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# On the forcing of seasonal changes in surface pressure over Antarctica

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**Abstract.** A 10-year record (1985-1994) of output statistics from the European Centre for Medium-Range Weather Forecasts (ECMWF) model shows that profound seasonal changes in surface pressure take place over the Antarctic continent. The most pronounced changes occur during the periods straddling the brief Antarctic summer, from September to December and again from January to April. Surface pressures atop the high Antarctic plateau often display changes in excess of 20 hPa during these periods. Temperatures in the lower troposphere also exhibit marked changes during these transitional periods; surface temperature changes during these 3-month periods reach a maximum near 40 K over the high interior of Antarctica. Hydrostatic considerations suggest that the thermal adjustment in the lowest levels of the atmosphere alters the vertical distribution of pressure with height and hence is consistent with the dramatic seasonal surface pressure changes over the elevated Antarctic ice sheets. A strong interplay exists between the thermal forcing and the katabatic wind circulation over the continent. The large seasonal changes in solar insolation reaching the Antarctic ice surface modulate the intensity of the katabatic wind regime and thus the resulting mean meridional circulation between the continent and the subpolar latitudes. It is proposed that the diabatic adjustment in the lower levels of the atmosphere over Antarctica disrupts the mean meridional circulation creating a seasonal mass imbalance and hence surface pressure changes. It is through the meridional transports that the mass and wind fields reach a quasi-equilibrium adjusted state. The seasonal mass movement over Antarctica requires large-scale mass compensation over much of the southern hemisphere and shows that the diabatic influences at the Antarctic surface have far-field impacts.

## 1. Introduction

Data collected at manned and automatic weather stations (AWSs) located atop the Antarctic continent suggest that rapid and profound changes in surface pressure accompany the austral autumn and springtime transition periods [*Keller et al.*, 1994; *Radok et al.*, 1996]. The largest surface pressure changes appear to occur over the highest reaches of the East Antarctic continent. AWS records from Dome C (123.0°E, 74.5°S), situated atop the East Antarctic interior at 3280 m elevation, suggest that annual surface pressure changes typically exceed 25 hPa. The periods of most significant change straddle the brief Antarctic summer. In particular, the 3-month periods January to April (hereinafter JA) and September to December (SD) exhibit the bulk of the surface pressure changes. Surface pressures over the continent undergo a dramatic autumn decrease and an even larger springtime increase. Previous work [e.g., *Schwerdtfeger*, 1960, 1967, 1984; *van Loon*, 1967, 1972] has emphasized that such large-scale changes over the continent imply that organized mass transport must occur between Antarctica and subpolar latitudes. *Schwerdtfeger* [1967] also has noted that the surface pressure changes affect slightly the sea level of the Southern Ocean and the mass moment of inertia of the Earth. In this paper the implications of Antarctic surface forcing on the surface pressure changes over the Antarctic continent will be examined. The physical mechanisms behind the mass transports form the basis of this discussion.



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There is no doubt that the continental ice massif of Antarctica acts as a powerful constraint on the atmospheric circulation patterns and transports over the high southern latitudes. The presence of a landmass to the south of the circumpolar Southern Ocean serves to accentuate the subpolar meridional horizontal temperature gradient. In addition, the elevated ice terrain serves as a cooling mechanism for the free atmosphere. The resulting enhancement of the thermal wind in the lower atmosphere accentuates the zonal circulations throughout the troposphere in the subpolar latitudes of the southern hemisphere (SH). Climatology [e.g., *van Loon*, 1972; *Schwerdtfeger*, 1984] has shown that the mean summertime zonal winds in the SH upper troposphere are greater than the mean wintertime zonal winds in the northern hemisphere (NH). This is no doubt a reflection of the fundamentally different polar geographies.

Additionally, the Antarctic orography acts as a buffer to the southward penetration of extratropical cyclones onto the face of the continent [*Mechoso*, 1980]. Potential vorticity considerations imply that a pronounced cyclonic circulation decrease must accompany the movement of low-pressure disturbances across the steep ice escarpment of the coastal stretches of Antarctica. This restricts the vigorous cyclonic parade to a path parallel to and just north of the continental coastline and ensures the existence of an intense baroclinic zone along the coastal periphery throughout the year. The continental ice topography is also responsible for the katabatic wind regime in the lowest few hundred meters of the Antarctic atmosphere.

This vast drainage network of radiatively cooled air serves as an important cold air transport mechanism between the continent and the subpolar regions. The well-documented persistence of the katabatic flow regime implies that a mean meridional circulation must exist over the high southern latitudes. This thermally direct circulation consists of a shallow, low level outflow from the katabatic wind over Antarctica, a region of rising motion just north of the coastal ice slopes, a broad but weak southerly return flow in the middle and upper troposphere, and subsidence over the continent. The attendant meridional circulation established between the Antarctic and the subpolar latitudes has important dynamical consequences. *Egger* [1985] noted that the meridional circulation induces convergence in the middle to upper levels of the troposphere over the Antarctic continent which feeds the katabatic wind regime. The convergence acts to generate cyclonic vorticity in the troposphere. In this sense the topography acts to anchor the upper tropospheric vortex over the continent to a degree unparalleled by the NH. *James* [1988, 1989], *Egger* [1991, 1992], *Parish* [1992], and *Juckes et al.* [1994] have also explored this relationship between the katabatic wind and the mean meridional circulation. There seems no doubt that the katabatic wind regime is an essential mass transport agent in the SH and must play a role in the atmospheric mass changes observed over Antarctica.

During the past decade the observational database for the Antarctic has grown tremendously. There are now well over 50 surface reporting stations in Antarctica, most of them being AWSs [*Stearns et al.* 1993]. However, data coverage is still sparse by midlatitude standards. Surface data over the vast Antarctic interior is collected at less than a dozen sites and upper level sounding coverage is restricted primarily to the coastal periphery about the continent. A total of 16 rawinsonde stations is listed by *Connolley and King* [1993], only two of which can be regarded as interior sites. Because of these data restrictions, it is still not possible to assemble a detailed, continent-wide, three-dimensional depiction of the Antarctic atmosphere based on the observational data alone. In this study we employ output from the European Centre for Medium-Range Weather Forecasts (ECMWF) model. Such an approach has advantages in that a complete and internally consistent data set is easily obtainable. The model output was obtained from the National Center for Atmospheric Research from the Tropical Oceans Global Atmosphere (TOGA) Archive II. The ECMWF data set consists of output reported twice daily (0000 and 1200 UTC) on a 2.5° latitude-longitude grid. The ECMWF output includes the standard state parameters at the surface and at 14 conventional isobaric levels from 1000 to 10 hPa. The horizontal resolution of the ECMWF model of T106 (triangular truncation at wavenumber 106) is sufficient to depict the major ice features of the Antarctic continent. Figure 1 illustrates the ECMWF representation of the Antarctic orography. Comparison with detailed topographic representations such as that shown by *Parish and Bromwich* [1987] shows that the T106 version is smoothed somewhat but retains most of the broadscale character of the ice sheets and is a vast improvement over the R-15 terrain depicted by *Parish et al.* [1994]. The resolution shown in Figure 1 is sufficient for addressing the topographically forced circulations which are prevalent over the continent [*Parish and Bromwich*, 1991]. This study of the surface pressure changes over Antarctica uses the ECMWF output record for the 10-year period 1985-1994.

Performance of numerical models in simulating atmospheric processes in the high southern latitudes has improved greatly this past decade. *Mitchell and Senior* [1989], *Simmonds* [1990], *Tzeng et al.* [1993, 1994], and *Parish et al.* [1994] have evaluated the performance of a variety of atmospheric general circulation models (GCMs) in simulating the present Antarctic climate. *Genthon and Braun* [1995] have explored the validity of ECMWF surface output and have shown that from a 6-year record the model depicts with some fidelity the surface temperatures, precipitation, and accumulation over both Greenland and Antarctica. *Bromwich et al.* [1995] have also examined the moisture budget of the Antarctic region and conclude that the ECMWF analyses generally provide good estimates of precipitation over the Antarctic continent. Recently, *Cullather et al.* [1997] have presented a comprehensive examination of the validity of numerical analyses over Antarctica and show close agreement between model output from ECMWF and pressure observations from the AWS network. The above work also notes the vast improvement in the model analyses during the 1985-1990 period.

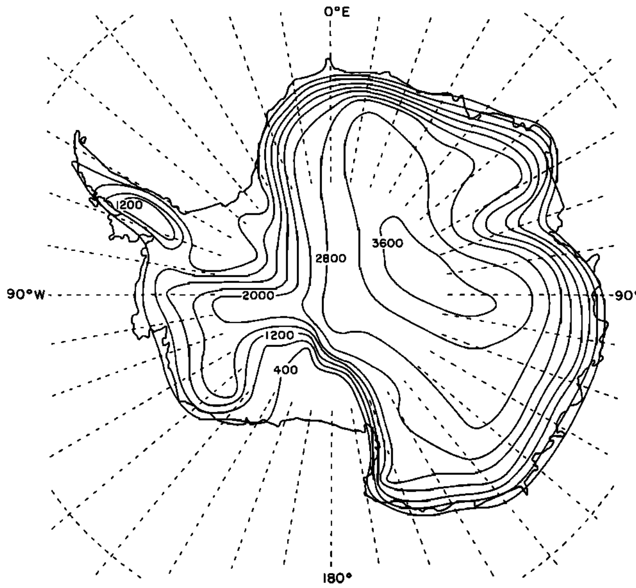


**Figure 1.** European Centre for Medium-Range Weather Forecasts (ECMWF) representation of Antarctic terrain, contour lines in meters.

## 2. Zonally Averaged Fields

The zonally averaged annual cycle of surface pressure deviations about the January mean over the high southern latitudes from the 10-year ECMWF record is illustrated in Figure 2a. It can be seen that the magnitude of the surface pressure deviations increases with latitude and reaches a maximum at the south pole. The most significant changes are seen at times surrounding the summer solstice period; the south pole surface pressure decreases by nearly 10 hPa from January to April and increases by approximately 13 hPa from September to December. It is apparent that the magnitude of the seasonal oscillation decreases rapidly north of the Antarctic coastline, and the phase of the cycle reverses near 60°S. Note also the well-defined semiannual oscillation (SAO) in pressure over the continent in which maxima are reached at the solstice periods with minima at the equinoxes. The SAO has been discussed by *Schwerdtfeger* [1960, 1967], *van Loon* [1967, 1972], *van Loon and Rogers* [1984], and more recently by *Meehl* [1991] and has been proposed to be the result of the differences in heating and cooling rates at different latitude belts ir the high southern latitudes.

A detailed examination of the magnitude of the JA and SD changes over the entire hemisphere based on the ECMWF 10-year output is shown in Figure 2b. The largest changes by far are seen over the Antarctic ice sheets. Conservation of mass

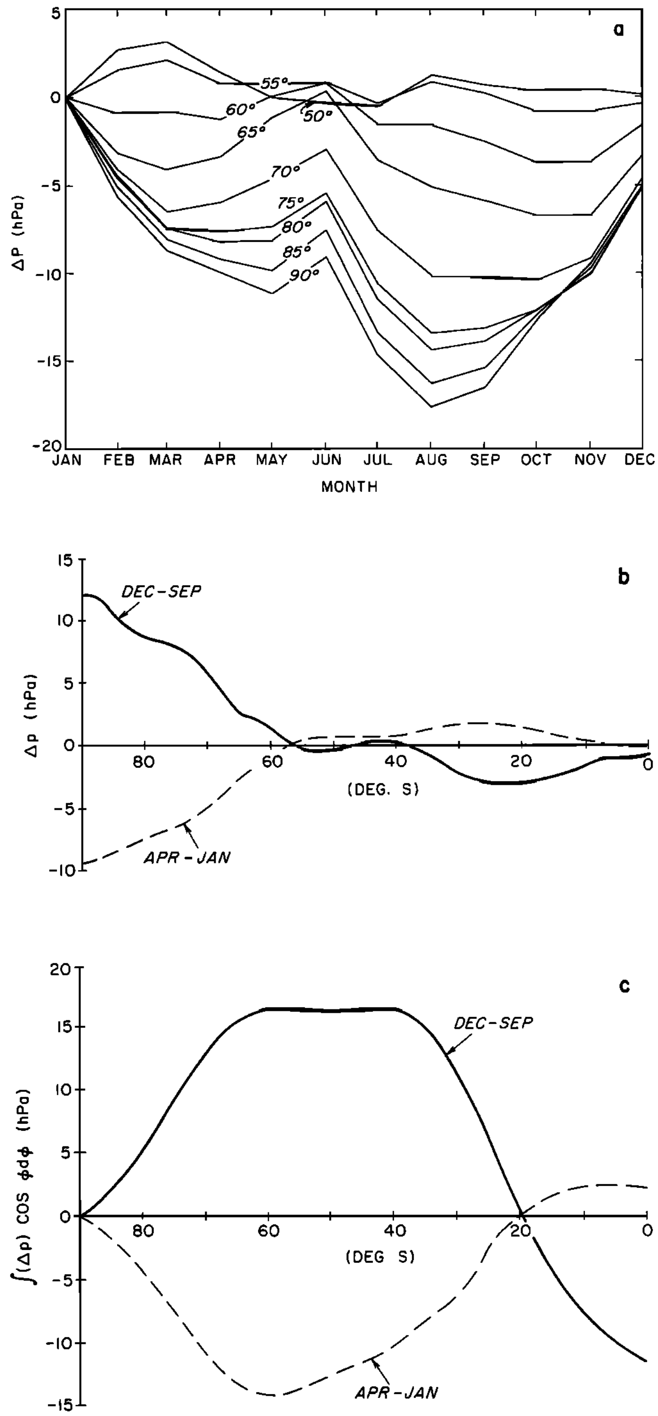


**Figure 2.** ECMWF 1985-1994 representation of (a) annual course of zonally averaged mean monthly surface pressure changes from mean January surface pressure, (b) mean monthly latitudinal variation of surface pressure differences December minus September and April minus January, (c) mean latitudinal area-weighted mass budget integrated northward from south pole for transition seasons January to April and September to December.

requires that the surface pressure changes observed over the Antarctic continent are compensated for by changes of the opposite sign at more northerly latitudes. Little organized surface pressure change takes place in the midlatitude belt from 40° to 55°S during the JA and SD transition periods. Most of the hemispheric surface pressure rises are situated in the subtropical latitudes centered around 25°S.

Pronounced seasonal changes in the atmospheric mass loading over Antarctica require an organized meridional transport of mass and compensating surface pressure changes northward. A representation of the mass transports during the transitional seasons can be obtained by integrating the surface pressure change, weighted by the area, over the SH from the south pole. Such a depiction provides insight as to the scale of the meridional transport required and the magnitude of the latitudinal mass flux. Figure 2c illustrates the integrated mass budget for both the JA and the SD transitional periods from the ECMWF 10-year record with positive values indicating a southward flux. In the austral autumn case, the net northward mass transport increases dramatically from the pole and reaches a maximum near 65°S. The strong mass divergence over Antarctica is apparent. Complete compensation for the significant Antarctic surface pressure changes during JA period is not attained until 20°S. During the austral springtime the situation is very similar except the direction of mass transport is reversed. It seems clear that during both transitional seasons the mass redistribution extends to the subtropics of the SH. From this it is apparent that the seasonal heating and cooling of the great Antarctic ice sheets has an associated far-field response.

Coincident with the abrupt seasonal changes in surface pressure, temperatures over the Antarctic ice surface also display marked changes. Figure 3a is a representation of the zonally averaged mean monthly surface temperatures for latitudes

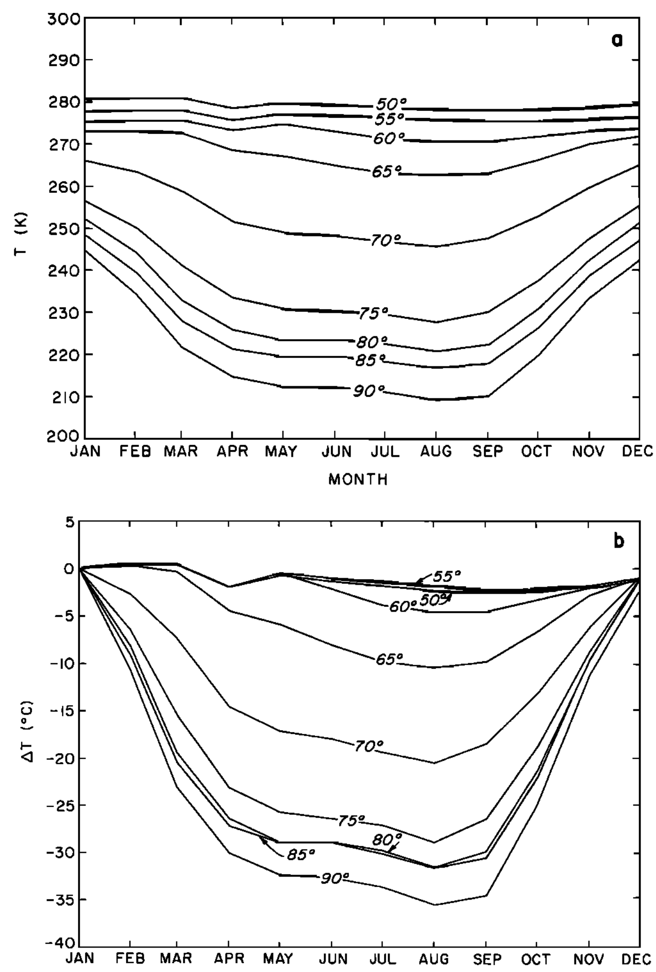


**Figure 3.** Annual course of zonally averaged (a) mean monthly surface temperatures, (b) mean monthly surface temperature differences from the January mean from ECMWF 1985-1994 analyses.

ranging from 90°S to 50°S from the 10-year ECMWF analyses 1985-1994. Note the dramatic contrast displayed by the surface temperature regime poleward of 70°S. The annual amplitude of the continental temperatures are far greater than seen over the oceanic regions to the north. In addition, the surface temperature trends display evidence of the so-called "coreless winter" over the Antarctic continent. Temperatures display a rapid drop from summer conditions in January so that by April a wintertime temperature regime has become established near the surface. The mean surface temperatures from 70°S to the pole show only a slight decrease from April through September suggesting that winter conditions prevail for at least half the year followed by a rapid increase during the austral springtime. Figure 3b illustrates the deviations of the 10-year mean monthly means shown in Figure 3a from the mean January temperatures. It is obvious that the amplitude of the annual surface temperature changes is dependent on latitude. Such temperature changes appear tied to the Antarctic ice sheets suggesting that continentality plays a major role in the establishment of the temperature regime. Strong horizontal temperature gradients at the surface between the Antarctic continent and the Southern Ocean in Figure 3b become enhanced during the transition months January to April and remain intense during the next 6 months before relaxing with the return of the solar heating of the following springtime period.

Seasonal temperature changes are also apparent in the lower troposphere. There is no doubt that the presence of an elevated ice sheet acts as a diabatic heating and cooling source for the troposphere. Figure 4 depicts the cross section of ECMWF temperature changes over the middle and high southern latitudes during the transitional time frames JA and SD for the period 1985-1994. The largest seasonal changes occur near the surface and in the stratosphere. Both are directly related to the solar insolation cycle with the statospheric austral springtime increase tied to the absorption of shortwave radiation by ozone. The magnitude of the change is greater in the stratosphere where temperature changes approach 50°C during the austral springtime. Surface temperature changes during the austral springtime and austral autumn periods are comparable and exceed 25°C. By comparison, the middle and upper tropospheric regions are less disturbed during the SD and JA periods with temperature changes generally 5°-10°C.

The marked lower tropospheric temperature changes illustrated in Figure 4 have important hydrostatic implications which relate directly to the observed pattern of surface pressure change over the Antarctic continent. During the austral autumn period the cooling of the lower atmosphere adjacent to Antarctica requires a more rapid pressure change with height. Assuming that sea level pressure remains constant, a seasonal mean temperature decrease of 10°C in the lower atmosphere implies that at an elevation of 2000 m the pressure will undergo a decrease of approximately 16 hPa. Similarly, the marked temperature increase during the austral springtime will imply that pressure will change more slowly with height and the pressure will appear to rise at a fixed level. From Figure 2 it is readily seen that the largest seasonal changes occur over the most southerly latitudes which, from an examination of the zonally averaged terrain illustrated in Figure 4, are also represent the greatest terrain elevation. From a hydrostatic viewpoint the surface pressure changes shown over the high plateau of Antarctica correspond roughly to a mean low-level temperature change of 8°-10°C which matches reasonably well with the observed changes near the continental periphery.

It is also important to realize that hydrostatic considerations alone cannot explain the seasonal surface pressure changes over the Antarctic ice sheets. For the pressure to decrease (increase) over the high Antarctic plateau, the column of air above the plateau must experience a net mass divergence (convergence). This implies that a net transport of mass out of (into) the vertical column must take place. Thus surface pressure changes over Antarctica have dynamical implications. The near-surface wind and temperature fields over the vast sloping Antarctic ice terrain are inextricably linked. The presence of a temperature inversion over the sloping ice surface implies the existence of a terrain-induced horizontal pressure gradient force. Such a forcing mechanism has been shown to be fundamental in shaping the wind field over the face of the continent [e.g., *Parish*, 1982].

Given the well-documented persistence of the katabatic regime over Antarctica [e.g., *Ball*, 1960; *Parish*, 1982] and geographical configuration of the high southern latitudes, it is not surprising that a mean meridional circulation develops between the continent and approximately 60°S. Since the katabatic winds and near-surface horizontal temperature gradients are strongest during the nonsummer months, it seems obvious that the most pronounced mean meridional circulation between Antarctica and the subpolar latitudes occurs during the nonsummer period. The vertical profile of wind over the Antarctic continent generally consists of a robust but shallow low-level outflow associated with the katabatic drainage and a

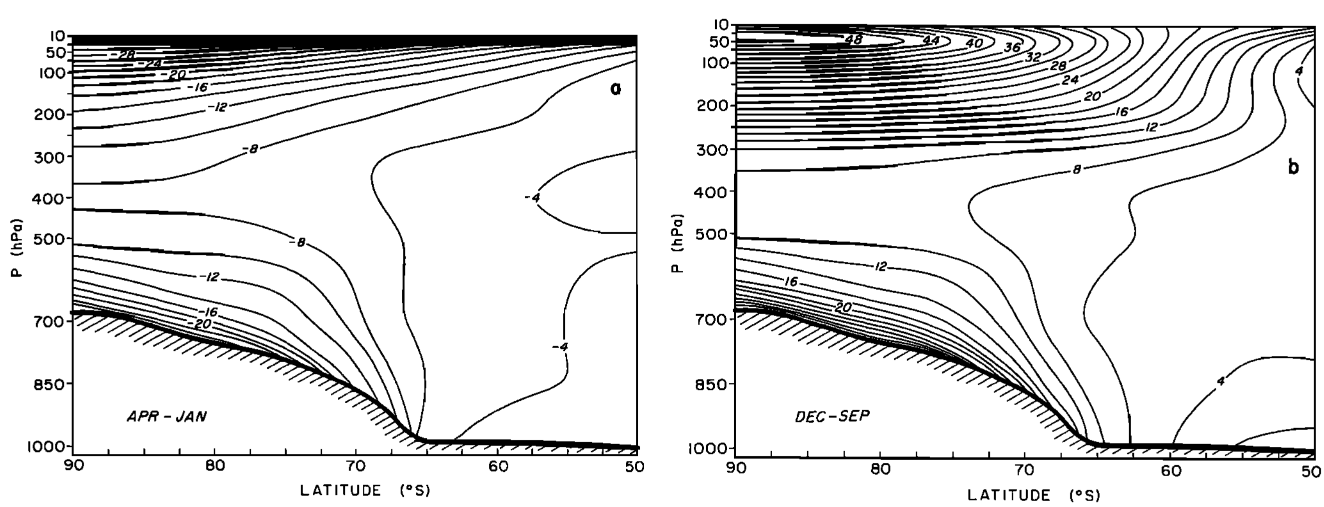


**Figure 4.** Zonally averaged cross section of mean (a) April minus January, (b) December minus September temperatures from ECMWF 1985-1994 analyses.

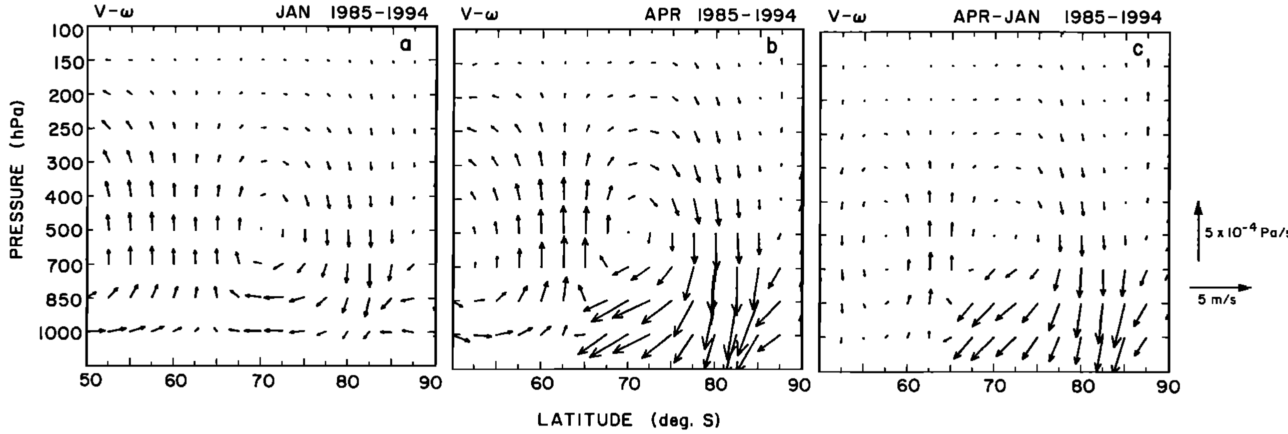


**Figure 5.** Zonally averaged mean vectors of meridional component of motion (m s$^{-1}$) and vertical velocity component omega (Pa s$^{-1}$ x -10$^3$; note upward motion positive) from ECMWF 1985-1994 analyses for (a) January, (b) April, (c) April minus January.

broad but weak inflow at upper levels. This secondary circulation is a dynamical response to the low-level diabatic forcing over the sloping ice terrain. The resulting mass transport is required in attempt to attain hydrostatic and geostrophic balance over the Antarctic ice sheet given the rapid changes in solar insolation.

Such a mean meridional circulation can be seen from the 10-year ECMWF analyses. Figures 5 and 6 illustrate the ECMWF mean meridional circulations of $v$ (northward directed wind component) and $\omega$ (vertical velocity component) for the transitional periods JA and SD, respectively. A mean meridional circulation is well defined throughout the year with intense, shallow outflow presumably associated with the katabatic wind regime below approximately 700 hPa, rising motion just to the north of the continent between 60° and 65°S, a broad return branch from approximately 400 hPa to well into the stratosphere, and subsidence over the continent. As expected, the most intense meridional circulation is seen during the nonsummer months. The outflow is only found over the sloping Antarctic terrain. The maximum wind speeds amount to approximately 2 m s$^{-1}$ and are found near the steepest zonally averaged terrain slopes.

The seasonal cycle of heating and cooling of the sloping ice terrain forces dramatic changes in the intensity of the katabatic wind circulation over Antarctica which leads to significant modulation of the meridional circulation. This is supported by Figure 5c, which illustrates the changes in the 10-year ECMWF zonally averaged mean meridional circulation of $v$-$\omega$ for the JA period. The difference in the $v$-$\omega$ circulation from January to April (Figure 5c) reveals an intensification of the meridional transports. By contrast, the low level outflow becomes substantially reduced during the austral springtime period (Figures 6a-6c). The maximum zonally averaged northward component of motion in December is reduced to less than 1 m s$^{-1}$, and the entire meridional circulation becomes weaker. The austral springtime adjustment of the $v$-$\omega$ circulation suggests again that the most significant changes are found near the surface. It can be seen that the most pronounced adjustment takes place at low levels over the sloping Antarctic ice surface. Only minor changes in the intensity of the return branch in the middle to upper troposphere are seen. This implies that the mean meridional circulation is forced by near-surface processes and that modification of the return branch follows.

Modulation of the mean meridional circulation has implications in terms of mass transport and corresponding surface pressure changes. The thermal adjustment and concomitant katabatic wind increase are both consistent with the nature of the surface pressure changes required during the JA and SD periods. Intensification of the katabatic wind associated with the low-level outflow branch during the austral autumn alters the mean meridional circulation by increasing the low-level mass transport. This suggests that a seasonal differential mass

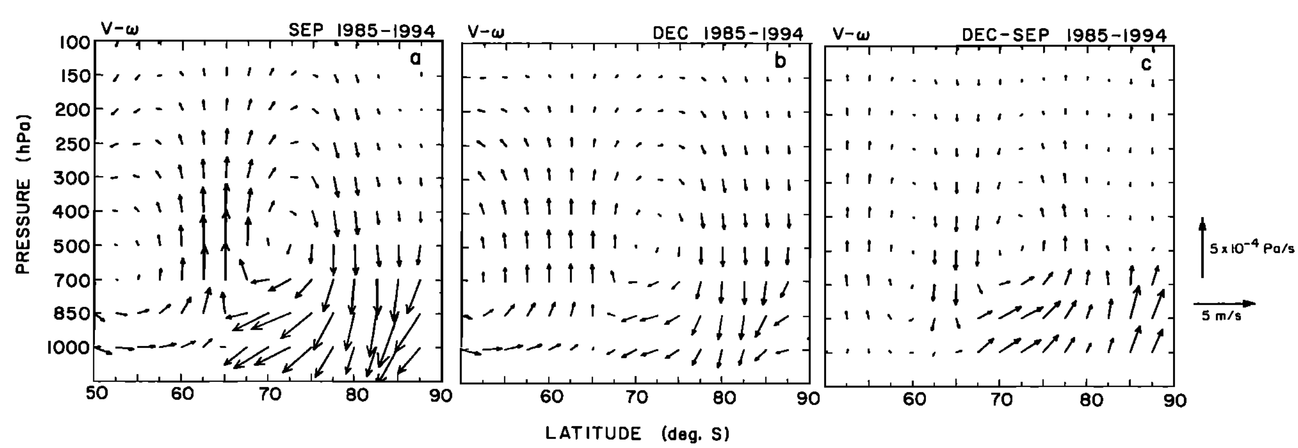


**Figure 6.** As in Figure 5 except for (a) September, (b) December, (c) December minus September.

transport takes place with the lower branch exporting more mass northward than the return branch moves southward. Such that a net mass transport away from the continent occurs during the JA period results in the observed surface pressure decrease. Likewise, during the austral springtime the solar insolation reduces the low-level outflow significantly. The net mass transport toward the Antarctic continent during the springtime is then the result of a weakened katabatic outflow and a less perturbed return flow at middle and upper levels which dominates the pressure tendency. A surface pressure rise over the continent results. Such a conceptual picture is supported at least qualitatively by the mean meridional circulations and seasonal differences during JA and SD as illustrated in the ECMWF mean $v$-$\omega$ cross sections in Figs. 5 and 6.

## 3. Spatial Patterns

Seasonal changes in the atmospheric mass loading over Antarctica during the JA and SD periods are apparent from the zonal averages. The spatial distribution of surface pressure changes over the Antarctic during the transitional periods from the ECMWF 1985-1994 record offers additional testimony to the conceptual mass exchange argument posed previously. Figure 7 depicts the seasonal surface pressure changes over the high southern latitudes for this 10-year period. Surface pressures rise during the austral springtime and fall during the austral autumn, and again the most significant changes are seen atop the high plateau of East Antarctica with magnitudes in excess of 13 hPa. The most impressive feature in Figure 7 is the close association of the seasonal pressure changes over the continent with the ice terrain contours. Isallobaric patterns in both JA and SD cases can be seen to mirror the Antarctic orographic contours with fidelity. The isallobaric gradient appears tied to the gradient of the Antarctic terrain as well. Note that the largest gradients of seasonal surface pressure change are situated along the steeply sloping coastal periphery of East Antarctica as well as along the stretch of the Transantarctic Mountains. Seasonal isallobaric patterns decrease rapidly away from the continental margin and appear to show little organization over the Southern Ocean. Presumably, this reflects the transient synoptic environment and may reflect changes in the long wave patterns in the subpolar latitudes.

*Parish et al.* [1997] have conducted continental-scale model simulations to demonstrate that a similar isallobaric pattern as shown in the JA period of Figure 7a occurs with the onset of the katabatic wind regime. Such numerical results depict the low level branch of the mean meridional circulation as the driving mechanism for the surface pressure changes and hence links the Antarctic katabatic wind regime with the austral autumn mass transport. Similarly, the austral springtime surface pressure changes are associated with modulation of the mean meridional circulation. This explanation emphasizes the surface thermal and dynamic forcing rather than the much discussed stratospheric overturning which occurs at approximately the same time to explain the austral springtime/autumn surface pressure increase/decrease. There is no doubt a stratospheric component to the seasonal surface pressure changes, and the somewhat larger magnitude of the SD surface pressure change is probably a reflection of the stratospheric influence.

Evidence for the modulation of the meridional circulation in the ECMWF record is especially apparent in the terrain induced katabatic wind regime. The time-averaged streamlines of the katabatic airflow [*Parish and Bromwich*, 1987] clearly depict the intimate coupling between the surface winds and the underlying terrain. The topographic control of the surface wind field is apparent in the ECMWF analyses as well. Figure 8 illustrates

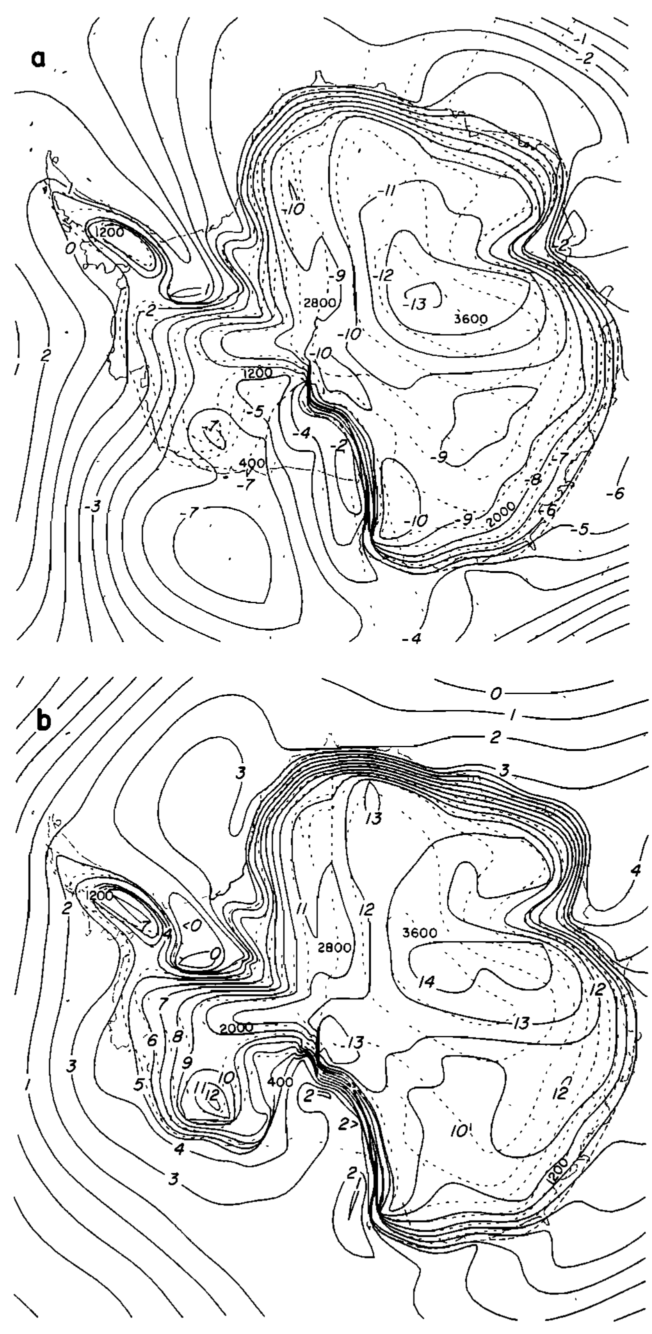


**Figure 7.** Mean monthly surface pressure differences (hPa) for (a) April minus January, (b) December minus September from ECMWF 1985-1994 analyses.

the 10-year average ECMWF surface streamline pattern over Antarctica during the six-month wintertime period April-September. The large-scale pattern is very similar to that inferred by *Parish and Bromwich* [1987, 1991] although the smoothed ECMWF orography does not permit resolution of the various cold air confluence channels depicted in the aforementioned studies. Streamlines indicate a confluence of the cold air drainage onto the Ross Ice Shelf near 180°E and less pronounced confluence zones near the Amery Ice Shelf (70°E) and the Weddell Sea region (45°W). Such confluence zones are prominent in the *Parish and Bromwich* [1987, 1991] representations as well.

Although the continental-scale streamline pattern of the katabatic wind regime over Antarctica displays little seasonal change, the intensity of the wind regime shows significant seasonal modulation. It is this aspect of the low level wind regime which is critical to the northward transport of mass away from the continent. Figure 9a depicts the corresponding ECMWF 10-year mean surface wind speeds over Antarctica for the wintertime months April to September. It can be seen that the intensity of the surface winds over the ice sheets during these months is dependent on the underlying topographic slope. Maximum mean winter wind speeds from the 10-year ECMWF averages are generally 8-10 m s$^{-1}$ within a coastal band extending approximately 200 km or so inland from the continental edge. Such speeds are in reasonable agreement with the mean wintertime wind speeds measured about the coast [*Parish*, 1982; *Stearns et al.*, 1993]. Localized maxima are seen within this coastal band which are probably the result of smaller-scale terrain configurations which induce channelling of the katabatic wind regime. The positions and magnitudes of the maximum wind speeds in Figure 9a agree well with the locations shown in the *Parish and Bromwich* [1991] simulation.

Seasonal diabatic modulation of the low level wind field by solar insolation is evidenced by Figure 9b which depicts the mean January minus April and December minus September changes in the magnitude of the surface wind field. Wind speeds during such transition periods show a decrease of generally 4-6 m s$^{-1}$ along the coastal regions of the Antarctic continent. This amounts to an approximately 50% decrease from the wintertime conditions. The seasonal disruptions of the mean meridional circulation suggest that during the autumn transition months JA, the katabatic wind regime intensifies and the lower branch of the meridional circulation becomes enhanced. As part of this seasonal adjustment, there appears to be a net mass movement away from the Antarctic continent. Similarly, the decrease in the katabatic drainage during the austral springtime SD period perturbs the mean circulation such that a net flooding of atmospheric mass occurs over Antarctica from inflow at the middle to upper levels of the troposphere.

## 4. Summary

Rapidly changing solar geometry during the austral autumn and springtime periods bring about pronounced patterns of heating/cooling of the Antarctic continent. The 10-year average temperatures from the ECMWF suggest that the lower atmosphere above the Antarctic ice sheet is subjected to the largest tropospheric changes during the austral autumn and springtime periods. Such a thermodynamic influence has profound dynamical implications and a major adjustment of the vertical distribution of pressure results. Observed seasonal changes are a reflection of this hydrostatic rearrangement of mass over the Antarctic continent. The katabatic wind field undergoes a significant seasonal oscillation which influences the mean meridional circulation between Antarctica and the subpolar latitudes, and it is proposed that the modulation of this drainage circulation is fundamental to the observed surface pressure changes. The intensity of the lower branch of the

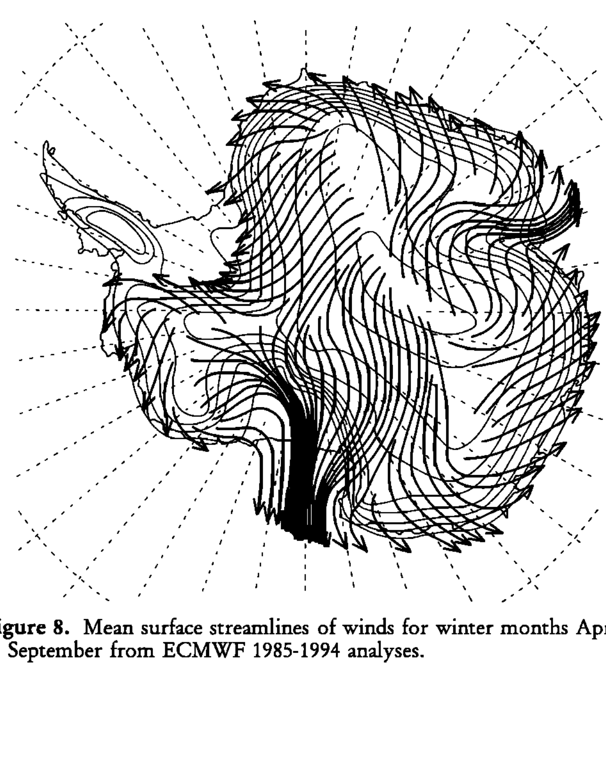

**Figure 8.** Mean surface streamlines of winds for winter months April to September from ECMWF 1985-1994 analyses.

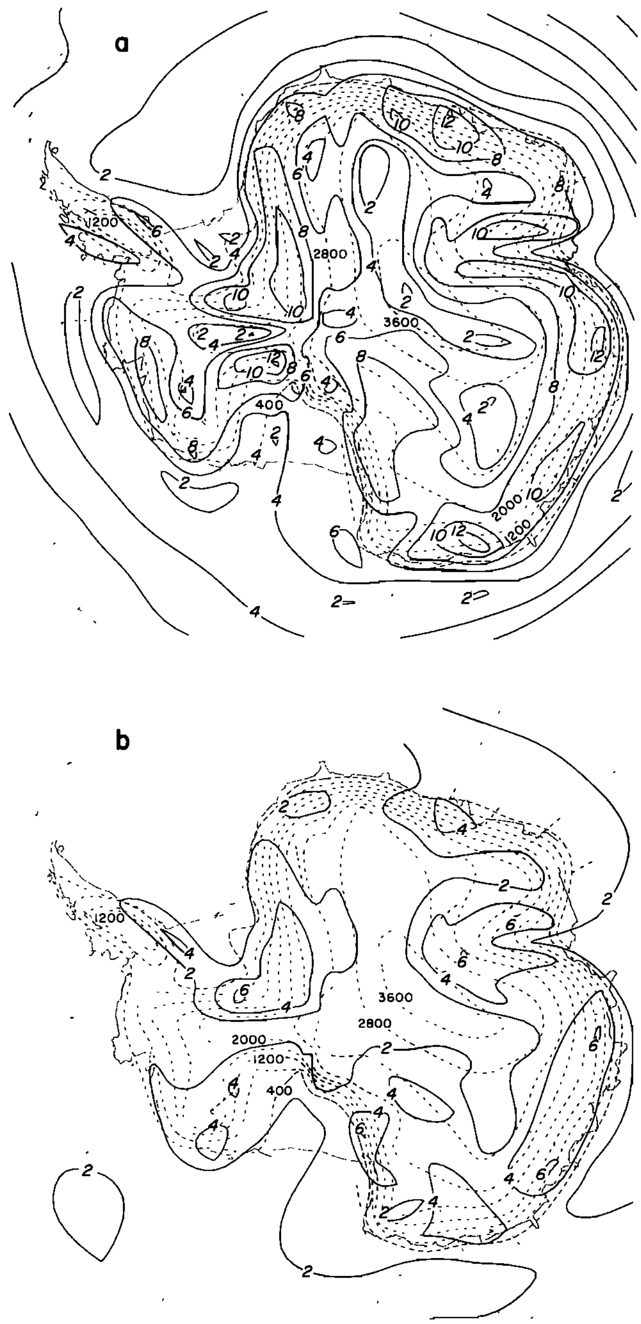


**Figure 9.** ECMWF 1985-1994 analyses of (a) mean wintertime surface wind speeds (m s$^{-1}$) for months April through September, (b) mean April minus January and September minus December wind speeds (m s$^{-1}$).

thermally direct circulation experiences an austral autumn enhancement and austral springtime decrease. The middle to the upper portion of the troposphere is subjected to less pronounced changes. Thus from a mean mass circulation perspective the column of air above Antarctica loses atmospheric mass during the austral autumn period of January to April and gains mass during the austral springtime months September to December. This conceptually simple picture is verified in a qualitative sense by the isallobaric patterns over the Antarctic continent during these transitional periods. Surface pressure changes indicate a close link with the underlying terrain with isallobaric patterns showing congruence with the underlying terrain. Such pressure changes are indicative of the diabatic changes in the lower atmosphere and the resulting hydrostatically induced changes in the vertical gradient of pressure.

It is interesting to note that the 10-year ECMWF output statistics show that the atmospheric column over Greenland is subjected to seasonal oscillations in surface temperature and pressure similar to that seen over the Antarctic. During the NH springtime period from March to June, surface temperatures over the Greenland ice sheet (not shown) increase in a pattern similar to that seen over Antarctica such that the surface temperature change contours mimic the underlying ice terrain. Surface pressure changes over Greenland during this springtime period also display a significant rise with isallobaric patterns also following closely the underlying ice terrain. The reverse of this situation can be seen during the NH autumn period. Such similar trends speak of the profound adjustment in the temperature over the lower levels of the high northern latitudes surrounding Greenland. Given the small size of the Greenland ice sheet as compared to Antarctica, the impact of the seasonal cycle of heating and cooling on the NH tropospheric circulations is undoubtedly smaller.

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## References

Ball, F. K., Winds on the ice slopes of Antarctica, in *Proceedings of the Symposium in Melbourne on Antarctic Meteorology*, pp. 9-16, New York, Pergamon, 1960.

Bromwich, D. H., F. M. Robasky, R. I. Cullather, and M. L. Van Woert, The atmospheric hydrologic cycle over the Southern Ocean and Antarctica from operational numerical analyses, *Mon. Weather Rev., 123*, 3518-3538, 1995.

Connolley, W. M., and J. C. King, Atmospheric water-vapour transport to Antarctica inferred from radiosonde data, *Q. J. R. Meteorol. Soc., 119*, 325-342, 1993.

Cullather, R. I., D. H. Bromwich, R. W. Grumbine, Validation of operational numerical analyses in Antarctic latitudes, *J. Geophys. Res.* (this issue), 1997.

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

Egger, J., On the mean atmospheric circulation over Antarctica, *Geophys. Astrophys. Fluid Dyn., 58*, 75-90, 1991.

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

Genthon, C., and A. Braun, ECMWF analyses and predictions of the surface climate of Greenland and Antarctica, *J. Clim., 8*, 2324-2332, 1995.

James, I. N., On the forcing of planetary-scale Rossby waves by Antarctica, *Q. J. R. Meteorol. Soc., 114*, 619-637, 1988.

James, I. N., The Antarctic drainage flow: Implications for hemispheric flow on the Southern Hemisphere, *Antarct. Sci., 1*, 279-290, 1989.

Juckes, M. N., I. N. James, and M. Blackburn, The influence of Antarctica on the momentum budget of the southern extratropics, *Q. J. R. Meteorol. Soc., 120*, 1017-1044, 1994.

Keller, L. M., G. A. Weidner, and C. R. Stearns, *Antarctic Automatic Weather Station Data for the Calendar Year 1992*, 356 pp., Dep. of Atmos. and Oceanic Sci., Univ. of Wisc., Madison, 1994. (Available from the Dep. of Atmos. and Oceanic Sc., Univ. of Wisc., Madison)

Mechoso, C. R., The atmospheric circulation around Antarctica: Linear stability and finite amplitude interactions with migrating cyclonese, *J. Atmos. Sci., 37*, 2209-2233, 1980.

Meehl, G. A., A re-examination of the mechanism of the semi-annual oscillation in the Southern Hemisphere, *J. Clim., 4*, 911-926, 1991.

Mitchell, J. F. B, and C. A. Senior, The antarctic winter; simulations with climatological and reduced sea-ice extents, *Q. J. Roy. Meteorol. Soc., 115*, 225-246, 1989.

Parish, T. R., Surface airflow over East Antarctica, *Mon. Weather Rev., 110*, 84-90, 1982.

Parish, T. R., On the role of Antarctic katabatic winds in forcing large-scale tropospheric motions, *J. Atmos. Sci., 49*, 1374-1385, 1992.

Parish, T. R., and D. H. Bromwich, The surface windfield over the Antarctic ice sheets, *Nature, 328*, 51-54, 1987.

Parish, T. R., and D. H. Bromwich, Continental-scale simulation of the Antarctic katabatic wind regime, *J. Clim., 4*, 135-146, 1991.

Parish, T. R., D. H. Bromwich, and R.-Y. Tzeng, On the role of the Antarctic continent in forcing large-scale circulations in the high southern latitudes, *J. Atmos. Sci., 51*, 3566-3579, 1994.

Parish, T. R., Y. Wang, and D. H. Bromwich, On the forcing of seasonal pressure changes over the Antarctic continent, *J. Atmos. Sci.*, in press, 1997.

Radok. U., I. Allison, and G. Wendler, Atmospheric surface pressure over the interior of Antarctica, *Antarct. Sci., 8*, 209-217, 1996.

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

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

Schwerdtfeger, W., *Weather and Climate of the Antarctic*, 261 pp., Elsevier, New York, 1984.

Simmonds, I., Improvements in general circulation model performance in simulating Antarctic climate, *Antarct. Sci., 2*, 287-300, 1990.

Stearns, C. R., L. M. Keller, G. A. Weidner, and M. Sievers, Monthly mean climatic data for Antarctic automatic weather stations, *in Antarctic Meteorology and Climatology: Studies Based on Automatic Weather Stations, Antarc. Res. Ser., 61*, edited by D. H. Bromwich and C. R. Stearns, vol. 61, pp. 1-21, AGU, Wahington, D.C., 1993.

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

Tzeng, R.-Y., D. H. Bromwich, T. R. Parish, and B. Chen, NCAR CCM2 simulation of the modern Antarctic climate, *J. Geophys. Res., 99*, 23131-23148, 1994.

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

van Loon. H., Pressure in the southern hemisphere, in *Meteorology of the Southern Hemisphere*, Meteorol. Monogr. Ser., vol. 35, pp. 59-86, Amer. Meteor. Soc., Boston, Mass., 1972.

van Loon, H., and J. C. Rogers, Interannual variations in the half-yearly cycle of pressure gradients and zonal wind at sea level on the Southern Hemisphere, *Tellus Ser. A, 36*, 76-86, 1984.

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