On the Role of the Antarctic Continent in Forcing Large-Scale Circulations in the High Southern Latitudes*

THOMAS R. PARISH

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

DAVID H. BROMWICH AND REN-YOW TZENG**

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

(Manuscript received 15 July 1993, in final form 12 April 1994)

ABSTRACT

The Antarctic topography and attendant katabatic wind regime appear to play a key role in the climate of the high southern latitudes. During the nonsummer months, persistent and often times intense katabatic winds occur in the lowest few hundred meters of the Antarctic atmosphere. These slope flows transport significant amounts of cold air northward and thereby modify the horizontal pressure field over the high southern latitudes. Three-year seasonal cycle numerical simulations using the NCAR Community Climate Model Version 1 (CCM1) with and without representation of the Antarctic orography were performed to explore the role of the elevated terrain and drainage flows on the distribution and evolution of the horizontal pressure field. The katabatic wind regime is an important part of a clearly defined mean meridional circulation in the high southern latitudes. The position and intensity of the attendant sea level low pressure belt appears to be tied to the Antarctic orography. The seasonal movement of mass in the high southern latitudes is therefore constrained by the presence of the Antarctic ice sheet. The semiannual oscillation of pressure over Antarctica and the high southern latitudes is well depicted in the CCM1 only when the Antarctic orography is included.

1. Introduction

It is widely accepted that the profound climatic differences between the North and South polar regions can be attributed to the different landforms of the respective areas. Unlike the Northern Hemisphere (NH), the Southern Hemisphere (SH) zonally symmetric arrangement of a continental Antarctic ice sheet around the South Pole surrounded by an ocean to the north acts to intensify the meridional temperature gradient. It is not surprising that the mean summertime circumpolar westerlies in the upper troposphere of the SH are comparable with the mean wintertime NH upper-tropospheric westerlies (see van Loon 1972). A brief summary of the north–south climatic differences is found in Schwerdtfeger (1984, pp. 223–227).

Orography is a potentially important factor responsible for the hemispheric climatic differences as well. Intense diabatic cooling of the sloping Antarctic ice surfaces establishes strong horizontal temperature gradients, which extend into the midtroposphere over the continental interior. Furthermore, the radiative cooling of the sloping ice fields is responsible for the development of the katabatic wind regime. This ubiquitous feature of the Antarctic boundary layer transports vast quantities of cold air northward and has previously been shown to influence circulations throughout the entire troposphere (Parish 1992a).

Here we investigate the role of the Antarctic orography in establishing observed large-scale circulation features of the high southern latitudes using the National Center for Atmospheric Research (NCAR) Community Climate Model Version 1 (CCM1). To infer the importance of the elevated Antarctic ice terrain on the mean climate, seasonal cycle runs were conducted with and without representation of the Antarctic topography. Previously, Mechoso (1981) has used the GFDL general circulation model (GCM) in a similar study. Here we examine in detail the role of the drainage wind regime over Antarctica, a feature which could not be explicitly resolved in the Mechoso work.

---

* Contribution Number 893 of the Byrd Polar Research Center.

** Current affiliation: Department of Atmospheric Science, National Central University, Chungli, Taiwan.

Corresponding author address: Prof. Thomas R. Parish, Dept. of Atmospheric Science, University of Wyoming, P.O. Box 3038, Laramie, WY 82071-3038.
E-mail parish@grizzly.uwyo.edu.

2. Aspects of the Antarctic orographic influence on climate

Antarctica is the highest continent on the planet with a mean elevation in excess of 2000 m. The massive dome of ice poleward of approximately 70°S acts as a formidable barrier to the southward penetration of extratropical cyclones. Parish (1982) noted that the power spectrum of surface pressure for stations on the Antarctic plateau showed little variance over synoptic timescales of 2.5–5 days when compared to coastal stations, reflecting the observed limited penetration of extratropical cyclones onto the high interior of the continent (e.g., Streten and Troup 1973). In the numerical experiments conducted by Mechoso (1981), it was noted that cyclonic systems do not frequently reach the high plateau of East Antarctica. The baroclinic nature of the coastal periphery of Antarctica encourages a robust direct thermal circulation. Mechoso (1981) notes that such a mean meridional circulation can be found in numerical experiments despite crude representation of the Antarctic boundary layer.

The katabatic wind regime is an integral part of the lower branch of the aforementioned direct thermal circulation in the high southern latitudes. A rising branch occurs just offshore of the steep coastal ice margin. Continuity requirements imply a southward motion in the middle to upper troposphere and a general subsidence over the Antarctic continent.

The katabatic wind regime modifies the horizontal pressure field in the high southern latitudes. The drainage flows transport mass from atop the continental plateau to the coastal margin. A northward-directed horizontal pressure gradient force becomes established over the oceanic regions adjacent to the continent. As the katabatic airstream moves northward, pseudoinertial turning occurs in absence of ambient horizontal pressure gradients and a geostrophically balanced low-level easterly flow prevails. The equivalent situation for the Ross Sea area has been modeled in detail by Bromwich et al. (1994). Schwerdtfeger (1984, p. 108) notes that the katabatic wind regime acts to reinforce and perhaps even maintain the observed sea level easterly winds, which circumscribe the continent within a band several hundred kilometers wide. The circumpolar zone of convergence also represents the southernmost extent of the sea level trough of low pressure surrounding Antarctica.

Katabatic winds may play an important role in other features of the tropospheric circulation about the continent as well. Bromwich (1991) and Carrasco and Bromwich (1993) have noted that Antarctic automatic weather station observations and satellite imagery indicate a close link between mesoscale cyclogenesis and katabatic winds just offshore of the continent. It has previously been shown that the drainage circulation is potentially significant in forcing upper-tropospheric features of the high southern latitudes (Egger 1985, 1992; James 1986, 1989; Parish and Bromwich 1991; Parish 1992a,b). The upper-level convergence required from continuity considerations generates cyclonic vorticity; in time, a circumpolar cyclonic vortex will develop about Antarctica in response to the katabatic wind regime.

3. Antarctic simulations using the NCAR CCM1

To assess the impact of the continental orography on the high southern latitude atmospheric circulations, a set of numerical experiments were performed using CCM1 with R15 (rhomboidal truncation at wavenumber 15) horizontal resolution. The relevant physical parameterizations in this model are described in Williamson et al. (1987). The model incorporates a terrain-following sigma coordinate system; a total of 12 vertical levels are contained in the model, 7 of which are in the troposphere. The lowest sigma level ($\sigma = 0.991$) corresponds to a height of approximately 65 m over Antarctica and 85 m over the ocean surface. The R15 horizontal resolution is equivalent to a grid mesh of 4.5° latitude by 7.5° longitude. This corresponds to a mean horizontal resolution of approximately 500 km, although the zonal resolution improves poleward because of the convergence of the meridians. However even at such resolution, the Antarctic topography becomes seriously degraded and certain details of the drainage "flows" cannot be replicated. Figure 1 illustrates the R15 topographic representation of the Antarctic orography. Note that the Antarctic continent extends several degrees north of the actual coastline. If the 200-m ice contour is considered the edge of the Antarctic continent in CCM1, the East Antarctic coastline then reaches to near 60°, approximately 7° farther north than the actual position. The CCM1 R15 Antarctic terrain configuration differs considerably from the actual ice profile as well. The slope of the CCM1 ice surface is actually steepest in the interior of the continent, becoming more gentle over the near-coastal region. In reality, the ice continent has a parabolic shape, with interior slopes being quite gentle and coastal slopes steep. The distortion of the Antarctic continent may lead to serious discrepancies with observations regarding the katabatic wind circulation in the boundary layer over Antarctica since the intensity of the drainage flows is proportional to the terrain slope. Furthermore, only two levels are found within the lowest 1000 m. At best CCM1 can only give a bulk representation of the katabatic wind effect (Tzeng et al. 1993).

To study the large-scale impact of the Antarctic continent, two 3-year seasonal cycle runs were conducted with the CCM1. The control run (hereafter CR) utilized the standard orographic representation of Antarctica; the second model experiment (hereafter FL) employed a flat continental ice sheet to represent Antarctica. Thus, the model experiments differ only in the topographic representation of the Antarctic continent. In each experiment, the assumed continent–ocean de-

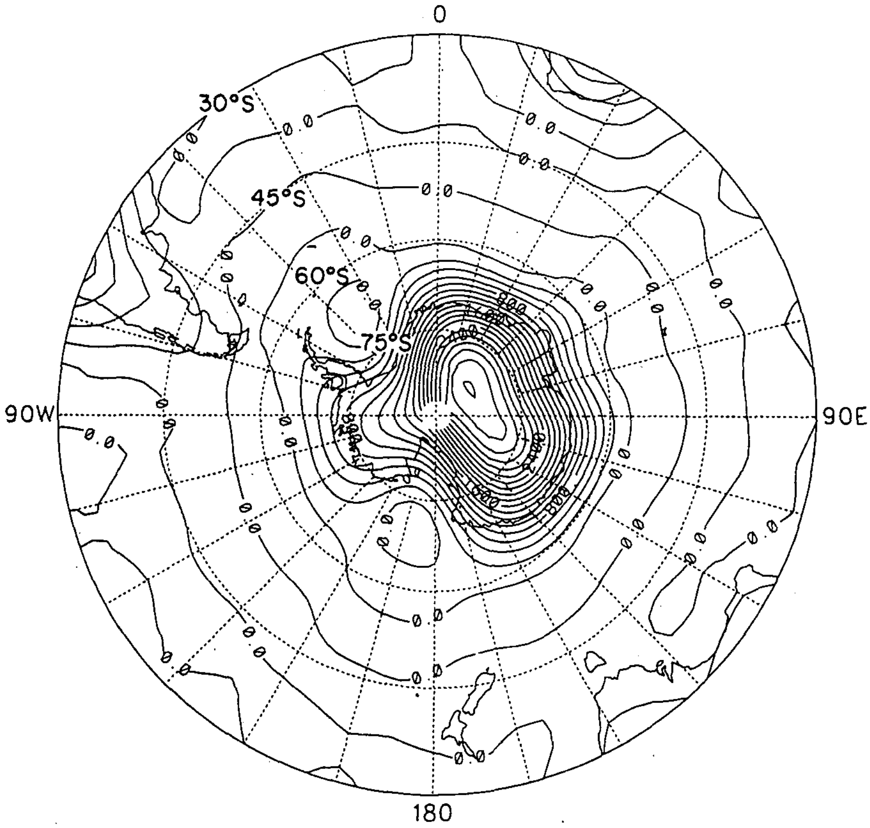

FIG. 1. CCM1 R15 topographic representation of the Antarctic continent. Contour lines in 200-m increments.

marcation is identical. Furthermore, all other inputs such as the oceanic boundary conditions correspond to modern values.

a. Seasonal variations in pressure over Antarctica

Figure 2 illustrates the observed seasonal cycle of monthly mean surface pressure about the yearly mean at three stations in the interior of Antarctica—Dome C, Vostok, and South Pole—and the corresponding seasonal cycle at grid points closest to the three stations from the CR and FL simulations. Data for Dome C were taken from the set of automatic weather station observations for the years 1984–91 (e.g., see Keller et al. 1993); the South Pole and Vostok records were taken from Schwerdtfeger (1984) and are for periods of 26 and 23 years, respectively. Observations (Fig. 2a) show the classic semiannual variation in pressure first described by Schwerdtfeger and Prohaska (1956), which is most pronounced on the high Antarctic interior. The percentage of the total variance accounted for by the sum of the first and second harmonics of the observed surface pressure trends exceeds 98%. The second harmonic amounts to nearly 40% of the total variance in these signals. Especially pronounced is the change atop the elevated Antarctic plateau from September to December when the surface pressure rises nearly 20 hPa.

Such surface pressure changes reflect large-scale meridional mass movement between middle and high southern latitudes in response to the north–south temperature gradient. Schwerdtfeger (1960, 1967), van Loon (1967, 1972), and more recently, Meehl (1991) have also commented on this phenomenon. The semiannual oscillation is simulated with impressive fidelity at grid points corresponding to Dome C, South Pole, and Vostok in the CR experiment (Fig. 2b). The CR seasonal changes in pressure are nearly identical in both phase and amplitude to those observed. Both the austral early autumn (January–March) surface pressure decrease and austral springtime (September–December) surface pressure increases over the Antarctic interior are well represented in CR. Note that no coherent semiannual oscillation signal is present at any of the three interior grid locations in the FL seasonal cycle (Fig. 2c). Such gross differences in the seasonal cycle of surface pressure of the high southern latitudes imply that the large-scale movements of mass toward high southern latitudes must be strongly influenced by the topographic configuration of the South Polar region.

To assess the geographical extent of the semiannual oscillation, the seasonal cycle of zonally averaged sur-

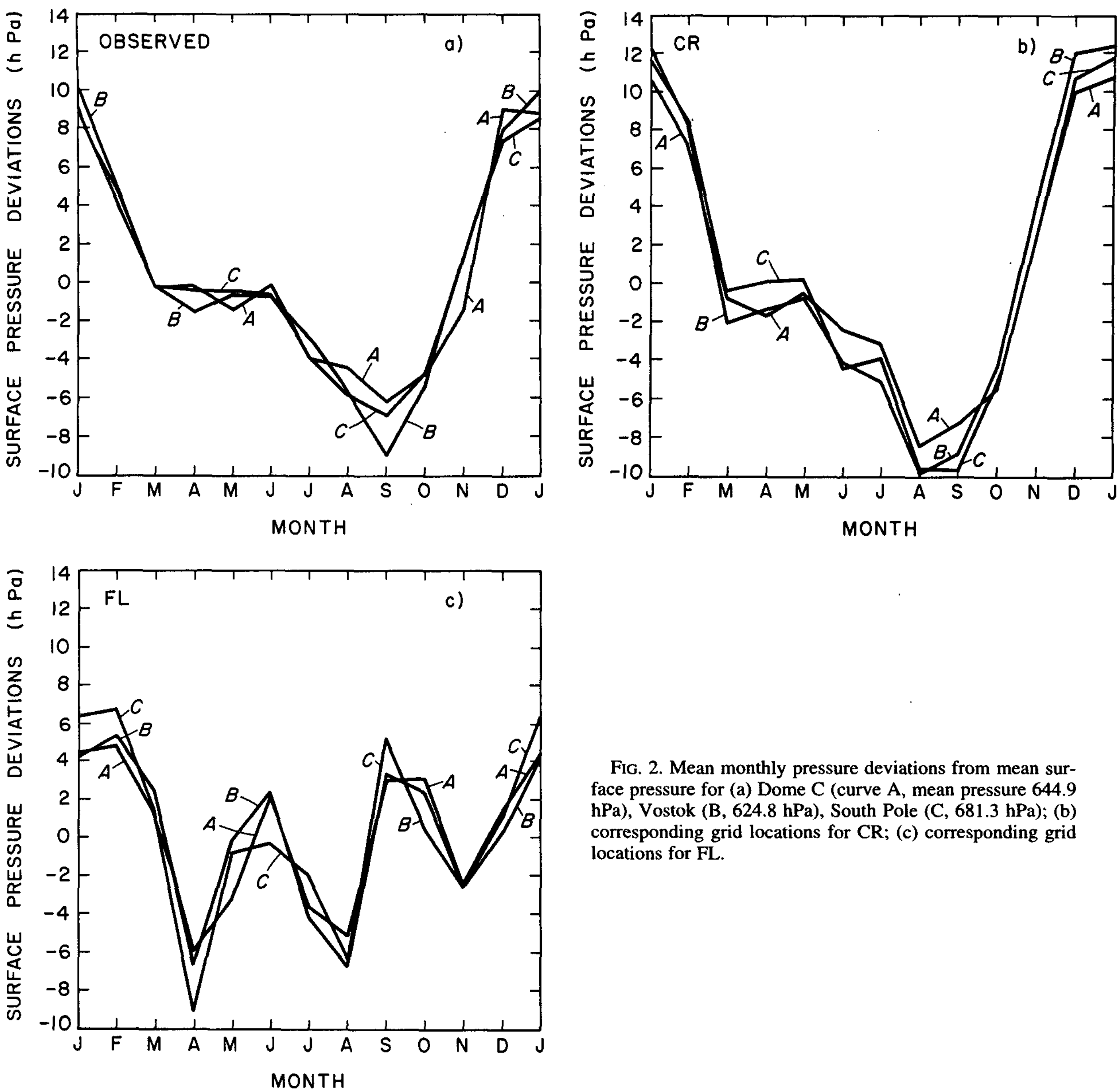

FIG. 2. Mean monthly pressure deviations from mean surface pressure for (a) Dome C (curve A, mean pressure 644.9 hPa), Vostok (B, 624.8 hPa), South Pole (C, 681.3 hPa); (b) corresponding grid locations for CR; (c) corresponding grid locations for FL.

face pressure deviations about the mean were computed. Figure 3 depicts the annual course of surface pressure change at latitudes corresponding to 86.4°, 77.7°, 68.9°, 60.0°, and 51.1°S (curves A–E, respectively) for both CR and FL. The amplitude of the semiannual pressure oscillation in the CR experiment is largest over the Antarctic interior, a result that agrees with observations (see Fig. 6.8 in Schwerdtfeger 1984). Note that the amplitudes of the zonally averaged semiannual oscillation are slightly less than displayed by individual grid locations atop the Antarctic high interior. This is no doubt a result of the nonaxisymmetry of the continent about the South Pole. Nevertheless, the latitudinal variations of the amplitude of the semiannual oscillation can be clearly identified. In general, the results of the CR mean seasonal cycle (Fig. 3a) suggest that the amplitude of this surface pressure oscillation decreases dramatically away from the Antarctic plateau. This is in agreement with analyses of Schwerdtfeger (1984, p. 223) based on multiyear records for individual stations in the Antarctic region. The CR results suggest that north of approximately 50°S the phase of the semiannual oscillation becomes reversed such that surface pressures rise in the austral autumn and fall in the spring. This demarcation also gives insight as to the scale of the mean meridional circulation responsible for the surface pressure oscillation. The phase transition is at least 10° farther north than obser-

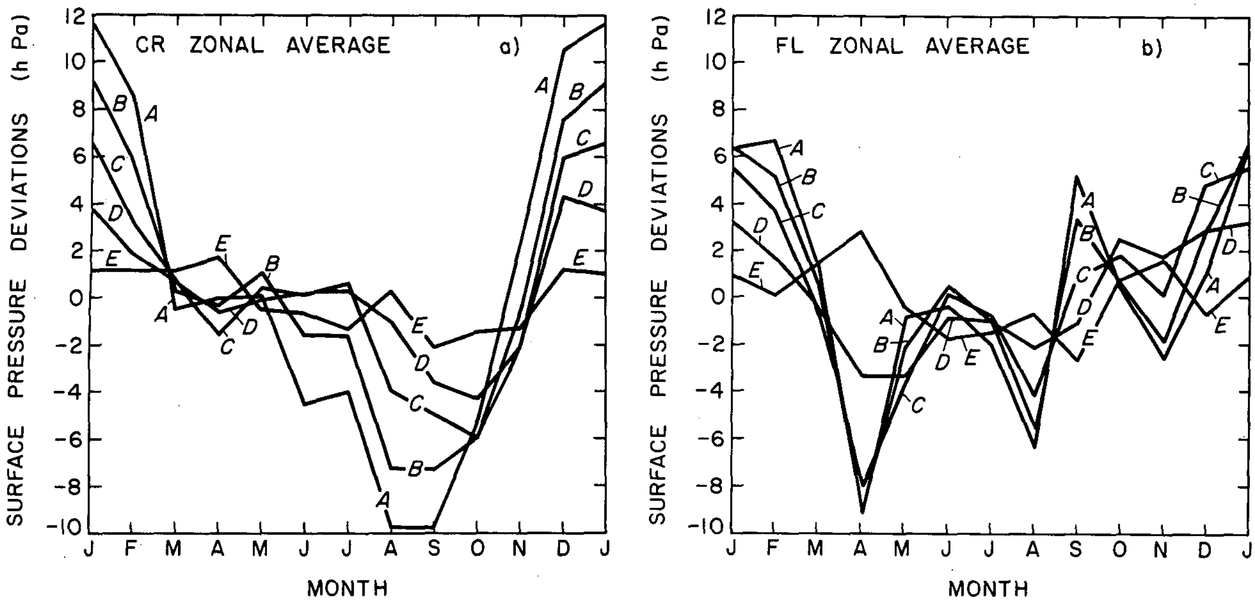

FIG. 3. Zonally averaged mean monthly pressure deviations from mean surface pressure at 86.4°, 77.7°, 68.9°, 60.0°, and 51.1°S (curves A–E, respectively) for (a) CR and (b) FL.

vations would suggest (van Loon 1972; Schwerdtfeger 1984). However, this not surprising considering that the smoothed CCM1 Antarctic continent extends a comparable distance north of the actual coastline.

By contrast with results of CR, analysis of FL (Fig. 3b) suggests little organized large-scale seasonal surface pressure change resembling the semiannual oscillation. Figure 3b indicates a more random seasonal march of surface pressure over both the interior of the flat ice sheet as well as over the coastal margin and oceanic regions to the north of the continent. There is only a hint of the equinoctial pressure minima in the surface pressure traces of FL.

The fact that the march of surface pressure in Fig. 3b differs considerably from results presented by Schwerdtfeger (1984, p. 222), as well as results from the CR experiment (Fig. 3a), is somewhat surprising. The semiannual pressure oscillation is thought to be a result of differential solar heating of adjacent latitude belts. As shown by Schwerdtfeger and Prohaska (1956), meridional differences of daily totals of solar radiation reaching the upper atmosphere between latitudes 50° and 80°S display maxima during the months of March and September. Van Loon (1967) has shown that the semiannual oscillation is a consequence of the difference between heating/cooling rates at different latitudes, implying that the nature of the underlying surface must be considered as well. This being so, the presence of the elevated Antarctic continent would not seem to be essential. The semiannual oscillation should be reflected in FL as well, given the roughly axisymmetric nature of the continental ice sheet and the pronounced latitudinal heating differences at the high southern latitudes.

Without question, eddy fluxes may play a more dominant role over the high southern latitudes in FL since cyclones freely penetrate onto the flat Antarctic ice sheet. Such cyclonic disturbances may disrupt the zonal symmetry of the mean motion fields, suggesting that an axisymmetric arrangement of continental landmasses may not be sufficient for a pronounced semiannual oscillation.

To illustrate in more detail the changes in surface pressure during the austral springtime, the September–December surface pressure changes have been prepared for both CR and FL for the entire SH south of 30°S (Fig. 4). The pressure increase over the Antarctic continent in CR (Fig. 4a) is most prominent on the high plateau of East Antarctica where an increase of nearly 25 hPa takes place. The magnitude of the surface pressure change drops off rapidly to less than 10 hPa over the rim of the CCM1 Antarctic continent. This is in very good agreement with observations as summarized by Schwerdtfeger (1984). Again, the transition latitude from pressure rise to pressure rise to pressure fall during the austral springtime in CR is considerably farther north of the position indicated by Schwerdtfeger (1984). One particular feature of this analysis is that the austral springtime isallobars appear to closely follow the height contours of the Antarctic terrain as represented in the R15 grid rather than simply being centered about the pole. The inescapable conclusion is that the elevated terrain itself must play a major role in the large-scale mass movements in the high southern latitudes.

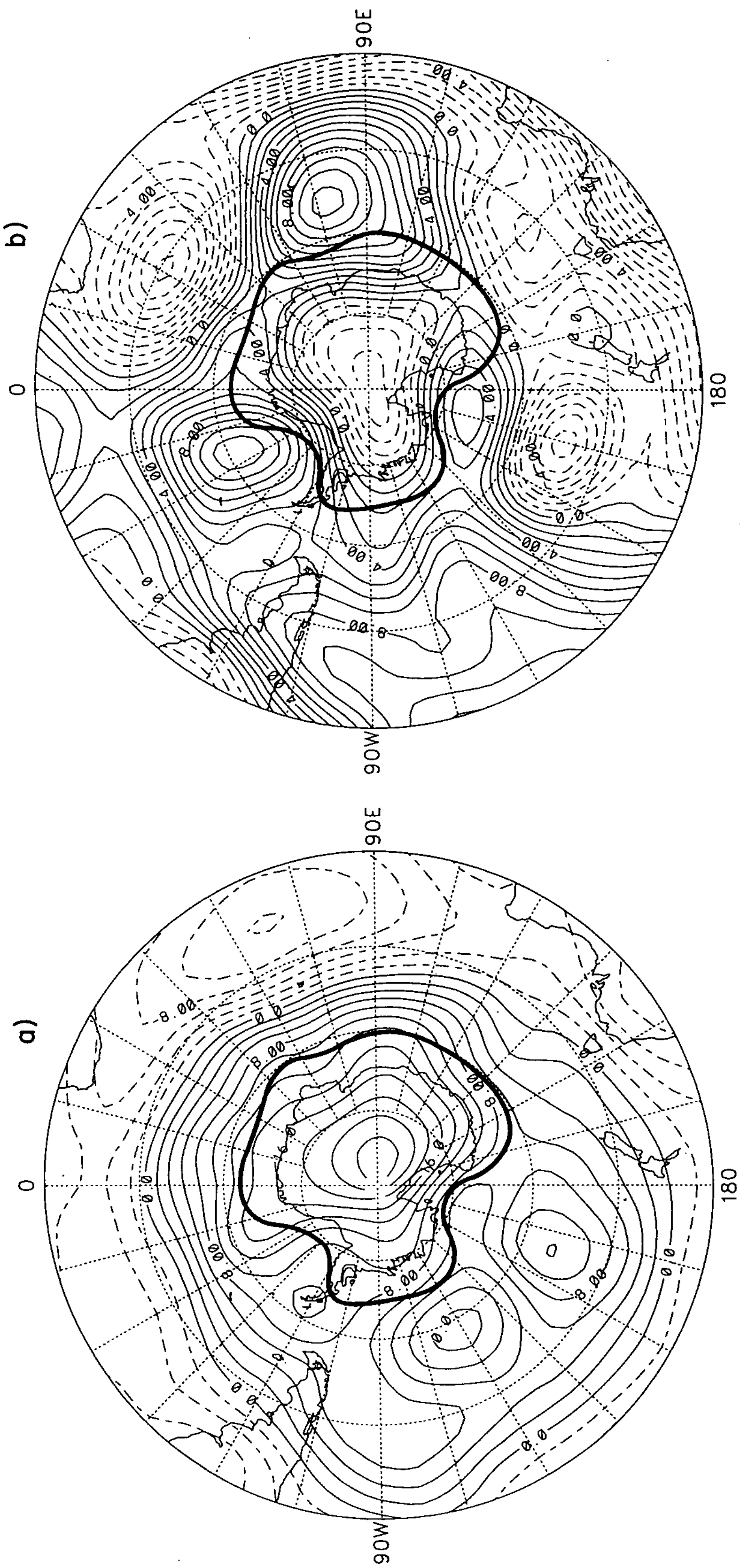

FIG. 4. Mean surface pressure difference (hPa), December − September, for (a) CR and (b) FL. Positive contours solid, negative contours dashed; interval 2 hPa. Thick solid line represents 200-m contour line of Antarctic CCM1 orography.

Surface pressure change patterns from September to December in FL (Fig. 4b) differ significantly from those in CR. Note that over the flat Antarctic continent, surface pressures actually fall during this period. The FL surface pressure change patterns in all likelihood reflect seasonal changes in the position and intensity of semipermanent cyclones and anticyclones. There seems to be no net southward mass flux from the SH midlatitudes toward the South Pole in FL during the austral springtime months. This also implies that no well-organized mean meridional mass circulation is present during this period. This topic will be addressed later.

The stark contrasts in the above analyses indicate that fundamentally different meridional transport processes are operating in the two numerical experiments to affect large-scale pressure change. The obvious difference is the influence of extratropical cyclones, which are free to move across the flat Antarctic ice sheet in FL and can influence the transport of cold air over the entire flat ice sheet. In CR, cyclonic activity is restricted to the coastal margins. It is probably not a coincidence that the two periods of most significant surface pressure change atop the plateau regions of Antarctica (January–March, October–December) are also periods of greatest change in the katabatic wind regime. The January–March pressure decrease in the Antarctic interior is concurrent with the rapid intensification of the drainage flows in response to the onset of winter. Likewise, the dramatic pressure increase over the Antarctic during the austral springtime period, previously linked to the rapid breakdown of the polar stratospheric vortex (Schwerdtfeger 1984, pp. 132–136), occurs at the same time that the katabatic flows diminish as increasing amounts of solar radiation strike the ice slopes. Note that such surface pressure changes are consistent with the changes in mass transports associated with the katabatic wind regime.

b. *The mean meridional circulation in high southern latitudes*

The mass redistribution brought about by an organized continental-wide katabatic wind regime over Antarctica implies that a mean meridional circulation should be present in high southern latitudes. Despite the smoothed R15 representation of the Antarctic terrain and relatively crude vertical resolution, Tzeng et al. (1993) showed that katabatic winds are prevalent at the lowest sigma level in the CCM1 simulations during the nonsummer period.

Katabatic winds as evidenced in CR reach maximum intensity over the most steeply sloping portion of the East Antarctic terrain representation with intensities on the order of 10 m s^{-1} during midwinter. Conceptually, only CR should depict a katabatic wind circulation, although Mechoso (1981) has pointed out that the direct thermal circulation in the high southern latitudes mimics the katabatic wind regime in his simulations with the GFDL GCM. Figure 5 illustrates the mean July wind vectors and resultant wind speeds for CR at the lowest sigma level, which corresponds to approximately 65 m above the terrain. The radial drainage off the Antarctic ice cap is evident; katabatic winds at the first sigma level display a more contour-parallel orientation as compared with the numerous surface-based observations (see Parish and Bromwich 1987). This may be the result of the elevated height of the first sigma level above the terrain. Observations (see Kodama et al. 1989) suggest a rapid wind shift with height such that flows above the surface layer appear to be directed in a more contour-parallel sense. It should be pointed out that although the coastal vicinity of Antarctica in CR is the site of frequent and intense cyclone activity, the mean winds over the continent reflect the underlying terrain slope (compare Fig. 5 with the terrain contours shown in Fig. 1). This feature of the Antarctic near-surface wind regime has been noted previously (Parish 1982) and illustrates the first-order importance of the orography in shaping the low-level wind field in CR.

Zones of maximum katabatic wind intensity can be seen near the Ross Sea region of the CCM1 orography (along 165°E) and near the Queen Maud Land topographic representation (along 15°E). These zones of strong katabatic winds are situated over broad areas in the interior portion of the CCM1 Antarctic continent, in contrast to observations which clearly show the strongest katabatic winds to occur in narrow bands over the steeply sloping coastal region. Such differences are obviously related to the CCM1 representation of the Antarctic continent. As is evident from the wind vectors in Fig. 5, broadscale confluence occurs in the Ross Sea section of the CCM1 orography, which may be responsible in part for the enhancement of the drainage flows. A similar confluence feature can be seen in the wintertime streamline map of Parish and Bromwich (1987) and in the recent numerical modeling by Bromwich et al. (1994).

By contrast, the near-surface winds over the flat Antarctic CCM1 representation appear to be dominated by synoptic-scale systems. Figure 6 shows the mean July wind vectors and wind speeds at the first sigma level over the flat Antarctic region. No organized radial flow pattern away from Antarctica is seen and, in fact, airstreams freely traverse the entire continental width. Organized cyclonic disturbances are evident about the periphery of the flat ice continent and the wind speeds and directions appear tied to the horizontal pressure fields associated with these disturbances. Note that wind speeds are quite low as compared to the CR simulation, generally only 1–2 m s^{-1} over the entire Antarctic region. It is clear that if a thermally induced wintertime meridional circulation exists in FL as a result of the proximity of ice sheet and an ice covered ocean, such a motion field must be weak.

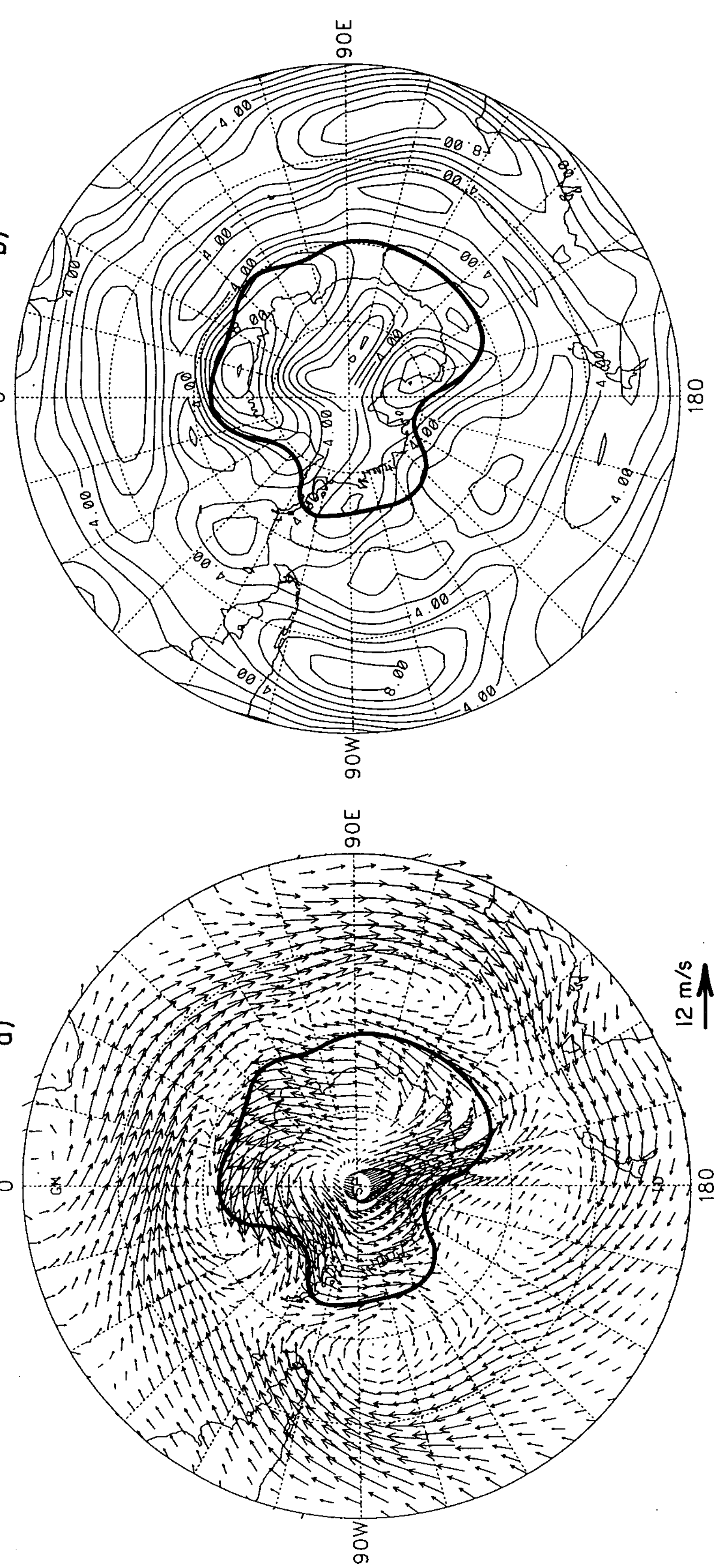

FIG. 5. Mean July (a) wind vectors and (b) resultant wind speeds at $\sigma = 0.991$ for CR (contour interval 1 m s^{-1}). Thick solid line represents 200-m contour line of Antarctic CCM1 orography.

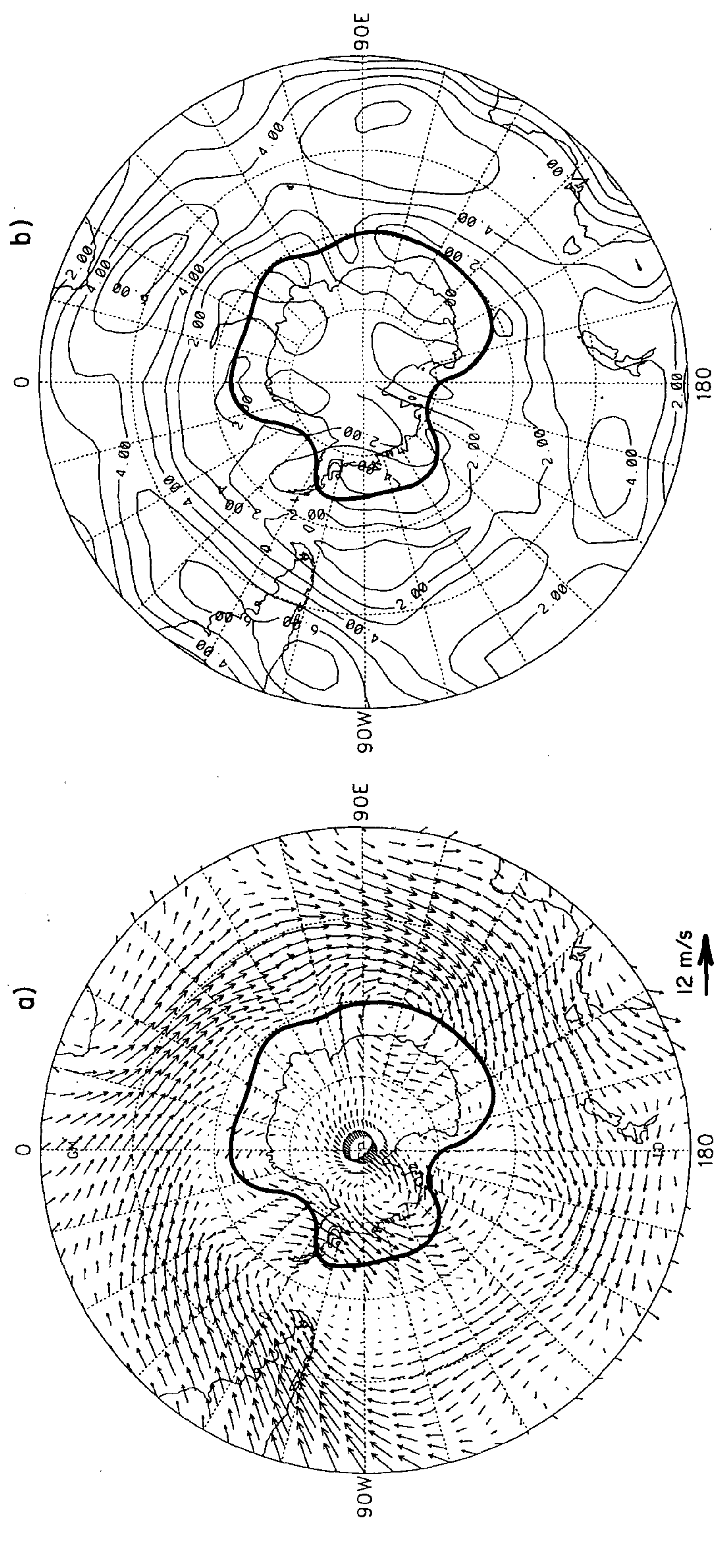

FIG. 6. As in Fig. 5 except for FL.

Mechoso (1980, 1981) has suggested that the barrier effect provided by the Antarctic massif on the southward movement of cyclonic eddies in the high southern latitudes acts to accentuate the meridional temperature gradient about the continent. This in turn helps induce a mean meridional circulation. It would seem apparent that such a thermally direct circulation would be further enhanced by the persistent and sometimes intense topographically induced katabatic drainage and it seems likely that the katabatic wind regime and mean meridional circulation are closely coupled.

To detect differences in the mean meridional circulation for the two experiments, zonal averages of the northward component of motion have been examined. Figure 7 depicts the latitudinal distribution of the zonally averaged meridional wind components at the lowest sigma level during January and July for both CR and FL. During summer the meridional wind components are quite weak and little difference can be seen between CR and FL. The solar insolation retards significantly the drainage flow over the sloping CR terrain such that only weak katabatic winds develop. The January mean wind vectors over the Antarctic continent in CR (not shown) illustrate that the katabatic wind regime is altered dramatically by the solar heating such that only poorly organized drainage flows can be detected. Over the flat terrain, surface winds reflect the horizontal pressure field associated with land–sea contrast and/or cyclonic activity. The similarity between the two model experiments during January suggests that the impact of the topography on the large-scale tropospheric flows is restricted during austral summer.

A more vigorous katabatic drainage is apparent in the July CR simulation. Although the zonal symmetry of the SH is much greater than that seen in the NH, the high plateau of East Antarctica is offset from the South Pole by about 10°. As can be seen by inspection of Fig. 5, the katabatic wind intensity would be more impressive if averaging were to take place centered about the interior plateau. Thus, the thermally direct mean meridional circulation implied by the mean drainage flows is displaced from the South Pole. Nevertheless, a well-developed thermally direct secondary circulation can be detected in the zonal averages of the meridional component in CR extending north of 60°. The zonal-mean northward transport is confined primarily to the first sigma level in July. In other months the katabatic wind regime can be traced up to the third sigma level, corresponding to approximately 1500 m. Such depths are comparable to observations of the Adelie Land katabatic wind regime (Kodama et al. 1989). The return branch is distributed over a broad layer above the katabatic outflow. Zonally averaged meridional wind components of less than 0.25 m s^{-1} from the north were present throughout the remainder of the atmosphere (not shown). Although weak, the return branch is clearly defined in the zonal averages.

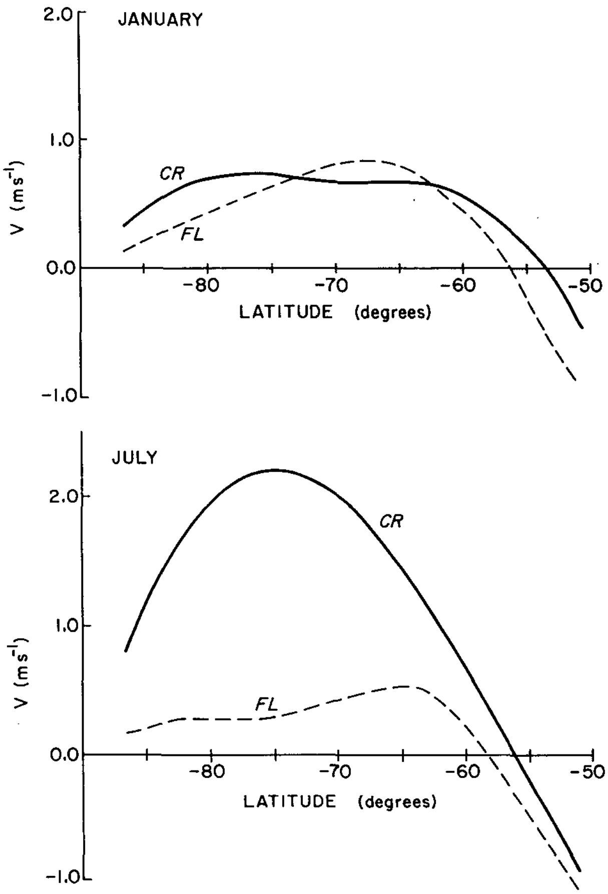

FIG. 7. Zonally averaged meridional components at $\sigma = 0.991$ during January (top) and July (bottom) for CR and FL.

The July meridional circulation in FL is considerably weaker than that found in CR. Mean meridional wind components at the lowest level over the flat Antarctic ice sheet are only approximately one-eighth the corresponding values in CR. Presumably this reflects the lack of organized drainage flows and perhaps the transient nature of the cyclonic activity over the flat ice continent. In addition, the meridional motion components throughout the remainder of the troposphere during July were weak although fairly consistently from the north. This suggests that a mean meridional circulation is also present in FL, although much less coherent than that seen in CR.

Coincident with the organized northward transport of mass over the Antarctic continent is the vertical motion field. Continuity requirements dictate that subsidence must be present in the lower and middle troposphere throughout the high southern latitudes as part of the mean meridional circulation; rising motions should be found in the sea level circumpolar zone of low pressure to the north of the continent. Figure 8 illustrates the mean zonally averaged vertical velocity fields for both CR and FL during July. The obvious feature in

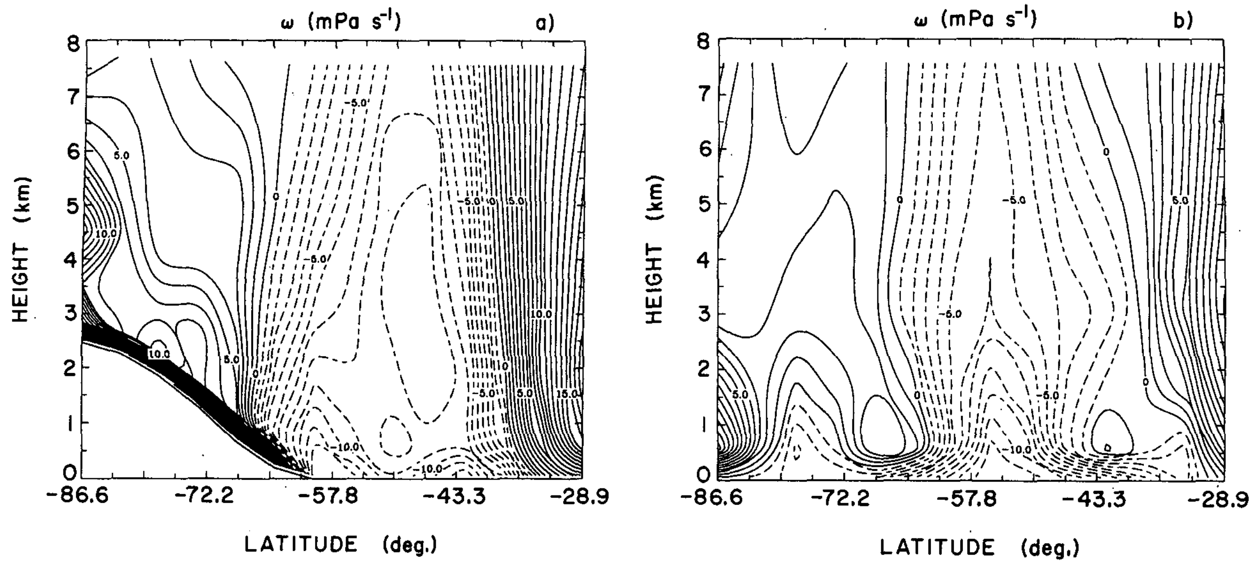

FIG. 8. Zonally averaged cross section of July vertical velocity field for (a) CR and (b) FL. Contour interval 1 mPa s^{-1} (approximately 0.1 mm s^{-1}). Negative contours (upward motion) are dashed; positive contours (downward motion) solid.

the CR July vertical velocity field (Fig. 8a) is the pronounced vertical motion accompanying the katabatic wind regime over the sloping Antarctic terrain. The very large values are primarily associated with the downslope motion of the slope flows and attendant subsidence into the katabatic layer. Note that zonally averaged subsiding motions occur over the entire Antarctic region in CR. A sharp demarcation exists between the sinking and rising branches that appears to be tied to the continental orography. North of approximately 64°S, the rising branch of the polar mean meridional circulation becomes established. This rising branch reflects the ensemble of extratropical cyclone events that result in the sea level low pressure trough as well as the low-level convergence resulting from the deceleration of the katabatic airstream as it moves away from the steep continental ice slopes.

An examination of Fig. 8a suggests two centers of rising motion in the lowest levels of the atmosphere; the first maximum in rising motion is situated just north of the continent and corresponds to the convergence induced by the northward movement and subsequent deceleration of the katabatic wind regime. This double maxima in rising motion is seen in most months in CR and, in all cases, seems to be directly tied to the katabatic wind regime. Only during the equinoctial months when the circumpolar zone of sea level pressure is farthest south do the two low-level centers of rising motion appear to merge. This feature is also noted in Tzeng et al. (1993), who associate the coastal maximum with mesoscale cyclogenesis.

The FL July mean meridional circulation in the high southern latitudes is less pronounced (Fig. 8b) than that seen in CR. The absence of a katabatic wind regime in FL appears to result in a weaker mean meridional circulation over Antarctica. Mean monthly vertical velocities are actually upward in the lowest level over the flat Antarctic ice sheet, in contrast to that in CR. The midtroposphere in the high southern latitudes is characterized by subsiding motion, but the magnitudes of the mean monthly vertical velocities are substantially less than the corresponding values in CR. The rising branch of the mean meridional circulation associated with the circumpolar low pressure band in FL is comparable to that seen in CR, and a well-defined Ferrel circulation is seen between the subtropics and midlatitudes. It can also be noted that the southward subsiding branch of the Hadley cell in FL is also not as well marked as that seen in CR. It can be surmised that the differences in the mean meridional circulation in the high southern latitudes between CR and FL are principally due to the orography and attendant katabatic wind regime. The organized nature of the CR thermal circulation combined with the aforementioned constraint on eddy penetration onto the elevated ice sheet implies that a significant component of the heat transport at southern polar latitudes must be provided by the mean meridional circulation.

c. *The sea level circumpolar low pressure trough*

The sea level circumpolar trough of low pressure situated at approximately 60° is a prominent SH feature, which has no NH counterpart. This band of low pressure about the Antarctic continent is represented in both CR and FL simulations. Figure 9 illustrates the mean July sea level pressure for both CR and FL. In general, the sea level pressures throughout the FL do-

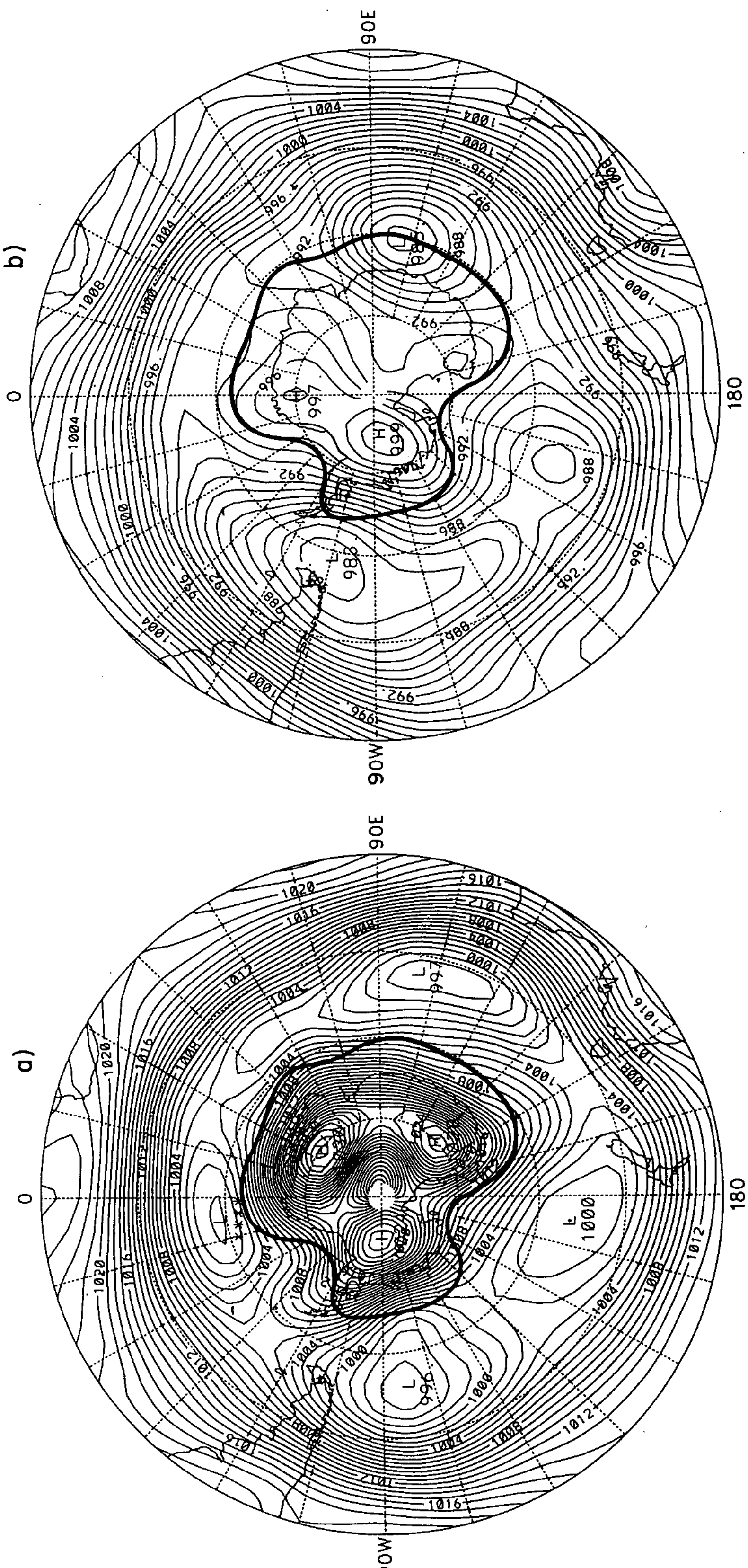

FIG. 9. July mean sea level pressure (hPa) for (a) CR and (b) FL. Contour interval is 1 hPa. Thick solid line represents 200-m contour of Antarctic CCM1 orography.

main are approximately 10 hPa less than those seen in CR. This is a result of keeping the total atmospheric mass the same in each simulation; removal of the Antarctic ice topography in FL implies that the atmospheric mass is distributed throughout a larger volume. The extremely high sea level pressures over the elevated Antarctic ice sheet in CR are artifacts of the reduction of surface pressure to sea level.

Note that the position of the low pressure trough about the Antarctic continent in the CR (Fig. 9a) is approximately 5° north of that seen in FL (Fig. 9b). As noted by Schwerdtfeger (1984), the circumpolar sea level low pressure trough is a reflection of the cyclonic activity about the Antarctic periphery. The southward penetration of cyclones in the FL thus appears to be enhanced, and the circumpolar trough is situated at the edge of the flat Antarctic ice sheet along the prevailing baroclinic zone. By contrast, the sea level low pressure trough in the CR run is several hundred kilometers to the north of the elevated ice sheet. Owing to the smoothed representation of the orography in CCM1, the CR circumpolar trough is positioned a few degrees north of the actual location, as evidenced from climatology as well (e.g., see Fig. 4.1.b in Schwerdtfeger 1984). As noted in Tzeng et al. (1993), this is a common problem in GCMs and without doubt is a reflection of the Antarctic topographic representation. However, the relative position of the sea level trough of low pressure with respect to the continental orography is in general agreement with observations.

Katabatic winds are of importance in establishing the horizontal pressure field in the offshore environment. The rising branch of the mean meridional circulation is situated at the northern extent of the katabatic outflow above the circumpolar trough. It is natural to conclude that some interaction occurs between the katabatic airstream and the polar easterlies situated on the south side of the circumpolar sea level low pressure trough. Note from Fig. 6b that the easterlies are poorly defined for the July FL simulation and reach a maximum intensity of only 4 m s^{-1}; the zonally averaged July speed of the polar easterlies associated with the flat Antarctic continent is less than 0.5 m s^{-1}. Other months show similarly weak easterly circumpolar sea level winds in FL. It appears as if the mean monthly low-level winds in FL respond to the synoptic-scale disturbances about the flat continental periphery since no organized radial movement of air from the center of the ice sheet is present.

Representation of the elevated Antarctic ice sheet in CR allows for the establishment of drainage flows and is responsible for stronger easterlies. The maximum zonal wind speeds at the lowest sigma level approach 10 m s^{-1} with the average easterlies nearly four times as strong as in FL. The intensity of this near-surface easterly wind regime is an indication of the horizontal pressure field in the coastal vicinity. It is likely that the combined effect of the deceleration of the katabatic airstream to the north of the continent and the blocking provided by the elevated Antarctic continent in CR serves to strengthen the horizontal pressure gradients just offshore from Antarctica. It is concluded that the presence of the elevated Antarctic ice sheet and attendant katabatic wind regime is fundamentally responsible for the existence of the polar easterlies at the surface about the Antarctic continent.

4. Summary

Although some of the hemispheric climatic variance can be ascribed to contrasts in landform, features such as the semiannual oscillation of surface pressure over the Antarctic interior and the circumpolar band of easterlies about the periphery of Antarctica appear to be influenced also by the continental orography of the South Polar latitudes. Three-year seasonal cycle runs using the NCAR CCM1 at R15 with and without representation of the Antarctic orography seem to verify the importance of the Antarctic ice topography in establishing these observed features of the high southern latitude mean circulations.

The elevated Antarctic continent appears to influence significantly the means by which atmospheric mass is transported. Zonally averaged meridional wind components show that a thermally direct mean wintertime circulation is far more pronounced in CR than FL. In addition, the sea level easterly wind pattern is much stronger in CR than in FL. This suggests that zonal symmetry alone is insufficient in the establishment and maintenance of observed sea level wind and pressure patterns in the high southern latitudes. Orography and the attendant katabatic wind regime appear to be essential.

The well-documented semiannual pressure oscillation at the surface over the high southern latitudes is depicted with impressive fidelity in CR but is not obvious in FL. We can speculate that the constraint on the southward penetration of cyclonic disturbances enables this semiannual oscillation to be pronounced over the Antarctic plateau. Transient cyclonic activity may mask the semiannual oscillation just as the land–ocean zonal contrasts disrupt the semiannual pressure oscillation in the Northern Hemisphere.

The mean sea level pressure fields illustrate the profound influence of the elevated Antarctic terrain. The wintertime sea level circumpolar trough of low pressure in FL is displaced approximately 5° south of that shown in CR, again reflecting the ability of extratropical cyclones to move southward in FL.

Observed climatological features in the high southern latitudes such as the pronounced semiannual pressure oscillation and circumpolar sea level easterly wind regime have often been considered a result of the axisymmetric nature of the SH and the latitudinal heating differences. It is proposed that the elevated Antarctic orography and associated katabatic drainage play a pri-

mary role in forcing the aforementioned features. Further, it is likely that the Antarctic katabatic wind regime is a major feature of the mean meridional circulation of the high southern latitudes, and the circumpolar belt of easterly winds is intimately linked to the large-scale mass movements associated with this continental-scale circulation.

Acknowledgments. This work was supported in part by NASA through Grants NAGW-2666 to TRP and NAGW-2718 to DHB and by the National Science Foundation through Grant DPP-9117202. The CCM1 simulations were performed on the Cray Y-MP of the Ohio Supercomputer Center, which is supported by the State of Ohio. Automatic weather station data was provided by Charles R. Stearns at the University of Wisconsin—Madison through Grants NSF-DPP 86-06385, 88-18171, and 90-15586.

REFERENCES

Bromwich, D. H., 1991: Mesoscale cyclogenesis over the southwestern Ross Sea linked to strong katabatic winds. *Mon. Wea. Rev.,* **119,** 1736–1752.

——, Y. Du, and T. R. Parish, 1994: Numerical simulation of winter katabatic winds from West Antarctica crossing Siple Coast and the Ross Ice Shelf. *Mon. Wea. Rev.,* **122,** 1417–1435.

Carrasco, J. F., and D. H. Bromwich, 1993: Mesoscale cyclogenesis dynamics over the southwestern Ross Sea. *J. Geophys. Res.,* **98,** 12 973–12 995.

Egger, J., 1985: Slope winds and the axisymmetric circulation over Antarctica. *J. Atmos. Sci.,* **42,** 1859–1867.

——, 1992: Topographic wave modification and the angular momentum balance of the Antarctic troposphere. *J. Atmos. Sci.,* **49,** 327–334.

James, I. N., 1986: Katabatic drainage flows over Antarctica and the polar vortex. *Second Int. Conf. Southern Hemisphere Meteorology,* Wellington, New Zealand, Amer. Meteor. Soc., 117–118.

——, 1989: The Antarctic drainage flow: Implications for hemispheric flow on the Southern Hemisphere. *Antarct. Sci.,* **1,** 279–290.

Keller, L. M., G. A. Weidner, and C. R. Stearns, 1993: Antarctic Automatic weather station data for the calendar year 1991, Research Report, Dept. Atmospheric and Oceanic Sciences, University of Wisconsin—Madison, 356 pp. [Available from the Department of Atmospheric and Oceanic Science, University of Wisconsin—Madison, Madison, WI 53706.]

Kodama, Y., G. Wendler, and N. Ishikawa, 1989: The diurnal variation of the boundary layer in summer in Adelie Land, Eastern Antarctica. *J. Appl. Meteor.,* **28,** 16–24.

Mechoso, C., 1980: The atmospheric circulation around Antarctica: Linear stability and finite-amplitude interactions with migrating cyclones. *J. Atmos. Sci.,* **37,** 2209–2253.

——, 1981: Topographic influences on the general circulation of the Southern Hemisphere: A numerical experiment. *Mon. Wea. Rev.,* **109,** 2131–2139.

Meehl, G. A., 1991: A reexamination of the mechanism of the semiannual oscillation in the Southern Hemisphere. *J. Climate,* **4,** 911–926.

Parish, T. R., 1982: Surface airflow over East Antarctica. *Mon. Wea. Rev.,* **110,** 84–90.

——, 1992a: On the role of Antarctic katabatic winds in forcing large-scale tropospheric motions. *J. Atmos. Sci.,* **49,** 1374–1385.

——, 1992b: On the interaction between Antarctic katabatic winds and tropospheric motions in the high southern latitudes. *Aust. Meteor. Mag.,* **40,** 149–167.

——, and D. H. Bromwich, 1987: The surface windfield over the Antarctic ice sheets. *Nature,* **328,** 51–54.

——, and ——, 1991: Continental-scale simulation of the Antarctic katabatic wind regime. *J. Climate,* **4,** 136–146.

Schwerdtfeger, W., 1960: The seasonal variation of the strength of the southern circumpolar vortex. *Mon. Wea. Rev.,* **88,** 203–208.

——, 1967: Annual and semi-annual changes of atmospheric mass over Antarctica. *J. Geophys. Res.,* **72,** 3543–3547.

——, 1984: *Weather and Climate of the Antarctic.* Elsevier, 261 pp.

——, and F. Prohaska, 1956: The semi-annual pressure oscillation, its cause and effects. *J. Meteor.,* **13,** 217–218.

Streten, N. A., and A. J. Troup, 1973: A synoptic climatology of satellite cloud vortices over the Southern Hemisphere. *Quart. J. Roy. Meteor. Soc.,* **99,** 56–72.

Tzeng, R.-Y., D. H. Bromwich, and T. R. Parish, 1993: Present-day Antarctic climatology of the NCAR Community Climate Model Version 1. *J. Climate,* **6,** 205–226.

van Loon, H., 1967: The half-yearly oscillations in middle and high southern latitudes and the coreless winter. *J. Atmos. Sci.,* **24,** 472–486.

——, 1972: Pressure in the Southern Hemisphere. *Meteorology of the Southern Hemisphere, Meteor. Monogr.,* No. 35, Amer. Meteor. Soc., 59–86.

Williamson, D. L., J. T. Kiehl, V. Ramanathan, R. E. Dickinson, and J. J. Hack, 1987: Description of the NCAR Community Climate Model (CCM1). NCAR Tech. Note, NCAR/TN-285+STR, 112 pp.