Chapter 4

Meteorology of the Antarctic

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4.1. Basic geographical characteristics

The great antarctic ice sheets and the surrounding Southern Ocean environs are large heat sinks in the global energy budget. Their geographical position limits the amount of solar insolation incident at the surface at such latitudes, and the high reflectivity of the ice fields of the Antarctic continent reduces the effective heating (see Carleton 1992). There are pronounced differences between the north and south polar regions. The Northern Hemisphere polar region consists essentially of an ice-covered ocean surrounded by continental landmasses, while the Southern Hemisphere features a continental landmass about the pole surrounded by an ocean. The most significant consequence of the vastly differing polar geographies is that the meridional temperature gradients become enhanced in the SH, resulting in a semipermanent baroclinic zone surrounding Antarctica and in effect thermally isolating the Antarctic continent to a degree unparalleled in the NH. As a result, Antarctica experiences the coldest and most harsh climate on earth. The intensified temperature contrast also supports a large west-to-east thermal wind component. Upper-tropospheric westerlies, which circumscribe the Antarctic continent, are considerably stronger than their NH counterparts (Schwerdtfeger 1984, pp. 223–226).

A second factor critical for the pronounced hemispheric polar contrast is the continental orography of Antarctica. With a mean elevation of nearly 2400 m, it is by far the highest continent on earth. There are dynamical constraints brought about by the continental orography that shape the meteorology of the high southern latitudes. Among these is the establishment of a mean meridional circulation between the continent and more northerly latitudes. The lower branch of this consists primarily of the katabatic wind regime, the ubiquitous feature of the lower atmosphere over the continent and an important mechanism for the transport of mass and cold air northward. The elevated antarctic terrain also serves as a barrier to the inland progression of extratropical cyclones, which frequent the continental periphery. There is evidence that the antarctic orography serves as an anchor for the upper-level tropospheric and lower-stratospheric circulations, thereby reducing the wandering of the center of the circumpolar vortex.

Figure 4.1 serves as a reference to the antarctic orography and some of the geographical features and stations. A complete listing of the historical antarctic stations and dates of operation can be found in Schwerdtfeger (1970); selected climatic records can also be found in Schwerdtfeger (1984). The Antarctic continent is essentially entirely covered with a permanent ice sheet that, in places over East Antarctica, exceeds 4000 m in thickness. Inspection of the antarctic ice topography reveals marked differences in the terrain slope over the continent. Both the gently sloping wide expanse of the Antarctic interior and the steep near-coastal ice slopes are meteorologically significant and control the near-surface wind and temperature regimes throughout the year. Depicted also in Fig. 4.1 is the mean seasonal extent of the pack ice in the high southern latitudes, from Gloersen et al. (1992) for the years 1978–87 based on satellite observations. The sea ice surrounding the continent undergoes vast seasonal variations, receding from a maximum area of approximately 2×10^7 km in early spring to 4×10^6 by autumn (Zwally et al. 1983). Such pronounced variations result in strong seasonal surface heat budget changes over the Southern Ocean. Carleton (1981, 1983) notes that the zonal frequency of new cyclones in high southern latitudes may be related to the advance and retreat of the sea ice edge.

4.2. The temperature and radiation regimes

Given its geographical position surrounding the South Pole and elevated ice surface, it is not surprising that the radiative budget of Antarctica is strongly negative for most of the year (Radok 1981). The snow

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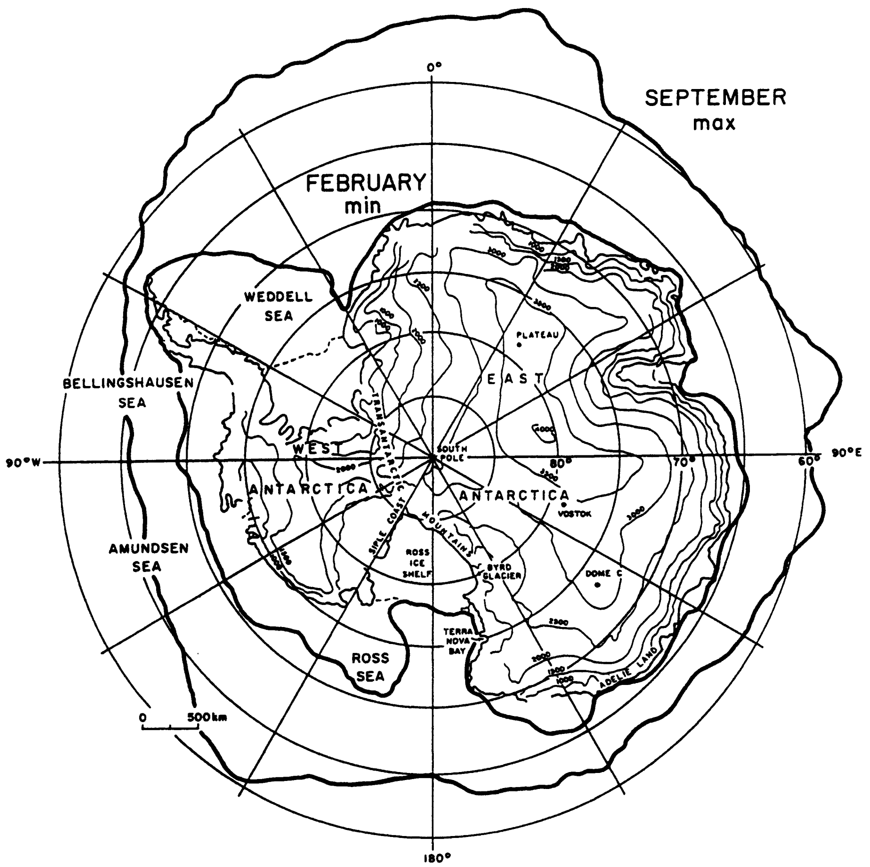

FIG. 4.1. The Antarctic continent and selected geographical references. Thin lines are height contours in meters. Thick lines are maximum and minimum sea-ice extents for the years 1978–87, after Gloersen et al. (1992).

and ice surface acts nearly as a black body; emissivity values in excess of 0.90 have been measured over the antarctic surface (Carroll 1982). Continental albedo values reported by a number of authors (e.g., Kuhn et al. 1977; Carroll and Fitch 1981; Wendler et al. 1988) are generally around 0.80 or higher, implying that only about 20% of the already weak solar insolation is available to warm the continental ice slopes. Back radiation from the warmer atmosphere above the inversion limits the surface cooling somewhat (Kuhn and Weickmann 1969; King 1996) but, except under dense stratus conditions, is far less than the surface radiative flux lost to space. Climatologically speaking, the extremely low water vapor content above the continent and the prevalence of clear sky conditions (Schwerdtfeger 1970; Yamanouchi and Kawaguchi 1992) restrict the downwelling atmospheric component.

A number of studies have examined the heat budget over the continental environs to show the importance of radiational forcing (Kuhn et al. 1977; Bintanja and van den Broeke 1995; King et al. 1995; King 1996). King et al. (1995) conducted a surface energy budget study over an ice shelf during winter and found that turbulent transports and heat conductivity through the ice are small compared to the radiative fluxes. Modeling work (Parish and Waight 1987) suggests that turbulent heat fluxes may form a significant component of the surface energy budget during strong katabatic wind episodes near the coast but are secondary to radiative fluxes over the gently sloping terrain of the vast Antarctic interior (see also King 1990, 1993a).

The result of the strong radiative deficit is the establishment of the great antarctic surface temperature inversion, which persists over nearly the entire continent during all but the brief midsummer period. Such inversions are generally contained within a depth of only a few hundred meters, with the most extreme vertical temperature changes in the lowest 100 m. Depictions of the pronounced inversions over the interior plateau of East Antarctica can be found in Kuhn et al. (1977) and are summarized in Schwerdtfeger (1984). Estimates of the mean wintertime inversion strength can be seen in the initial work of Phillpot and Zillman (1970) and the slightly modified version shown in Schwerdtfeger (1970). An illustration of the wintertime inversion strength (warmest tropospheric temperature minus the near-surface value) is shown as

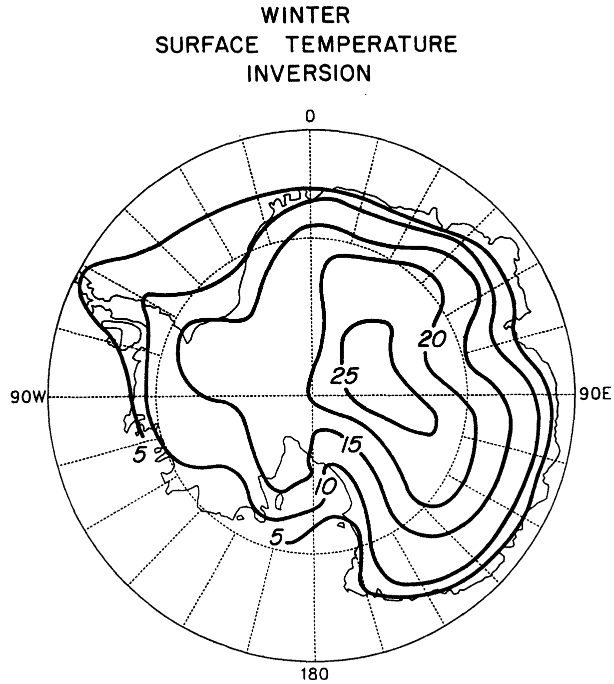

FIG. 4.2. Mean wintertime (June–September) inversion strength (°C) over Antarctica (after Phillpot and Zillman 1970; Schwerdtfeger 1970).

Fig. 4.2. The isopleths of inversion strength in some sense mirror the underlying terrain, with the strongest inversions in excess of 25 K over the highest portions of the continent. Daily measurements from the high interior stations such as Plateau and Vostok indicate that inversions approaching 35 K are not uncommon. The terrain slope is probably as important as elevation in the development or destruction of the great temperature inversion over the continent. The steeply sloping surfaces encourage a vigorous vertical momentum exchange in the lowest portion of the atmosphere via the katabatic wind regime, which limits the strength of the near-coastal inversions. Ample observational evidence exists to support mechanical mixing as an important process in destroying the inversion over the interior (Kuhn et al. 1977). In addition, Carroll (1994) has shown that a strong correspondence is seen between warming events at the South Pole and the longwave radiation budget. The influx of thick cloud shields over the continent, which are associated with cyclonic activity near the coast, can also disrupt the radiative budget over the interior and lead to a breakdown of the inversion.

Antarctica experiences extreme continentality, owing to its geographical location and physical characteristics of the ice surface. Large seasonal temperature changes are evident on the high plateau of Antarctica in response to the solar and longwave radiational forcing. Automatic weather station (AWS) data (Keller et al. 1994, for example) for the period 1980–91 indicate that Dome C, like other sites situated in the Antarctic interior, undergoes a pronounced annual temperature cycle, with the coldest mean monthly temperatures 35°C colder than those found during the summer months (see Fig. 4.3). The outstanding features of this temperature regime are the rapid seasonal transitions and the peculiar flat midwinter temperature trend. The summer period is very short, only six weeks or so in duration, centered around 1 January. Individual three hourly records from the Dome C AWS indicate that autumn temperatures become obvious by early February and the onset of winter is rapid. Mean monthly surface temperatures over the high interior decrease by nearly 25°C in the two-month period from late January to late March. The winter temperature regime over the Antarctic interior becomes established by April, and only minor variations in temperature are seen for the next five months. As suggested in Fig. 4.3, the "coreless winter" is pronounced at all interior stations. Temperature records for stations situated near the coast suggest that the coreless winter phenomenon is still present, although for a shorter period of time—from approximately May through August (see Bromwich et al. 1993, for example).

The coreless winter has been discussed by many authors since first described in the early part of this century. Schwerdtfeger (1970, 1984) and Wendler and Kodama (1993) have summarized early studies. The coreless winter is a consequence of the radiatively forced heat budget near the surface over the Antarctic interior. As the solar insolation of the ice slopes decreases, a pronounced net cooling of the surface takes place. The outgoing longwave radiation from the snow surface, which radiates nearly as a black body, exceeds the sum of the incoming radiation and downward sensible heat flux and other smaller heat fluxes toward the surface, such as heat conduction from the ground and sublimation. As the surface cools, the emitted longwave radiation from the surface decreases according to the Stefan–Boltzman law. Eventually, a near balance is reached between the upward radiation from the surface and the combined effects of primarily

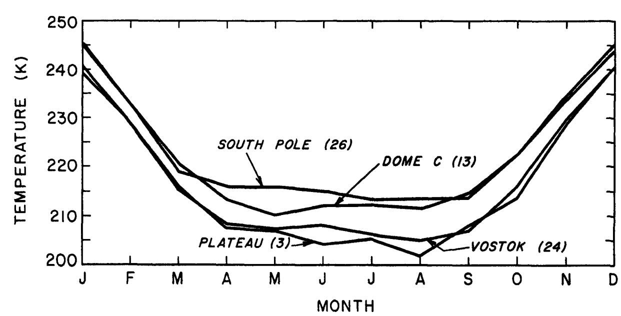

FIG. 4.3. Mean monthly temperatures at interior stations South Pole, Dome C, Vostok, and Plateau, based on multi-year records. Number in parentheses indicates the number of years in each record.

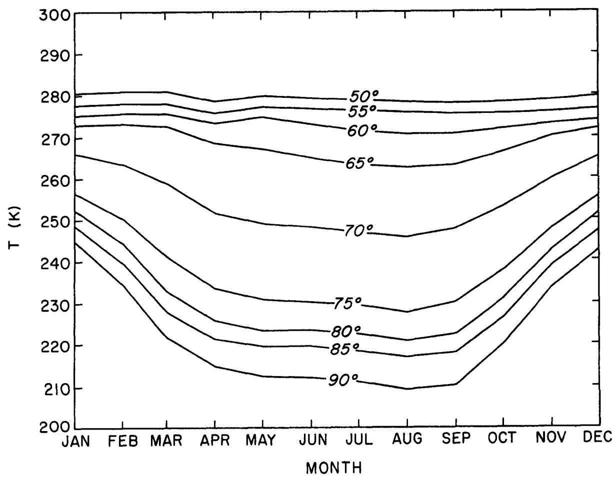

FIG. 4.4. Zonally averaged mean monthly surface temperatures for latitudes 50°–90°S, based on ECMWF analyses, averaged for 1985–94, in K.

the downwelling radiation and sensible heat exchange from the now much warmer atmosphere just above the surface. It may also be the case that as the surface cools past −80°C or so, the efficiency of the cooling process decreases. At such low temperatures the maximum longwave radiation emitted from the surface shifts toward longer wavelengths. The atmosphere becomes increasingly opaque to longwave radiation beyond a wavelength of 15 μm or so, due to absorption by CO_2. This implies that a natural buffer exists to prevent the surface temperatures from decreasing past a certain point in an absolute sense as well. The lowest surface temperature ever recorded on the surface of the earth was −89.2°C at Vostok in 1983.

Surface temperatures over the high southern latitudes are greatly influenced by the antarctic ice sheets. As an illustration, Fig. 4.4 represents the zonally averaged mean monthly surface temperatures from the ECMWF (see Trenberth 1992) model for a 10-yr period, 1985–94. Recent work has shown that the ECMWF model output reveals close agreement with available surface and upper-air observations using a variety of statistical measures for this time period (e.g., Cullather et al. 1997); in addition, climatological analyses of snow accumulation and surface temperature match time-averaged ECMWF depictions (Genthon and Braun 1995). Continent–ocean contrasts are evident in the annual course of surface temperature over high southern latitudes. South of approximately 70°, the range of the annual cycle of surface temperature exceeds 20 K and approaches 30 K south of 80°S. The meridional surface temperature gradients between Antarctica and the subpolar latitudes also show an annual cycle. The latitudinal surface temperature differences increase dramatically during austral autumn and remain large until the return of the sun at antarctic latitudes in the springtime, at which time the gradients relax.

4.3. The surface wind regime

The strong radiative deficit over the continental ice slopes of Antarctica has important dynamical constraints on the near-surface windfield. The often intense radiative cooling of the sloping ice surface implies that a density contrast becomes established with the coldest and hence most dense air near the surface. A horizontal pressure-gradient force thus becomes established in the lowest portion of the atmosphere over the sloping terrain, directed in a downslope sense. Lettau and Schwerdtfeger (1967) coined the phrase "sloped-inversion" pressure-gradient force to underscore the fundamental roles of both the sloping terrain and temperature inversion near the surface in producing this force. Radok (1973, 1981) has also discussed the forcing of the katabatic wind regime and the potential role of the drainage circulation in the energetics of the antarctic atmosphere. The intensity of the katabatic wind is proportional to the steepness of the underlying terrain, and consequently the most intense katabatic winds are found near the steep coastal stretch of the continent. As is seen from Fig. 4.1, the coastal stretch of East Antarctica contains especially steep ice slopes and is the site of the most intense surface wind conditions found on earth. Parish (1982a, 1988) describes some of the fundamental characteristics of the katabatic wind and has listed multi-year resultant wind statistics for a number of the historical stations. Such records underscore the importance of the terrain in forcing the surface wind over Antarctica.

A number of other factors have been suggested as potentially significant in forcing the continental drainage flows as well. Radok (1973) and Wendler and Kodama (1984) have noted that along-slope temperature gradient from the coast of Adélie Land to Dome C situated on the high plateau of East Antarctica is generally superadiabatic. This implies that as the air moves downslope, it is colder than the air it replaces and hence is subject to acceleration. Others have commented on the potential role of drift snow in enhancing the drainage flows (e.g. Radok 1973; Loewe 1974; Kodama et al. 1985; Gosink 1989). It is thought that the sublimational cooling of embedded snow particles may enhance the downslope forcing of the airstream.

There is now a vast assortment of surface wind data from the Antarctic continent and some of the main features of these drainage winds are now well described and understood. Since 1980, the number of wind observations has been enhanced considerably with the development of AWS (e.g., Stearns and Savage 1981; Stearns 1982; Allison and Morrissy 1983; Stearns et al. 1993). Currently, more than 50

AWS units are operating, and much of the data collected has been made widely available (Keller et al. 1994, for example). Some of the deployments have enabled detailed assessments of the katabatic wind regime, such as the arrays of stations in Adélie Land (Wendler et al. 1993; Périard and Pettré 1993) and inland of Terra Nova Bay (Bromwich et al. 1993).

The katabatic wind system is among the most persistent surface flow regimes in the world, rivaling even the trade-wind regime (Radok 1973). The directional constancy, a ratio of the vector-average wind speed to the scalar-average wind speed, is generally 0.90 or greater in analyses of annual wind statistics for antarctic stations (Parish 1982a, 1988; Wendler and Kodama 1984, 1985), indicating the unidirectional nature of the katabatic winds. In nearly all cases, the resultant wind direction is oriented to the left of the fall line some 20°–50°, consistent with Coriolis deflection of a pure gravity-driven flow. It is significant that the wind directions at antarctic stations are constrained to follow topographic pathways. This implies that the topographically induced forcing is the predominant forcing mechanism. Observations of manned and automatic stations along the katabatic-prone stretch of coastal East Antarctica show that approximately 90% of the wind observations occur in a narrow directional sector of 30° or so (see Madigan 1929; Loewe 1974; Keller et al. 1994). This is especially impressive given the frequency and intensity of cyclonic disturbances in the highly baroclinic zone along the periphery of the Antarctic continent.

Much of the early literature (Ball 1956, 1957, 1960; Streten 1963; Mather and Miller 1966, 1967a; Lettau and Schwerdtfeger 1967; Schwerdtfeger and Mahrt 1968; Weller 1969; Radok 1973) explored the dynamical relationship between the inversion strength, terrain slope, and friction to explain the observed katabatic wind characteristics. Subsequent observational (e.g., King 1989, 1993b) and modeling efforts (Parish 1984; Parish and Waight 1987; Parish and Wendler 1991; Gallée and Schayes 1992, 1994; Gallée et al. 1996; Hines et al. 1995) have also examined the terrain-induced forcing. It became clear that, to a first approximation, the near-steady flows in the interior of the Antarctic continent could be envisaged as a result of the balance between the terrain-induced horizontal pressure gradient force, the Coriolis force, and the friction force, as modified by the horizontal pressure gradient force in the free atmosphere. Recent work by Neff (1992, 1994) and Carroll (1994) based on measurements from acoustic sounders (Neff 1981) near the South Pole suggests that transitory forcing from synoptic influences presents a complicated boundary-layer structure and that the upper-level forcing is important in the lower atmospheric flow regime. Coastal flows can become highly non-uniform, and ample evidence (Tauber 1960; Streten 1968, 1990; Wendler and Kodama 1985; Sorbjan et al. 1986; Parish et al. 1993a,b; Yasunari and Kodama 1993; van den Broeke and Bintanja 1995) exists to suggest that the synoptic environment acts to modulate their intensity. In particular, Parish et al. (1993a) and Yasunari and Kodama (1993) show that the strongest katabatic winds are associated with favorable synoptic-scale pressure gradients, which generally imply relatively weak upper-level westerly winds that accompany the strong lower-tropospheric easterlies. Modeling work by Murphy and Simmonds (1993) has also shown the importance of synoptic forcing in producing strong katabatic wind conditions at Casey near the coast of East Antarctica.

Observations also show significant seasonal modulation is present in the continental-scale katabatic wind regime, with marked winter maxima at exposed coastal stations (Mather and Miller 1967b). Wendler et al. (1988) and Kodama et al. (1989) have conducted detailed field studies during summer periods over the near-coastal region of Adélie Land and shown that wind speeds undergo a modest diurnal variation due to solar radiation, with the maximum wind speeds seen during the early morning hours and minimum speeds early in the afternoon (see also Périard and Pettré 1993). One unexpected finding was that the directional constancy remained high throughout the observing period, despite the relatively strong solar insolation, due to the pressure gradient associated with the land–ocean thermal contrast.

Parish and Bromwich (1987) have shown that a qualitatively accurate diagnosis of the time-averaged winter pattern of the surface airflow over the Antarctic continent is possible given reasonable estimates of the sloped-inversion pressure gradient force and some representative value of friction. Such an analysis exploits the strong control of the underlying terrain on the surface windfield and the attendant high directional constancy of the wind. Figure 4.5 is adapted from that work and illustrates the preferred cold-air drainage channels over the face of the continental ice sheets. Available evidence, including both surface observations and surveys of sastrugi orientation (Parish and Bromwich 1987; Parish 1988), offers support to the simulated broad-scale streamline pattern. As seen in Fig. 4.5, the drainage pattern is not uniform. Rather, katabatic wind streamlines become concentrated in a finite number of channels over the continent. The convergence of drainage streamlines implies that cold, negatively buoyant air from a broad horizontal area becomes concentrated into a restricted pathway. Such confluence zones represent areas of enhanced cold-air supplies available to feed katabatic winds downstream. The accumulation of negatively buoyant reserves allows the downstream katabatic wind regime to become anomalously intense and persistent.

Confluence regions upslope from the very windy areas in Adélie Land (Parish 1981, 1984; Parish and Wendler 1991; Wendler et al. 1993; Wendler et al.

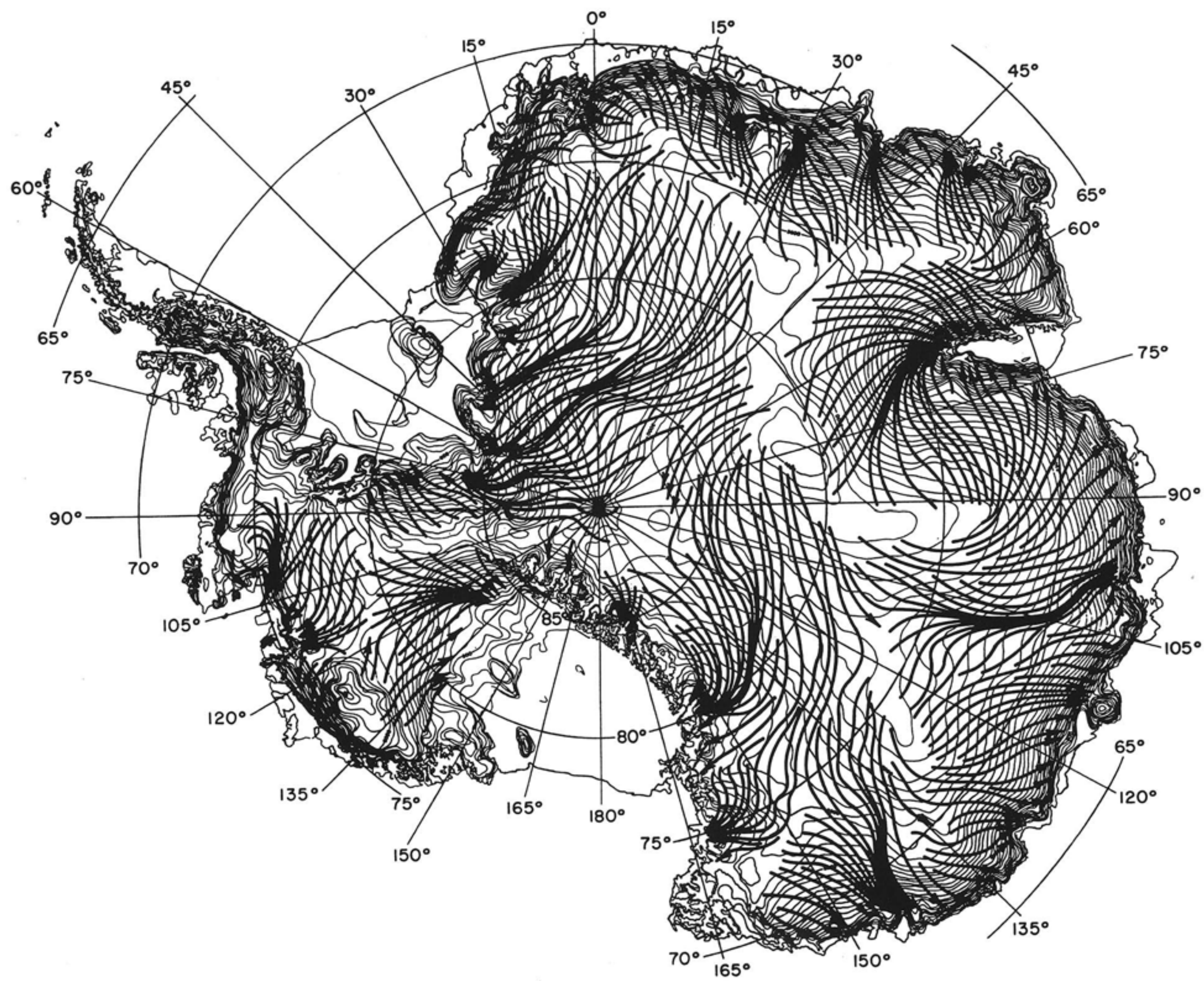

FIG. 4.5. Time-averaged wintertime streamlines (bold lines) of surface airflow over Antarctica, after Parish and Bromwich (1987). Thin lines are elevation contours in increments of 100 m.

1997) and at Terra Nova Bay (Bromwich and Kurtz 1984; Bromwich 1989a,b; Parish and Bromwich 1989; Bromwich et al. 1993) have previously been discussed. The katabatic wind at Adélie Land is especially impressive. Mawson's 1911–14 expedition set up the base camp of Cape Denison, at which katabatic winds were incessant for nearly two years. The wind statistics are impressive (Mather and Miller 1967b; Loewe 1972, 1974). The mean wind speed during the two-year period of observations was 19.8 m s^{-1}. The highest mean monthly wind speed was 24.9 m s^{-1} during July 1913; the windiest day was recorded on 16 August 1913, during which time the mean wind speed was 36.0 m s^{-1}. Three-hour reports of wind speeds in excess of 20 m s^{-1} were recorded on approximately 50% of all days. Even the lowest mean monthly wind speed during the two-year period (11.7 m s^{-1} during February 1912) is exceptional, since it is comparable to the typical winter monthly mean wind speed at katabatic-prone coastal stations.

Local intensification of katabatic airstreams is also suggested in the simulation along the Siple Coast stretch of West Antarctica, upstream from Byrd Glacier in the Transantarctic Mountains and the western side of the Amery Ice Shelf, with numerous smaller confluence zones along the coastal stretch of East Antarctica from 0° to 60°E. Strong evidence (Bromwich 1986, 1989a; Bromwich et al. 1992; Bromwich and Liu 1996; Breckenridge et al. 1993; Carrasco and Bromwich 1993) has been presented that supports the confluence zones at both the Siple Coast and Byrd Glacier sites. The drainage through the Siple Coast region can be enhanced by the prevailing synoptic situation. Bromwich et al. (1992, 1994) note that cyclone centers frequently pass north of the Ross Ice Shelf and over the Amundsen Sea and act to intensify

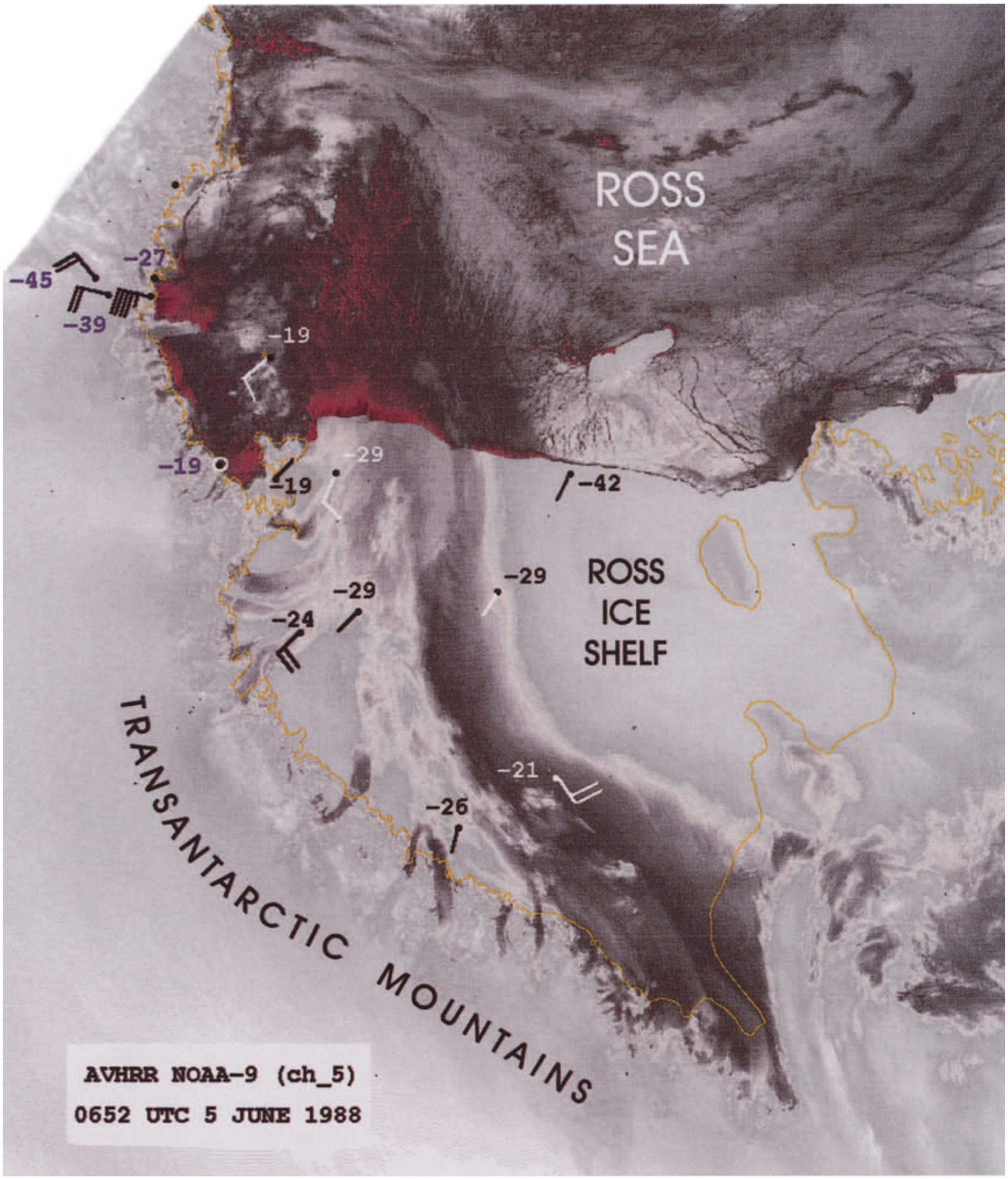

FIG. 4.6. Thermal infrared satellite image (0652 UTC 5 June 1988) of winter katabatic flow from Siple Coast crossing the Ross Ice Shelf (dark and warm signature) to the Ross Sea. Simultaneous AWS observations of air temperature in °C and near-surface winds using conventional notation are plotted. Brightness temperatures near 0°C over the Ross Sea are shown in red to resolve areas of open water and/or thin ice.

the drainage flow through and beyond the confluence zone (Fig. 4.6).

A similar favorable synoptic pressure field over the Ross Ice Shelf also supports the flow through the various glaciers in the Transantarctic Mountains (Bromwich 1989a,b), as can be seen in Fig. 4.6. Breckenridge et al. (1993) note that thermal infrared imagery reveals evidence of katabatic flows through glacier valleys on over 50% of the days on which satellite coverage is obtainable, and they suggest that such drainage conditions are found on nearly 100% of the cloud-free days. The presence of a katabatic wind signature on thermal infrared images was first proposed by Swithinbank (1973), who noticed a number of dark (warm) streaks issuing from the major glacier valleys off the high plateau of East Antarctica. The paradox of dark (i.e., warm) signatures representing what should be predominantly a negatively buoyant katabatic airstream has been discussed by a number of authors including D'Aguanno (1986), Bromwich (1989a,b), Bromwich et al. (1992), Breckenridge et al. (1993), and Carrasco and Bromwich (1993). The extreme horizontal extent of the thermal signatures supports the notion of a negatively buoyant drainage current. In addition, the aircraft observations by Parish and Bromwich (1989) near Terra Nova Bay, in which the airstream was potentially colder than the environment by approximately 5°C and yet appeared dark on the thermal infrared imagery, supports the concept of negatively buoyant airstreams. The dark signature may reflect the strong mixing process associated with katabatic winds, which may result in warmer skin temperatures as compared to the more tranquil surrounding areas (Bromwich 1989a,b), a result that can also be inferred from numerical modeling of surface winds and temperatures (Parish and Waight 1987).

The persistence of the katabatic wind regime over the face of the continent is also a bit puzzling since the coastal periphery about Antarctica is the home of frequent and intense cyclonic disturbances. The horizontal pressure gradients associated with these Southern Ocean cyclones are often large and extend over wide geographical areas. The cyclones, however, tend to follow the strong baroclinic zone, which generally follows the continental perimeter with limited penetration into the interior of the continent (e.g., Mechoso 1980; Parish 1982a). On occasion, when cyclones move onto the ice continent, the antarctic orography acts to reduce the circulation. This can be understood in terms of the conservation of potential vorticity. As a cyclone impinges upon the continent, it experiences a sharp increase in the height of the ice surface. The depth of the vortex column, associated with the circulation of the cyclone, must therefore decrease. The process is much the same as the well-observed vertical shrinking and consequent circulation decrease of extratropical cyclones in North America as the Rocky Mountain barrier is reached. The fact that the ice sheet serves as a natural orographic buffer is one reason in explaining the well-documented persistence of the continental katabatic wind circulation.

To provide some insight as to the natural variability of the continental katabatic wind streamlines, analyses from the ECMWF model for a period of rapid pressure change over the Antarctic continent and high southern latitudes in the winter of 1988 were examined. The analyses are based on twice-daily (0000 and 1200 UTC) reports gridded to a 2.5° latitude/longitude scale. Figure 4.7a illustrates the streamlines of the surface wind for 0000 UTC 28 June 1988. The resolution of the antarctic orography is relatively coarse as compared to the actual terrain, as illustrated in Fig. 4.5, and certain details of the interior ice topography have been smoothed considerably. The broad-scale katabatic wind pattern in Fig. 4.7a is, however, similar to that in Fig. 4.5, with radially diffluent drainage off the high interior of East and West Antarctica. A number of intense cyclonic disturbances can be seen in the streamline depiction of Fig. 4.7a. In each case it is evident that the horizontal pressure gradients associated with the cyclonic circulation draw in cold continental air and thereby appear to enhance the katabatic wind regime on the western flank of the cyclone. At the same time, there is little evidence that even intense cyclones result in upslope motion on the eastern side

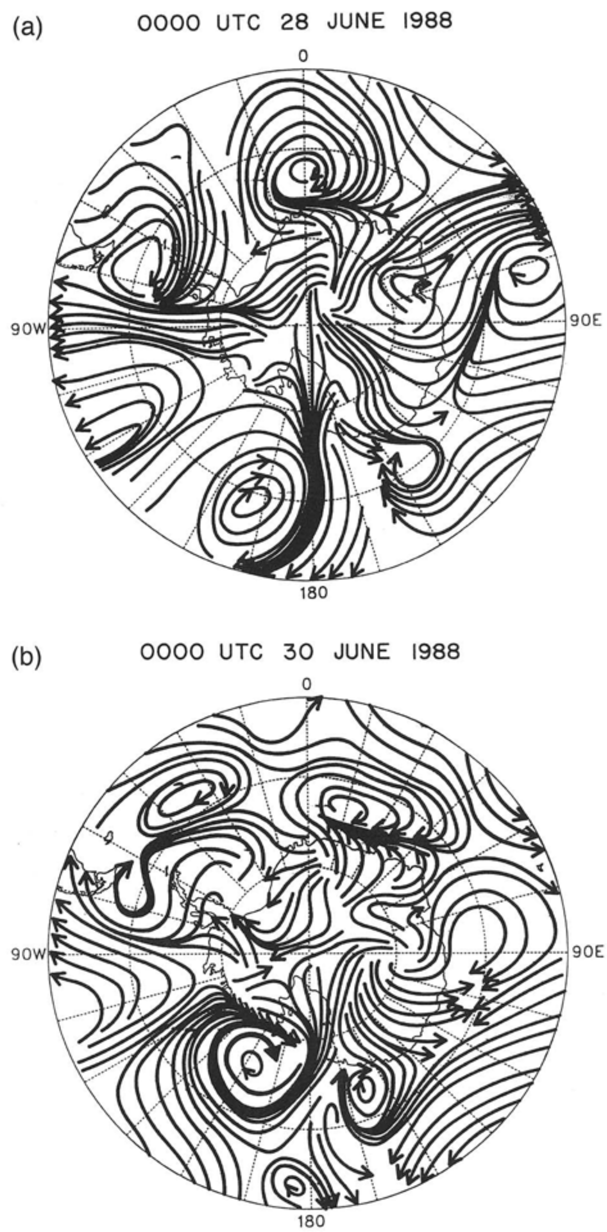

FIG. 4.7. Surface-wind streamline pattern over the high southern latitudes, based on ECMWF analyses for (a) 0000 UTC 28 June 1988 and (b) 0000 UTC 30 June 1988.

of the circulation pattern. The continental katabatic wind regime in the ECMWF maintains the downslope tendency over the steep coastal slopes of East Antarctica. Figure 4.7b illustrates the surface wind streamlines on 0000 UTC 30 June 1988. Inspection of the katabatic wind streamlines in the vicinity of the cyclonic vortices along the coastal rim north of the continent suggests synoptic interaction. Again, there is little evidence that the ambient horizontal pressure gradients are able to force upslope motion on the eastern half of the cyclone. Note that pronounced lines of convergence appear over the ocean to the east of the cyclone centers, with streamlines over the continent reflecting climatological drainage patterns. There is a suggestion that drainage paths become altered over the large interior ice dome in East Antarctica in response to the position and intensity of the cyclonic activity. The katabatic drainage through the Ross Sea corridor on 0000 UTC 30 June taps cold-air reserves over a much larger area of the Antarctic interior than that seen on 28 June. Wind shifts of up to 90° occur over a section of the gently sloping East Antarctic plateau, although the broad-scale drainage off the continent is not appreciably different. Model evidence supports the plethora of observations, which suggest that the continental-scale katabatic windfield over the continent is remarkably robust.

As the katabatic winds move northward across the coastline of Antarctica, the horizontal pressure gradient force decreases abruptly. The ageostrophic offshore propagation distance of katabatic airstreams varies considerably, from typical dissipation in hydraulic jumps close to the East Antarctic coastline (Pettré and André 1991; Schwerdtfeger 1970; Gallée et al. 1996) to frequent propagation for tens to hundreds of kilometers offshore from Terra Nova Bay (Bromwich 1989a; Parish and Bromwich 1989). Gallée (1997) explains the latter behavior as being due to offshore spreading of the laterally confined katabatic airstream blowing from Terra Nova Bay. The adjustment of these airflows to the offshore circulation is responsible for a mass increase to the north of the continent. This piling up of mass offshore from the continental coastline is responsible for the development of a northward-directed horizontal pressure gradient force in the lowest levels of the atmosphere. This pressure field supports a low-level easterly current that nearly encircles the continent. Numerical simulations of the katabatic wind regime, as shown in Parish et al. (1997), clearly depict this band of easterlies, which extend several hundred kilometers northward from the coast. These circumpolar easterlies are prominent climatological features of the low-level wind regime about the Antarctic continent. It has been proposed (Parish et al. 1997) that such a band of sea level easterlies derive dynamical support from the mass flux associated with the time-averaged katabatic wind regime. Such an idea is not new. Previously, Kidson (1947; see also Court 1951) echoed the same idea, noting that the cold-air accumulation just offshore from the Antarctic continent produces a pressure surplus of approximately 6 hPa and that such effects extend some 300 km from the coast. Schwerdtfeger (1984, p. 108) has also proposed that the katabatic winds act "to reinforce and maintain the circumpolar easterlies near sea level."

An alternate way of viewing the circumpolar easterlies is in terms of simple inertial turning of the cold katabatic airstream as it outruns its continental forcing. The horizontal scale and intensity of the easterlies roughly match this idealized picture. The damming of cold air up against the steep continental escarpment provides the northward-directed horizontal pressure gradient force. In this sense the easterlies are an example of a "barrier" wind (Bromwich 1988). Schwerdtfeger (1975, 1979) was the first to describe this motion. The initial antarctic application was along the Antarctic peninsula. He reasoned that as cold, stable air is advected by east winds across the Weddell Sea and reaches the mountain chain, the air resists moving over the barrier and becomes dammed up against the windward side. The hydrostatic increase in pressure supports a low-level southerly airflow directed parallel to the mountains. Numerical experiments (Parish 1983) suggest that the barrier winds may extend some 300 km or more away from the foot of the mountains and that the damming effect may result in a pressure surplus of up to 8 hPa. Similar barrier wind phenomena have been proposed along the Transantarctic Mountains on the western Ross Ice Shelf (Schwerdtfeger 1984; Slotten and Stearns 1987; O'Connor and Bromwich 1988; Bromwich et al. 1992; O'Connor et al. 1994) and have been documented along mountain ranges in middle latitudes as well (Parish 1982b).

4.4. Variations in atmospheric pressure

There is no doubt that the circumpolar belt surrounding the Antarctic continent and extending into the Southern Ocean is one of the most active cyclonic regions on earth (e.g., Streten and Troup 1973). As noted by Schwerdtfeger (1984), the band of low pressure surrounding the continent is reflective of the highest frequency of cyclones. Synoptic analyses have long been hampered by the relative lack of reporting data. In addition, construction of sea level pressure fields over the antarctic orography is difficult, owing to inherent problems of reduction to sea level. Extrapolation of pressure through several kilometers of ice typically results in excessively high sea level values. Thus, sea level synoptic analyses over the high plateau regions are subject to considerable uncertainty. Observations from manned coastal stations, as well as reports from numerous AWS units, clearly show considerable synoptic variability in the surface pressures. Parish (1982a) has noted that significant differences in the variation of surface pressure exist between the Antarctic coastal regions and high continental plateau,

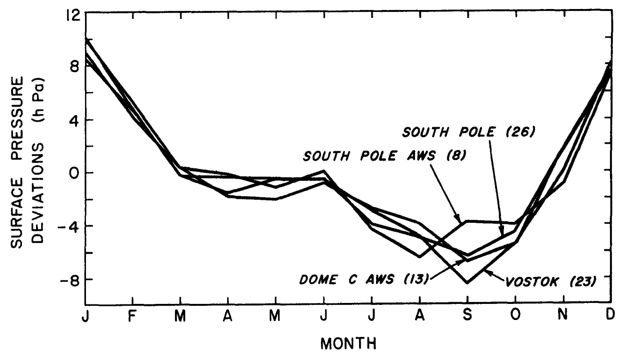

FIG. 4.8. Mean monthly surface-pressure deviations from mean annual surface pressure at interior stations South Pole, Dome C, Vostok, and South Pole AWS. Number in parentheses indicates the number of years in each record.

which can be attributed to the diminishing influence of cyclones on the interior sites. It is instructive to examine the relative importance of synoptic events in contributing to the total variance in surface pressure. The results of power spectrum analyses from the year 1958 for numerous coastal and interior manned stations show that the percentage variance of surface pressure explained over the synoptic time periods of 2.5 to 5 days for coastal stations is nearly three times greater than at the interior sites. Recent work using AWS records near Terra Nova Bay (Parish 1992a; Bromwich et al. 1993), as well as output from the ECMWF 10-yr averages, validates the above conception and again indicates the role of the antarctic orography in buffering the interior plateau from the influence of transient cyclones.

Antarctic orography is also responsible for a large-amplitude seasonal pressure cycle over the high southern latitudes. As an example, Fig. 4.8 illustrates the multi-year averages of mean monthly pressure deviations from the mean annual surface pressure over the interior of the continent for the South Pole and Vostok manned stations, as well as the Dome C and South Pole AWS. Data from the South Pole and Vostok records were taken from Schwerdtfeger (1984) and are for 26 and 23 yr, respectively. The Dome C data were obtained from the AWS records from 1980–93, and the South Pole AWS data record spans 1986–93 (e.g., Keller et al. 1994). Surface pressures at each site display rapid and pronounced changes, which are especially evident during the transitional periods September–December and January–April. Surface pressures over the high plateau undergo a decrease of approximately 12 hPa from January to April and a rise of 16 hPa from September to December. Such changes in the atmospheric mass loading over Antarctica reflect the large-scale thermodynamic and dynamic adjustment near the surface of the continent associated with the rapid changes in the intensity of solar insolation (Radok et al. 1996; Parish and Bromwich 1997). Of note also is the secondary maximum during the midwinter period. A second harmonic is apparent in the annual course of surface pressures over Antarctica, with maxima at the solstices and minima at the equinox periods. The SAO in surface pressure has been discussed extensively (e.g., Schwerdtfeger and Prohaska 1956; Schwerdtfeger 1960, 1967; van Loon 1967, 1972a; van Loon and Rogers 1984; Meehl 1991; Hurrell and van Loon 1994). Schwerdtfeger and Prohaska (1956) suggest that the SAO is based on the differential solar heating of different latitude belts and point out that the meridional difference in solar insolation between 50° and 80°S reaches maxima in March and September. Van Loon (1967) and, more recently, Meehl (1991) note that the SAO mechanism involves the different annual temperature cycles between the Antarctic continent and the surrounding oceans. A discussion of the SAO and modeling considerations are given by Meehl in chapter 10 of this monograph.

Figure 4.9 illustrates the mean monthly zonally averaged surface pressure deviations from the January mean for the years 1985–94 from the ECMWF analyses. It can be seen that the phase of the SAO reverses between approximately 55° and 60°S. The meridional pressure differences between, for example, 70° and 50°S reach maxima during the equinox periods. This phase reversal is responsible for a semiannual oscillation in the geostrophic winds in the lower troposphere surrounding Antarctica (e.g., Schwerdtfeger 1970). The second harmonic in ECMWF surface pressure output from the 1985–94 period explains nearly 40% of the total variance at latitudes 65°–70°S and approximately 25% over the antarctic latitudes 75°–80°S.

Surface pressure changes are especially pronounced during the austral springtime (September–December) and autumn (January–April) transition periods. The largest changes during both periods appear to be maximized over the high interior of Antarctica and

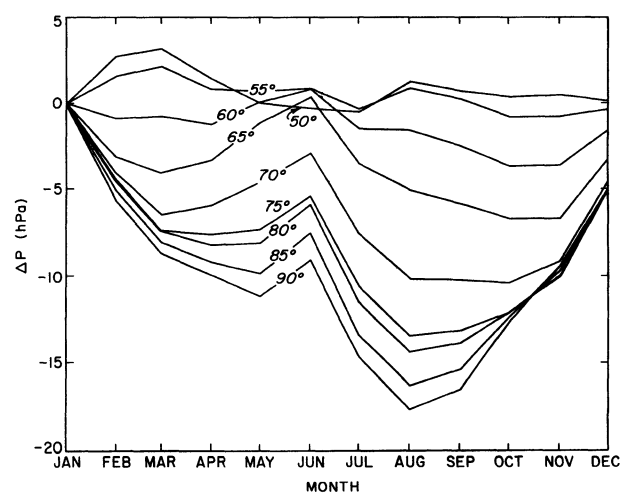

FIG. 4.9. Zonally averaged mean monthly surface-pressure deviations from January mean for latitudes 50°–90°S, based on ECMWF analyses, averaged for 1985–94, in hPa.

FIG. 4.10. Mean monthly surface-pressure difference, April–January, from ECMWF analyses, averaged for 1985–94, in hPa. Dashed lines are elevation contours in 400-m increments.

decrease rapidly northward from the continental periphery, such that the phase of the mass loading cycle becomes reversed between 50° and 60°S. As an example, Fig. 4.10 illustrates the mean monthly changes in surface pressure from January to April based on the ECMWF analyses for the years 1985–94. Such a depiction is consistent with surface observations, as well as data collected by AWS atop the Antarctic interior (e.g., Keller et al. 1994). Parish et al. (1997) and Parish and Bromwich (1997) have shown that similar patterns of surface pressure increase occur during the austral springtime period, which match the changes discussed in Schwerdtfeger (1984, see his Fig. 6.8).

Observed surface pressure changes in Fig. 4.10 appear to be intimately linked to the underlying antarctic orography. The pattern of pressure differences appears to follow the general orientation of the topography. This is especially obvious along the steeply sloping coastal region, which in Fig. 4.10 is the site of a strong pressure-difference gradient. Such a seasonal pressure-difference pattern is the result of the rapid diabatic cooling of the sloping terrain and lower levels of the atmosphere in response to the diminishing intensity of solar insolation over the continent. Hydrostatic considerations suggest that the pressure difference between vertical levels is dependent on the mean temperature of the atmospheric column. As the mean temperature in a particular atmospheric column decreases, the pressure difference between the surface and some vertical level increases. Assuming sea level pressure does not change appreciably, cooling of the lower layers will appear to result in an apparent pressure decrease at a fixed height. Such is the case over Antarctica during the austral autumn transition period. Figure 4.11 depicts a vertical cross section of the zonally averaged temperature changes during the austral autumn months from January to April, 1985–94. The largest changes are seen near the surface and in the stratosphere.

Hydrostatic considerations alone, however, cannot explain the seasonal surface pressure changes. The decrease in pressure observed over the interior of the Antarctic continent implies a net northward mass flux away from Antarctica. Parish et al. (1997) propose that the mean meridional circulation between Antarctica and the subpolar latitudes becomes modulated at low levels during the austral autumn period. It is the

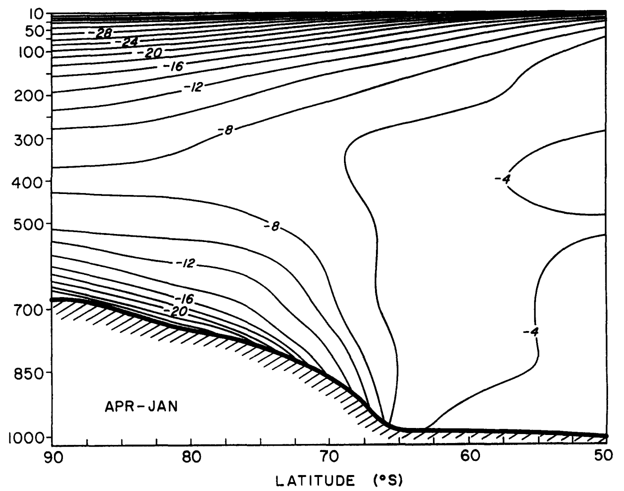

FIG. 4.11. Vertical cross section of mean April minus January zonally averaged isobaric temperatures for latitudes 50°–90°S, based on ECMWF analyses, averaged for 1985–94, in K.

katabatic wind regime that undergoes the most significant change and is the fundamental agent of the northward mass transport during autumn. Midtropospheric level transports toward Antarctica do not undergo the same magnitude of change as the near surface flows, and, hence, a net imbalance in mass transport occurs. During the austral springtime, the sequence of events reverses. The rapidly increasing solar insolation tends to reduce the northward transport via the katabatic wind regime. As a result, the net inflow toward the pole in the middle to upper troposphere, and in the stratosphere, exceeds the outflow in the lower levels, and atmospheric mass loading over Antarctica occurs (Wendler and Pook 1992; Radok et al. 1996). In each seasonal example, the low-level changes in wind and temperature are mutually consistent, and the changes in surface pressure can be viewed as a consequence of the large-scale adjustment process over Antarctica.

4.5. Precipitation characteristics

Precipitation over the grounded antarctic ice sheets is a significant aspect of sea level variations because it represents a removal of water from the global ocean amounting to 7 mm yr^{-1}. For steady-state conditions, an equal amount of water substance is returned to the sea by ice flow and calving and melting at the margin. An increase in precipitation following from circulation anomalies happens essentially instantaneously, but the increase in ice flow to restore steady-state balance takes much longer, resulting in a sea level decrease that persists for hundreds to thousands of years. Understanding precipitation controls is also important to interpreting the climatic records from cores drilled from the ice, as this fell as snow in the distant past.

Direct determination of precipitation amounts in Antarctica is frustrated by a number of factors particularly relating to wind effects, which in cold climates are a notorious obstacle to accurate gauge measurements of precipitation (e.g., Groisman et al. 1994). An additional complication arises for the interior of the continent, where snowfall amounts are very small and are invariably less than the minimum resolution of snow gauges (Bromwich 1988). Accumulation of snow provides a convenient approach for depicting the time-averaged spatial distribution of annual precipitation (Fig. 4.12, after Giovinetto and Bentley 1985). The effects of sublimation to the atmosphere, melting, and drift snow transport are thought to be small on the continental scale in relation to precipitation, and thus, to first order, precipitation equals accumulation. There is growing evidence, however, that the neglect of sublimation, which becomes largest in the summer half-year, may be an invalid assumption (e.g., Stearns and Weidner 1993). Figure 4.12 shows that precipitation decreases by an order of magnitude from the coast to the interior of East Antarctica in conjunction with the dramatic increase in surface elevation. The precipitation rate over West Antarctica is much higher than East Antarctica. This follows from the much greater impact of synoptic forcing and from the time-averaged flow of moisture into this area in conjunction with the circumpolar vortex (Lettau 1969; Bromwich et al. 1995).

Many aspects of antarctic precipitation characteristics are accessible via indirect methods. A promising approach uses the atmospheric moisture budget derived from numerical analyses. The difference between precipitation and evaporation/sublimation ($P - E$) for an area is calculated from the convergence of the moisture transport into the overlying atmospheric volume plus the impact of moisture storage changes (Yamazaki 1992; Budd et al. 1995; Bromwich et al. 1995); note that $P - E$ or net precipitation closely approximates the accumulation rate. This approach is appropriate for averages over large areas and for time periods of seasons and longer. The ECMWF analyses have been compared against antarctic rawinsonde moisture transports and found to closely reproduce these input observations (Bromwich et al. 1995). To begin, Fig. 4.13 shows the derived $P - E$ for the Antarctic continent from the atmospheric moisture budget. The convergence values have been derived at the individual gridbox level and then adjusted to achieve dry-air mass balance (Trenberth 1991). The ECMWF data are sampled at 2.5° resolution from the original spectral data and, as a result, aliasing effects occur that are particularly noticeable in the convergence field (Trenberth 1992, see p. 80). Here, zonal averaging on a length scale of 250 km is used to obtain numerical stability for the estimates. In polar regions, this method is appropriate because the spectral data describe information on progressively smaller

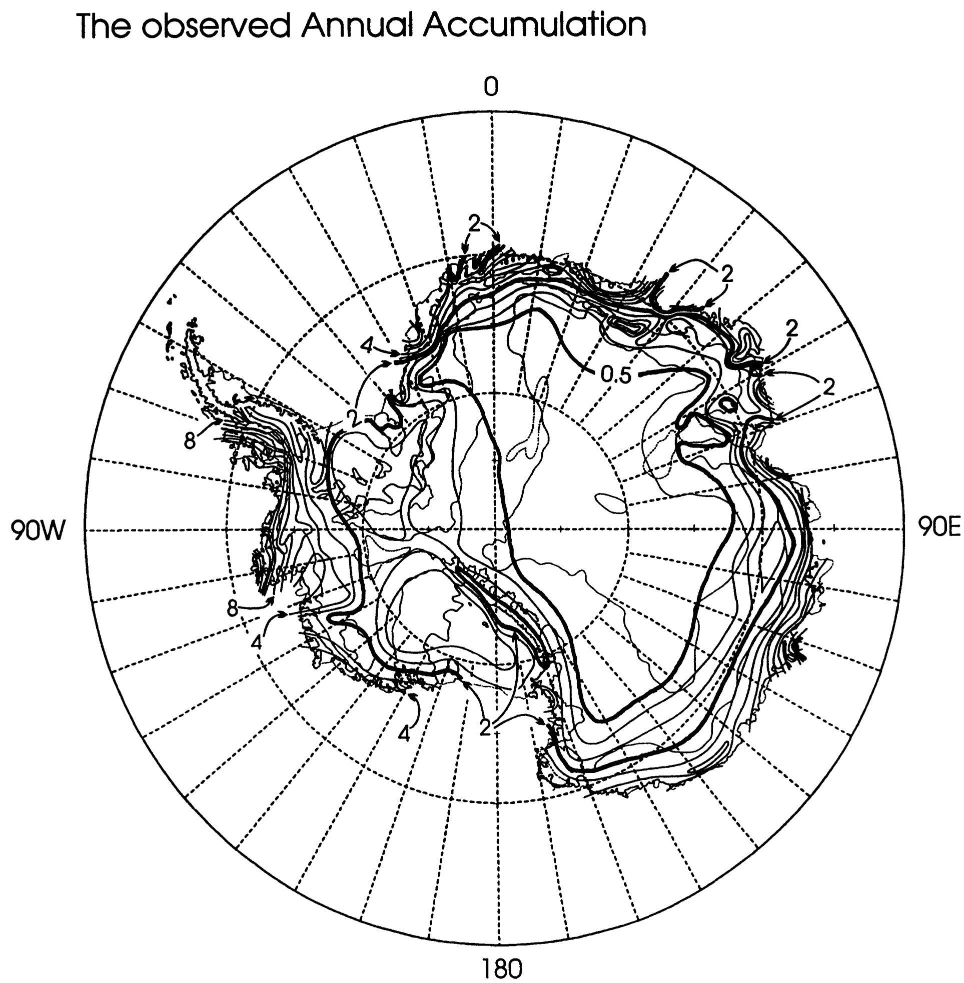

FIG. 4.12. Annual accumulation for Antarctica, adapted from Giovinetto and Bentley (1985). Solid lines are accumulation isopleths in 100 kg m^{-2} yr^{-1} (or, equivalently, 100 mm yr^{-1}); 0.5 and 2.0 contours are bolded. Light solid lines are elevation contours in km.

and more unrealistic spatial scales with increasing latitude. The loss of precision using gridpoint data must be considered negligible relative to the expected accuracy in data-sparse polar regions.

As in the observations, large values are found along the coast of East Antarctica in Fig. 4.13, and an extensive area with values less than 5 cm yr^{-1} (or 0.5 of the units used in Fig. 4.12) is located over the East Antarctic plateau. The moisture budget calculation resolves the marked accumulation gradient across West Antarctica and the large values along the Bellingshausen Sea coast and the west side of the Antarctic peninsula. Significant problems are evident in the Ross Sea–Ross Ice Shelf area; however, this sector is characterized by large decadal variability of moisture convergence (Cullather et al. 1996) that may invalidate the comparison between the 1985–94 moisture budget calculation and the long-term accumulation depiction. The negative accumulation values ($E > P$) in East Antarctica are close to and not much larger in area than net ablation zones resolved by Giovinetto and Bentley (1985). To summarize, there is a good overall fit in terms of features and magnitudes between the observed accumulation pattern (Fig. 4.12) and that calculated from the atmospheric moisture budget (Fig. 4.13).

Figure 4.14 shows the annual cycle of $P - E$ for the Antarctic continent, derived from the ECMWF analyses. There is a broad winter maximum and a summer minimum, consistent with earlier evaluations (Bromwich 1988). In addition, there is a suggestion of semiannual maxima in the fall and spring. Precipitation and accumulation records from the Weddell Sea and Antarctic peninsula areas show that this semiannual signal dominates in that region (e.g., Eicken et al. 1994), due to the semiannual cycle in the intensity and latitudinal location of the circumpolar trough (Turner et al. 1997). Similar annual precipitation cycles apparently characterize the ocean areas just to the north of Antarctica (van Loon 1972b). Also included in Fig. 4.14 is the derived annual cycle for areas above 1500 and 2500 m elevation contours, following Budd et al.

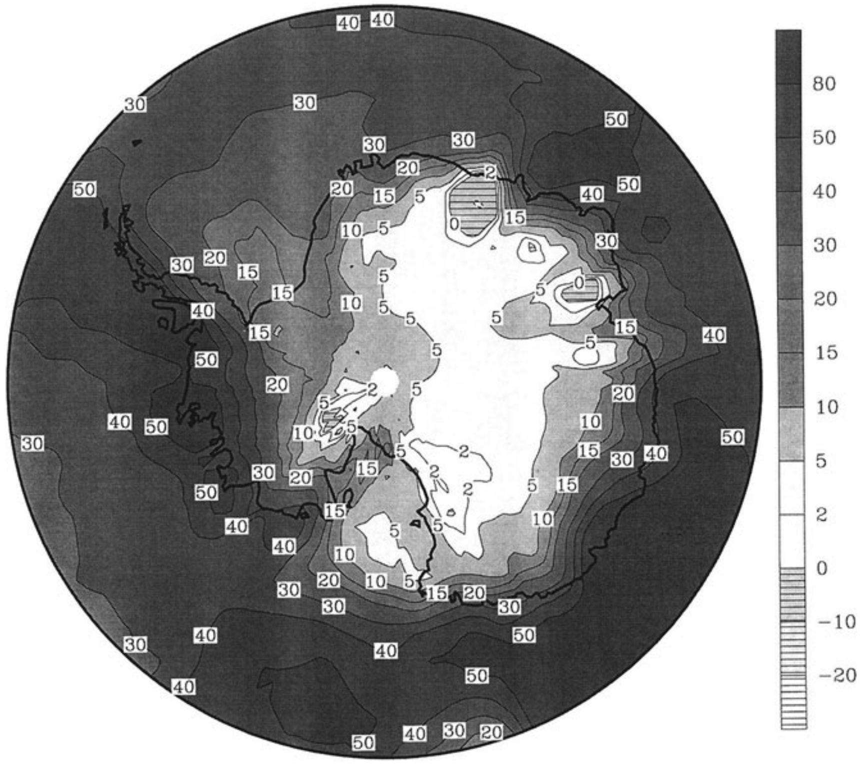

FIG. 4.13. Average accumulation distribution for Antarctica, computed from the ECMWF atmospheric moisture budget for 1985–94, in cm yr^{-1}.

(1995). Values are nearly constant from March to October, with little evidence of a semiannual variation; this is contrary to the results of Budd et al. (1995), but consistent with the limited surface observations (Bromwich 1988). The southward dissipation of the semiannual precipitation cycle from the Southern Ocean to the East Antarctic plateau is consistent with the parallel decrease of the importance in the semiannual pressure oscillation (section 4.4).

Episodic synoptic processes dominate precipitation formation in the coastal margins (e.g., Turner et al. 1995). As an illustration of this, Fig. 4.15 shows the annual mean eddy moisture transport vectors in relation to the sea level pressure field. The eddy transports (with respect to monthly means) are larger just to the east of the quasi-stationary lows in the circumpolar trough, as can be seen more clearly in rawinsonde-derived transports (Bromwich 1988). The eddy transports are almost everywhere directed poleward. For the continent as a whole, about 90% of the moisture convergence (or equivalently $P - E$) is due to the eddy component. The impact of synoptic forcing decreases with elevation in East Antarctica (compare Jonsson 1995) such that the semicontinuous fall of ice crystals from apparently clear skies becomes the dominant precipitation formation mechanism (Radok and Lile 1977; Schwerdtfeger 1984; Bromwich 1988).

In at least some coastal areas, mesoscale cyclones are found to contribute significantly to the total precipitation, as suggested by some general circulation model studies (e.g., Tzeng et al. 1993). To the north of McMurdo Station on Ross Island lies the very active mesoscale cyclogenesis area near Terra Nova Bay (Bromwich 1991; Carrasco and Bromwich 1994, 1996), which is associated with that area's intense katabatic winds. Rockey and Braaten (1995) estimate that about 38% of the McMurdo Station precipitation is associated with mesoscale cyclones. Modeling studies by Gallée (1996) reveal how this phenomenon occurs and resolve a persistent, moist return flow, which could contribute to the precipitation over the Antarctic interior.

Temporal variability in antarctic precipitation is also accessible via the atmospheric moisture budget. Cullather et al. (1996) examined the ECMWF analyses from 1980 to 1994 and found that the greatest variability in moisture convergence took place in the South Pacific sector of the continent. As Fig. 4.16 illustrates, the variability for part of this area (120°W–180°, 75°–90°S) was highly correlated and in phase with the SOI from 1980 to 1990 but became anticorrelated after 1990, coinciding with the start of the extended series of ENSO events in the early 1990s (Trenberth and Hoar 1996). The ENSO variability is associated with

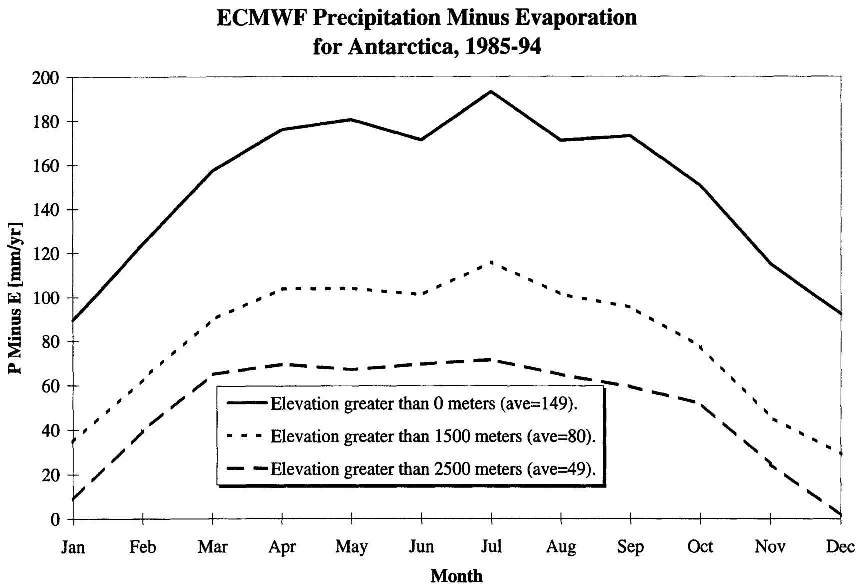

FIG. 4.14. The annual variation in accumulation rate derived from the ECMWF atmospheric moisture budget for various elevation domains, averaged for 1985–94, in cm yr^{-1}.

migrations in the Amundsen low. As shown in Fig. 4.17 during normal precipitation periods in this West Antarctic sector, here characterized by 1980 (left), the Amundsen Sea low is located near its long-term average position to the northeast of the Ross Sea, and moisture enters the West Antarctic sector from almost due north. During reduced precipitation periods (1982, right), the Amundsen Sea low is 1500 km to the east of its position in 1980, and the moisture wraps around the low to enter the sector mostly from the east. Marked blocking was found to persist over the Wilkes Land part of East Antarctica, starting in 1991 and extending to at least 1994; this coincided with the establishment of the anticorrelation between the SOI index and West Antarctic sector precipitation.

The moisture budget analyses also provide some idea of the temporal trends in antarctic precipitation. Figure 4.18 depicts net precipitation for Antarctica and its adjacent permanent ice shelves from 1980 to 1994. A statistically significant upward trend of 3 mm yr^{-1} (or 2% yr^{-1}) is found, consistent with an earlier synthesis of mostly ground-based accumulation observations from the 1960s and 1970s (Bromwich and Robasky 1993). The confidence in this trend is tempered by the lower reliability of the WMO version of the ECMWF analyses (Trenberth 1995) than the WCRP archive (Cullather et al. 1996) and the major impact of the 1982/83 El Niño event. In glaciological studies, mention is often made of the high spatial correlation between long-term averages of accumulation and surface air temperature (e.g., Robin 1977). To test whether this idea applies to temporal variations, the 500-hPa temperatures (surface temperatures were not available for the entire period but gave similar results for 1985–94) are compared in Fig. 4.18 with the derived antarctic accumulation amounts. On the annual timescale, accumulation and temperature have little association ($r = 0.37$), but there is an upward trend over the 15 years that is as significant as that for accumulation. The latter suggests that, over the decadal timescale, accumulation and temperature are positively correlated; dividing the temporal regression slopes gives a sensitivity of about 20% precipitation increase per °C temperature rise, consistent with that quoted in some glaciological studies (compare Morgan et al. 1991).

4.6. Far-field impacts of high southern latitude processes

Given the persistence of the radially diffluent katabatic wind regime over the continental surface, it is not surprising that the low-level drainage elicits a large-scale tropospheric response throughout the high southern latitudes. Continuity requirements dictate that the low-level divergence associated with the katabatic drainage must be compensated by an inflow of relatively warm air at middle to upper levels of the troposphere over Antarctica, which converges and subsides over the continent. It is through this process that the katabatic wind regime is resupplied. The katabatic wind regime thus forms a significant component of the lower branch of a time-averaged thermally direct meridional circulation. As an example of the time-averaged conditions, Fig. 4.19 depicts the zonally averaged meridional and vertical velocity components for the month of July, based on analyses from the ECMWF 12-hourly output for the 10-yr period 1985–

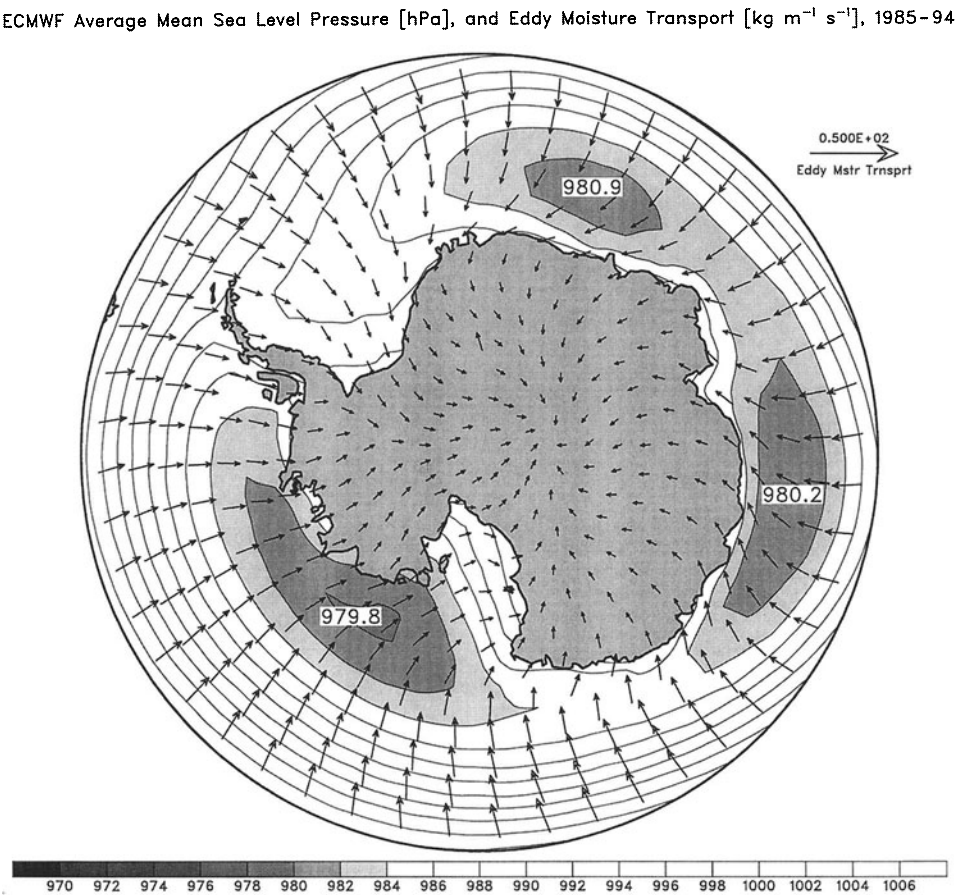

FIG. 4.15. Average MSLP field for 1985–94, contoured every 2 hPa, with average vertically integrated eddy moisture transport (arrows), in kg m^{-1} s^{-1}.

94. The meridional circulation is well defined and consists of broad subsidence over the continent south of approximately 70°S, which feeds the lower-level circulation including the katabatic wind regime. The return flow toward Antarctica in the middle and upper troposphere is deep and relatively weak. The lower-level branch is by far the most intense segment of the meridional circulation and primarily represents the katabatic component. Both ECMWF and the Community Climate Model Version 1 of the National Center for Atmospheric Research (NCAR CCM1; Parish et al. 1994) analyses suggest that this mean meridional circulation extends throughout most of the troposphere. The rising branch situated between 65° and 55°S appears to be associated with cyclone activity to the north of the Antarctic continent. There may, however, be some forcing of this rising motion from the katabatic outflow. As the drainage flows move away from the continental terminal slopes, deceleration occurs as the airstream outruns the dynamic support provided by the sloping ice surfaces. The attendant convergence of the katabatic flow just offshore from Antarctica supports the rising motion branch adjacent to the continent.

The existence of this time-averaged circulation has been discussed by a number of authors, including Radok (1973) and Mechoso (1980, 1981). Egger (1985) and James (1988, 1989) have noted that such a mean meridional circulation has important dynamic constraints on the circulation in the free atmosphere. The middle- to upper-tropospheric convergence over the Antarctic continent implies that cyclonic vorticity is continually being generated. James (1989) suggests that the drainage flow off the Antarctic continent may help center the polar vortex over Antarctica. This "anchoring" of the upper-tropospheric vortex over Antarctica has also been suggested by Parish (1992a). The mean July 300-hPa circumpolar vortex from the 1985–94 ECMWF record (Fig. 4.20) shows a zonal flow pattern tied to the Antarctic continent. There is little evidence of the time-averaged standing waves seen in the NH. In addition, the center of the vortex is directly over the Antarctic continent, in contrast to the more diffuse position of the NH vortex center. Two-dimensional numerical simulations by Egger (1985), James (1989), and Parish (1992a,b) show that an upper-level vortex forms in response to the meridional

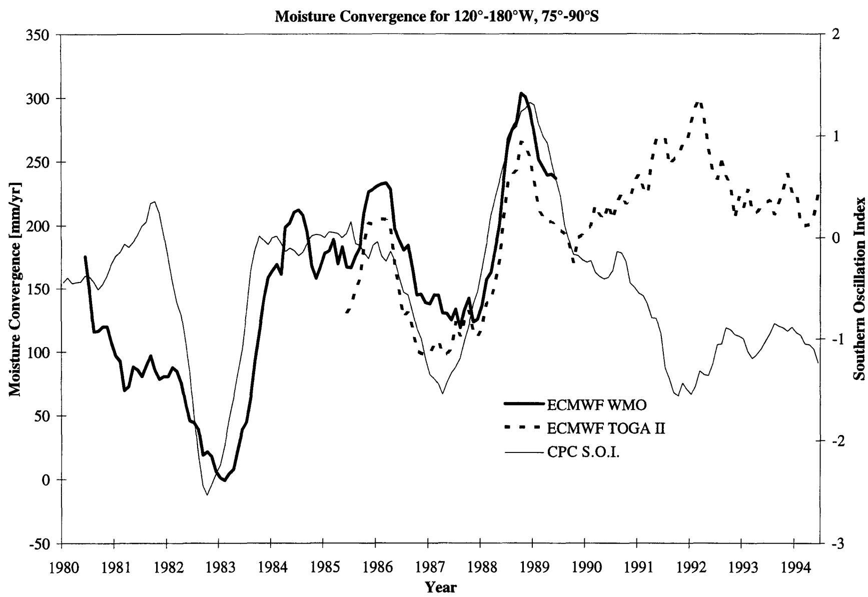

FIG. 4.16. Twelve-month centered running mean moisture convergence (mm yr^{-1}) for West Antarctic sector bounded by 75°S and 120°W–180° in relation to the SOI (hPa). Adapted from Cullather et al. (1996).

convergence above the Antarctic continent (see also Simmonds and Law 1995). Horizontal pressure gradients develop in the upper troposphere, which oppose the katabatic wind regime and, on the timescale of a week or so, reach anomalously large values such that the drainage flow spuriously decays. Egger (1985) and James (1989) note, in contrast to the depictions by the above axisymmetric experiments, that the real atmosphere over Antarctica must rid itself of cyclonic vorticity to prevent the upper-tropospheric vortex from reaching such an intensity as to completely shut down the katabatic circulation. Egger (1985, 1991, 1992) and James (1989) suggest that synoptic eddies are responsible for the transport of angular momentum northward so as to relieve the high southern latitudes of this vorticity buildup. Recently, Juckes et al. (1994) have evaluated the momentum budget over the Antarctic continent using results from a GCM simulation. Their results support the idea that the eddy mass flux associated with transient cyclones transports angular momentum northward from the high southern latitudes.

The mean meridional circulation between Antarctica and subpolar latitudes is also responsible for the seasonal cycle of mass loading onto the continent during the austral springtime and net transport away during the austral autumn. As indicated earlier, such mass transports are the result of large-scale thermodynamic and dynamic adjustments in response to the solar insolation cycle. The magnitude of the surface pressure changes and the areal extent, as illustrated in Fig. 4.10, suggests that significant mass fluxes take place across the Antarctic coastline, and a response in the more northerly latitudes of the SH must occur. Figure 4.21a depicts the zonally averaged surface pressure changes during the transition periods January–April and September–December, based on the ECMWF 12-h analyses for the years 1985–94. The antarctic surface pressure changes are by far the largest, yet there is a compensating surface pressure change that extends to the subtropics. Assuming that most of the pressure change signal is the result of SH processes and little mass transport from the NH is seen, it appears as though the seasonal surface pressure changes over Antarctica influence mass redistribution over nearly the entire hemisphere. An approximate mass budget can be obtained by weighting the surface pressure changes by the cosine of the latitude and then integrating northward from the South Pole. The results for the ECMWF 1985–94 period are illustrated in Fig. 4.21b and show that the surface pressure changes over the Antarctic continent require a compensating atmospheric mass adjustment that reaches the subtropics. Implications of this seasonal transport of atmospheric mass across the Antarctic are not known, although there appears to be a teleconnection with surface pressures over the continental landmasses of Australia, southern Africa, and South America, which show pressure trends of opposite sign during the transition periods (not shown).

The surrounding oceanic region to the north of Antarctica is the site of numerous transient cyclonic disturbances, which significantly influence the day-to-day wind and pressure fields along the coast and the time-averaged fields north of the continent. As noted by Schwerdtfeger (1984), the circumpolar sea level low pressure belt is a reflection of the maximum in

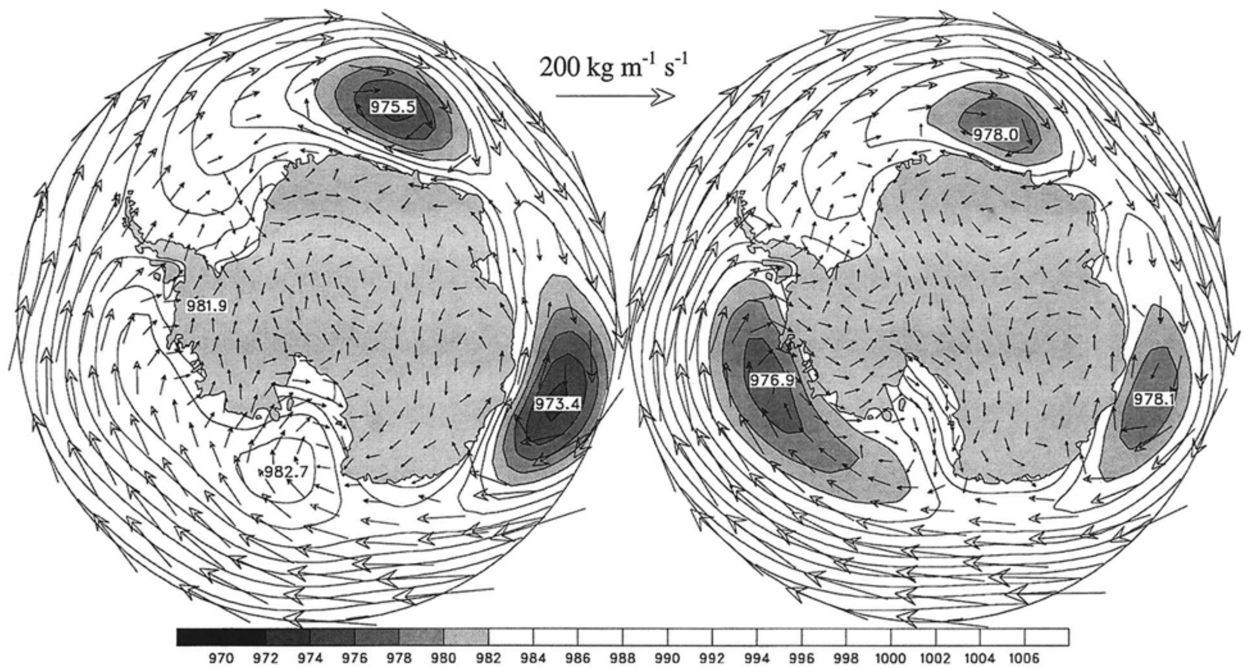

FIG. 4.17. Typical annual MSLP patterns for normal (left, 1980) and reduced (right, 1982) West Antarctic precipitation events. Vectors represent vertically integrated moisture flux (plotted maximum vector is 200 kg m^{-1} s^{-1}). MSLP field is contoured every 2 hPa. Adapted from Cullather et al. (1996).

cyclonic activity. Figure 4.22 is a depiction of the mean sea level pressure field for July based on the individual 0000 and 1200 UTC ECMWF analyses for the years 1985–94. The position of the circumpolar trough is seen to be situated between 58° and 66°S, some 400–700 km north of the coastline. Schwerdtfeger (1984) estimates the mean position of the sea level trough to be about 62°S adjacent to the East Antarctic coastline and 65° elsewhere. The position of the individual low pressure centers in Fig. 4.22 fits well with the mean climatology, as indicated in Tzeng et al. (1993). It is probably more than coincidence that the low centers at 150°W and 100°E seem to be situated on the western side of noted confluence features. Such a synoptic configuration maximizes the cold-air transport from the continent by tapping into the katabatic confluence zones. Bromwich et al. (1992) have noted that strong katabatic surges are common over the Ross Sea when synoptic-scale low pressure disturbances are present over the western Amundsen Sea. It may be the case that the topographically constrained drainage features play a role in establishing preferred locations of cyclonic disturbances about the continent.

There is increasing evidence that teleconnections exist between Antarctica and the subtropics. In particular, evidence of the ENSO signal in antarctic data has been documented. Such a relationship between ENSO events and antarctic conditions was first reported by Savage et al. (1988), who observed that the 1983 air temperature at the South Pole was the coldest since observations began in 1957. They noted that this was accompanied by an increase in the surface winds over a wide area of the continent. These changes followed the strongest ENSO event this century during the 1982/83 austral summer (National Research Council 1983). Smith and Stearns (1993a,b) continued this work by examining the surface pressure and temperature records from Antarctica and found distinct pattern changes from the year before to the year after the minimum in the SOI index (closely associated with El Niño events in the SSTs of the tropical Pacific Ocean) in composites of the six "warm events" between 1957 and 1984. No physical basis for the observed teleconnections was provided by these studies. Karoly (1989), Kitoh (1994), and Chen et al. (1996) note that the behavior of the split jet stream over the South Pacific Ocean is associated with the SOI variations. As shown by Fig. 4.23, adapted from Chen et al. (1996), the subtropical jet near 30°S strengthens in conjunction with SOI minima, whereas the polar front jet near 60°S is strongest during periods when the SOI is near zero or is positive. Using the 1986–89 time period as a case study, when a moderate warm phase was immediately followed by a pronounced cold phase, Chen et al. showed that the subtropical jet variations were a direct consequence of the tropical heating anomalies associated with the Pacific sea surface temperature changes. The acceleration of the polar front jet in the La Niña event of 1988/89 (SOI $>$ 0) was

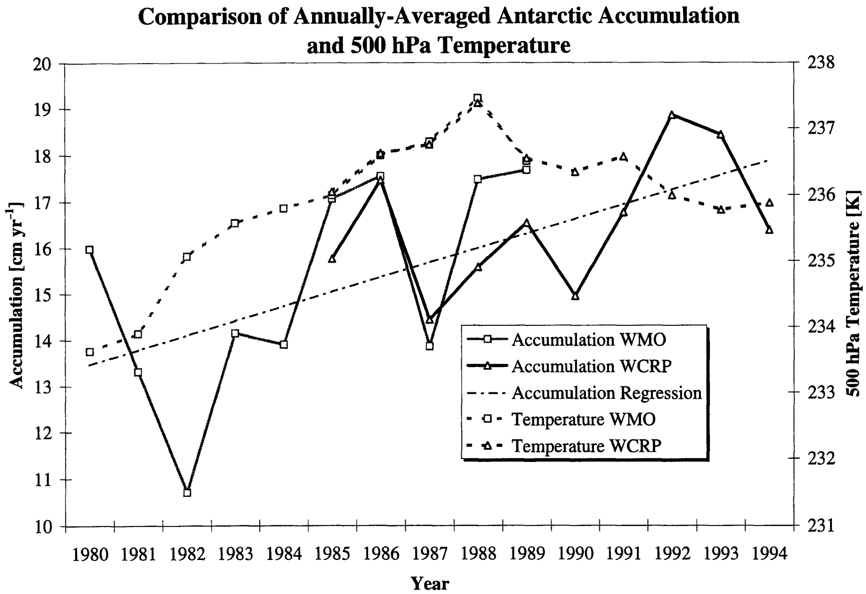

FIG. 4.18. Comparison of annually averaged antarctic accumulation (cm yr^{-1}), computed from the ECMWF atmospheric moisture budget, and spatially averaged 500-hPa temperature (K), for 1980–94.

found to result from the poleward propagation of cyclonic disturbances from the SPCZ and the equatorward propagation of disturbances from Antarctica.

This ENSO teleconnection is responsible for the zonal migrations in the Amundsen Sea low discussed earlier and the strong modulation of the precipitation rate over West Antarctica. Particularly numerous are reports of an ENSO impact on antarctic sea-ice extent (e.g., Chiu 1983; Carleton 1989; Xie et al. 1994; Simmonds and Jacka 1995; Gloersen 1995). Xie et al. (1994) present results showing strong correlations between sea-ice extent and equatorial SST anomalies and refer to the relation between ENSO events and antarctic sea ice as the Southern Oceanic Oscillation. Because of the broad variety of observations including sea-ice extent and meteorological records, the SOI phenomenon in Antarctica is perhaps the most thor-

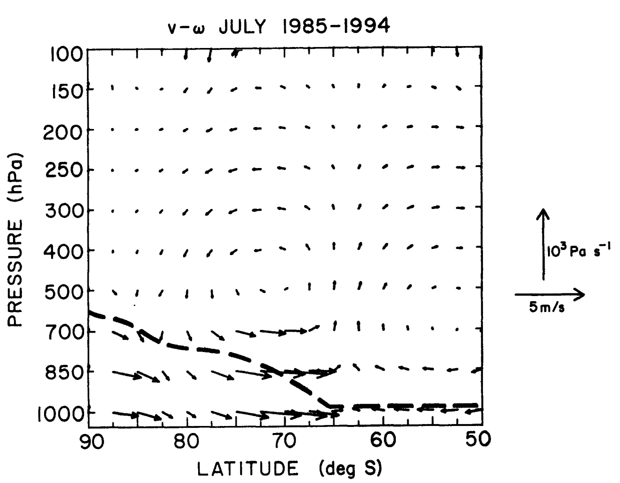

FIG. 4.19. Zonally averaged mean meridional circulation (v–w) interpolated to standard isobaric levels for July, based on ECMWF analyses for the 10-yr period 1985–94. Thick dashed line represents zonal-mean orography of Antarctica.

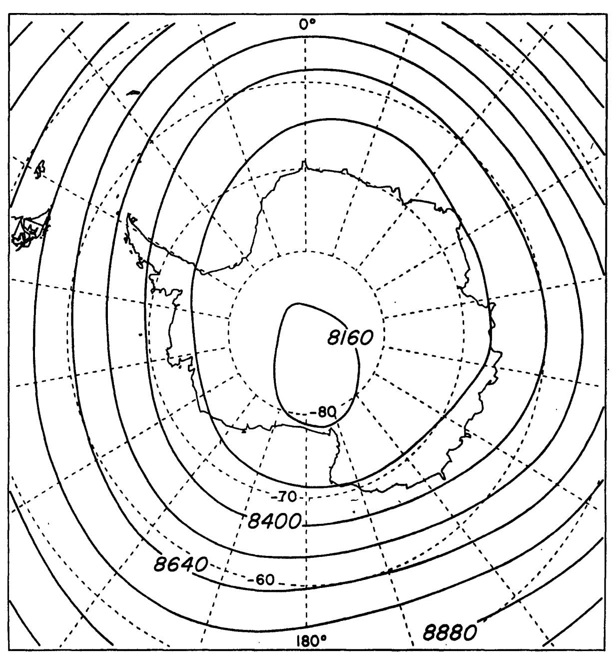

FIG. 4.20. Mean 300-hPa height field (in gpm) for July, based on ECMWF analyses for the 10-yr period 1985–94.

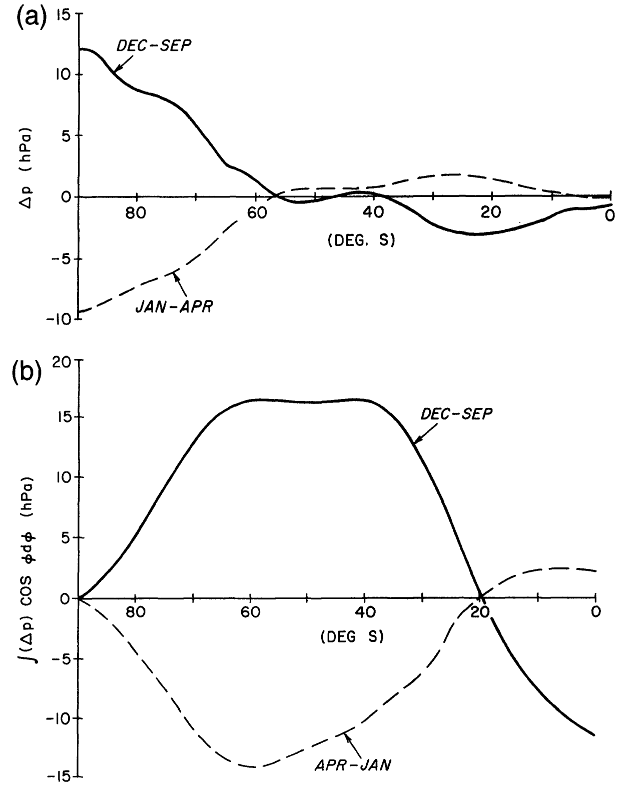

FIG. 4.21. Zonally averaged representation of (a) mean monthly latitudinal variation of surface-pressure differences December minus September and April minus January; and (b) mean latitudinal area-weighted mass budget integrated northward from South Pole for transition seasons April–January and December–September, based on ECMWF analyses for the 10-yr period 1985–94.

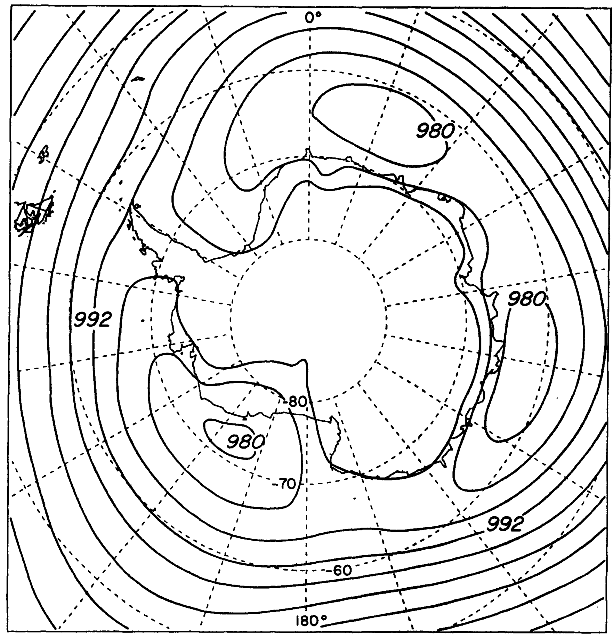

FIG. 4.22. MSLP pattern for July, based on ECMWF analyses for 10-yr period 1985–94.

oughly documented interannual variability in high southern latitudes.

4.7. Discussion

The vast antarctic ice sheet plays fundamental roles in its perpetuation (e.g., Oglesby 1989). The height and reflectivity of the surface guarantee that minimal melting of the ice sheet will be confined to the margins during the short antarctic summer. The blocking effect of the ice sheet limits the poleward propagation of cyclones, with most precipitation falling on the flanks of the ice sheet and leaving little moisture to precipitate in the high interior. Thus, the ice sheet exerts fundamental controls on the atmosphere that help to maintain its present configuration, where snow accumulation is nearly balanced by ice flow to the ocean.

The antarctic katabatic wind regime, which is a consequence of the strong radiative cooling adjacent to the elevated and sloping ice surface, is found to exert influences far beyond the shallow boundary layer. The need to supply the near-surface air blowing to the ocean couples the entire troposphere to the boundary layer. The coupling between the troposphere and the stratosphere is a relatively unexplored topic that may have major consequences for the low winter stratospheric temperatures that are a prerequisite for the recently enhanced springtime depletion of ozone, known as the antarctic ozone hole (see chapter 6). Mass imbalances that arise in the katabatic wind circulation during seasonal transitions result in large mass exchanges between high and middle/low latitudes. The consequences of variations in this exchange's timing and magnitude offer the potential of a major role for Antarctica in Southern Hemisphere climate variability.

The broader-scale importance of antarctic meteorology discussed above, in conjunction with the acknowledged role of the antarctic hydrologic cycle on eustatic change, strongly argues for increased monitoring of the antarctic climate. At present, however, the total amount of manned station observations, particularly the number of upper-air reports, is in decline as a result of former Soviet base closures (Cullather et al. 1997). Data scarcity places additional importance on the remaining observational resources, particularly automatic weather station and satellite data. For example, the 500-hPa geopotential height over the Antarctic interior can be reasonably estimated from AWS surface pressure and temperature readings (Phillpot 1991; Radok and Brown 1996). In the future, however, the maintenance of an adequate observational network will have to become a priority if a complete understanding of the antarctic climate system and its remote impacts is to be realized.

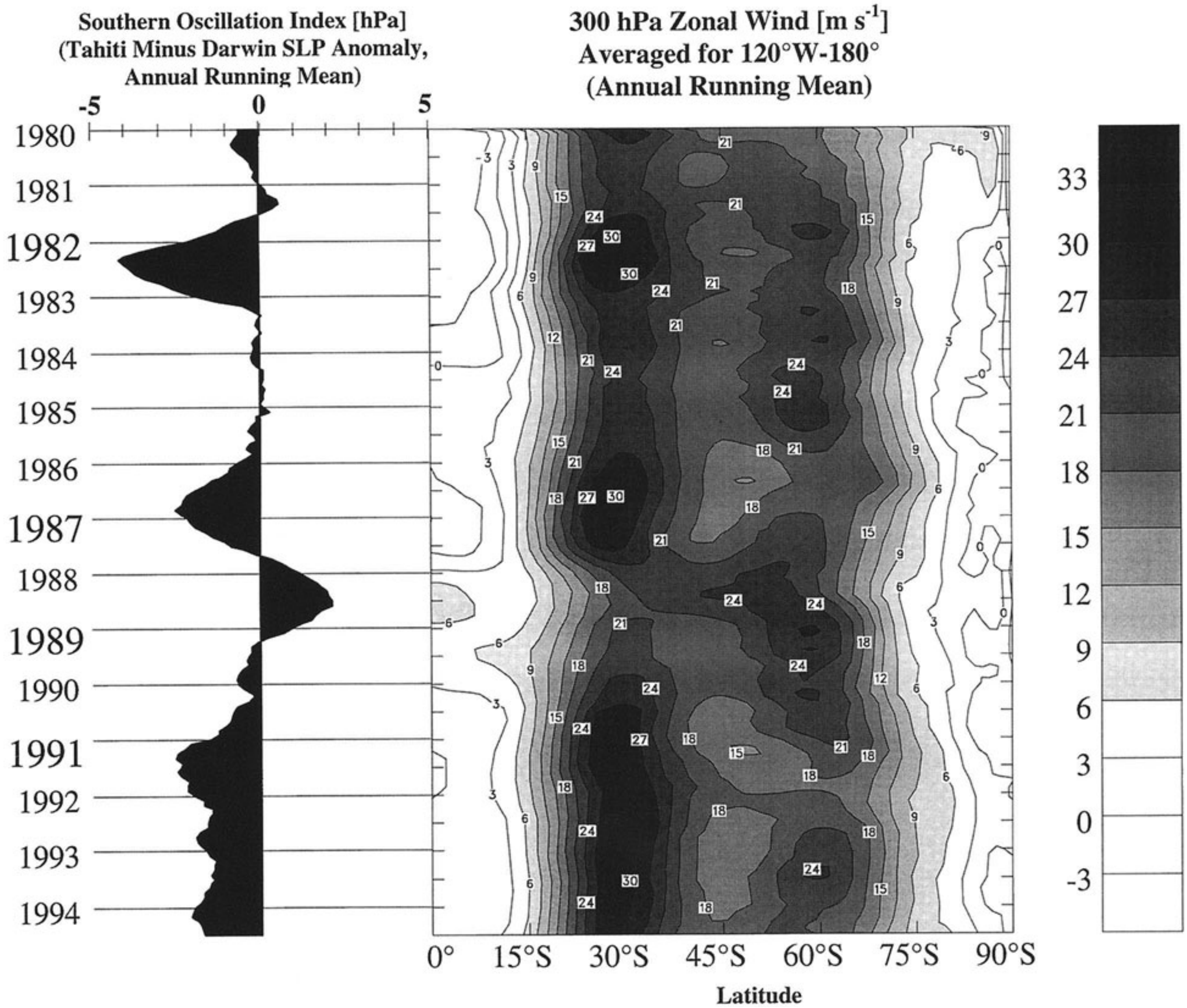

FIG. 4.23. Hovmöller diagram of annual running mean 300-hPa zonal wind, averaged over 120°W–180°, from ECMWF analyses, in m s^{-1}. On the left is the annual running mean SOI, in hPa. Adapted from Chen et al. (1996).

The increased importance of utilizing all available observations in a comprehensive data assimilation has stimulated an international collaboration to examine analyses and forecasts produced by the operational weather forecasting centers. Under the FROST program (Antarctic First Regional Observing Study of the Troposphere; Turner et al. 1996), an assessment is being made of the capability to utilize meteorological data over and around Antarctica and improve the derivation of atmospheric products from satellite data for the region. As can be seen from the present results based on ECMWF output, the availability of a complete and dynamically consistent dataset allows many aspects of antarctic atmospheric behavior to be explored in a more comprehensive fashion than previously.

Numerical modeling is increasingly important in attempts to understand the antarctic atmospheric environment and provides a physically consistent approach to interpolation between the sparse observation points. Substantial improvement in the performance of general circulation models in high southern latitudes has been achieved over the last decade, such that many aspects of antarctic climate (surface temperature, inversion strength, accumulation, surface winds, etc.) can now be captured with some fidelity (Schlesinger 1984; Simmonds 1990; Tzeng et al. 1994; Connolley and Cattle 1994; Krinner et al. 1997). Improvements in climate model simulations of the Southern Hemisphere extratropical circulation have been related to higher resolution, which is necessary for resolving the steep antarctic coastal slopes (chapter 10). Mesoscale models are being used to study katabatic winds, as extensively discussed earlier; airflow around complex terrain (Seefeldt 1996); mesoscale cyclone formation (e.g., Engels and Heinemann 1996); and coastal polynya formation (Gallée 1997), among other things. Initial efforts have been made to couple GCM and mesoscale models for antarctic latitudes (Hines et al. 1997a). A prerequisite for almost all such investigations is adaptation of the planetary boundary-layer parameterization to treat the stable antarctic conditions (e.g., Hines et al. 1995; Krinner et al. 1997). In addition, major problems can occur in the simulation of the atmospheric hydrologic cycle, such as the gross oversimulation by some models of the cloud amount and thickness over the East Antarctic plateau during winter (Hines et al. 1997b) and anomalous moisture diffusion over the coastal slopes (Connolley and King 1996).

For long-term investigations, there is a vital need to obtain a more complete picture of the spatial and temporal variability of antarctic atmospheric behavior. A primary goal of the International Trans-Antarctic Scientific Expedition is the collection and annual interpretation of environmental parameters (accumulation rate, temperature, etc.) on a continent-wide basis for the last 200 years through the use of shallow ice cores (Mayewski 1996). Should the full potential of this project be realized, Antarctica will be transformed from the continent with the most poorly documented climatic variations to one of the better known.

In summary, antarctic meteorology has evolved considerably in recent years due to the increased effort in numerical modeling and greater availability of satellite and automatic weather station data. These advances augment what is otherwise the most data-sparse land area on earth. Resulting analyses have revealed a complex atmospheric circulation that has large seasonal and interannual variations and *interacts* with lower latitudes on a variety of timescales.

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