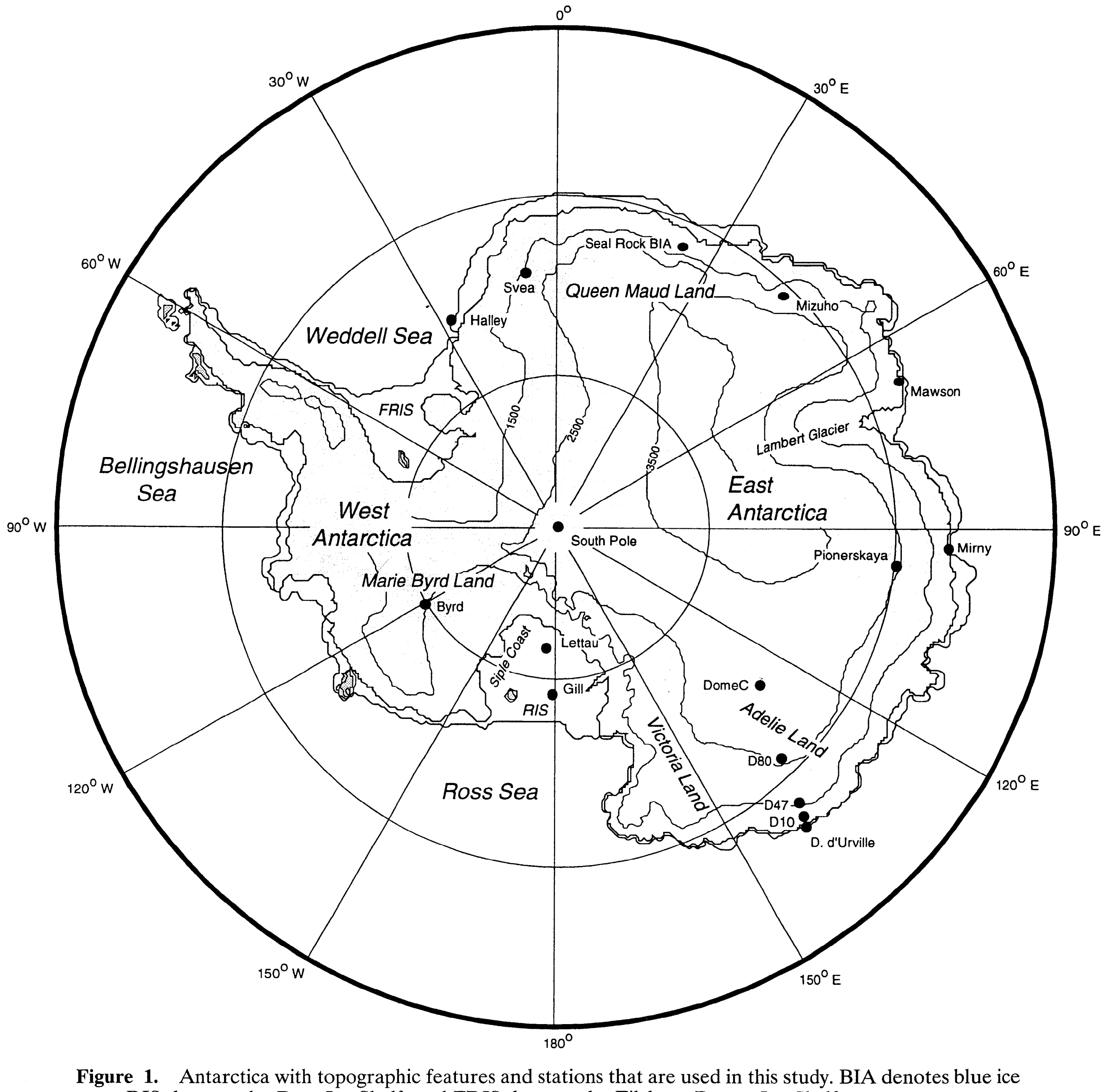


Figure 1. Antarctica with topographic features and stations that are used in this study. BIA denotes blue ice area; RIS denotes the Ross Ice Shelf; and FRIS denotes the Filchner-Ronne Ice Shelf.

[1979] and later updates [*Louis et al.*, 1982]. Over the ice sheet of Greenland this scheme tends to overestimate the sensible heat flux in very stable conditions [*Ohmura et al.*, 1994] but underestimates it in moderately stable conditions over the melting zone [*van den Broeke*, 1996b]. For a more detailed description of the model physics the reader is referred to *Roeckner et al.* [1992].

3. Comparison With Observations

We can express the latent heat flux of sublimation LHF as

$$\mathrm{LHF} = -\mathrm{SU}\, L_s = -\rho L_s \overline{(w'q')}_{h_s} = \rho L_s u^* q^* \qquad (1)$$

where SU is the sublimation rate (mm water equivalent (w.e.) s^{-1}), L_s is the latent heat of sublimation ($L_s = 2.84 \times 10^6$ J kg^{-1}), ρ is the air density, and $(w'q')_{h_s}$ is the turbulent moisture flux at the surface. A latent heat flux of -1 W m^{-2} (negative values indicate sublimation) is roughly equal to a yearly sublimation of 11 mm w.e. Simplifying a little bit, the sublimation in the stably stratified surface layer (which is often defined as the lowest 10% of the ABL) is determined by the moisture gradient between the surface and the overlying air (represented by the scale of turbulent moisture fluctuations, q^*) and the intensity of the turbulence generated by wind shear (u^*). Because the capacity of the air to hold moisture is controlled by its temperature, both wind speed and temperature should be well represented in the model in order to enable an accurate simulation of sublimation rate. In this section we look at the ability of the model to simulate these parameters over Antarctica. Figure 1 shows the locations of the stations on Antarctica that were used in this study. For a more detailed comparison between modeled and observed Antarctic kata-

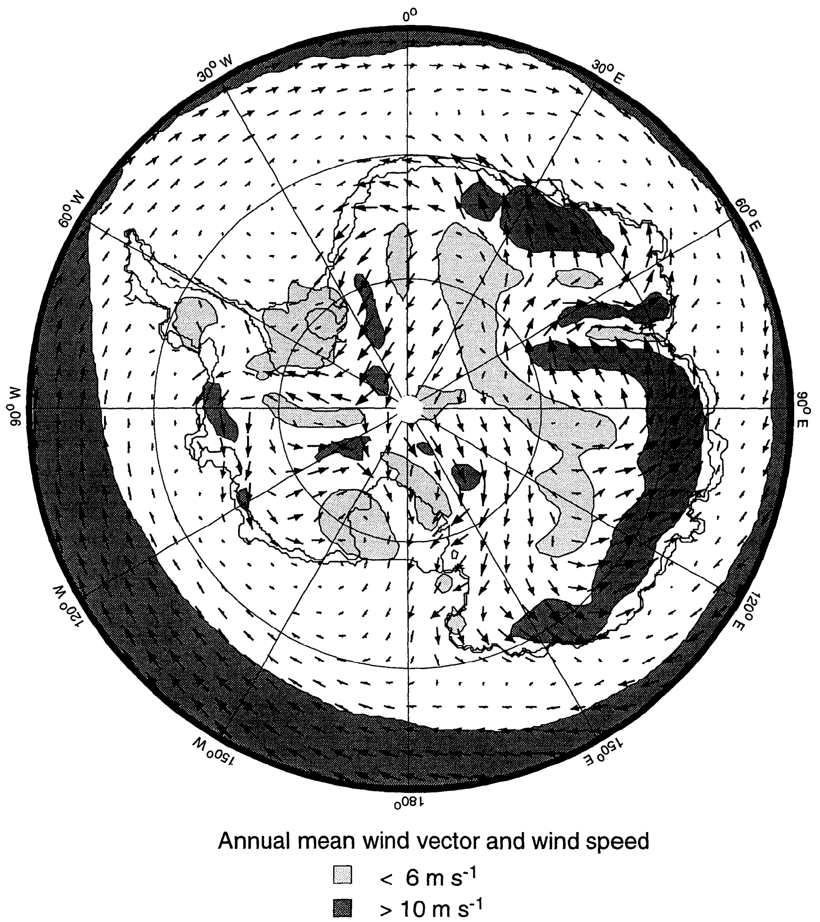


Figure 2. Annual average modeled 10 m vector wind field. The dark shaded area denotes an annual average wind speed of >10 m s^{-1}, and the light shaded area denotes an annual average wind speed of <6 m s^{-1}.

batic winds the reader is referred to *van den Broeke et al.* [1997].

3.1. Katabatic Winds

Katabatic winds are forced by the continuous cooling of air overlying the sloping Antarctic ice sheet, and they can have a large impact on the (local) mass balance of an Antarctic snow surface: they generate increased turbulence that is needed for effective sublimation and redistribute the snow by drift transport. Figure 2 shows the simulated average 10 m wind vectors as well as areas where annual mean wind speeds are <6 m s^{-1} (light shaded) and >10 m s^{-1} (dark shaded). Note that the vectors in this figure are composed of the mean components: the length of the vector only equals the annual mean wind speed if the wind blows from one direction all the time, i.e., if the directional constancy is 1. Over the continent we see a well-developed katabatic wind system, the surface winds being deflected to the left of the topographic fall line by the Coriolis force. Weak winds are modeled over the high plateau, and the highest annual mean wind speeds are simulated over the steep coastal slopes of East Antarctica. At those places where the topography forces the surface winds to converge [*Ball*, 1960; *Parish and Bromwich*, 1991], annual mean wind speeds reach values in excess of 14 m s^{-1}. Once arrived at sea level, the flow ceases quickly, and further away from the coast, the circumpolar westerlies determine the wind field. In between we find a belt with low directional constancy (low vector mean wind speed) where migrating cyclones are active, so that both westerlies and easterlies occur at the surface.

Figure 3 directly compares modeled and observed mean annual wind speeds at 29 Antarctic stations. Data for this graph were taken from *Schwerdtfeger* [1970], *Smith and Stearns* [1993], and *Allison et al.* [1993]. Although the overall agreement is fair, the model tends to underestimate the high wind speeds at the foot of the coastal slopes and overestimate the weak winds that are observed in the plateau region. This is caused by representation of the Antarctic topography in the model that tends to smoothen out the steep elevation gradients near the coast; the overestimated slope inland of the coast generates too strong a downslope flow, while the opposite is true for the foot of the slope, where the surface slope is underestimated (flow too weak).

3.2. Near-Surface Temperature

Surface temperature is the controlling variable for moisture exchange between Antarctica and the overlying atmosphere. During the Antarctic winter, water vapor pressures at both the surface and in the air are so low that sublimation rates become very small. In summer the lowest parts of the ice sheet heat up sufficiently to allow for widespread sublimation. Figure 4 presents a direct comparison between observed and simulated annual mean 2 m temperatures at 30 Antarctic stations. Data for this graph were taken from *Schwerdtfeger* [1984], *Smith and Stearns* [1993], and *Allison et al.* [1993]. The model is generally

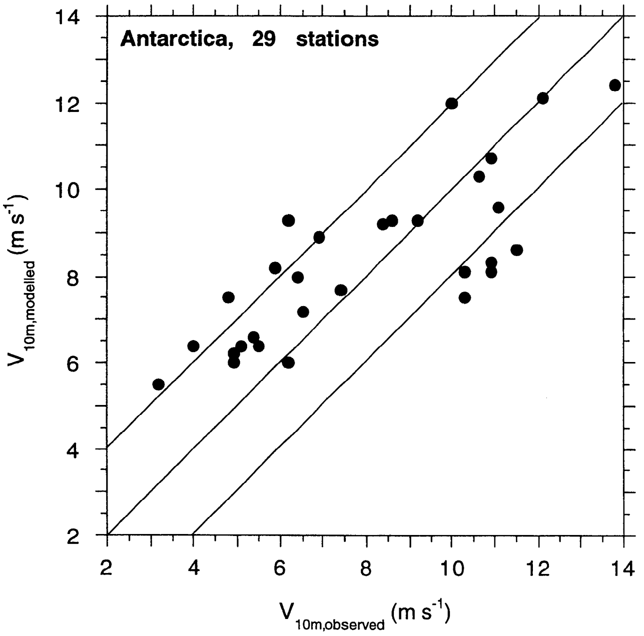


Figure 3. Modeled (y axis) versus observed (x axis) annual mean wind speed for 29 Antarctic stations. Observations from *Schwerdtfeger* [1970], *Smith and Stearns* [1993], and *Allison et al.* [1993]. The solid lines indicate the 1:1 line ± 2 m s^{-1}.

able to predict the temperature to within 3 K of the observations, which is a good result given the complex thermal structure of the boundary layer overlying Antarctica, with large vertical and horizontal temperature gradients [*Phillpot and Zillman*, 1970]. The group of outliers represents stations on ice shelves where the model, because of an erroneous physical description of the ice shelves as sea ice, overpredicts the winter temperatures. Summer temperatures in these regions are well predicted. The annual cycle of temperature is also well represented by the model, as is demonstrated in Figure 5 for an array of automatic weather stations (AWSs) in Adélie Land [from *Allison et al.*, 1993]. The increasing amplitude of the annual temperature cycle toward the higher stations and the elevational temperature gradient agree well with the observations.

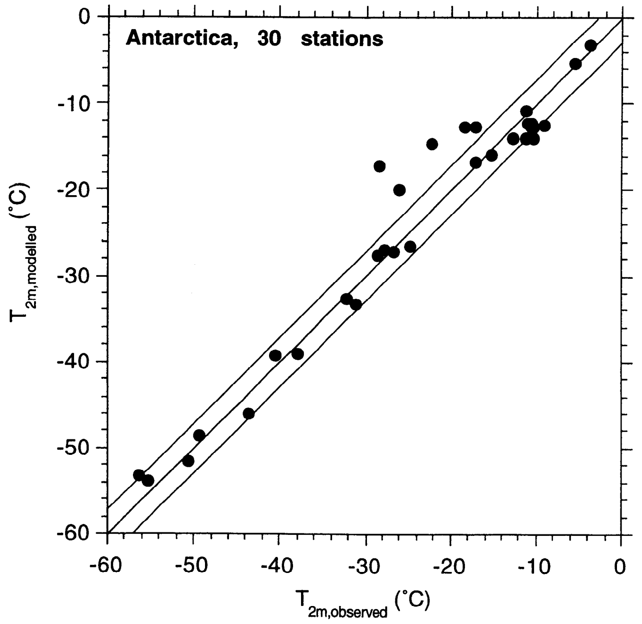


Figure 4. Modeled (y axis) versus observed (x axis) annual mean 2 m temperature for 30 Antarctic stations. Observations from *Schwerdtfeger* [1984], *Smith and Stearns* [1993], and *Allison et al.* [1993]. The solid lines indicate the 1:1 line ± 3 K.

3.3. Sublimation

Sublimation in Antarctica occurs mainly in the summer months in the lower lying parts of the ice sheet. It is well known that surfaces with a relatively low albedo, such as blue ice areas, show significantly higher evaporation rates than snow surfaces. This can be attributed to the higher surface temperature, a direct result of the enhanced absorption of solar radiation [*Orheim and Luchitta*, 1988; *Winther et al.*, 1996]. For instance, *Fujii and Kusunoki* [1982] calculate a latent heat flux of −21 W m^{-2} in the vicinity of Mizuho station (2230 meters above sea level (masl)) over a glazed ice surface. *Ohata et al.* [1985], at almost the same location but over a snow surface, obtained a value of only −7 W m^{-2}. They attributed the difference to the differences in albedo. In another study, *Bintanja and van den Broeke* [1995] calculated a latent heat flux of −29 W m^{-2} over blue ice (α = 0.56) and −15 to −22 W m^{-2} over the adjacent snow surfaces (α = 0.81) at Svea (1250 masl). They found that besides the differences in surface albedo, surface roughness and the local meteorological conditions [*van den Broeke and Bintanja*, 1995a] also influence the sublimation rate.

Because the model albedo is set equal to that of snow, we restrict ourselves to a comparison with the limited amount of observations of sublimation over Antarctic snow, unless observations over blue ice have been made during winter (Table 1). It should be noted that nearly all "observations" in Table 1 are derived from measurements of the mean gradients of potential temperature, specific humidity, and wind speed, using surface layer similarity theory. General agreement is fair, although the model does not calculate winter deposition at Halley but rather

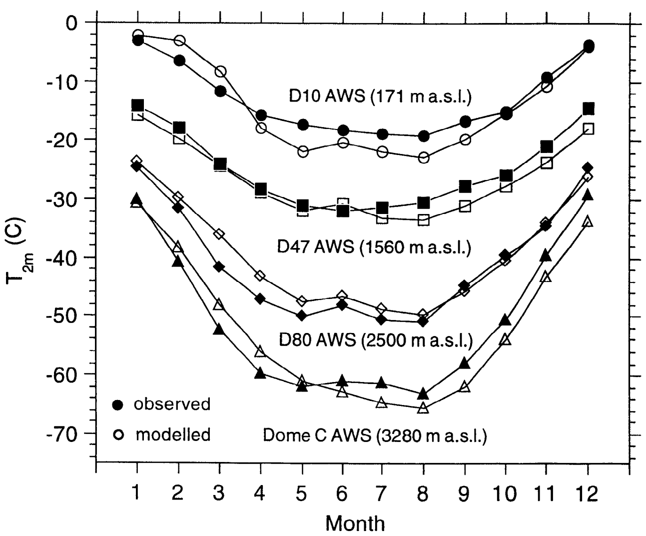


Figure 5. Modeled (open symbols) versus observed (solid symbols) annual cycle of 2 m temperature for an array of automatic weather stations (AWSs) in Adélie Land. Observations from *Allison et al.* [1993].

Table 1. Observed and Modeled Latent Heat Fluxes Over Antarctic Snow Surfaces

Reference	Location	Period	Observed, W m^{-2}	Model, W m^{-2}
Weller [1981]	BIA near Mawson (16 masl)	July 1965	−6	−6.7
Ohata et al. [1985]	Mizuho (2230 masl)	June 27 to July 20, 1980	0	−1.3 (July)
		Dec. 12–19, 1980	−7.8	−7.0 (December)
Wendler et al. [1988]	D-47 AWS (1560 masl)	Nov. 20 to Dec. 22, 1985	−8.7	−7.7 (December)
Takahashi et al. [1992]	Seal Rock BIA (950 masl)	April 28 to Aug. 29, 1989	−17.2[a]	−12.2 (May–August)
Bintanja and van den Broeke [1995]	Svea (1150 masl), site 5	Dec. 28 to Feb. 10, 1993	−22.1	−15.3 (January)
King et al. [1996]	Halley (23 masl)	March–August 1991	+0.8	−4.9

Negative values indicate fluxes away from the surface (sublimation). Measurements at Mawson and Seal Rock were performed over blue ice areas (BIA) but were retained here because the lower albedo of the surface probably does not influence the sublimation during winter.
[a]Derived from stake ablation measurements.

a persistent sublimation. This could be a result of the erroneous treatment of ice shelves as sea ice in the model, resulting in overestimation of the surface temperature of the ice shelves in winter. Because processes other than sublimation influence the mass balance of a snow surface (precipitation, erosion, and sublimation of drifting snow [e.g., *King et al.*, 1996]), it is often difficult to check the accuracy of the observations, i.e., to compare the calculated sublimation rates with the actual removal of mass from the surface.

This problem does not exist over blue ice, where precipitated snow is removed from the smooth surface by strong winds, and winter ablation can thus be easily measured with stakes to represent an equivalent latent heat flux. Not many winter observations of stake heights have been made, but some observations by *Takahashi et al.* [1992] are available for an especially interesting location, the blue ice area in the lee of Seal Rock (71 31°S, 24 05°E, and 950 masl), situated in the lower katabatic wind zone in East Queen Maud Land. Exactly in this region the model predicts significant winter sublimation rates, which are confirmed and even exceeded by the observations [Table 1].

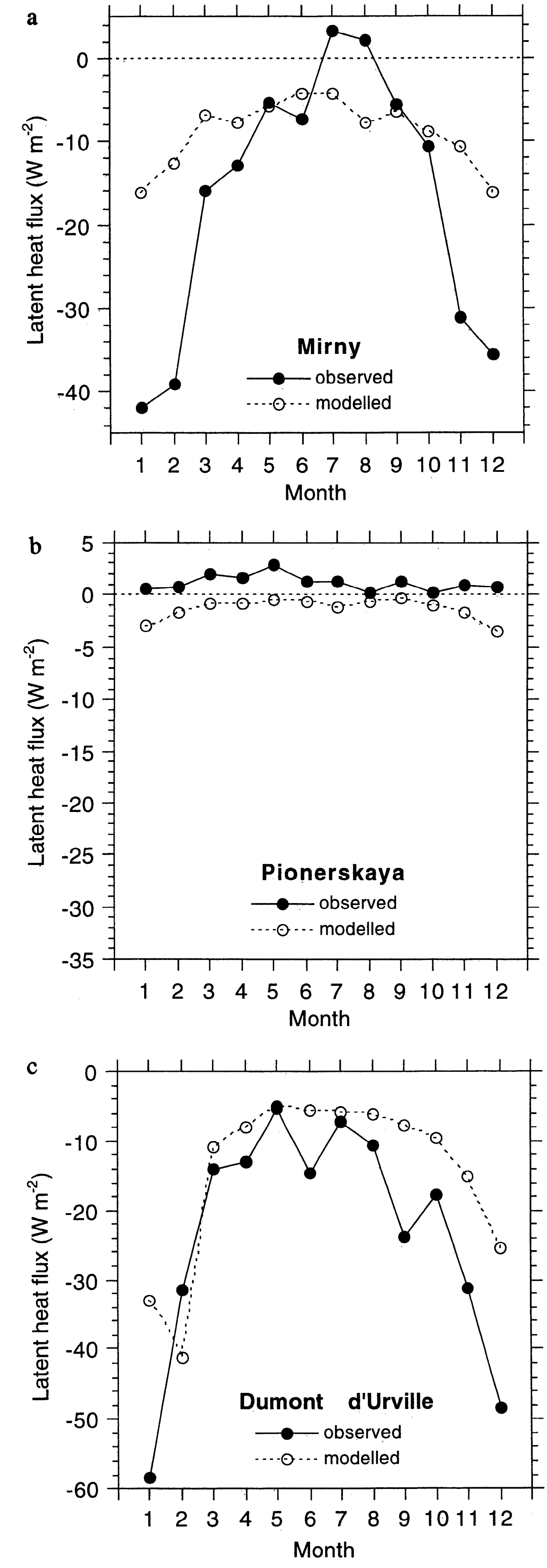
Rusin [1961] used surface layer similarity theory to calculate the annual cycle of sublimation rates at several stations on the basis of profile measurements performed during the International Geophysical Year (IGY), 1957–1958. In Figures 6a–6c we compare the results for Mirny (30 masl; annual mean temperature −11.3°C, and wind speed 11.5 m s^{-1}), Pionerskaya (2740 masl, −38.0°C, and 10.6 m s^{-1}) and Dumont d'Urville (43 masl, −10.7°C, and 10.9 m s^{-1}) with model calculations. Clearly, the model underestimates sublimation rates during summer at Mirny and fails to simulate the small amount of winter deposition. For Pionerskaya, Rusin's calculations suggest small deposition throughout the year, while the model calculates small sublimation. However, the validity of these observations appears doubtful; *Loewe* [1962], for instance, uses another calculation method that suggests continuous sublimation at Pionerskaya. The simulated yearly cycle for Dumont d'Urville appears reasonable, although a conspicuous maximum sublimation rate is modeled in February, and summer ablation rates are underestimated. This underestimation is partly associated with the tendency of the model to underestimate wind speed in the coastal zone [*van den Broeke et al.*, 1997]. Furthermore, the meridional gradient of sublimation (as for almost all variables) is very large in the coastal zone, which complicates a direct comparison of model and observations. Errors in the calculations and the disturbed local surroundings of the stations further complicate a direct comparison. Dumont d'Urville, for instance, is situated on a rocky outcrop in the ocean, 5 km north of the glacial slopes with open water in between [*Mather and Miller*, 1967].

More homogeneous conditions are found on the Ross Ice Shelf, where *Stearns and Weidner* [1993] calculated the annual cycle of the latent heat flux from observations performed with AWSs. Data of two of these AWSs, Gill and Lettau, which are situated far away from the Transantarctic Mountains (Figure 1), are used to compare with model calculations (Figures 7a and 7b). The yearly cycle is qualitatively well simulated, but the model overestimates summer ablation, especially in November. The treatment of ice shelves in the model leads to an overestimation of winter temperatures (see previous section) which is probably the reason for the slight overestimation of winter sublimation. Confluence of air streams from the plateau and west Antarctica in the vicinity of Siple Coast (Figure 2) [*Bromwich and Liu*, 1996] causes higher wind speeds and temperatures in the southern part of the Ross Ice Shelf [*Stearns et al.*, 1993], a phenomenon that is qualitatively captured by the model. This causes the higher sublimation at Lettau AWS compared to Gill AWS, although the former station is situated further to the south. The occurrence of significant sublimation over the Ross Ice Shelf has interesting implications for the local ABL moisture budget, as will be discussed in section 5.

4. Modeled Spatial and Temporal Variation of Sublimation

Figure 8a presents the modeled summer (DJF) latent heat fluxes over Antarctica (note that fluxes over open water represent evaporation). The evaporation maxima that are modeled off the coast of Adélie Land and Victoria Land are caused by the advection of cold air over open water, where no sea ice is present during the months of January and February. Over the ice sheet itself, significant summer sublimation (−5 to −15 W m^{-2}) occurs generally below 2000–2500 masl. Interestingly, large absolute values up to 40 W m^{-2} are modeled in some areas of east Queen Maud Land (the sector between 0 and 30°E), over the Lambert Glacier basin, and on the southern part of the Ross Ice Shelf. Figure 8b shows that in the same areas, significant (−5 to −10 W m^{-2}) sublimation persists during winter (JJA) in spite of the low temperatures. Observations by *Weller* [1981] and *Takahashi et al.* [1992] confirm this (Table 1). Significant winter sublimation, on average −14 W m^{-2} for the period April 1, to October 15, 1986, was also reported by *Clow et al.* [1988] over Lake Hoare in the dry valleys (Victoria Land).

Figure 9 presents the total annual sublimation. Net removal of mass is predicted for the entire continent, except for the



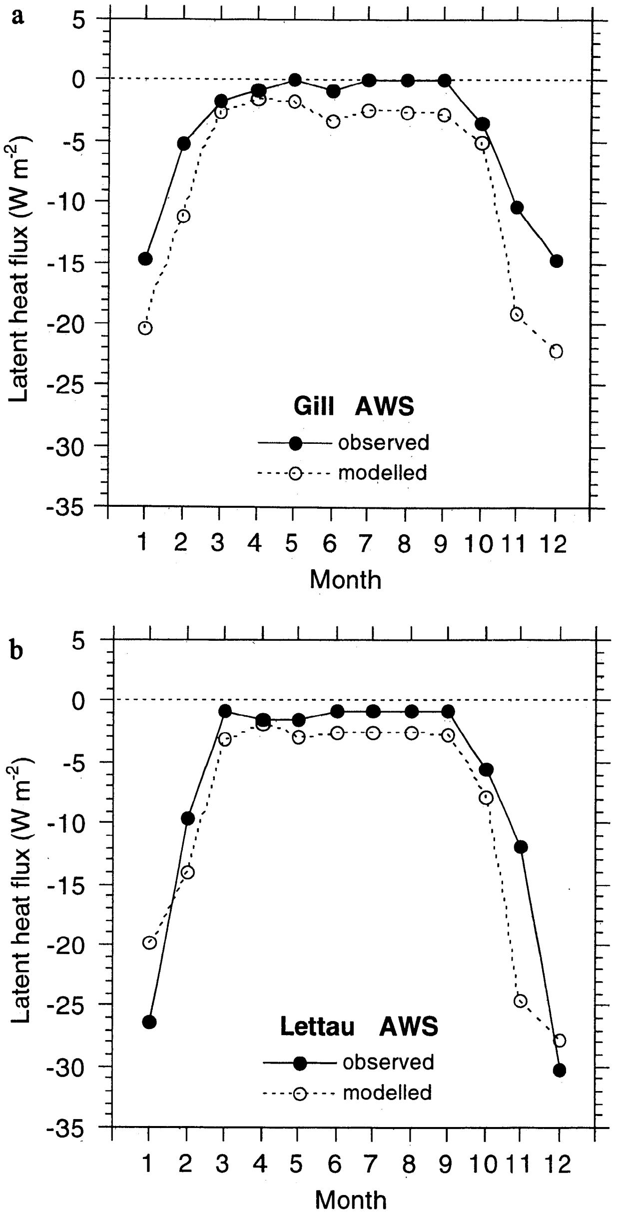
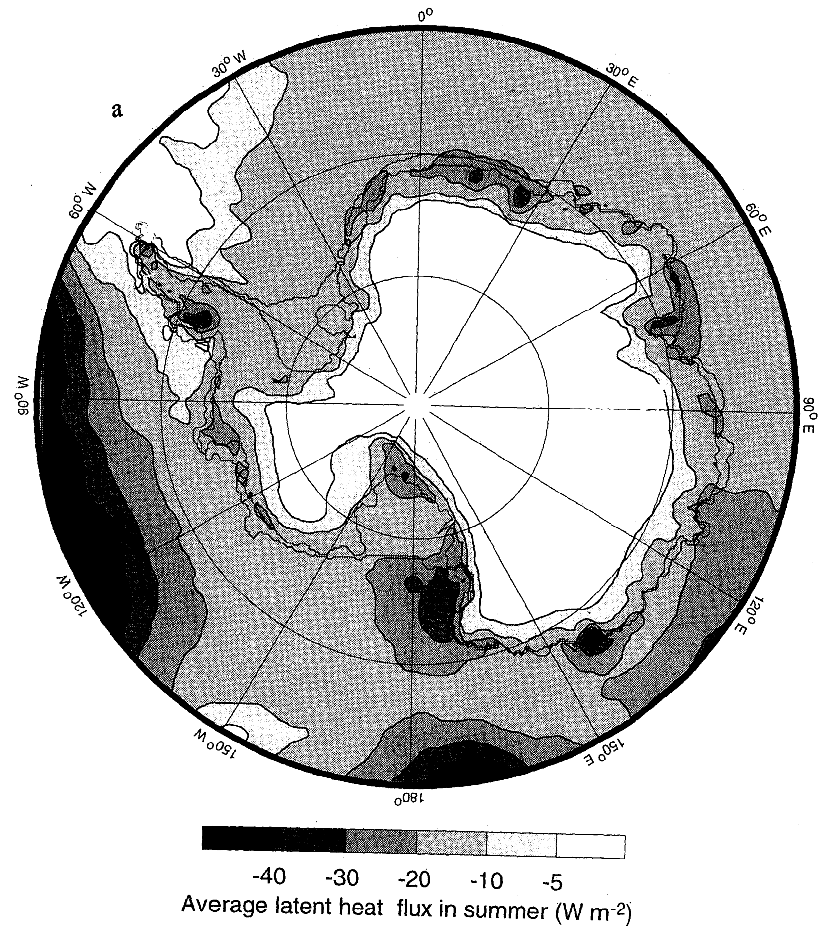


Figure 7. Modeled (open symbols) versus observed (solid symbols) annual cycle of the latent heat flux (negative values indicate sublimation) at (a) Gill AWS and (b) Lettau AWS. Observations from *Stearns and Weidner* [1993].

highest point of West Antarctica (hatched area in Figure 9). We find small annual sublimation on the East Antarctic plateau (generally <10 mm w.e. per year, equivalent to a LHF of -0.9 W m^{-2}). It is generally assumed that on an annual basis, small deposition occurs over the high Antarctic plateau. The fact that the model does not reproduce this large-scale deposition could well be connected to the absence of leads in the sea ice parameterization. This could lead to a general underestimation of atmospheric moisture content and overestima-

Figure 6. (opposite) Modeled (open symbols) versus observed (solid symbols) annual cycle of the latent heat flux (negative values indicate sublimation) at (a) Mirny, (b) Pionerskaya, and (c) Dumont d'Urville. Observations from *Rusin* [1961].



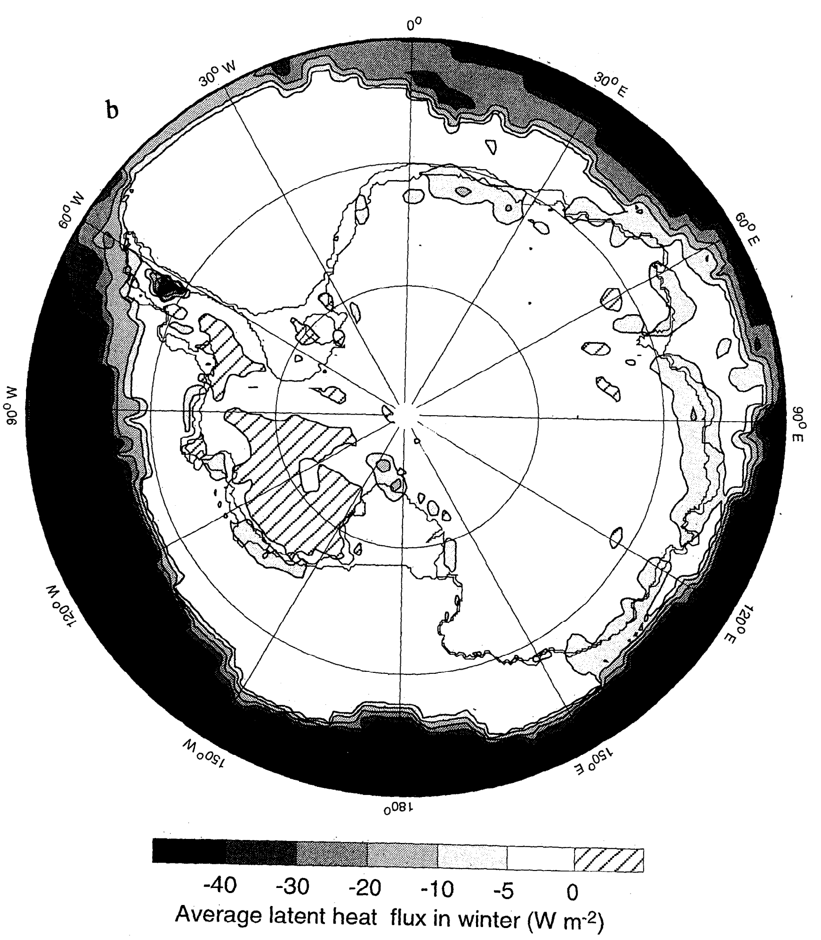


Figure 8. Modeled average latent heat flux during (a) summer (DJF) and (b) winter (JJA).

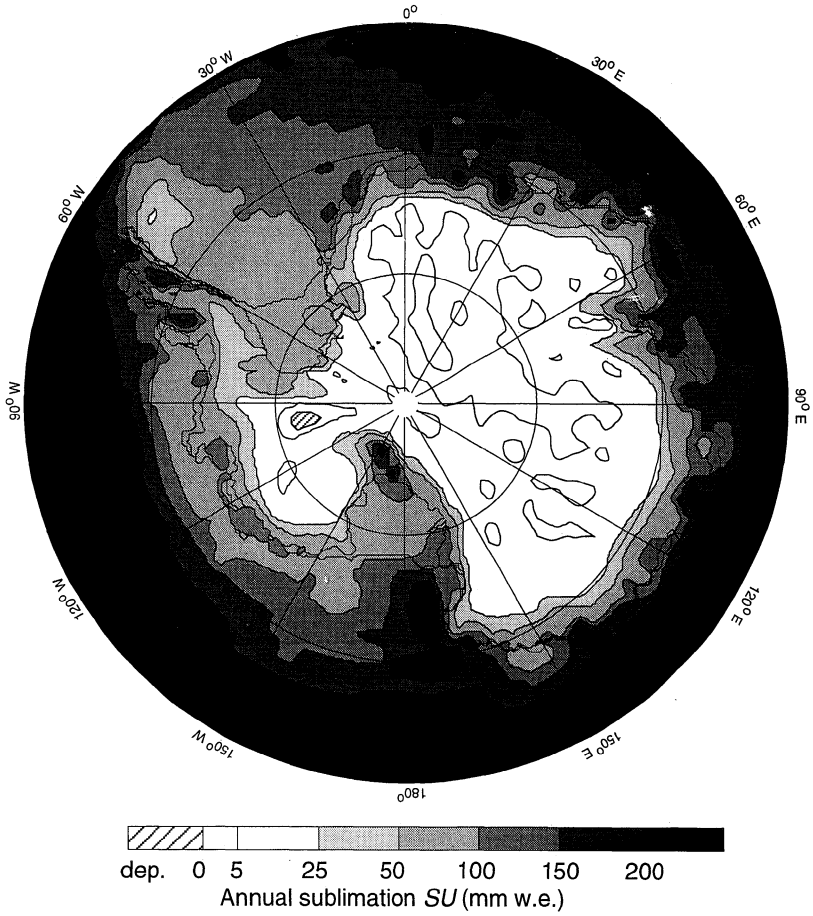


Figure 9. Modeled total annual sublimation SU (mm water equivalent (w.e.)).

tion of the sublimation. However, less humidity in the atmosphere will also lead to less absorption of longwave radiation in the atmosphere, fewer clouds, and lower surface temperatures, which in turn, suppresses sublimation. This shows that there is no straightforward relation between atmospheric moisture content and the surface latent heat flux.

With respect to evaporation and sublimation, coastal Queen Maud Land is an especially interesting area: sea ice that is produced in the Weddell Sea area and transported eastward by the predominant currents clearly suppresses evaporation in the sector 60°W − 30°E (Figure 9). This causes the relatively dry and cold climate of coastal Queen Maud Land, when compared to other parts of the East Antarctic coast [*Giovinetto and Bentley*, 1985]. That makes this part of Antarctica especially susceptible to the formation of blue ice fields. To isolate the effect of sublimation on the local mass balance, Figure 10 shows the annual fraction SU/PR. Four areas, where sublimation on an annual basis removes more than 70% of the precipitation, clearly stand out in Figure 10: East Queen Maud Land, the Lambert Glacier basin, Victoria Land, and the southern part of the Ross Ice Shelf. All these areas are well known for their low surface mass balance [*Giovinetto and Bentley*, 1985] and the occurrence of blue ice fields, where the snow layer has been totally removed from the underlying ice and the local mass balance is negative [e.g., *Swithinbank*, 1988]. This suggests that sublimation, besides erosion due to horizontal divergence of drifting snow [*van den Broeke and Bintanja*, 1995b], could play an important role in the formation of blue ice areas, a subject that will be explored in a forthcoming paper.

Averaged over the continent, the model predicts that 14% of the annual precipitation over Antarctica is removed by sublimation. Assuming that the model overestimates annual precipitation by 50 mm w.e. [*Ohmura et al.*, 1996], this fraction would be even larger, 18%. However, because the model also appears to somewhat overestimate sublimation (section 3), a conservative estimate would be that 10–15% of the annual precipitation over Antarctica is removed by sublimation. From ECMWF analyses, *Genthon and Braun* [1995] arrived at a figure of 12% (excluding the ice shelves). During the summer months this fraction can be as high as 30%, when precipitation amounts are lower than average and sublimation reaches a maximum.

5. Discussion

It is often assumed that areas with high sublimation rates coincide with places where strong katabatic winds prevail [i.e., *Rusin*, 1961]. However, judging from Figures 2 and 9, this is not a sufficient condition to explain the variations of sublimation along the East Antarctic coast. We propose here that enhanced horizontal advection of dry air within the ABL accounts for the occurrence of anomalous high annual sublimation rates, i.e., a combined effect of wind speed and horizontal moisture gradient.

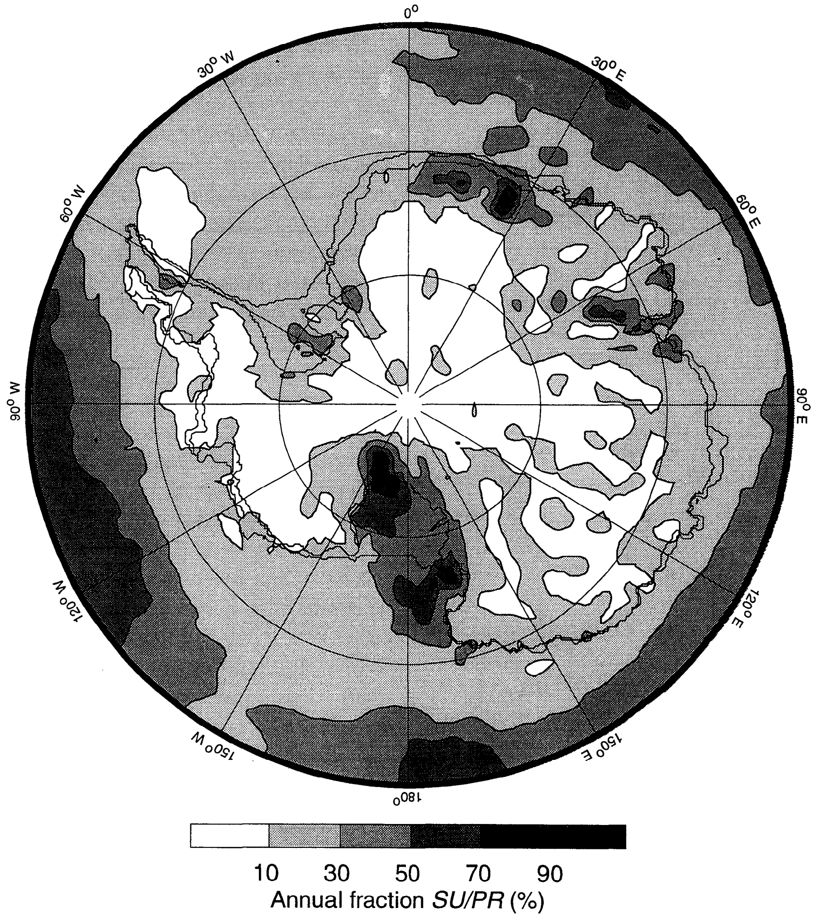


Figure 10. Modeled fraction of the annual precipitation PR that is removed from the surface by sublimation SU, expressed as a percentage (%).

5.1. Simplified Moisture Budget of the ABL

In anticipation of a more sophisticated analysis we present an order of magnitude estimate of the ABL moisture budget in this section. By assuming steady state conditions the vertically integrated moisture budget in the ABL reduces to a simple balance:

$$\frac{\partial Q}{\partial t} = 0 = -\left(U\frac{\partial Q}{\partial x} + V\frac{\partial Q}{\partial y}\right) + \frac{w_e \Delta q + \overline{(w'q')_{h_s}}}{H} \quad (2)$$

where U, V, and Q are the characteristic (vertically integrated) ABL values of meridional wind speed, zonal wind speed, and specific humidity, respectively. H is the characteristic depth of the ABL, $w_e\ \Delta q$ is the flux of moisture at the top of the ABL caused by turbulent entrainment (where w_e is the vertical entrainment velocity and Δq is the moisture difference between the ABL and the free atmosphere), and $(w'q')_{h_s}$ represents the turbulent moisture flux at the surface. Equation (2) states that in steady state conditions, horizontal advection (first two terms on the right-hand side) is balanced by the vertical divergence of the turbulent moisture flux in the ABL (third term), which is expressed as the difference between surface sublimation and entrainment at the ABL top. *Van den Broeke* [1996a] mentioned the role of moisture advection in the ABL over the melting zone of the Greenland ice sheet, where the ABL typically contains more moisture than the overlying atmosphere. For typical Antarctic conditions it is often assumed that the contrary is valid, i.e., that moisture content of the free atmosphere just above the ABL is higher than that in the ABL [*Fortuin and Oerlemans*, 1992]. This indicates that turbulent entrainment at the ABL top represents a moisture source in (2), so that in areas where sublimation occurs at the surface, horizontal advection of dry air is the only moisture sink in the budget.

5.2. Dry Air Advection in the Coastal Zone by the Mean Flow

To make an order-of-magnitude estimate of the advection term in the moisture budget in (2), we assume that the monthly mean 2 m specific humidity and 10 m wind components are representative of the entire vertical extent of the ABL, i.e., that they equal their characteristic values. By doing this we assume a well-mixed ABL, which is probably a better approximation for the coastal zone (high wind speeds) than for the interior. Moreover, by using monthly mean values, we only take into account the moisture advection by the mean flow and neglect the contribution of transients. It is generally assumed that transients are responsible for the majority of moisture transport in the free atmosphere over Antarctica, but since the ABL flow in Antarctica is generally constant in direction, their contribution to the ABL moisture transport is probably small. This is confirmed by an analysis of *Bromwich* [1978] of wind and moisture profiles at Mirny station. Again, this assumption is likely to hold better in the coastal zone than in the interior.

The magnitude of the advection term thus obtained is presented in Figures 11a and 11b for summer and winter, respectively, where we expressed the rate of moisture change owing to advection $(\partial Q/\partial t)_{\text{adv}}$ in g kg^{-1} per day. The negative numbers in Figure 11 indicate that the ABL in the entire coastal zone of Antarctica experiences drying through advection, but with large variations from place to place. Qualitatively, areas where high advection rates occur coincide with high sublimation rates in Figure 9. Are these advection rates large enough to explain the observed sublimation rates? If we assume a typical summertime ABL depth in the katabatic wind zone of 1000 m [e.g., *Kodama et al.*, 1989; *Gallée et al.*, 1996], we obtain via (2) that a moisture sink by advection of -0.3 g kg^{-1} day^{-1} (a high value in Figure 11a) balances a moisture input that is equivalent to a latent heat flux of -10 W m^{-2}, which represents a significant part of the sublimation that occurs (Figure 8a). However strong this simplification, it shows that advection of dry air plays an important role in the summer moisture budget.

During the winter both the absolute values and horizontal gradients of specific humidity decrease because of lower temperatures. However, the katabatic winds are stronger in the winter, and are generally directed more downslope, which means that typical values of $(\partial Q/\partial t)_{\text{adv}}$ in the East Antarctic coastal zone are still typically -0.1 g kg^{-1} day^{-1} (Figure 11b). If we now take $H = 1500$ m, this advection is able to balance a surface latent heat flux of -5 W m^{-2}. For most coastal regions, this represents close to all of the actual sublimation (Figure 8b), indicating that the role of horizontal advection is probably even more important in the winter than in the summer.

Variations in dry air advection as shown in Figures 11a and 11b result from variations in the katabatic wind field and the strong temperature dependence of ABL moisture content. The specific humidity gradient, like temperature, is directed more or less parallel to the fall line of the topography (i.e., is primarily determined by elevation gradients). This means that the advection of dry air is enhanced in areas where the magnitude of the downslope component of the katabatic wind and/or the topographic slope is large. For instance, the pronounced dry air advection in the area where the Transantarctic Mountains border the Ross Ice Shelf is clearly associated with the steep transition from the plateau (2500–3000 masl) to the ice shelf (100 masl). The strong sublimation rates remove a large part of the annual precipitation in this area (Figure 10), resulting in the frequent occurrence of blue ice areas. In reality, this is especially true on the surface of outlet glaciers that serve as "air highways" between the plateau and the ice shelf [*Swithinbank*, 1988], but the model topography does not capture these individual glaciers. On the eastern border of the Ross Ice Shelf at Siple Coast, where the gently sloping ice streams from West Antarctica prevent effective dry air advection at the foot of the ice streams, the maximum advection occurs higher up the slope and to the south, where the katabatic winds are stronger (Figure 2).

Summarizing this section, maxima in dry air advection in the coastal zone of East Antarctica are identified as places where strong downslope winds are active in combination with a steep surface slope (e.g., Adélie Land, the basin of the Lambert Glacier, and East Queen Maud Land). The strongest winds are usually found on the eastern side of south-north directed promontories in the ice sheet topography that force the katabatic winds to converge, accelerate, and have a large downslope component. These areas are easily identified in Figures 11a and 11b.

5.3. Horizontally Homogeneous Conditions

In the special case of horizontally homogeneous conditions the advection term will be small, and (2) states that in stationary conditions, sublimation/deposition at the surface is balanced by entrainment of dry/humid air at the top of the ABL. Figures 11a and 11b suggest that this balance could approximately hold on the East and West Antarctic plateau and on both large ice shelves. The general assumption that small net deposition occurs on the plateau thus indicates entrainment of moist air at the top of the ABL. This agrees with the general picture of vertical moisture distribution in the lower Antarctic atmosphere.

Things are different for the southern part of the Ross Ice Shelf, where significant net sublimation is observed at the surface (section 3 [*Stearns and Weidner*, 1993]). Because the advection term is negligible here as well, dry air must be entrained at the top of the ABL to maintain the balance expressed in (2). This is not in disagreement with the general circulation in this area: the semipermanent low-pressure cell in the Ross Sea forces warm and humid air masses toward the coast of Marie Byrd Land (Figures 1 and 2), where they release their snow load. After that the air passes the saddle area near Byrd station and descends toward Siple coast on the Ross Ice Shelf, thereby warming and drying. Here it encounters, and flows over, the colder katabatic air that originates from the East Antarctic plateau, as is confirmed by recent observations in this area [*Bromwich and Liu*, 1996; *Liu and Bromwich*, 1997]. While descending, the West Antarctic air becomes highly unsaturated, which, upon entrainment into the ABL, enables the pronounced surface sublimation that is observed in this part of the Ross Ice Shelf (Figure 8a).

6. Conclusions

GCM-produced sublimation rates over Antarctic snow are in general agreement with the small number of available observations. The annual cycle of sublimation is qualitatively well modeled, although the model tends to overestimate sublimation during winter. However, turbulent moisture fluxes in Antarctica have seldom been directly measured, and the uncertainties in the observations are large. We estimate that 10–15% of the yearly precipitation on Antarctica is removed by sublimation. Sublimation rates in the coastal zone of East Antarctica show large spatial variations that cannot be explained by the occurrence of strong katabatic winds alone. Analysis of the simplified moisture budget of the ABL showed that

1. Horizontal advection of dry air plays an important role in the moisture budget of the ABL in the Antarctic coastal zone, where it represents the primary moisture sink. It follows that high annual sublimation rates (150–250 mm w.e.) occur at places where advection of dry air is enhanced, i.e., where (1) katabatic flow is strong and has a large downslope component and (2) where there is a steep transition from the plateau toward the coastal zone. A combination of these factors is found eastward of south-north-directed promontories in the Antarctic topography, for example, in Adélie Land and in East Queen Maud Land.

2. In areas with horizontally homogeneous conditions, like the plateau region and the large ice shelves, horizontal advection is small and sublimation at the surface must be balanced by entrainment of dry air at the ABL top. Since in Antarctica the ABL is generally overlain by moist air, it requires special

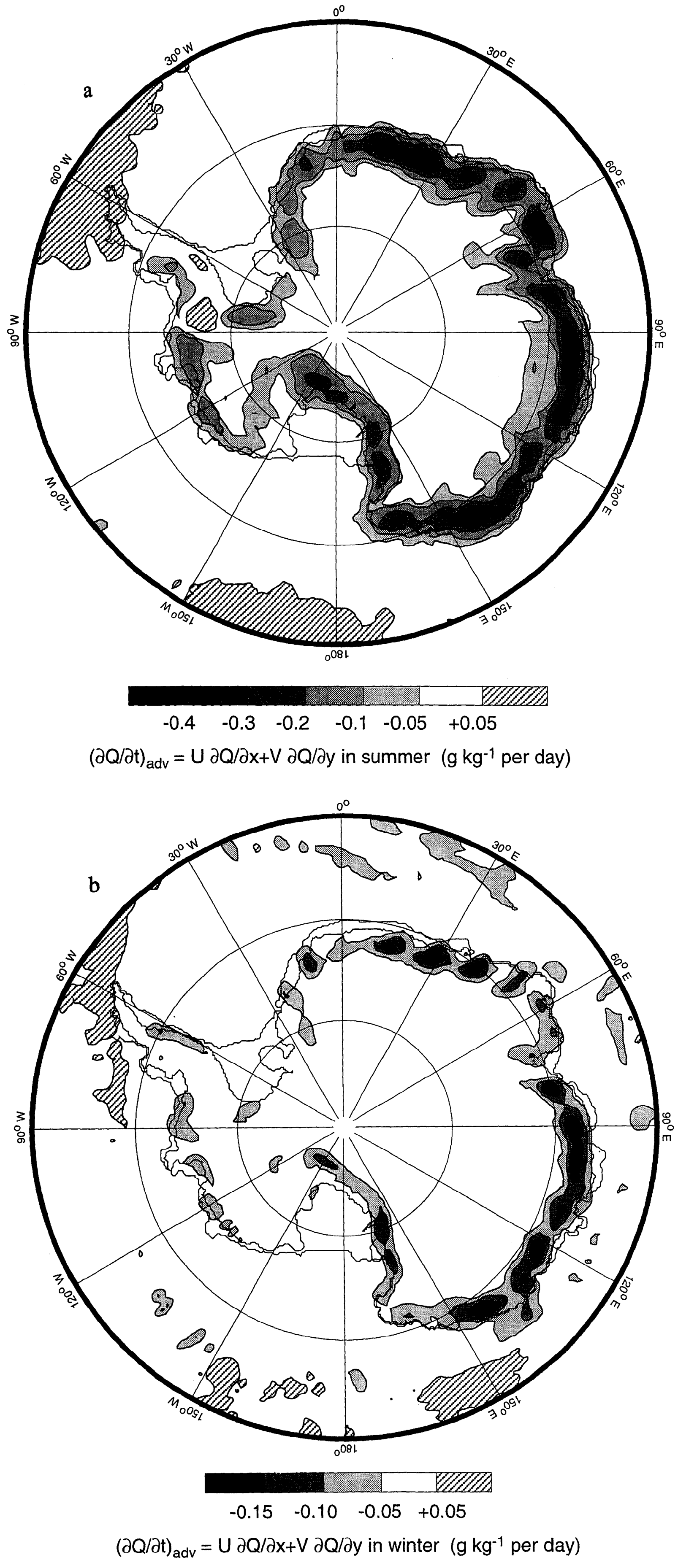


Figure 11. Modeled average magnitude of advection by the mean flow in (a) the summer (DJF) and (b) the winter (JJA).

conditions for significant sublimation to occur at the surface. For the southern part of the Ross Ice Shelf these conditions are provided by dry air descending from West Antarctica.

We found that the modeled geographical distribution of areas where annual sublimation rates remove a large part of the annual precipitation coincides roughly with the present-day distribution of blue ice areas. This suggests that sublimation might play an important role in the formation of blue ice.

It is clear that more observations of the energy balance over snow are needed to thoroughly check the performance of GCMs over Antarctica and also over Greenland. The employment of automatic weather stations [*Stearns and Weidner*, 1993] could prove to be a powerful tool in this respect, in combination with models to calculate the surface energy balance [*Bintanja et al.*, 1997].

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