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A Review of Precipitation-Related Aspects of West Antarctic Meteorology

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SUMMARY

An overview is presented of the factors associated with snowfall over the West Antarctic Ice Sheet. The flux of atmospheric moisture across the coast, the synoptic proceses over the South Pacific Ocean, the large-scale atmospheric controls, and numerical modeling of the West Antarctic environment are all discussed. Suggestions are made for research needed to substantially upgrade the status of knowledge in these closely-interrelated topic areas.

1. INTRODUCTION

The goal of this overview is to provide a summary of the status of knowledge concerning the primary atmospheric input to the West Antarctic ice sheet, namely snowfall. The document follows the organization of the SeaRISE document (Bindschadler, 1990). The atmospheric transport of water vapor across the coast from the Southern Ocean, whose convergence equals the average net precipitation rate over the ice sheet, is discussed in Section 2. Study of this quantity is needed because there are substantial obstacles to directly measuring snowfall over polar ice sheets (e.g., Bromwich, 1988), and this water balance approach provides a way to calculate the rate from variables which are usually readily available.

The atmospheric water balance provides a composite description of snowfall over the ice sheet, but does not resolve the individual precipitation events. Cyclonic activity causes the spatial patterns and temporal variability of the moisture fluxes, and these processes are surveyed in Section 3. Synoptic processes express the broader scale atmospheric, oceanic and ice sheet conditions. An understanding is needed of the dominant patterns of variability and how they interact in order to deduce correctly the record of past large-scale atmospheric patterns from synoptically-dominated records of individual ice cores. Section 4 addresses such aspects, focussing on El Niño Southern Oscillation (ENSO) events which are manifested on the multiannual time scale. Numerical models are primary tools in the study of the atmospheric processes that determine the precipitation and other aspects of the Antarctic climate both at present and for different boundary conditions (i.e., past and future). Global and regional models are applicable, and their status is discussed in Section 5. The final section offers some thoughts on research needed to advance the state-of-the-art.

2. MOISTURE FLUX INTO WEST ANTARCTICA

This evaluation must first consider the situation for the Antarctic continent as a whole. In general, the available estimates of poleward moisture transport from atmospheric measurements are deficient. Bromwich (1990) compared the annual moisture transport convergence values (= annual net precipitation) for Antarctica from two recent climatological atmospheric analyses with those inferable from the multiannual accumulation analysis of Giovinetto and Bentley (1985). For the continent as a whole the atmospheric-derived estimates were only one-third to one-half the terrestrial values; for 80-90°S the two approaches yielded comparable results. It was concluded that the primary causes of the large discrepancy for the continent were deficiencies in atmospheric diagnoses of the transport contributions of cyclones and surface winds near the coast. A secondary cause was the small systematic underestimate by radiosondes of the atmospheric moisture content during the cold polar night.

Table 1 (from Giovinetto et al., 1991) provides a historical overview of the estimated water vapor transports across 70°S from atmospheric and surface-based observations. The values are arranged by publication date, and only analyses drawing upon data collected during or after the International Geophysical Year (IGY) are considered. Pre-IGY evaluations were primarily conjectural because of very limited observations. There is a marked contrast between the terrestrial and atmospheric estimates. The former reveal little trend with publication year, fluctuating around a poleward transport of 6.0 kg $m^{-1}s^{-1}$. With steadily improving spatial coverage and enhanced measurement techniques, the accumulation-based estimates can be regarded as fairly reliable. The atmospheric values show a strong trend with publication year, changing from weakly equatorward to a poleward transport of 5.3 kg $m^{-1}s^{-1}$, illustrating the above weaknesses of the atmospheric analyses. Of course, the variable record lengths for the atmospheric studies complicates this comparison. It can be concluded that although the atmospheric analyses show steady improvement they are not yet suitable for continent-wide studies of the atmospheric water balance. However, for 80-90°S and perhaps a large fraction of East Antarctica (Bromwich, 1990) they can be used for this purpose.

The explanation for the above results can be sought in part in the distribution of radiosonde stations which are the primary source for the wind and moisture profiles from which moisture transports are calculated. Figure 1 (from Bromwich, 1990) describes the array of radiosonde stations available for the climatological atmospheric analyses of Peixoto and Oort (1983), and Howarth (1983) and Howarth and Rayner (1986): PO and HR respectively. The situation is rather similar today. The coverage is adequate for determination of poleward moisture transports along most of the East Antarctic coast and around the 80° latitude circle. The coast of West Antarctica is unmonitored, and the upper air station at Byrd has not operated since the early 1970s. It is probable that the former gap contributed significantly to the deficiencies of the atmospheric analyses in Table 1. The temporal trend of increasing atmospheric poleward moisture transports in Table 1 corresponds to the degree of monitoring of atmospheric processes over the ocean areas surrounding the continent. During the IGY-winter the Southern Ocean was almost completely devoid of observations. The Peixoto and Oort (1983) analysis relied on radiosonde data, but the Howarth (1983) and Howarth and Rayner (1986) diagnosis profited from the incorporation of oceanic satellite observations (from imagery and soundings). During 1979, there was a comprehensive drifting buoy program in the Southern Ocean (Hollingsworth, 1989), and this data source appears to have been one key to the markedly improved analysis by Masuda (1990).

Studies focussing specifically on moisture transports into West Antarctica were conducted by Lettau (1969) and Rubin and Giovinetto (1962), and primarily drew upon IGY-era data. The presence of upper air stations at Byrd and Little America V (northeastern edge of the Ross Ice Shelf) was a critical aspect for both studies. From a continental atmospheric mass budget and assumed moisture values, Lettau (1969) inferred that 40% of the vapor transported into Antarctica enters in this sector with the time-averaged and storm transports contributing equally. Notice that no direct moisture budget was attempted because of skepticism about the quality of the radiosonde humidity measurements at low air temperatures; the present authors do not share this viewpoint but do recognize the need for caution in using such data. The importance of cyclonic events for West Antarctic snowfall was underscored by the work of Vickers (1966), and implies that interannual variability may be high. Rubin and Giovinetto (1962) showed that the broad spatial patterns of snow accumulation were consistent with the moisture flux directions and humidity characteristics at radiosonde stations surrounding the ice sheet; once again no moisture budget analysis was attempted.

Although recent atmospheric analyses need to be checked it appears that to conduct meaningful diagnostic analyses of the atmospheric moisture budget over West Antarctica the data base must be enhanced. The most effective action would be to improve the oceanic drifting buoy program so that coverage approaches that during 1979 (see Hollingsworth, 1989). Radiosonde programs (or equivalent) should be implemented at any manned station set-up by the United States in West Antarctica to replace Siple. Finally, satellite remote sensing offers much potential, and vigorous efforts are underway to solve the difficulties associated with soundings over sea-ice and ice-sheet surfaces (e.g., Claud et al., 1988).

3. SOUTH PACIFIC SYNOPTIC ACTIVITY

Much of our understanding of synoptic processes over the extensive middle and high latitude oceans of the Southern Hemisphere is based on only about 30 years of widely-spaced station sea-level-pressure (SLP) observations. These comprise principally the following climatologies:

(a) The 18-month period of the IGY of 1957-58 (e.g., Astapenko, 1964; Taljaard, 1967).

(b) The South African hemispheric analyses that continued into the mid-1960s (Taljaard et al., 1969; Newton, 1972).

(c) The Australian Numerical Meteorology Research Center (ANMRC) hemispheric analyses that began in the early 1970s (Streten, 1980a; LeMarshall and Kelly, 1981; LeMarshall et al., 1985).

(d) The European Center for Medium-Range Weather Forecasting (ECMWF) global-scale analyses dating from the First GARP Global Experiment (FGGE) of 1979.

With specific regard to the South Pacific, the coverage was particularly deficient in (b), and only improved from the early 1970s; first with the regular incorporation of satellite information (c), and then with the inclusion of ocean drifting buoys and automatic weather station (AWS) data for the Antarctic (d). These SLP analyses reveal the following general features of the synoptic atmospheric circulation.

(1) On a monthly and seasonal basis, a low amplitude long wave trough is located through the South Pacific in association with a relatively zonal circulation (Trenberth, 1979-- his Fig. 1; Streten and Troup, 1973). Pressures decrease into the circumpolar trough, which is located between about 60° to 74°S, depending on longitude considered and also month/season (Streten, 1980a-- his Figs. 12, 13). For West Antarctica, the circumpolar trough is generally located between about 68-72°S (Fig. 2).

(2) On shorter (daily) time scales, the circulation may be considerably more meridional, with high pressure ridges interrupting the circumpolar trough. Preferred longitudes for this activity in the West Antarctic sector are between about 80-70°W, and concentrated in the autumn and winter (Streten, 1980a-- his Fig. 15). However, this activity is considerably reduced compared with that of cyclones, which peaks between about 170-130°W in this region (Fig. 2).

(3) The circumpolar trough is the summation of individual frontal cyclones moving in from middle latitudes, which dissipate and stagnate preferentially in the major Antarctic embayments. In the West Antarctic these are the eastern Ross Sea, the Amundsen/Bellinghausen seas, and the Weddell Sea (Fig. 2).

(4) The circumpolar trough undergoes a dominant semi-annual oscillation in position and intensity. It is closest to Antarctica and deeper in the equinoctial months (January, June) compared with the solsticial months (March, September) (Streten, 1980a-- his Fig. 12). Similarly, the strength of the zonal index (westerlies) for the latitude zone 40-60°S is highest in February/March and September/October (Streten, 1980a-- his Fig. 10). In this regard, the sector from 180° eastward to 90°W is no exception (Streten, 1980a-- his Fig. 9). The semi-annual oscillation is somewhat reflected in the seasonal distribution of precipitation around West Antarctica (van Loon, 1972; Bromwich, 1988). The semi-annual oscillation involves changes in the hemispheric waves, particularly over the Indian and South Pacific oceans and in the colder part of the year (van Loon and Rogers, 1984). These changes are, in large part, responsible for the "coreless" winter observed at many Antarctic stations, particularly in the Ross Sea sector. Over middle latitudes, the changes in the waves associated with the semi-annual oscillation are manifest in marked changes in the preferred longitudes of polar lows between June and September (Carleton and Carpenter, 1990).

(5) On an interannual basis the circumpolar trough undergoes a marked variation in mean latitude for the Ross, Amundsen and Bellingshausen sea sectors. This exceeds 8° of latitude for the early autumn, early winter and late spring, but is much smaller (less than 4°) in the summer and late winter/spring, at least for the period 1972-77 (Streten, 1980a).

(6) Anomalies of SLP for the Pacific are often out-of-phase between low/high and middle latitudes, and between low and high latitudes (Mo and White, 1985). These teleconnections are associated with the Southern Oscillation, particularly in summer. They are associated with strengthening and weakening of the westerlies in alternating latitude belts (Rogers and van Loon, 1982), and are such that stronger (weaker) trades tend to have associated stronger (weaker) westerlies north (south) of about 45°S (Trenberth, 1981). In winter, SLP anomalies are often out-of-phase between the Australasian and Antarctic

Peninsula/South American regions. These correspond with the Trans-Polar Index (TPI) of Pittock (1984), which is the SLP anomaly difference between Hobart and Stanley. Variations in TPI correlate with variations in Scotia Sea pack ice conditions (Rogers and van Loon, 1982).

(7) On decadal time scales, there are variations apparent in the frequencies of cyclones and their mean longitudes of occurrence for the West Antarctic. Data for the IGY and subsequent years (Taljaard et al., 1969) show a weaker mean low in the vicinity of the Ross and Weddell seas compared with the later climatologies (Streten, 1980a), particularly in the 1978-82 period (LeMarshall et al., 1985). Thus, there have also been variations *within* the time period of the ANMRC 10-year climatology (LeMarshall et al., 1985). These point up the highly variable nature of the Southern Hemisphere circulation on a range of time scales, even given the effects of increased data and the changes in analysis procedure (LeMarshall and Kelly, 1981).

4. ENSO RELATIONSHIPS WITH THE ANTARCTIC

The relatively short period of conventional meteorological data in the Antarctic does not facilitate a full description of ENSO teleconnections to Antarctica. However, there are tantalizing hints of the teleconnection that require further exploration as the data record lengthens, and as numerical models become more sophisticated. In particular, the analysis of ice cores should shed considerable light, assuming that the regional expression of ENSO and correlations among its descriptor variables remain relatively stable from event to event (either positive or negative phase). There are indications that this has not been the case, even for the tropical centers of action (Elliot and Angell, 1988). The following are some important observations for the Antarctic.

(1) An analysis of the time evolution of global-scale SLP anomalies (Krishnamurti et al., 1986) shows strong variance on ENSO time scales over Antarctic latitudes. In addition, a northward propagation of zonally-averaged anomalies from the south polar to north polar latitudes took place in the period 1961-71, but reversed after that time. Additional support for these longer-term Antarctic influences on global climate is given in Fletcher et al.'s (1982) study of historical sea-surface temperature and surface-wind observations over the Southern Ocean south of Australia (40-50°S).

(2) A hint of a quite strong higher latitude manifestation of ENSO is apparent in hemispheric composites of SLP anomalies associated with the peak years of warm events compared with the years immediately prior (van Loon and Shea, 1985). These suggest the existence of quite strong pressure reversals over the Weddell Sea, south Indian Ocean, and possibly also over the southeast Pacific south of 50°S (their Figs. 1a, b). They were confirmed, at least for the Weddell Sea sector, by Carleton (1988), who also showed the existence of substantial associated anomalies in sea ice concentration for that region.

(3) Regional-scale anomalies in the sea ice extent and concentration of the Antarctic embayments are strongly associated with changes in temperature, pressure and winds -- hence, the role of cyclonic activity noted earlier.

Accordingly, changes in sea ice conditions (extent, concentration) are an indicator of climate anomalies. Chiu (1983) finds a significant association between the SOI (Southern Oscillation Index) in March and April and the Antarctic sea ice area in the following July-December period, and also an apparent lag of the SOIs with sea ice area in the latter part of the year. The study was extended by Carleton (1989), who considered regional-scale sea ice changes associated with ENSO and the hemispheric long waves. There is also an apparent ENSO signature in the patterns of subsynoptic-scale cyclogenesis ("polar lows") over the South Pacific and southern Indian Oceans, apparently in response to the large-scale changes in the long waves and associated outbreaks of colder air toward lower latitudes (Carleton and Carpenter, 1990).

(4) Using the period of record for the South Pole and AWS data in the Ross Sea area for the 1982-83 ENSO event, Savage et al. (1988) identify a lagged effect of ENSO in Antarctic temperatures and surface winds (Fig. 3a, b). Very low temperatures at South Pole apparently resulted in enhanced cold air drainage and higher katabatic wind speeds reported near the coast at that time.

(5) Available general circulation modeling studies (e.g., Mitchell and Hills, 1986; Simmonds and Dix, 1986) suggest quite strong and, for the most part, significant tropical pressure and height responses to prescribed anomalies of the Antarctic wintertime sea ice extent. These appear to have an ENSO signature. Changes in cyclonic activity occur in the circumpolar trough; however, the magnitude and even sign of the SLP departures appears to be model dependent (cf., Mitchell and Hills, 1986; Simmonds and Dix, 1986).

It is apparent from longer-term indices of ENSO that the 'poles' of the Southern Oscillation and the frequency of high magnitude events have changed during the past 100 years or so. An index of the Oscillation back to 1600 A.D. and derived from analysis of tree rings, suggests even longer-time scale changes in the frequency of low-index (warm) events (Lough and Fritts, 1985). These appear to have been less frequent in the nineteenth century compared with the eighteenth and twentieth centuries. Also, the warm events of 1792-93 and 1815-16 may have been of comparable magnitude to the major 1982-83 event. The analysis of Antarctic ice core data could be used to extend the ENSO record back even further. However, this assumes (a) the existence through time of a stable and coherent teleconnection to the Antarctic circulation, precipitation and temperature regimes; and (b) the identification of ice-core drilling sites within such center(s) of action. From the foregoing discussion, the Pacific sector of the West Antarctic appears to be such a place; however, the dominance of the annual snowfall regime by relatively few cyclonic events is problematic. A candidate mechanism for the tropical-Antarctic teleconnection is the South Pacific Cloud Band (SPCB). This feature is an important avenue for the transports of energy and moisture, and also has a strong ENSO signature (Streten, 1975; Trenberth, 1976; Meehl, 1988). The possible impact of such low-frequency changes in the SPCB for the accumulation on the West Antarctic ice sheet is unknown at this time.

5. NUMERICAL MODELING OF THE WEST ANTARCTIC ENVIRONMENT

Studies using atmospheric general circulation models (GCM) and high resolution regional models are needed to improve our understanding of the planetary, synoptic and mesoscale atmospheric processes over Antarctica. Incorporation into GCMs of knowledge gained from diagnostic studies such as those outlined above will make it possible to commence a realistic assessment of the interactions between Antarctica and the rest of the planet. Complete exploration of this topic will require coupling of GCMs to realistic ocean and sea-ice models.

An early assessment of the ability of GCMs to reproduce the present Antarctic climate (Schlesinger, 1984) revealed large systematic errors in temperature, pressure, precipitation and cyclonic simulations. Model deficiencies of this magnitude preclude their use to understand the present climate or to describe how it might have changed in the past or might do so in the future. This situation persists for some models, as indicated by the NCAR Community Climate Model being unable to simulate major Antarctic environmental changes within the last 3 million years (Elliot et al., 1991). Simmonds (1990) demonstrates that the veracity of many models has continued to improve through the end of the 1980s, and presents convincing simulation fields of sea-level pressure, strength of the surface temperature inversion over the ice sheets during winter, and annual precipitation, to illustrate this contention. As an example, Figure 4 taken from Mitchell and Senior (1989) shows a qualitatively reasonable simulation of the Antarctic surface winds by the British Meteorological Office GCM. Simmonds points out that it is difficulty to verify models because real climatic variables are not known to a high degree of confidence. This argues for a vigorous effort to fill in the large gaps in the observational network, particularly over the South Pacific Ocean, the coast of West Antarctica, and the interior of the ice sheet.

Numerical simulation of high latitude atmospheric phenomena using sophisticated, high resolution models is an extremely promising avenue of future research. Mesoscale (10-300 km) processes such as katabatic wind circulations (Parish, 1984; Parish and Bromwich, 1986, 1987, 1991) and polar lows (Bromwich, 1989; 1991) are frequently observed in Antarctic regions and may play a significant role in the heat and momentum exchanges between polar and tropical latitudes. Such processes are at best only crudely parameterized within the context of GCMs (see, for example, Mitchell and Senior, 1989); it is extremely important that effects of such mesoscale processes on larger-scale circulations and transports be quantified before definitive GCM studies can be undertaken.

To date, a large gap exists in modeling applications of regional-scale Antarctic processes. Only specialized applications involving mesoscale models have been attempted. As an example, mesoscale models have been used to understand the temporal and spatial evolution of katabatic winds. Parish and Waight (1987) have used a two-dimensional numerical model to simulate the development of katabatic drainage. Emphasis was placed on the evolution of radiative and sensible heat transports in the lower atmosphere on the forcing of the katabatic flow. Parish and Wendler (1990) have used a hydrostatic, three-dimensional model to depict the forcing of the anomalous katabatic wind regime near Adelie Land, Antarctica. A similar katabatic wind study has been completed by van Meurs and Allison (1989) for a section of East Antarctica along 112°E. Parish and Bromwich (1991) have used a numerical model to portray the katabatic wind pattern over the Antarctic continent. The irregularity of the katabatic drainage pattern into "confluence zones" modulates the intensity of coastal katabatic winds and is thought to influence the cyclogenetic potential of the near-coastal periphery (Bromwich, 1991). Most of these model simulations encompass relatively short time periods on the order of 12 hours to a few days. Longer time-scale studies will be necessary to integrate these regional simulations with GCM results. For example, Egger (1985) and James (1989) have noted that the katabatic wind circulation is tied directly to the large-scale circumpolar vortex about the Antarctic continent. Using simplified models to represent the radiative cooling of the sloping terrain, both authors showed that the shallow katabatic winds were responsible for the development of an upper tropospheric vortex on a time-scale of approximately several days to a week or more. They conclude that the katabatic wind circulations must act in unison with propagating cyclones in the evolution of the upper level vortex. Intensification of the upper level vortex pattern tends to suppress further katabatic wind development; cyclonic intrusion is thought to disrupt the circumpolar vortex which then allows the katabatic wind circulation to become reestablished. Thus, a significant scale-interaction is suggested.

A critical component of future numerical studies will be the incorporation of extratropical cyclones and the resulting moisture and heat fluxes into mesoscale models. As shown by Bromwich (1988), a significant moisture flux onto the Antarctic continent is the result of cyclonic activity. Inclusion of such processes within detailed regional models is prerequisite to detailed GCM studies of Antarctic ice sheet variability and climate change.

6. CONCLUSIONS

Implicit to the preceding discussion is that West Antarctic meteorology must be viewed within the context of the atmospheric dynamics of high southern latitudes, and that the broadscale ice sheet configurations in both the eastern and western hemispheres coupled with the general atmospheric circulation results in the atmospheric processes governing snowfall over West Antarctica. Central to the advancement of basic knowledge is the need to eliminate the data void over the South Pacific Ocean and West Antarctica. Strategies to address this problem include deployments of AWS on the ice sheet and on offshore islands, and of free-floating buoys in the ocean areas. Radiosonde programs should be instigated at at all manned stations established in the future. Polar orbiting satellite data can help fill the data gap, and vigorous exploitation of the satellite imagery and soundings routinely collected at McMurdo and Palmer stations is needed. These two sites can provide complete high resolution coverage of West Antarctica several times a day.

For the moisture fluxes the first requirement is to establish an adequate observational system so that the temporal and spatial modes can be characterized and related to the large-scale atmospheric circulation, synoptic processes and oceanic boundary conditions (e.g., sea ice and sea-surface temperatures). A deeper quantitative understanding of these interactions is critical because it will allow accumulation variations, which are difficult to measure everywhere on the ice sheet, to be inferred from more viable measurements of the factors that determine the accumulation pattern.

Very little is known about cyclonic processes over West Antarctica. There is a need to characterize the formation, tracks and dissipation of cyclones in this area together with the associated variability; both synoptic and mesoscale cyclones may be important and may interact in significant ways. Of particular importance is an examination of the frequency of and mechanisms by which cyclones penetrate deep into the interior of the ice sheet. A 10- to 15-year daily synoptic data base established from all available observations is required for such studies, and is becoming feasible.

The connections between the large-scale and synoptic-scale processes must be understood on time scales ranging from weekly and seasonal through interannual to decadal. As above, a 10- to 15-year combination of satellite and operational analyses is needed to describe the variability of the large-scale processes and the interactions among the component parts.

Interactive evaluations of numerical modeling/theoretical studies and observational analyses are required to extract the maximum understanding and realism from all approaches. Understanding the important processes and their sensitivity to orographic, sea-ice and sea-surface temperature characteristics as well as the CO_2 content of the atmosphere is vital for the study and prediction of the West Antarctic ice sheet in particular, and of sea-level changes in general.

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Table 1: Comparison of annual meridional water vapor transport estimates ($kg\ m^{-1}\ s^{-1}$) across 70°S since the International Geophysical Year (1957-1958). Negative values are directed toward the South Pole.

ATMOSPHERIC		MULTIANNUAL SURFACE-BASED	
+0.73	Starr et al. (1969) for 1958	-5.6 to -7.2	Rubin (1962) from accumulation data*
-3.0 (PO)	Peixoto and Oort (1983) for 1963-1973	-5.4	Baumgartner and Reichel (1975)
-3.7 (HR)	Howarth (1983) and Howarth and Rayner (1986) for 1973-1978 and 1980-1984	-5.8 to -6.0	Bromwich (1990)*
-5.3	Masuda (1990) for 1979	-6.3 ±1.1	Giovinetto et al. (1991)

*Transport across the coast of the Antarctic continent converted to transport across 70°S using ratio of the two values given by Baumgartner and Reichel (1975).

Fig. 1. Antarctic radiosonde stations whose data primarily determined the high latitude atmospheric moisture fluxes obtained by PO and HR: filled circles denote sites contributing to both studies and filled squares to only one. Notice the measurement gap along the West Antarctic coast (to the left); no upper air observations have been collected at Byrd Station (80°S) since the early 1970s. Thin continuous lines are elevation contours in meters, starting at 2000 m. Adapted from Bromwich (1990).

Fig. 2. Main schematic features of the surface circulation; inner hatched area denotes the region of the sub-Antarctic trough within which the mean seasonal axis varied between 1972 and 1977; black area shows the region of the quasi-high pressure over the interior within which monthly mean relative pressure maxima were located between 1972 and 1977; hatched histograms along 60°S represent the relative frequency of monthly mean low pressure centers in the Antarctic trough between 1972 and 1977. Adapted from Streten (1980b).

Fig. 3(a). Distribution of annual mean temperatures at Amundsen-Scott South Pole Station, Antarctica, 1957-1986. (b). Normalized time series of the annual values of the Southern Oscillation Index (SOI: Tahiti minus Darwin sea level pressure) and of the annual mean temperatures from the following year (lag +1) at the Amundsen-Scott South Pole Station. Stippling shows the seven ENSO episodes that have occurred since 1955. Adapted from Savage et al. (1988).

Fig. 4. Low level winds: (a) Model winds at $\sigma = 0.987$, July to September. The wind speed is proportional to the length of the arrows, and the scale is given in the bottom left-hand corner. (b) Time-averaged near-surface wintertime streamlines of cold air drainage over Antarctica (after Parish and Bromwich, 1987). The thin lines are ice sheet elevation contours at intervals of 100 m. Adapted from Mitchell and Senior (1989).

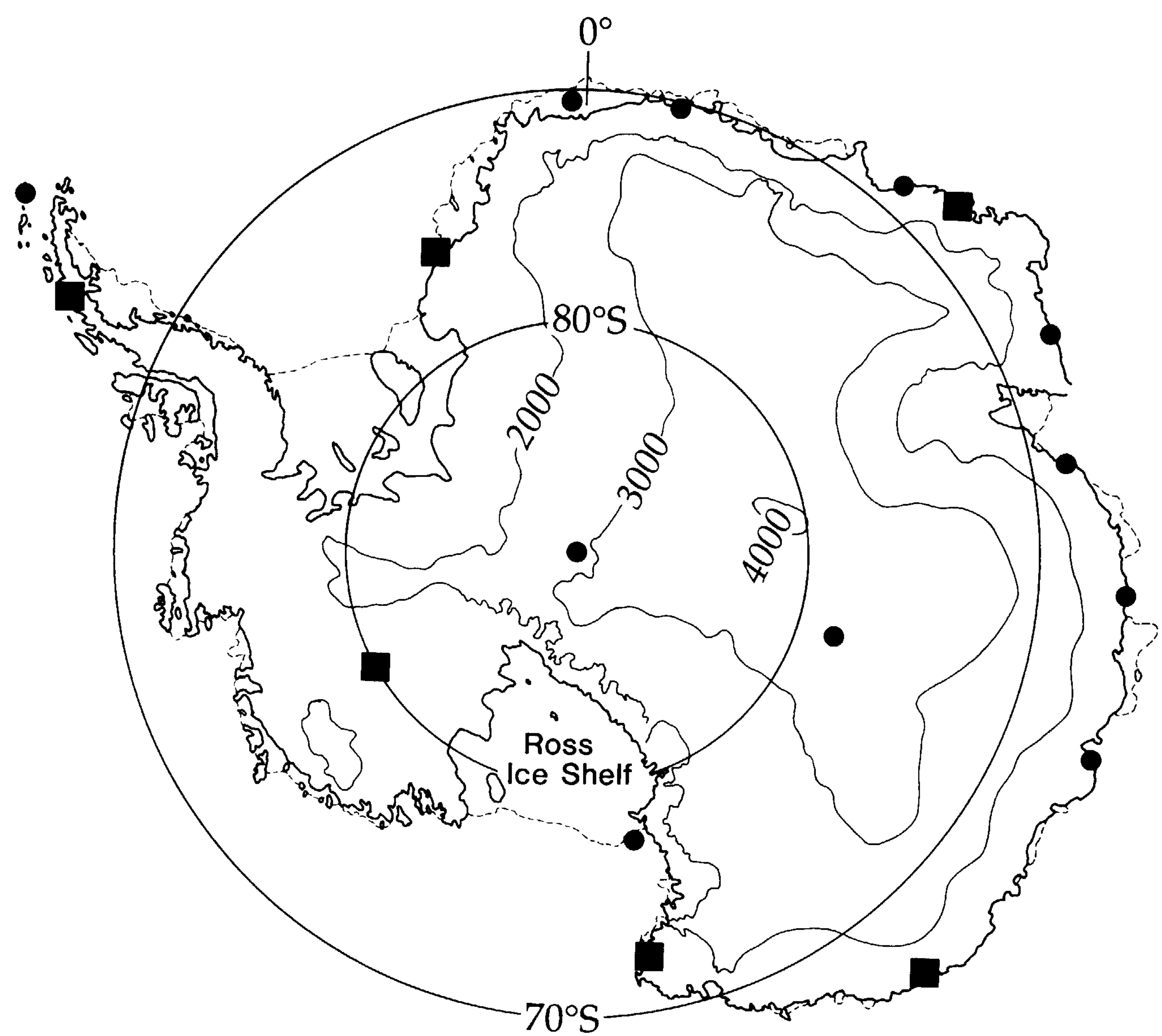


Figure 1.

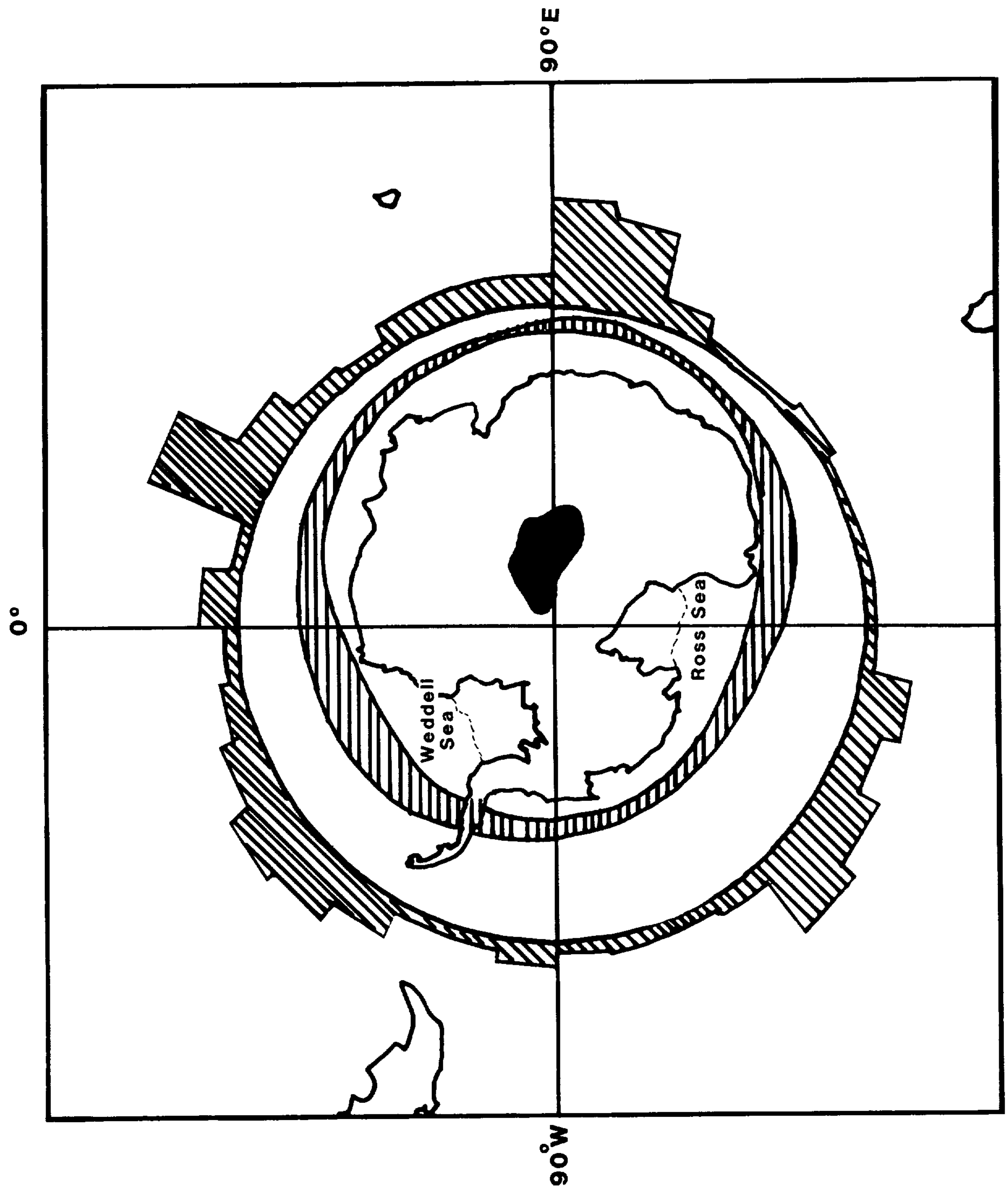
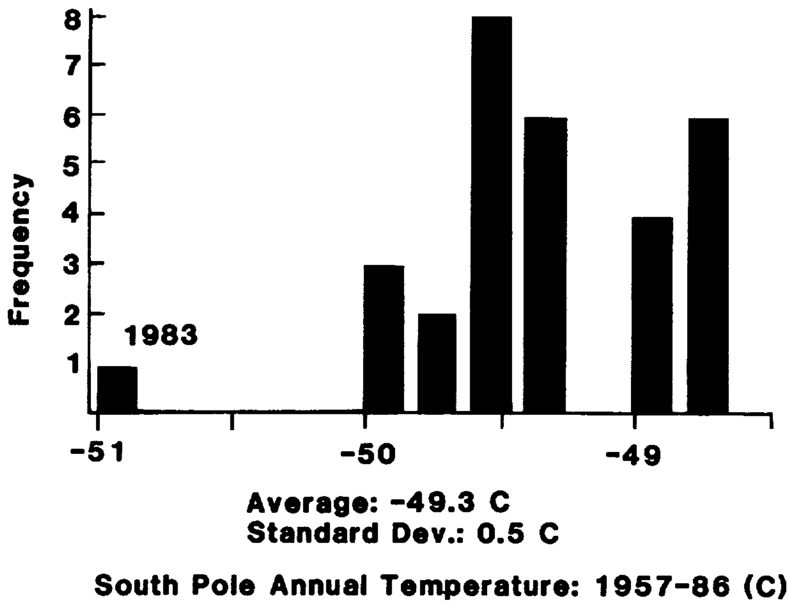


Figure 2.

(a)


8
7
6
5
4
3
2
1
Frequency
1983
-51
-50
-49
Average: -49.3 C
Standard Dev.: 0.5 C
South Pole Annual Temperature: 1957-86 (C)

(b)

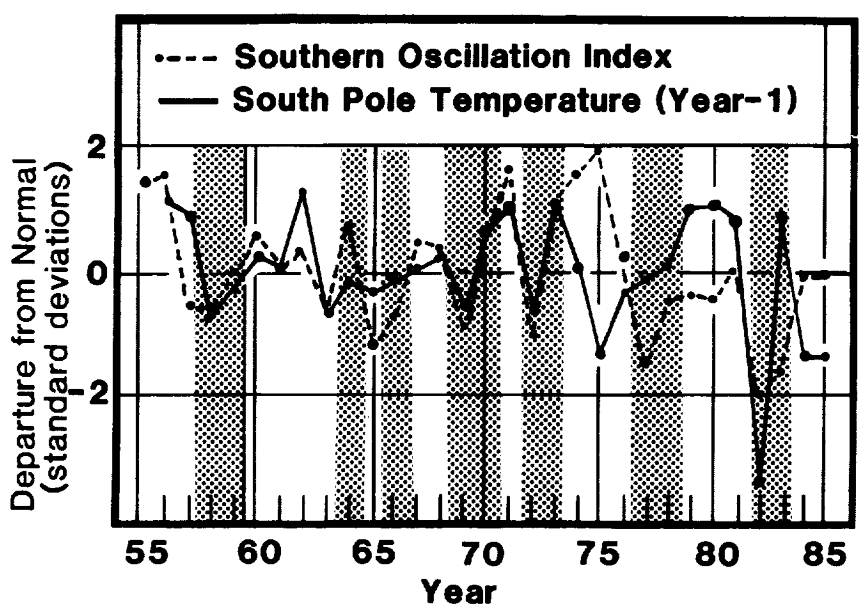
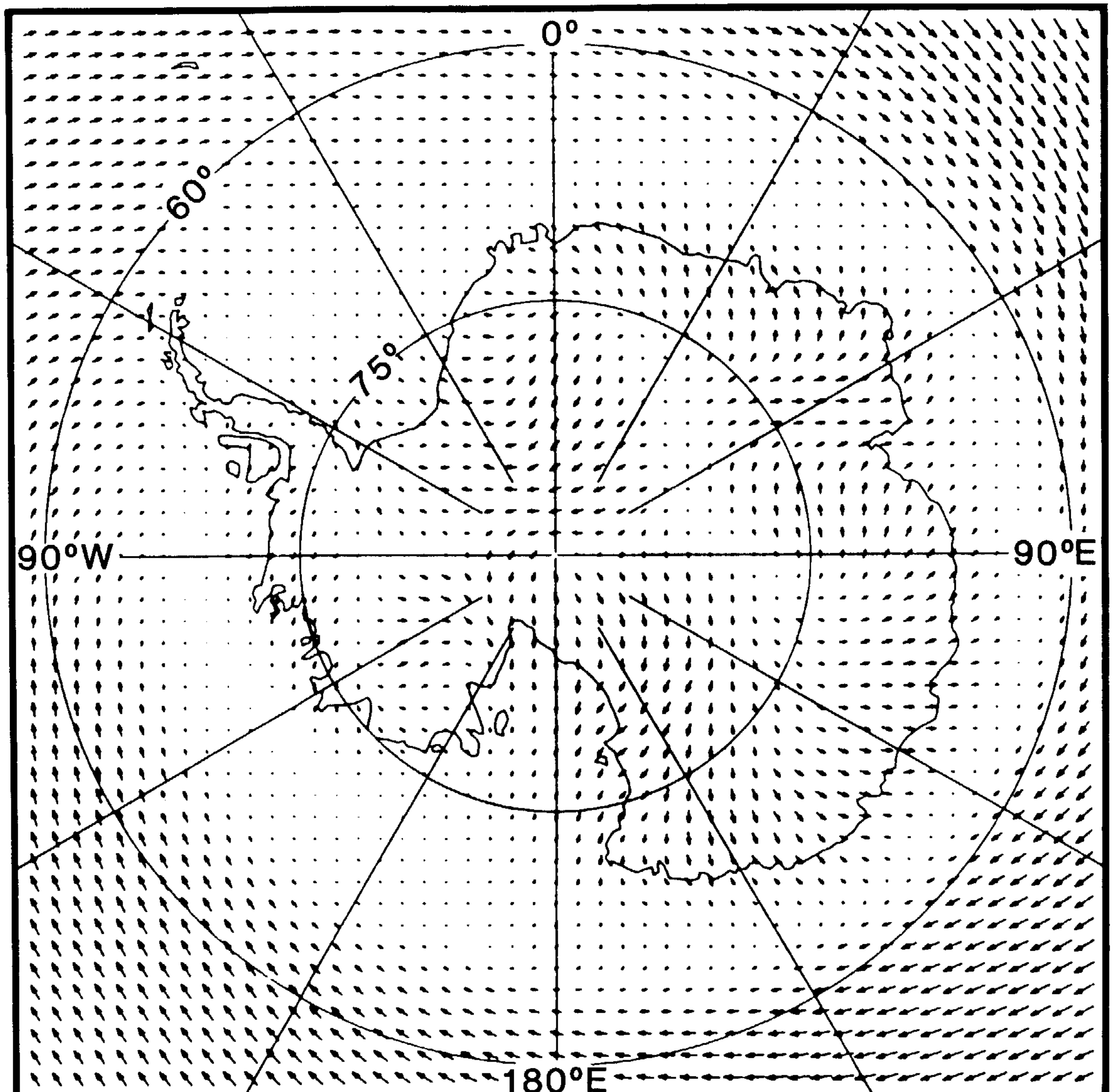

Southern Oscillation Index
South Pole Temperature (Year-1)
2
0
-2
Departure from Normal
(standard deviations)
55
60
65
70
75
80
85
Year

Figure 3.



(a) → Represents 20 M/S

Figure 4.

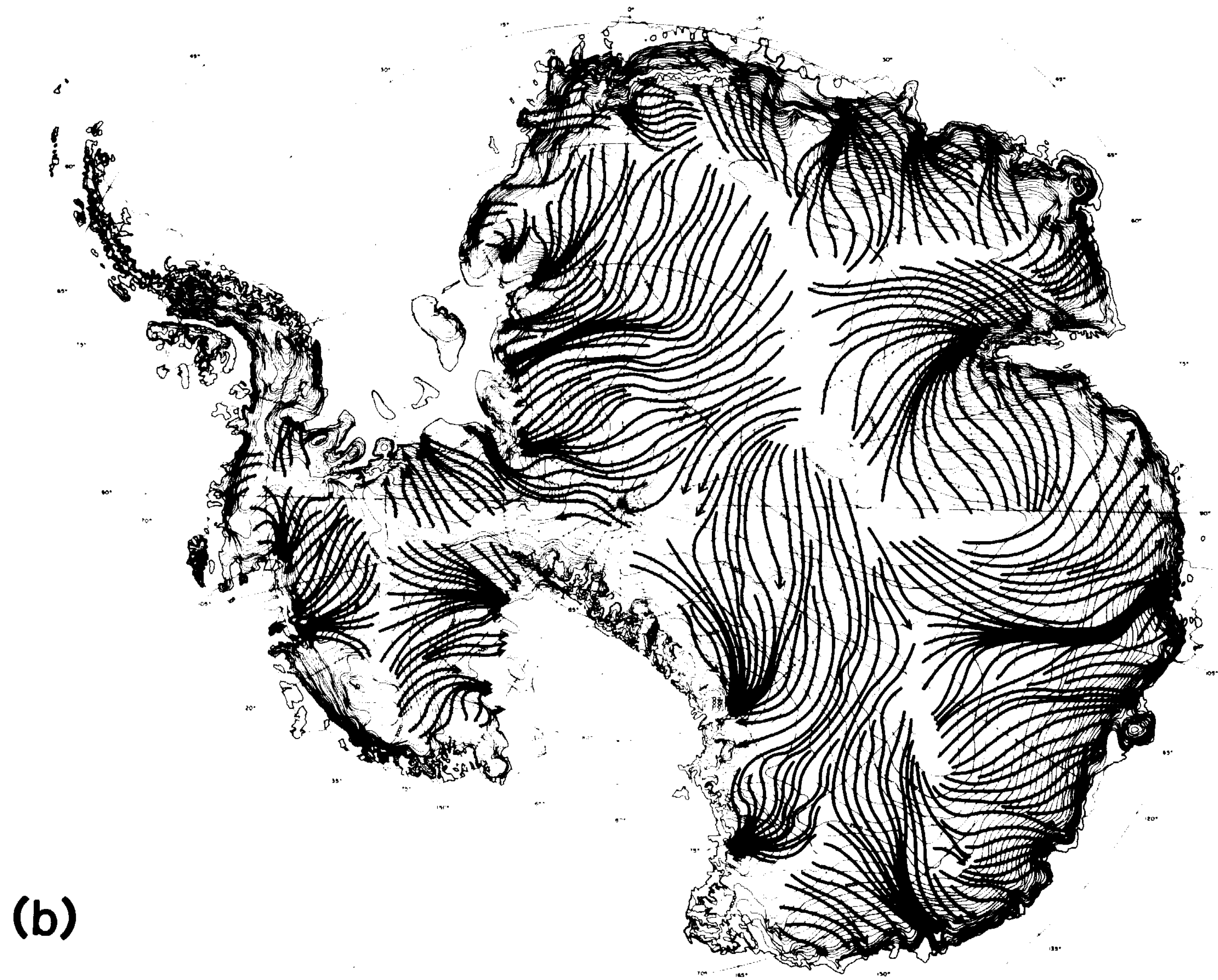


Figure 4 (continued).