Continental-Scale Simulation of the Antarctic Katabatic Wind Regime*

THOMAS R. PARISH

Department of Atmospheric Science, University of Wyoming, Laramie, Wyoming

DAVID H. BROMWICH

Byrd Polar Research Center, The Ohio State University, Columbus, Ohio

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ABSTRACT

Katabatic winds are a common feature of the lower Antarctic atmosphere. Although these drainage flows are quite shallow, there is increasing evidence that the low-level circulations are an important component in establishing large-scale tropospheric motions in the high southern latitudes. Three-dimensional numerical simulations of the Antarctic katabatic wind regime and attendant tropospheric circulations have been conducted over the entire continent to depict the topographically forced drainage patterns in the near-surface layer of the atmosphere. Results of the simulation enable a mapping of katabatic wind potential and identification of coastal regions which may experience anomalously intense katabatic winds. A large upper-level cyclonic circulation forms rapidly in response to the evolving katabatic wind structure in the lower atmosphere, suggesting that the drainage circulations are an important component in prescribing the resulting circumpolar vortex. These results imply that some representation of the Antarctic katabatic wind regime is necessary in general circulation models in order to properly simulate the large-scale circulations about the continent.

1. Introduction

In the past few decades, significant advances have been made in understanding the dynamics of the surface wind regime over the Antarctic continent (Ball 1960; Lettau and Schwerdtfeger 1967; Mahrt and Schwerdtfeger 1970; Schwerdtfeger 1970; Radok 1973). The strong radiational cooling of the sloping ice field produces a horizontal pressure gradient force directed in a downslope sense and leads to the development of the persistent and often intense katabatic wind regime in the lowest portion of the Antarctic atmosphere. Katabatic winds at the steep terminus of the coastal ice slopes are among the strongest surface winds ever recorded; sites such as the Cape Denison station (see Fig. 1) situated along the coast of East Antarctica experiences yearly average winds of approximately 20 m s^{-1}. Recent research has emphasized the nonuniformity of the drainage flow off the central plateau of the elevated Antarctic ice cap and resulting impact on coastal katabatic winds. Parish (1981, 1984) notes that some sections of the continental interior are characterized by a concentration of cold air drainage streamlines; the flow confluence acts to enhance the supply of negatively buoyant air available to downslope stretches. Such "confluence zones" have been linked to anomalously intense katabatic wind regimes such as those that exist near Cape Denison (Parish 1981) and Terra Nova Bay (Bromwich and Kurtz 1982, 1984; Kurtz and Bromwich 1985; Bromwich 1989a; Bromwich et al. 1990). The continental-scale drainage pattern produced by Parish and Bromwich (1987) suggests that numerous interior confluence zones may be found over the Antarctic continent and that the intense katabatic winds of Cape Denison and Terra Nova Bay may be duplicated elsewhere about the continental perimeter.

Although a significant body of literature exists pertaining to katabatic winds, little research has focused on the impact of Antarctic near-surface winds on the atmospheric circulation in the middle and upper troposphere over Antarctica and the high southern latitudes. Nearly 80 years ago, Hobbs proposed the so-called "glacial anticyclone" theory in which he envisaged a fixed, permanent anticyclone situated over ice caps. This theory led Hobbs to explain the climate of the Greenland ice cap as well as the main attributes of Pleistocene glaciation. Although some of the original arguments are flawed (Hare 1951), the seeds of truth are evident in some basic tenets of the theory. The radially diverging boundary-layer drainage currents off the ice cap and across the coastline require a compensating influx of warmer air masses in the middle tro-

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Corresponding author address: Prof. Thomas R. Parish, Department of Atmospheric Science, University of Wyoming, Room 6034, Engineering Building, Laramie, WY 82071-3038.

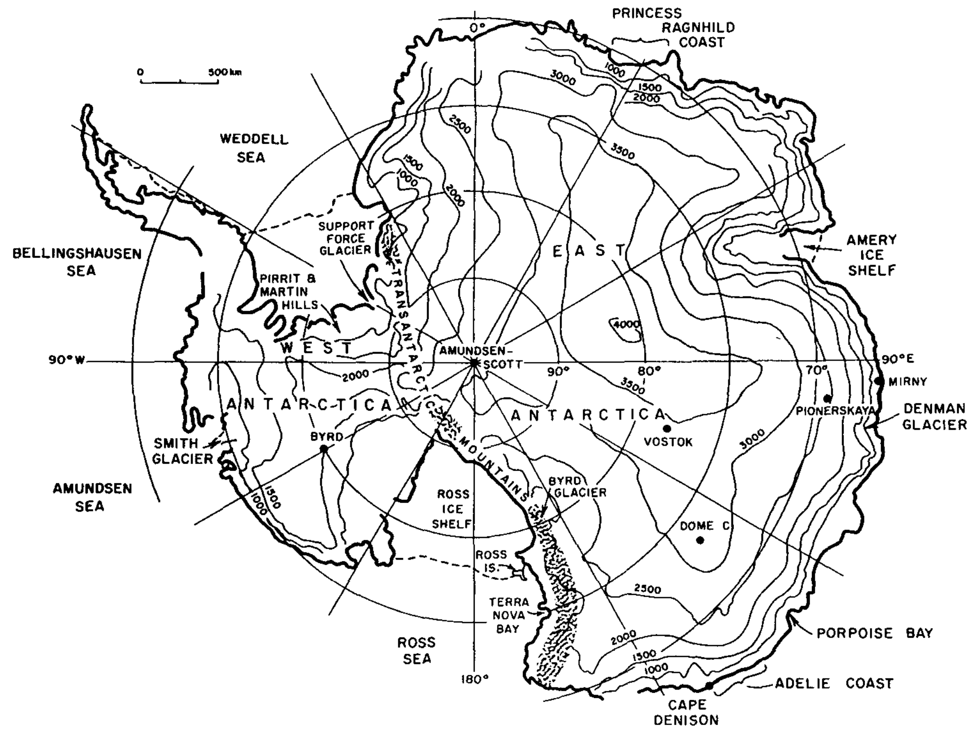


FIG. 1. The Antarctic continent with selected geographical features.

posphere above the continent and general subsidence over the Antarctic continent. Thermal wind considerations arising from the radiatively cooled layer of air near the surface suggests an abrupt wind shift in the lower atmosphere above the inversion, and the eventual establishment of a cold-core low pressure system with height centered over the continent (Lettau and Schwerdtfeger 1967). Schwerdtfeger (1967) notes that the circumpolar vortex as represented on time-averaged 500-hPa maps is remarkably asymmetric with respect to the mean 500-hPa isotherms. Kutzbach and Schwerdtfeger (1967) have attributed this asymmetry to the occurrence of differential temperature advection patterns about the continent. In particular, warm air advection and rising motion are frequently found in the upper troposphere over West Antarctica with the opposite conditions prevailing over East Antarctica.

Recently, a series of papers has illustrated the potential importance of the Antarctic katabatic wind regime on the large-scale tropospheric circulation in the high southern latitudes. Egger (1985) has used an axisymmetric model of the Antarctic to simulate the three-dimensional mass circulation associated with the low-level drainage flows. The results of the numerical experiment suggest that an upper-level vortex develops rapidly in response to the katabatic wind circulation. James (1986) has also conducted numerical experiments of the Antarctic katabatic wind circulation using an axisymmetric framework. Mass continuity requires that the diverging boundary-layer drainage currents be balanced by convergence in the middle troposphere; the convergent inflow generates cyclonic vorticity. The vorticity generated by the meridional circulation induced by the katabatic drainage has been estimated to be comparable to the vorticity generated by the differential heating and attendant temperature gradient between the ice surface and ocean (James 1986). Kottmeier and Stuckenberg (1986) have used a quasi-geostrophic analytical model to describe the relationship between the temperature field over the sloping Antarctic terrain and the mean circulation features over Antarctica. Their results suggest a strong interplay between the terrain and overlying potential temperature fields. James (1989) notes that the vorticity induced by the drainage flow may well be an important component of the large-scale, upper-tropospheric circulation in the high southern latitudes. The axisymmetric model experiments also produced some interesting and somewhat unexpected results. In both Egger (1985) and James (1989), the katabatic winds in the boundary layer decayed over a time scale of a few days because of the opposing horizontal pressure gradient force of the developing upper-level vortex. This is in contrast with numerous observations at both interior and coastal Antarctic stations, which suggests that the katabatic wind regime is highly persistent. Both authors have attributed the anomalous dissipation of the katabatic circulation to the lack of northward transport of cyclonic vorticity in the upper troposphere above Antarctica. They state that three-dimensional eddy motion, associated with extratropical cyclones, is the most likely means by which the atmosphere removes vorticity from the upper atmosphere over Antarctica.

This paper will address two issues. First, development of the katabatic wind circulation within the Antarctic boundary layer will be examined using a three-dimensional primitive equation model. The model simulations have been conducted using the actual terrain representation for Antarctica so as to enable comparison with available wind data. The resulting katabatic wind streamlines will serve as a check on the earlier analysis of Parish and Bromwich (1987) which used the diagnostic approach of Ball (1960) to infer drainage streamlines. Second, the development of the circumpolar vortex will be investigated to assess the interaction between the drainage patterns in the lower troposphere with upper-tropospheric circulations. The sensitivity of the vortex evolution to the katabatic wind regime implies that it may be necessary to incorporate such processes in general circulation model (GCM) studies to properly prescribe the meridional temperature gradient and attendant wind structure.

2. Model description

A three-dimensional version of the numerical model described in Parish and Waight (1987, hereafter PW) was used in this study of Antarctic surface winds. The model is a modified form of that presented in Anthes and Warner (1978) and includes prognostic equations for both horizontal momentum components, temperature, and continuity of mass. The model grid is of Cartesian form with the Coriolis parameter set to -1.3×10^{-4} s^{-1}; all equations are written in sigma coordinates to allow for orography. The momentum and continuity equations are expressed in flux form following Anthes and Warner; the thermodynamic equation is written in an advective form as suggested by Seaman and Anthes (1981). The advective form of the thermodynamic equation was shown to be slightly more stable in the numerical experiments conducted by the above authors. The model employs open boundary conditions in which mass and energy are permitted to leave the model domain. Prognostic variables are extrapolated outward to the boundaries to help reduce spurious reflection. The exact form of the model equations and details of the integration strategy can be found in PW.

One significant difference between the present three-dimensional simulations and the earlier two-dimensional simulations of PW is the form of the boundary layer representation. In PW, a 15-level model was used with explicit representation of turbulent heat and momentum fluxes within the boundary layer. In addition, explicit radiative flux calculations were used to drive the drainage flows. Here the model contains six vertical levels (sigma levels 0.98, 0.95, 0.85, 0.60, 0.35, 0.10); a bulk parameterization of the boundary layer was used in which the entire katabatic regime is represented by a single layer. The boundary-layer height is set at approximately 125 m and corresponds to the top of the first sigma level. No explicit radiational cooling is attempted. Rather, a constant cooling of the katabatic layer is specified. No radiative cooling is prescribed for the levels above the first sigma surface although mixing processes and large-scale circulations act to transport cold air aloft. The cooling rate was obtained from the results of PW using the more detailed boundary layer form (for example, Fig. 7 in PW). This simplification reduces computational time without introducing unjustified assumptions. As can be seen in PW, the cooling rate of the katabatic layer remains roughly constant after a start-up period of approximately 6 h; from 12 to 24 h the cooling rate remains nearly constant. The net cooling of the katabatic layer can be seen to be strongest over the steep coastal slopes owing primarily to the strong downward turbulent heat flux associated with strong katabatic winds. Cooling rates near 100 W m^{-2} are suggested by PW near the coast within the katabatic layer. Over the more gentle inland ice slopes, model results imply the cooling rates in the katabatic layer decrease by approximately one-third. This variation in cooling rates has been incorporated into the bulk version of the model; constant cooling rates were specified by altitude and vary from approximately 110 W m^{-2} at the coast to 60 W m^{-2} over the high plateau.

To compare results of the bulk model with those obtained from the high resolution model, a series of 24-h simulations were conducted using the two-dimensional form of the model equations. The idealized ice topography of PW was used in this two-dimensional comparison. Each model run was initialized about a state of rest using the same initial temperature profile. Figure 2 illustrates the evolution of surface temperature and the downslope component of the wind speed at the lowest level at interior and near-coastal grid points for each model. Differences in the surface temperature during the first few hours of model integration are evident in Fig. 2a. Presumably this is due to the effect of radiative flux divergence near the surface in the full model and the lack of significant katabatic flow acting to mix the lower atmosphere. Note that by 6 h at the near-coastal grid point and 9 h at the interior grid point, the drainage flows (Fig. 2b) become established in the high resolution model. At this time, surface temperatures actually rise in response to the increased mixing processes in the lower atmosphere, which transport warmer air above the katabatic layer to the surface. After the initial stages of katabatic wind development, reasonable agreement in both downslope wind component at the lowest level and surface temperature is seen between models. There is a tendency for the bulk layer to produce katabatic winds approximately 1 to 2 m s^{-1} greater than seen in the high resolution model after the 24-h integration. Because such differences are well within the uncertainty of such simulations, the

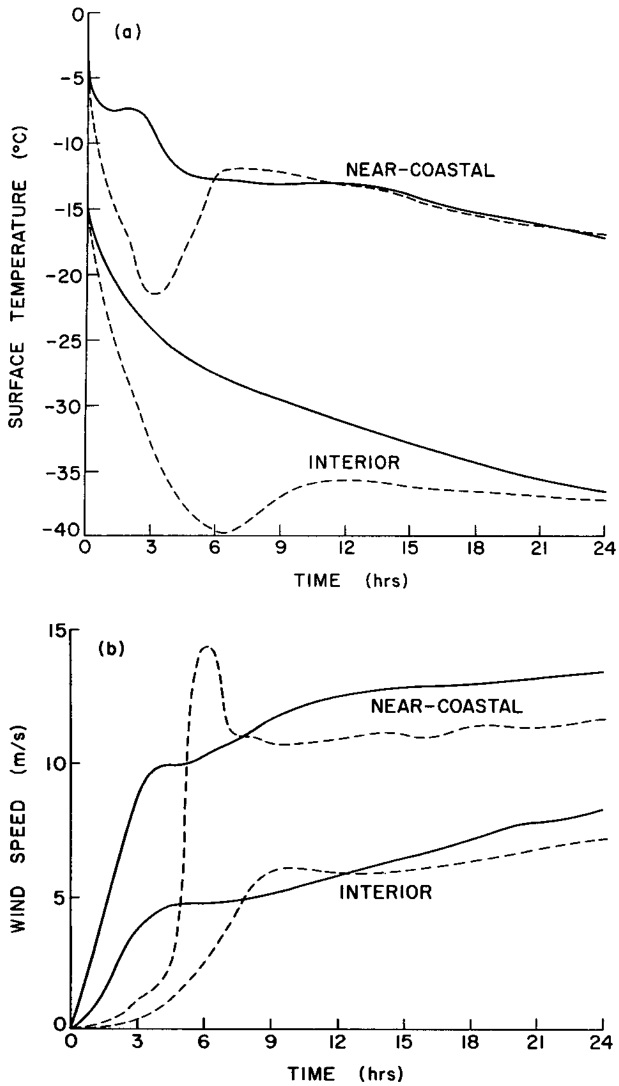


FIG. 2. Comparison of bulk model (solid lines) with multilevel model (dashed lines); (a) surface temperature (°C), (b) katabatic wind speed (m s^{-1}).

results of the model comparisons are encouraging. It can be concluded that the bulk model is able to capture the gross features of the katabatic flow regime with acceptable fidelity.

In this simulation, the heights of the actual Antarctic ice terrain were used. The model domain consists of a square grid (60 × 60 points) centered on the South Pole with a grid spacing of 100 km. The height data were obtained from the digitized version of the detailed Antarctic topographic map presented in Drewry (1983; height values may be obtained on magnetic tape from the National Snow and Ice Data Center in Boulder, Colorado). No explicit smoothing algorithms have been applied to the raw height data. The unsmoothed point values of Antarctic heights retain representation of the steep terrain gradients encountered near the coastal slopes, an essential factor in the simulation of strong drainage flows near the coast. Although the grid representation cannot adequately resolve small-scale details frequently encountered in regions of mountainous terrain, the general shape of the ice topography and major ice rises are well depicted.

3. Model results

To assess the influence of the Antarctic continent and attendant katabatic wind regime on the larger-scale tropospheric circulations, the model equations were initialized about a state of rest; geostrophic winds at all levels were set to zero. Thus, at the start of the model simulation, no horizontal pressure gradients were present. The initial temperature profile is moderately stable (Brunt–Väisällä frequency of 0.01 s^{-1}) and follows that used in PW. Additional simulations have been conducted in which the initial temperature profile was allowed to vary over a wide range of conditions from isothermal to near adiabatic. Some minor differences were observed in the intensity of the drainage circulations with the strongest katabatic winds being associated with the lowest ambient stabilities. However, the form of the continental drainage patterns remained essentially the same. It was therefore concluded that the initial temperature profile is only of secondary importance in the development of katabatic wind circulations.

A 48-h integration period was used in the model experiment; katabatic winds began to form in the first few hours, and after approximately 12 h into the simulation did not show significant change. Longer integration times were attempted with only limited success. Numerical instabilities began to appear after approximately 72 h. The source of the instabilities was traced to the discrete nature of the terrain. Height changes in excess of 2000 m over the 100-km grid spacing are depicted near the Transantarctic Mountains. Such steep gradients produce anomalous accelerations after extended integration time periods and eventually begin to influence the solutions at adjacent grid points. Later experiments with a smoothed version of the Antarctic continent were free of such instabilities after integration periods in excess of 10 days. However, smoothing of the terrain seriously degraded the fidelity of the resulting katabatic wind patterns and the results will not be presented.

Figures 3a and 3b show the resulting streamlines and wind speeds of the katabatic flows, respectively, in the lowest layer of the model after the 48-h integration period. Figure 3a is nearly identical to the large-scale streamline map prepared by Parish and Bromwich (1987) despite the radically different approaches. The close agreement provides additional confirmation of the utility of Ball's steady-state equation system in estimating gross characteristics of the Antarctic windfield.

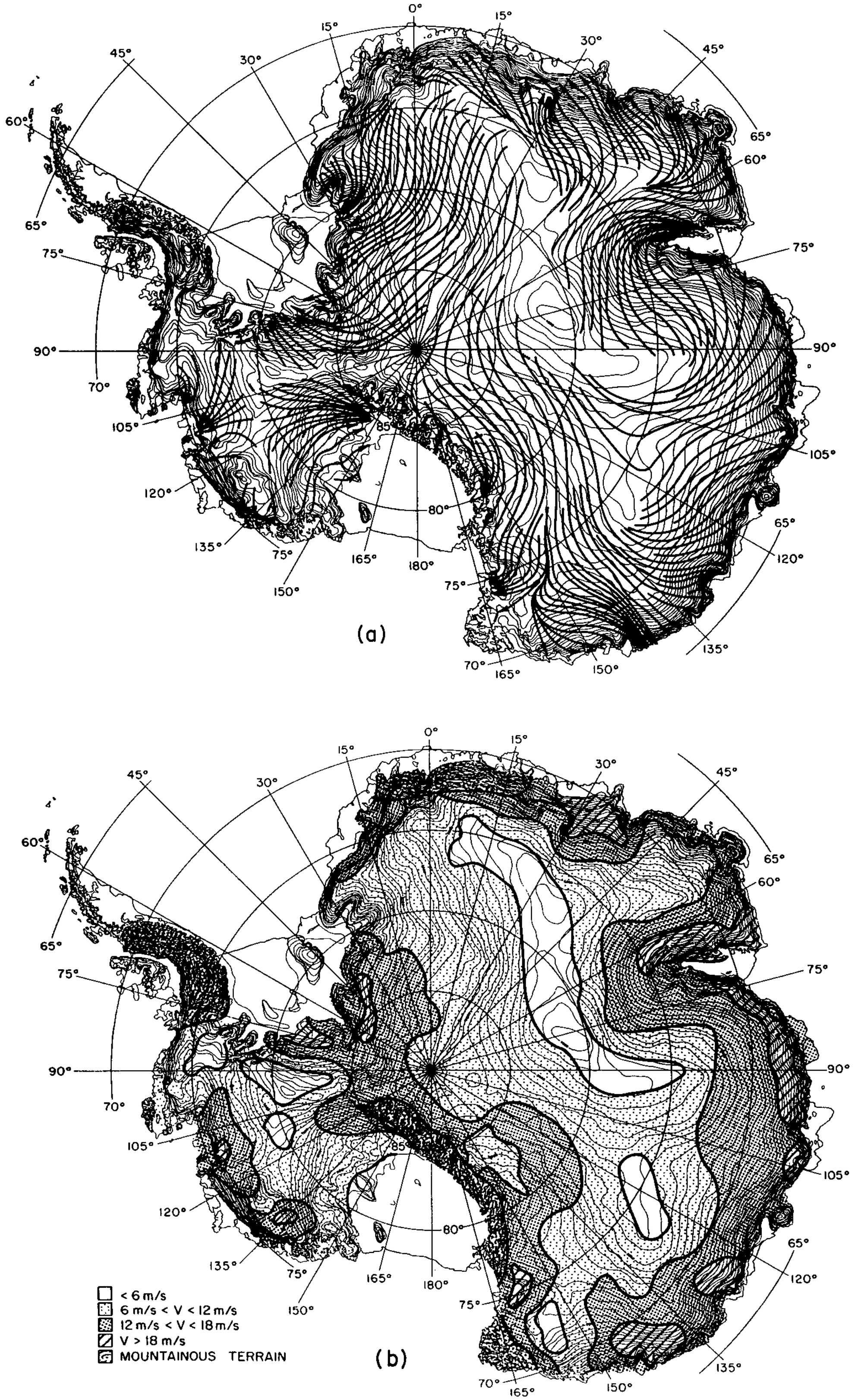


FIG. 3. Results of 48-h model simulation; (a) streamlines of the katabatic windfield, and (b) katabatic wind speed (m s^{-1}).

The outstanding feature of the streamline map is the highly irregular drainage pattern in the lowest level of the Antarctic atmosphere. The main drainage occurs in a radially outward pattern originating atop the various interior ice lobes. Significant irregularity in the streamline patterns can be seen over the interior and near-coastal regions of the continent. In certain locations, such as upslope from the Adelie Land coast and Terra Nova Bay, a marked confluence of the drainage patterns can be seen. As noted by Parish (1981, 1984), Parish and Bromwich (1987), and Bromwich et al. (1990), such confluence zones act as anomalously large sources of negatively buoyant air, which enhance katabatic winds downwind of such features. The model simulation illustrates a number of such confluence zones; most prominent are the confluence features upwind from Adelie Land and west of Amery Ice Shelf.

The 100-km resolution of the Antarctic terrain is insufficient to capture all confluence features. It is well known that strong katabatic winds issue from nearly all glacier valleys along the coastal range situated on the western edge of the Ross Ice Shelf. The small scale of such features (often on the order of 10 km) preclude representation in the present model study. One prominent example is the Byrd Glacier. Detailed terrain maps clearly show a topographic depression from the head of the glacier extending over 100 km into the interior. Thermal infrared satellite imagery often reveals evidence of katabatic drainage within and beyond the glacier valley (see Bromwich 1989b). Only a hint of the confluence feature upwind from Byrd Glacier can be seen in the simulation. In general, small-scale confluence features under 200 km are not resolved in this study and must await higher resolution modeling attempts.

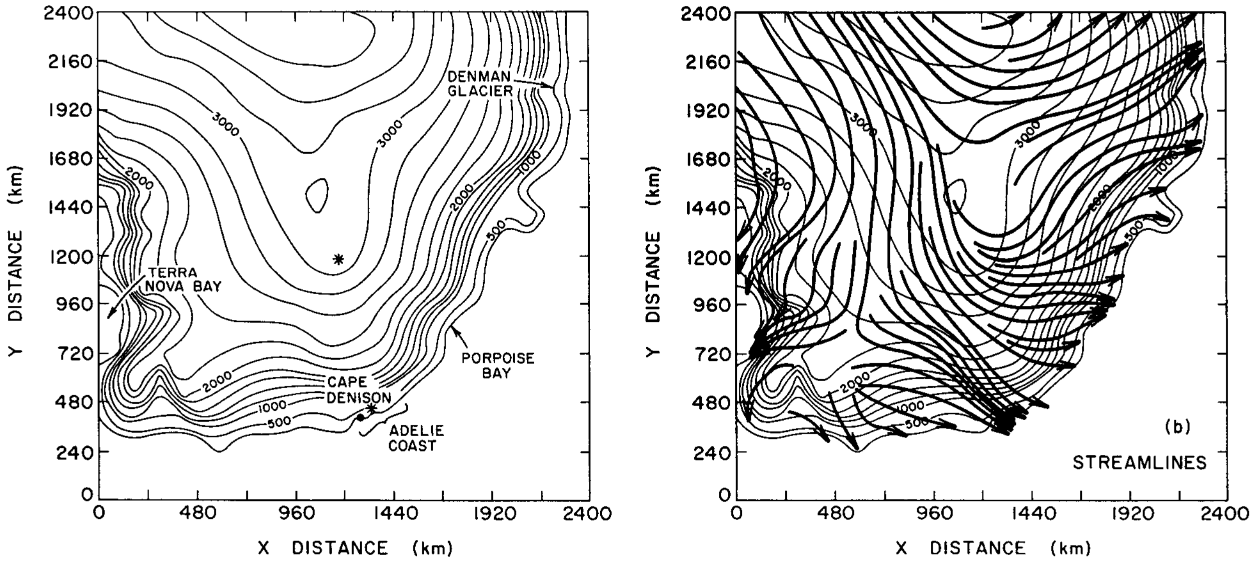
The pattern of katabatic wind speed over the entire continent after the 48-h time integration is shown in Fig. 3b. It should be pointed out that the simulated wind speeds have been produced under idealized conditions of wintertime radiative cooling in a cloud-free atmosphere over a two-day period without the disruptive influences of extratropical cyclones. Thus, the wind speeds should be viewed as mature katabatic wind episodes rather than as representative time-averaged winds. In nearly all cases, resultant wind speeds at particular sites are less than shown in Fig. 3b. A comparison between multiannual resultant wind speeds at various stations with corresponding grid point values of wind speed is shown in Table 1. Simulated katabatic winds are more intense than the resultant winds by a factor of two in some cases, although the simulated wind direction often is in good agreement with observation. This is not surprising since Antarctic surface winds have exceptionally high wind constancy values, indicating nearly unidirectional flow.

TABLE 1. Comparison of multiannual resultant wind data from selected Antarctic stations with model winds at the nearest grid point.

Station	Resultant wind V (m s^{-1})	Resultant wind dd (deg)	Model wind V (m s^{-1})	Model wind dd (deg)
Byrd	6.4	013	6.6	005
Vostok	4.1	243	8.2	220
Pionerskaya	9.3	131	14.5	139
Amundsen-Scott	4.6	039	8.9	045
Dome *C*	2.0	205	4.4	204
Adelie Land (C. Denison)	19.0	161	22.6	157
Mirny	9.7	127	20.8	125

In general, the weakest katabatic winds follow the backbone of the east Antarctic continent. The highest elevations are associated with the most gentle terrain slopes and hence weakest drainage flows. The wind speeds increase away from the ice ridges in a monotonic manner in response to increasingly steeper terrain slopes. Effects of drainage confluence begin to modify the relationship between wind speed and terrain slope near the coast. Note that the simulated katabatic wind speeds along the coastal perimeter of Antarctica show a wide range; from the rather tranquil winds over much of the West Antarctic coastline adjacent to the Ross Sea to localized regions of strong katabatic flows near Adelie Land and the Amery Ice Shelf. Clearly depicted are the well-documented intense katabatic wind regimes of Cape Denison (Mawson 1915; Mather and Miller 1967; Loewe 1974; Parish 1981) and Terra Nova Bay (Bromwich and Kurtz 1982, 1984; Bromwich 1989a; Parish and Bromwich 1989). The analysis also suggests that other broad-scale areas may be prone to intense, persistent katabatic winds. Regions of enhanced katabatic winds in East Antarctica are shown along the western shore of Porpoise Bay (67°S, 128°E), near Denman Glacier situated approximately 90 km west of the Bunger Hills (67°S, 100°E), along the western edge of the Amery Ice Shelf (72°S, 65°E), along the Princess Ragnhild coast (71°S, 30°E), and near the head of the Support Force Glacier (83°S, 45°W). While not explicitly depicted in Fig. 3b, there is some evidence to suggest that strong katabatic winds may prevail along both Slessor and Recovery glaciers, which are situated approximately 300 km northeast from the Support Force Glacier. The regions of West Antarctica with the greatest katabatic wind potential appear to be in the vicinity of Smith Glacier (75°S, 112°W) and the coastal regions near the Martin and Pirrit Hills (82°S, 82°W). The zones of enhanced katabatic winds in West Antarctica have been described in Parish and Bromwich (1986), and evidence supporting the Smith Glacier (adjacent to the Dotson Ice Shelf) confluence zone is presented. In nearly all cases, confluence zones can be located in Fig. 3a upwind and along these zones of strong katabatic wind potential.

Coastal Adelie Land is, without question, the most infamous katabatic wind-prone section of the Antarctic continent. Mawson's Australasian Antarctic Expedition 1911–14 wintered two seasons at the base camp of Cape Denison where the resultant wind for the entire observing period was over 19 m s^{-1}, the most intense surface wind regime on earth. Figure 4 is a detailed representation of the model results for this region. The topography and geographical references are shown in Fig. 4a. The strong katabatic wind zones associated with Terra Nova Bay and Porpoise Bay can also be seen in this analysis. The streamlines (Fig. 4b) suggest that the flow is channeled upwind from each of the enhanced katabatic wind zones. Wind speeds (Fig. 4c) reveal well-defined katabatic wind maxima with speeds in excess of 22 m s^{-1} for both Adelie Land and Porpoise Bay; Terra Nova Bay katabatic wind speeds are somewhat less although in excess of 20 m s^{-1}. Parish and Wendler (1990) have recently conducted simulations of the Adelie Land katabatic wind regime using a more detailed topographic representation with a grid spacing of 20 km. Their results are in general agreement with the results shown in Figs. 4b and 4c; the simulated wind speeds near Adelie Land in Parish and Wendler are 2–3 m s^{-1} stronger. The zone of strong winds at Adelie Land in the present study is elongated; Parish and Wendler suggest two distinct katabatic wind maxima, one at the coast and a second situated some 100 km upwind of Adelie Land. The streamline patterns shown in Fig. 4b are consistent with those in Parish and Wendler. Slight directional differences in the flow orientation are present but nearly identical large-scale patterns and zones of confluence can be seen. It appears as if the 100-km grid resolution results in slightly less



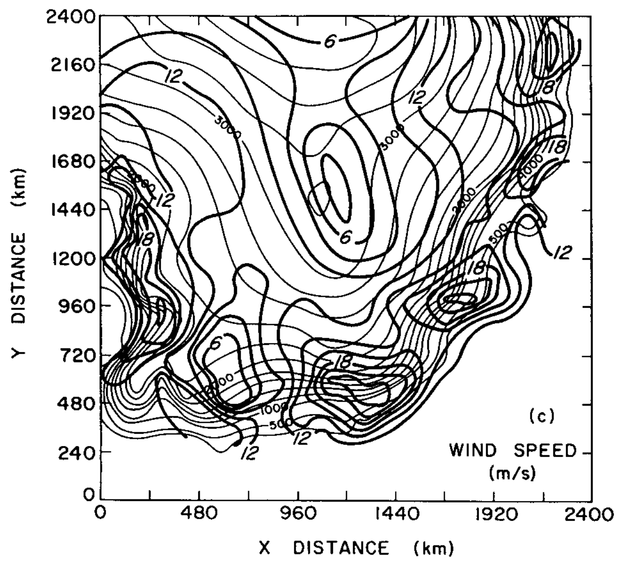


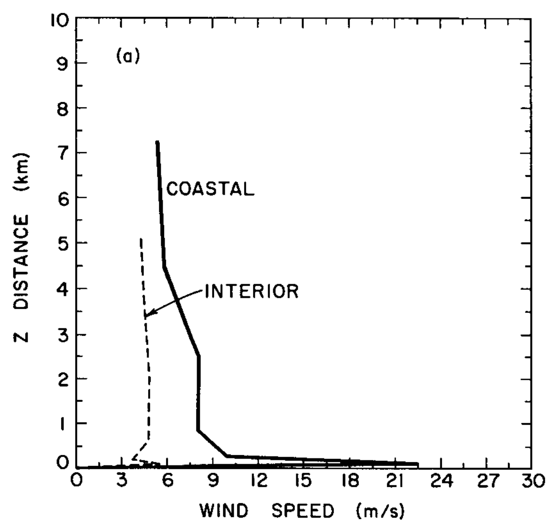
FIG. 4. Results of 48-h model simulation for the Adelie Land sector of Antarctica; (a) topography, (b) streamlines of the katabatic windfield, and (c) katabatic wind speed (m s^{-1}).

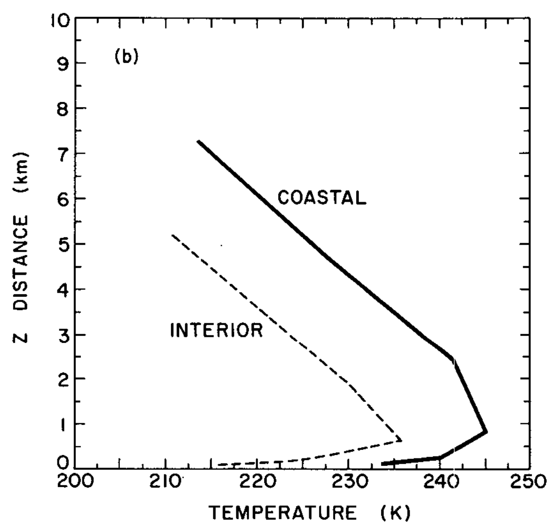
intense katabatic winds directed an additional 5°–10° in a slope-parallel direction when compared to the fine-scale terrain representation.

As would be expected for katabatic winds, strong wind shear exists between the first and second sigma levels. Figure 5 illustrates vertical profiles of wind and temperature for an interior and a coastal site; the locations of these sites are indicated in Fig. 4a. Owing to steeper terrain, the katabatic wind at the coastal location is more intense than that found over the interior (Fig. 5a). Katabatic winds in excess of 20 m s^{-1} are evident in low levels over the coastal periphery. Considerably weaker drainage flows are found over the gently sloping interior.

Both coastal and interior temperature profiles (Fig. 5b) are characterized by low-level inversions. The coastal temperature inversion is weaker due to attendant mixing processes associated with the strong katabatic winds. Inversion strengths of 20 K are indicated over the interior. Such values are well within the climatological range. The wind hodographs for the two sites are shown in Fig. 5c. The transition from predominantly anticyclonic flow near the surface to cyclonic flow at middle and upper levels is apparent; the transition takes place by the third sigma level, corresponding to a vertical distance above the ice surface of less than 1000 m. The veering of the wind with height, indicative of cold air advection, is illustrated by the interior site.

Verification of the intense katabatic wind zones is understandably difficult due to the general paucity of observations. However, being adjacent to Japanese manned stations, the strong katabatic wind zone near Princess Ragnhild Coast can be reasonably well constrained; it should be noted that the present simulation differs in this area from that given by Parish and Brom-





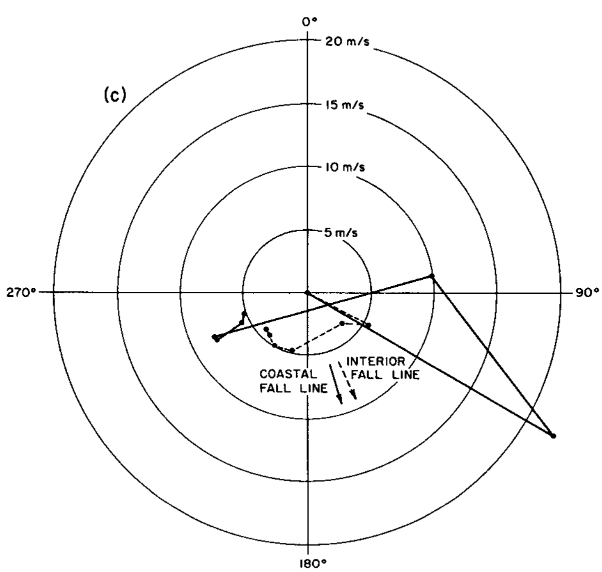


FIG. 5. Vertical profiles of (a) wind speed, (b) temperature and (c) hodographs for an interior and coastal grid point. Location of sites indicated by asterisks on Fig. 4a.

wich (1987) due to the latter's omission of the advective terms in the equations of motion (Kikuchi and Ageta 1989). Manned stations just to the east and west of the strong wind zone experience comparatively strong winds; annual mean speeds at Mizuho (2230 m elevation, 43°E longitude) and Asuka stations (965 m elevation, 24°E longitude) are 10 (Schwerdtfeger 1984, p. 60) and 13 m s^{-1} (Yamanouchi et al. 1988). Limited observations (Inoue et al. 1983) demonstrate that much stronger winds are experienced in the strong wind zone at Yamoto A site (2217 m elevation, 37°E longitude). Such conditions favor the formation of extensive blue-ice areas due to horizontal divergence of the drifting snow transport (Takahashi et al. 1988) during winter.

Other indications of strong katabatic winds may be inferred from satellite imagery. Zwally and Gloersen (1977) note that zones of reduced microwave brightness temperature extend about 500 km inland from major glacier outlets, and that strong winds can be inferred from reduced sea-ice concentrations or summer polynyas (areas of open water surrounded by ice) offshore from many of these continental signatures. Specific mention is made of Ninnis and Mertz glaciers (Adelie Land), Frost Glacier (Porpoise Bay), and areas near Denman Glacier.

4. The relationship between katabatic winds and large-scale tropospheric circulations

Observations have revealed that the Southern Hemisphere circumpolar vortex is more intense and uniform than its Northern Hemisphere counterpart. One reason for this difference arises in the nature of the land–sea contrasts in each hemisphere. The Southern Hemisphere consists of a polar land/ice mass surrounded by ocean. Due to radiative differences, strong thermal gradients form along the boundary of the Antarctic continent and open ocean to the north. The southern geography thereby acts to enhance the meridional temperature gradient. By contrast, the Northern Hemisphere polar region is essentially an ice-covered ocean extensively surrounded by large landmasses. During winter significant heat conduction occurs through leads and/or the relatively thin ice cover of the polar regions. The coldest regions are therefore found in the center of the Eurasian landmass thousands of kilometers removed from the pole. Thus, the Northern Hemisphere geographical configuration, in simplest terms, acts to reduce the wintertime meridional baroclinicity.

It is clear that the low-level thermal gradient, owing to the position of the Antarctic continent, has a profound influence on the positioning and stability of the circumpolar vortex. In addition, however, there is increasing evidence that attendant Antarctic katabatic wind circulations play a significant role in larger-scale tropospheric circulations in the high southern latitudes as well. Owing to the near-parabolic shape of the Antarctic ice sheet, the terrain slopes vary by several orders of magnitude from the gentle ice slopes in the high interior to the steep coastal terrain. The intensity of the drainage circulation mirrors the terrain slope with strongest katabatic winds situated over the steep coastal terrain. Pronounced horizontal divergence therefore occurs in the lowest layer of the atmosphere over the continent as a result of the predominant radial drainage off the elevated plateau and the associated katabatic wind speed increase. Mass continuity requires that a meridional mass circulation need be established over the high southern latitudes. Divergence over the lower levels of the Antarctic atmosphere necessitates predominant subsiding motion in the middle troposphere and hence upper-level convergence.

As a consequence, geostrophic wind circulations must undergo a sharp reversal with height. Near the surface the geostrophic wind vectors suggest an anticyclonic vortex due to the cooling of the adjacent terrain slopes; at upper levels a large cyclonic vortex must prevail. Such a flow reversal is suggested by the geostrophic wind analyses of Kottmeier and Stuckenberg (1986); monthly climatological geostrophic wind vectors over Antarctica showing the anticyclonic circulation may be found in Jenne et al. (1974). The three-dimensional mass circulation is shown in conceptual form in Fig. 6. The results of this 48-h integration suggest that a circumpolar vortex develops in an abrupt manner in response to the cooling of the Antarctic ice slopes and attendant katabatic winds.

To illustrate the development of the circumpolar vortex, the 500- and 250-hPa geopotential height field was computed regularly during the course of the model integration. The heights were determined using an upward integration of the hypsometric equation; temperatures were linearly interpolated between the sigma surfaces. Since the model was initialized about a state of rest, isobaric surfaces are oriented horizontally at the start of the model run. The radiative cooling of the sloping ice surface results in a horizontal pressure gradient force directed in a downslope sense; the isobaric surfaces eventually deform in response to the horizontal temperature contrast. The geopotential height patterns at the 500- and 250-hPa levels after model integration periods of 24- and 48-h are shown in Fig. 7. The cir-

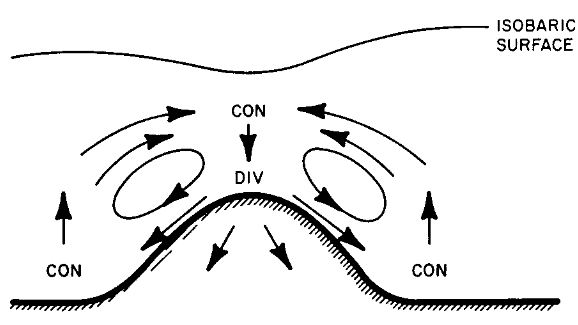


FIG. 6. Conceptual depiction of the meridional mass circulation over Antarctica (adapted from James 1989).

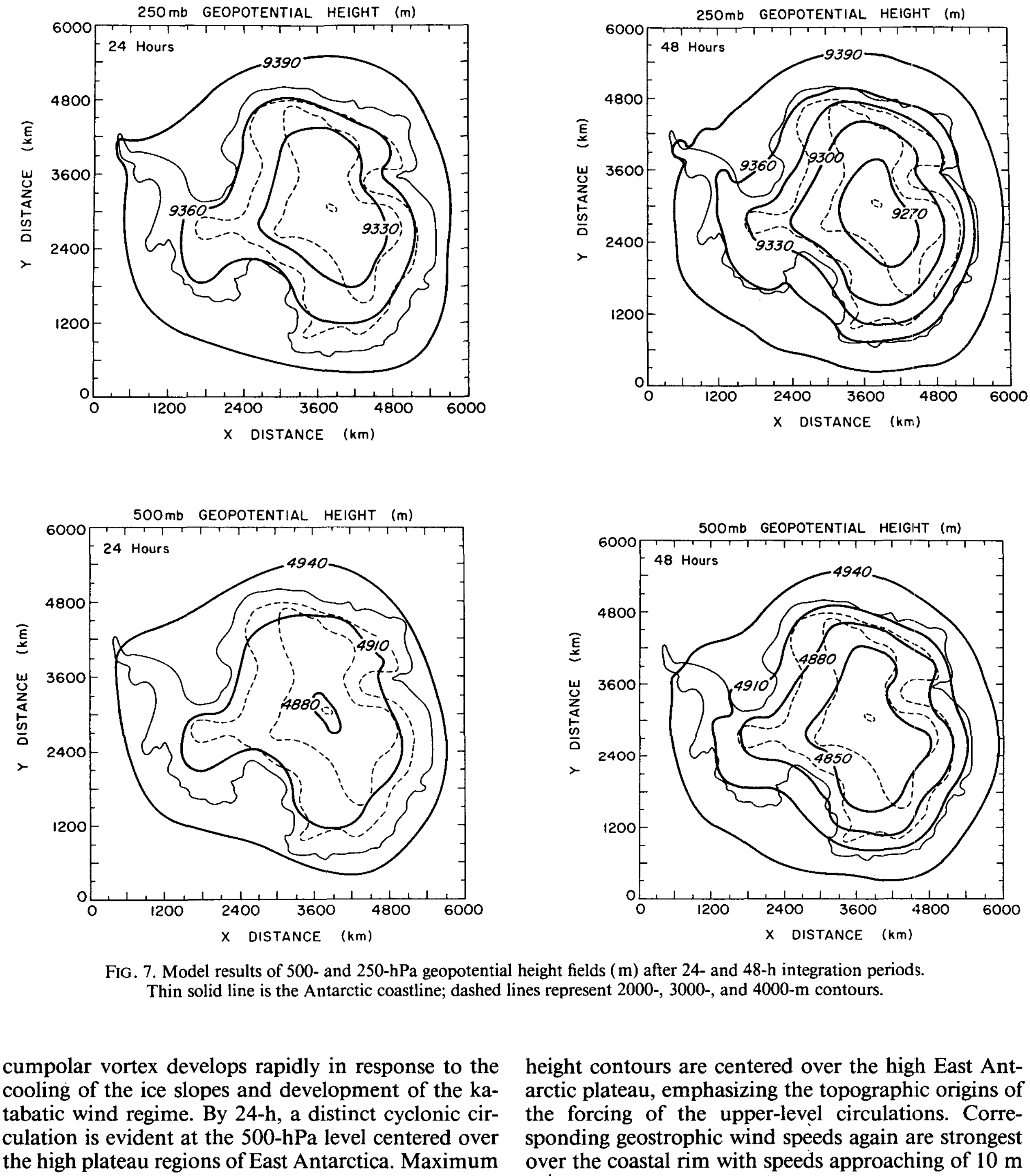


FIG. 7. Model results of 500- and 250-hPa geopotential height fields (m) after 24- and 48-h integration periods. Thin solid line is the Antarctic coastline; dashed lines represent 2000-, 3000-, and 4000-m contours.

cumpolar vortex develops rapidly in response to the cooling of the ice slopes and development of the katabatic wind regime. By 24-h, a distinct cyclonic circulation is evident at the 500-hPa level centered over the high plateau regions of East Antarctica. Maximum geostrophic wind values associated with this geopotential field are generally less than 5 m s^{-1}. The gradient of geopotential heights is a maximum over the coastal periphery, presumably in response to the steep slopes and ice–ocean boundary which act to enhance the horizontal temperature contrast and hence the thermal wind. At the 250-hPa level the vortex is stronger, suggesting that appreciable horizontal temperature contrasts are present above the 500-hPa level. Again the height contours are centered over the high East Antarctic plateau, emphasizing the topographic origins of the forcing of the upper-level circulations. Corresponding geostrophic wind speeds again are strongest over the coastal rim with speeds approaching of 10 m s^{-1}. Note that the 500- and 250-hPa height topography is a mirror image of the underlying Antarctic terrain with the lowest geopotential heights situated over the highest portions of the continent.

By 48 hours the cyclonic vortex has become significantly stronger at both levels. The center of the vortex has remained positioned over the highest ice topography of East Antarctica at both 500- and 250-hPa levels and the tightest gradient of the geopotential heights again occurs over the coastal sections. Maximum geostrophic winds at 500 hPa have increased to 10 m s^{-1} above sections of the continental rim; the strongest 250-hPa geostrophic winds are approximately 15 m s^{-1}. It is interesting to note that the strongest upper-level geostrophic wind conditions are situated above zones of intense katabatic winds in the near-surface layer such as Adelie Land and Princess Ragnhild coast. This suggests that the influence of intense katabatic winds may be observed throughout the troposphere. As noted earlier, the upper-level circulations such as presented in the time-averaged maps of Schwerdtfeger (1970, 1984) show distinct asymmetry with respect to the height contours of the elevated plateau of East Antarctica. This offset, due at least in part to differential temperature advection over the ice sheets of East (cold air advection) and West (warm air advection) Antarctica, is not duplicated in the 48-h simulation. This suggests such differential temperature advection patterns may be the result of synoptic-scale forcing which is not represented in this work or requires a longer time integration period to establish such flow patterns.

James (1986) has conducted model simulations with and without topography and concludes that the additional vorticity induced by the drainage flows is comparable with that associated with the temperature contrast between the continent and the ocean. Although in the strictest sense such an evaluation is difficult since strong coupling exists between the temperature and katabatic wind fields, there is reason to believe that the shallow katabatic winds may be an essential ingredient in the development of the southern circumpolar vortex.

5. Summary and implications

Katabatic winds show significant variation over the Antarctic continent. To a first approximation, the intensity of the drainage flow is proportional to the steepness of the underlying terrain. Katabatic winds are relatively weak over the gently sloping elevated central plateau and increase during the course of descent to sea level in response to the increasingly steep ice terrain. Over the steep coastal perimeter, katabatic winds show significant variation. Converging drainage currents in the interior of the continent provide enhanced regions of negatively buoyant air along various coastal sections. Such confluence effects have been previously shown to account for anomalously intense katabatic wind regimes. Continental-scale numerical simulations again confirm the importance of interior confluence zones and suggest that a number of coastal sections may be prone to enhanced katabatic wind spells.

The radiative cooling of the continent and attendant katabatic wind regime is partly responsible for the development of a pronounced circumpolar vortex in the middle and upper troposphere. The close coupling of the upper tropospheric circulations with the Antarctic terrain implies a significant scale interaction is present in the high southern latitudes. The shallow continental-scale drainage flows appear to be essential in prescribing larger-scale circulations. Formulation of the energy exchanges between the Antarctic continent and overlying atmosphere including depiction of the katabatic wind regime may be necessary in GCMs in order to properly simulate the large-scale tropospheric circulations in the Southern Hemisphere (compare Mitchell and Senior 1989; Herman and Johnson 1980). The attendant meridional mass transport provided by the katabatic wind regime may form a significant component of the heat flux in the lower atmosphere and thereby help alleviate the intense baroclinicity in the coastal periphery of the continent.

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