Surface Airflow Over East Antarctica

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ABSTRACT

Surface winds over the Antarctic interior occur mainly due to the strong radiational cooling of the ice slopes. As a consequence, such winds exhibit a high degree of persistence with a predominant direction closely related to the terrain orientation. Using detailed contour maps of the interior ice topography and representative values of the mean wintertime strength of the temperature inversion, it is possible to infer the terrain-induced accelerations. A simple diagnostic equation system is formulated, from which a time-averaged surface airflow pattern of East Antarctica is generated. The results appear consistent with observations. The occurrence of localized, anomalously strong katabatic winds is explained as a result of topographically forced patterns of cold-air convergence depicted in the airflow analysis.

1. Introduction

It has only been in the last few decades that man and his instruments have sampled the Antarctic interior. As Fig. 1 shows, the station coverage over the continental hinterland is quite sparse. Furthermore, not all interior stations operate on a continuous basis. Some are in use only during summer months; others have been abandoned long ago following the International Geophysical Year (IGY) (Mather and Miller, 1967). Despite these severe data limitations, progress has been made in an effort to understand the characteristics of the surface-wind regime in interior Antarctica.

One of the unique features of the surface wind is its extreme persistence. Often the winds in the interior blow at approximately the same speed while maintaining the same general direction for periods up to weeks at a time (Schwerdtfeger, 1970a). Surface winds in the Antarctic interior are perhaps the most persistent on earth. Mean yearly directional constancy values (a ratio of the resultant wind magnitude to the average wind speed) in excess of 0.90 have been recorded. Table 1 shows the mean annual surface resultant wind statistics for the seven interior stations shown in Fig. 1.

Another characteristic revealed in Table 1 is the large deviation angle between the wind and the fall line. The surface winds are not simply directed down the ice contours. Rather, the wind component parallel to the ice contours can be considerably larger than the component directed down the fall line. In general, the winds tend to be of only moderate speed and do not exhibit the spectacular features of the katabatic winds found along coastal stretches. Contrary to normal conditions, the surface wind in the Antarctic interior is usually stronger and much more persistent than winds above the inversion layer. Lettau and Schwerdtfeger (1967) note that this unusual behavior implies, in a meteorological sense, the presence of a negative thermal wind, arising as a consequence of the nearly ever-present temperature inversion over the ice slopes. The strong temperature inversion over sloping terrain produces a horizontal, "sloped-inversion" pressure gradient force which is responsible for the extreme persistence of the interior winds. The close relationship between the terrain and the surface wind is illustrated in Fig. 2. The main ridge of the central plateau is located between the stations Vostok, Komsomolskaya and Sovietskaya. Despite their close proximity, each station exhibits a different resultant wind direction clearly reflecting the local ice topography.

2. Theoretical considerations

As first noted by Lettau (see Dalrymple *et al.*, 1966), a distinction should be made between the strong katabatic winds near the steep coastal escarpment and the persistent surface winds over the gently sloping (of the order of 10^{-3}) Antarctic interior regarding atmospheric dynamics. Coastal katabatic flow is typically a time-dependent wind regime. On the other hand, the interior surface winds can be thought of as a steady-state balanced flow between forces due to the sloped-inversion pressure gradient, the Coriolis acceleration, and friction as modified by the pressure gradient in the free atmosphere above the inversion layer. The term "inversion wind" has been coined to describe the equilibrium flow in the continental interior and will be used hereafter.

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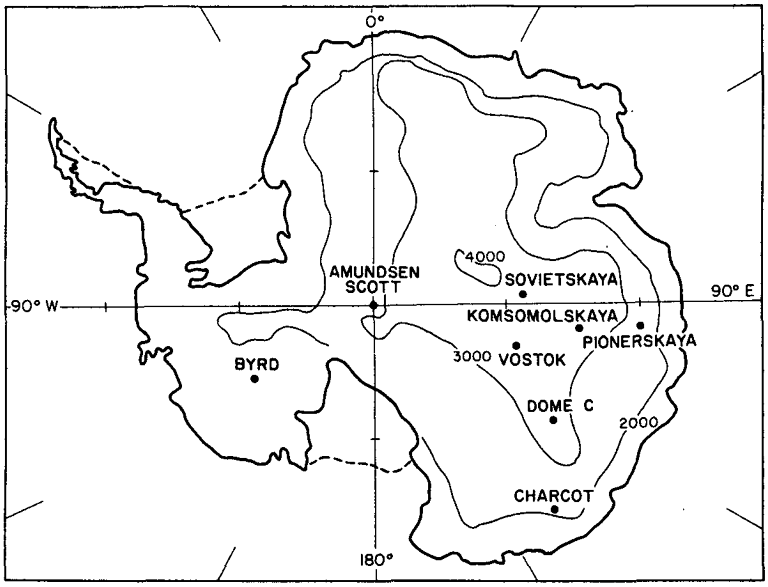

FIG. 1. The Antarctic continent: contour lines drawn for 2000, 3000 and 4000 m only.

Lettau and Schwerdtfeger (1967) first discussed the role of atmospheric dynamics in shaping these inversion winds. They showed that the sloped-inversion effect was responsible for the formation of a thermal wind, directed parallel to the ice contours. The vector difference between the geostrophic wind above the inversion layer and the thermal wind yields the surface geostrophic wind. The actual surface wind is somewhat weaker than the surface geostrophic wind and is deflected to the right due to frictional influences. In the original analysis, data from the interior station Byrd were used to test the inversion wind theory; in a later work (see Schwerdtfeger, 1970a), wind data from the stations Vostok and South Pole were analyzed. The conclusions reached by the above investigators has been summarized as follows: "the surface winds should be strongest where and when a strong inversion is present and the direction of the geostrophic flow above the inversion is approximately opposite to the direction of the thermal wind due to the slope effect" (Lettau and Schwerdtfeger, 1967). The terrain slope and the surface wind are so intimately related that the prevailing surface wind direction and speed can well be estimated if the topography is known (Schwerdtfeger, 1970a).

3. Role of synoptic forcing on the inversion winds

Examination of the synoptic weather maps for the IGY clearly indicates the importance of passing cyclones on the coastal wind regime. Streten (1968) concludes that katabatic winds at the coastal station Mawson (63°E, 68°S) rarely persist for more than 24 hours without strong synoptic support. However, effects of synoptic forcing seem to be of secondary importance on the surface winds in the interior of Antarctica. As discussed earlier, the winds display a high degree of persistence. If passing cyclones were important on the surface wind regime, the directional constancy values could not be so high. Furthermore, an analysis of storm tracks during the IGY (Taljaard and van Loon, 1962) shows most cyclones tend to be found in the near-coastal baroclinic regions.

To estimate the relative contribution of synoptic systems on Antarctic surface winds, normalized power spectra of surface pressure were calculated for various coastal and interior stations. The data records consist of 1460 six-hourly surface pressure values for the year 1958. A five-value running average scheme was used to filter the extremely high frequency periods. The relative importance of cyclones on the wind regime at a particular station can be

TABLE 1. Mean yearly resultant wind (m s^{-1}) statistics for stations in the Antarctic interior. N refers to the length of the data record in years; the deviation angle is the angle between the resultant wind and fall line of the ice terrain.

Station	N	Resultant wind	Directional constancy	Deviation angle
Pionerskaya	1	9.3, 131°	0.92	54°
Charcot	1	8.6, 163°	0.91	47°
Vostok	16	4.1, 243°	0.81	42°
Komsomolskaya	1	3.7, 151°	0.82	59°
Amundsen-Scott	16	4.6, 039°	0.79	~60°
Byrd	14	6.6, 013°	0.86	47°
Sovietskaya	1	2.6, 085°	0.68	~40°

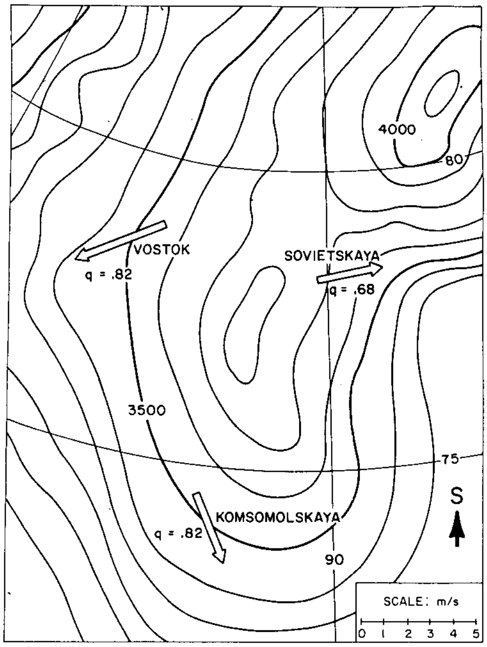

FIG. 2. Topography of the high-plateau region of East Antarctica; contour lines in meters. Included are mean yearly resultant winds for stations located about the ridge.

qualitatively assessed by noting the percent variance explained over the synoptic time period of 2.5–5.0 days. Figs. 3 and 4 illustrate the variance spectra for several coastal stations and various interior stations, respectively. The outstanding feature in Fig. 3 is the large peak at the 2.5–5.0 day period, presumably due to the transient cyclones. On the contrary, Fig. 4 indicates relatively little variance over the above-defined synoptic time period. This evidence indicates that the effects of passing cyclones are of a much less importance in shaping the surface wind regime of the interior than the coastal regions.

Further evidence can be obtained from the wind record of the newly installed automatic weather station located atop the large ice ridge known as Dome C (123°E, 74°S) well into the Antarctic interior. The station appears to sit on the crest line and no appreciable terrain slope exists in the immediate vicinity. Thus, the sloped-inversion thermal wind is nonexistent or, at most, quite weak. The surface winds recorded at Dome C depend primarily on the pressure gradient forces in the free atmosphere as modified by friction. As expected, the wind data for February 1980–March 1981 show markedly different characteristics than those found at stations located on the interior ice cap where terrain slopes are more appreciable. The mean monthly resultant wind magnitude for the Dome C station was only 1.7 m s^{-1} with a directional constancy of 0.54. This suggests that the mean geostrophic winds above the inversion layer over this part of the Antarctic continent are relatively weak and not nearly as persistent as the inversion winds.

4. Diagnosis of time-averaged surface winds in the Antarctic interior

The sloped-inversion thermal wind is the key component in understanding the surface winds over the Antarctic interior. The analysis of Lettau and Schwerdtfeger (1967) and Schwerdtfeger (1970a) requires wind information from the free atmosphere as well as the surface in order to estimate the thermal wind. This information is only available from the interior stations at which radiosonde ascents are regularly made. It is possible, however, to infer this thermal wind by theoretical means. The magnitude of the thermal wind is proportional to the strength of the temperature inversion and slope of the ice terrain. Assuming the inversion layer to be of uniform thickness, this thermal wind (V_T) can be written (Schwerdtfeger, 1974)

$$V_T = \frac{g}{f}\frac{\Delta T}{\bar{T}}\mathbf{G} \times \mathbf{k}. \qquad (1)$$

The notation is defined in Table 2. Phillpot and Zillman (1970) have determined time-averaged temperature inversion strengths over East Antarctica and have mapped their results over the continental hinterland. Also, much progress has been made in recent years in accurately determining the ice contours of the Antarctic ice sheet. The aircraft radio echo sounding technique developed by the Scott Polar Research Institute (Drewry, 1975) yields contour heights accurate to within 60 m; very detailed contour maps of a large portion of East Antarctica are presented in the work. Using the abovementioned sources, it is possible to arrive at estimates of the sloped-inversion thermal wind over much of the continent without need for wind observations.

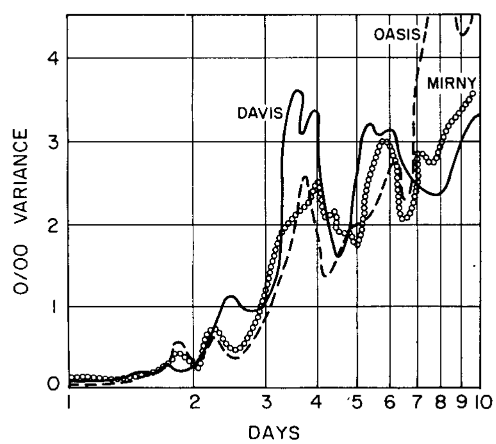

FIG. 3. Normalized variance spectra of surface pressure for three Antarctic coastal stations—Mirny, Davis (78°E, 69°S) and Oasis (101°E, 66°S).

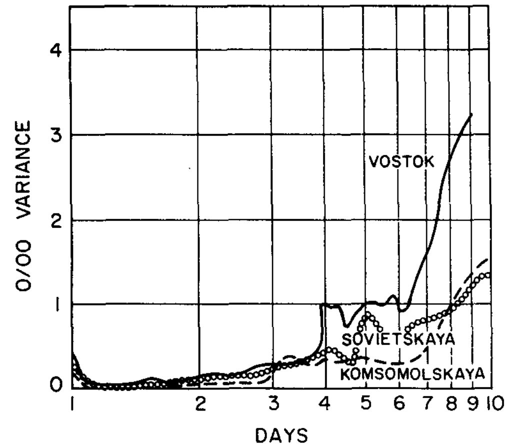

FIG. 4. Normalized variance spectra of surface pressure for three Antarctic interior stations.

As discussed earlier, the inversion winds are characterized by extreme persistence. The equations of this steady motion may be expressed as

$$0 = -g\frac{\Delta T}{\bar{T}}\frac{\partial h}{\partial x} - \alpha\frac{\partial p}{\partial x} + fv - \frac{KVu}{H}, \quad (2)$$

$$0 = -\alpha\frac{\partial p}{\partial y} - fu - \frac{KVv}{H}. \quad (3)$$

The x coordinate in the above system is taken perpendicular to the trend of the ice contours. The first two rhs terms in (1) represent the sloped-inversion pressure gradient force and the pressure gradient force in the free atmosphere, respectively. The third term is the Coriolis force; the fourth term is a quadratic drag formulation for the frictional force. The frictional constant K was set at 5.0×10^{-3} following Ball (1960). It can be shown (Ball, 1960; Parish, 1981) that the solution to the above equation system, neglecting the synoptic pressure gradient force, is

$$V = \left(\frac{hF}{K}\right)^{1/2}\cos^{1/2}\beta = \frac{F}{f}\sin\beta, \quad (4)$$

$$\beta = \cos^{-1}(1 + J^2)^{1/2} - J, \quad (5)$$

where

$$J = \frac{hf^2}{2KF}, \quad (6)$$

$$F = -g\frac{\Delta T}{\bar{T}}\frac{\partial h}{\partial x}. \quad (7)$$

It is instructive to determine the role of topography in shaping the surface wind as prescribed by the above equation system. A test was made using various ratios of the sloped-inversion thermal wind to the geostrophic wind in the free atmosphere. Fig. 5 is a summary of surface wind calculations for ratios of V_T/V_g of 0.0, 2.0 and 4.0. The circles connect endpoints of the wind vectors calculated for each ratio. At the end of each vector the direction of the upper-level geostrophic wind is shown. The fall line is directed to the right. The most important feature seen in Fig. 5 is that as the ratio of V_T/V_g increases, the angular variation of the calculated surface wind decreases. As noted by Schwerdtfeger (1970b), the exceptionally high values of directional constancy displayed by the surface winds over the Antarctic interior can be explained by the occurrence of a strong, persistent inversion over the ice slopes, which dominates over the synoptic pressure gradient force. In the absence of the sloped inversion effect (ratio 0.0), the calculated surface wind is directed 32° across the isobars. Haltiner and Martin (1957) list 35° as a typical cross-isobar flow angle for winds at high latitudes under stable conditions.

5. Airflow over East Antarctica

By employing the simple diagnostic equation system presented in the previous section, it is possible to infer the surface winds over the entire East Antarctic interior where the topography is known in detail. Only those surface winds above approximately the 2000 m contour line were considered, since the inversion wind application is restricted to the gentle interior ice slopes. An array of approximately 1200 grid points evenly spaced 50 km apart was set up. Terrain slopes were calculated by means of a five-point centered finite difference scheme using ice-contour heights from the Drewry (1975) map. The mean wintertime strength of the temperature inversion was obtained from Phillpot and Zillman (1970). The synoptic pressure gradient forces were neglected in (2) and (3), in accordance with the qualitative results of Section 3.

TABLE 2. Definition of symbols used.

Symbol	Definition
f	Coriolis parameter
g	acceleration due to gravity
$\mathbf{G}$	terrain slope vector
h	height of ice terrain
H	mean thickness of inversion layer (~300 m)
$\mathbf{k}$	unit vector in vertical direction
K	frictional constant ($=5 \times 10^{-3}$)
q	directional constancy
p	pressure
$\bar{T}$	mean temperature of inversion layer
ΔT	strength of temperature inversion
u	scalar velocity x-direction [$=V\cos\beta$]
v	scalar velocity y-direction [$=V\sin\beta$]
V	wind speed [$=(u^2 + v^2)^{1/2}$]
V_T	thermal wind vector
V_g	geostrophic wind in free atmosphere
x, y	horizontal cartesian coordinates
α	specific volume
β	deviation angle; angle of wind from fall line

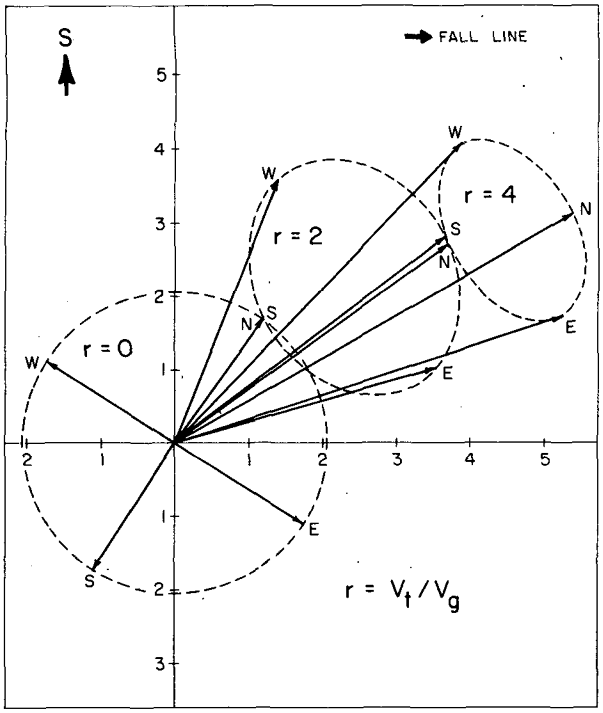

FIG. 5. Surface winds from the equation system discussed in text computed as a function of the sloped-inversion thermal wind and geostrophic wind in the free atmosphere. Plotted at the end of each wind vector is the direction of the geostrophic wind, W referring to a west wind, N to a north wind, etc.

The calculated inversion winds over the continent range from ~2 m s^{-1} to greater than 10 m s^{-1}, depending on terrain slope. This is in general agreement with the mean yearly resultant winds shown in Table 1. Of greater importance is the pattern of air drainage in East Antarctica. Fig. 6 is a streamline analysis of the mean wintertime calculated winds. It must be mentioned that the figure represents a time-averaged surface-flow pattern; the actual drainage pattern at a given instant in time may be somewhat different. Furthermore, the streamlines represent lines everywhere tangent to the velocity vectors; the spacing of such lines does not correspond to wind speed.

Qualitatively, the outstanding feature of the surface airflow pattern is the diffluent radial drainage pattern away from the broad plateau regions of the interior. The winds maintain a large component directed parallel to the ice slope. The large-scale features of the streamline analysis are in agreement with time-averaged flow maps composed by Mather and Miller (1967), based on available surface wind observations and sastrugi orientation.

6. Implications

One of the most intriguing problems of Antarctic meteorology over the past 70 years concerns the exceptionally intense katabatic winds recorded at Cape Denison, the base camp of the Australasian Antarctic Expedition of 1911–14. The group's leader, Douglas Mawson, has published a popular account of the experience, aptly-titled the *Home of the Blizzard* (1915), in which he describes the nearly ceaseless periods of intense katabatic winds. The mean wind for the roughly two-year period was 19.3 m s^{-1}, far surpassing all previous surface wind records. A French expedition to nearby Port Martin in 1950 encountered similar intense katabatic winds. A concise summary article by Loewe (1974) concluded that the Cape Denison katabatic wind problem remained as yet unsolved.

The Cape Denison-Port Martin region is downslope of a zone of streamline confluence as shown in Fig. 6. Such a cold air concentration implies an abnormally large supply pool. One limitation to the strength and persistence of katabatic winds at the coast is the supply of cold air available upslope in the interior of the continent. Lettau and Schwerdtfeger (1967) note that even moderate katabatic winds rapidly exhaust an existing pool of cooled air "as similarly, the bursting of a dam drains a water reservoir." Thus, it appears the convergence of drainage currents in the interior can be extremely important in determining the nature of the katabatic wind regime. A nearly inexhaustible supply of cold air is available upslope of Cape Denison and Port Martin; the extreme strength and persistence of the katabatic winds at these coastal stations may result from the enhanced cold-air reserves (Parish, 1981).

Similar, though not as intense, katabatic wind conditions are found along the coast of Terra Nova Bay. The strong winds were first recorded by Scott's Northern Party in 1912. The persistent winds act to agitate the surface waters, thereby preventing ice formation in Terra Nova Bay. The streamline analysis in Fig. 6 shows a strong confluence upslope of Terra Nova Bay. Again, a large cold air reservoir would seem to be available from which katabatic winds may feed.

A third area of streamline confluence is located along the eastern side of the central plateau, extending toward the coastal station Mirny. Since much of the convergence is situated somewhat deeper into the interior than the previously discussed examples, it is not apparent what role, if any, this enhanced supply plays on the coastal wind regime downslope. However, the mean wind direction at the katabatic-prone coastal station Mirny is somewhat anomalous and deserves comment. According to Mather and Miller (1967), the ice contour lines upslope of Mirny trend east–west. Yet, the mean yearly resultant wind direction over the 15-year period 1957–73 is 127°, some 53° from the fall line. During the winter months (April–September) when the katabatic component should be most pronounced, the resultant wind at Mirny is from 131°. This is in con-

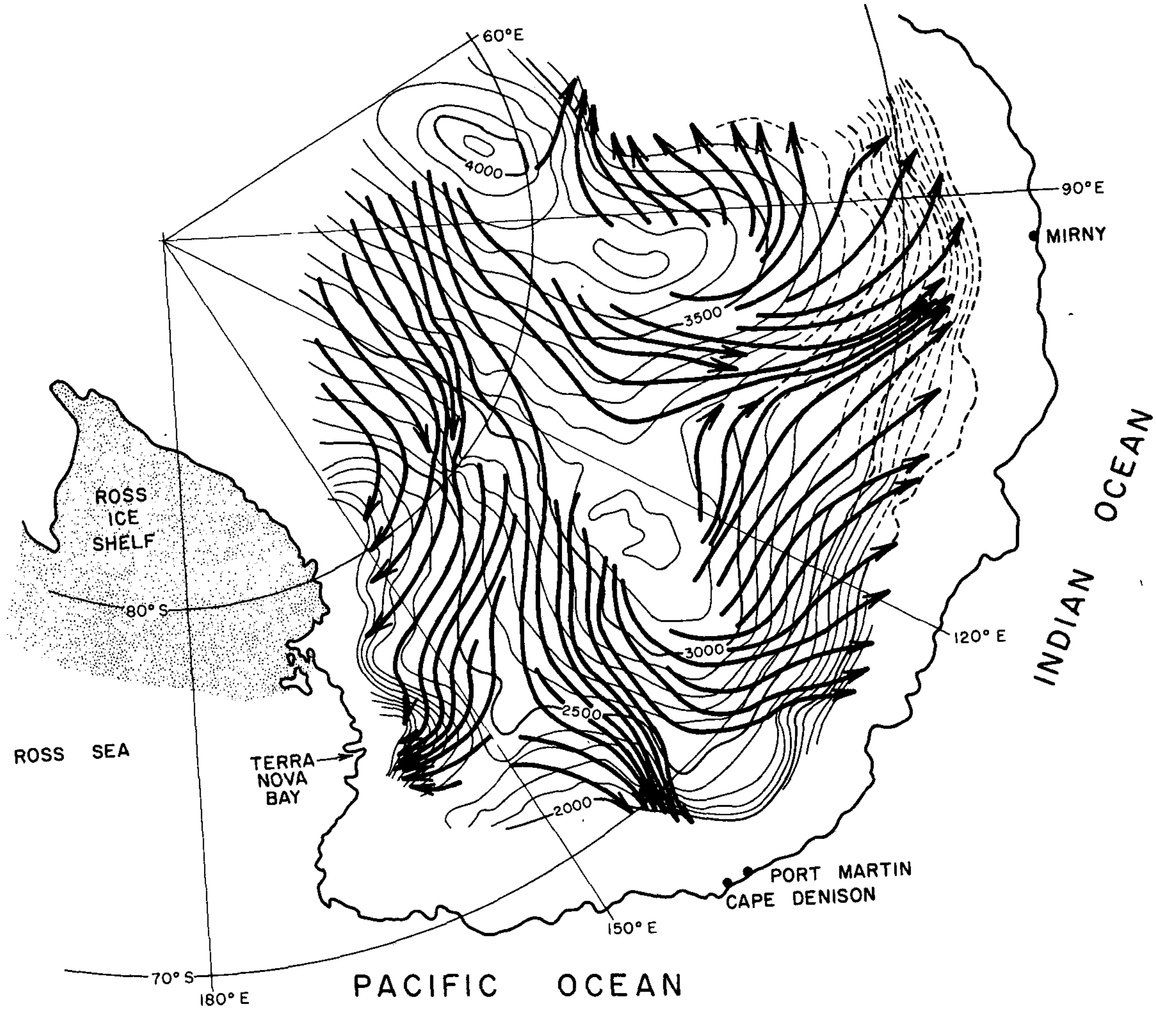

FIG. 6. Time-average winter flow pattern over the surface of the Antarctic interior based on results of wind calculations of the equation system discussed in text.

trast with most data from coastal stations haunted by katabatic spells and with nearly all katabatic wind studies which suggest the wind should be directed nearly downslope (for example, Mather and Miller, 1967).

It can be argued that the synoptic pressure gradient may have a significant influence on the resultant wind at Mirny. At present, however, the quantitative importance of such large-scale forcing is not known with any certainty. Fig. 6 shows that the cold air convergence channel in the interior of the continent is located approximately upwind of Mirny. This enhanced supply of negatively-buoyant air may also influence the mean direction of the drainage flow. In fact, daily observations at Mirny during IGY winter months show extended periods of strong winds from the direction of the interior confluence zone. Until further field experiments are conducted at Mirny, the roles played by the synoptic wind component and katabatic wind component are likely to remain uncertain.

7. Conclusion

Topography controls the surface wind over the Antarctic interior. The high directional wind constancy values and mean yearly resultant wind directions at interior stations offer indisputable evidence. By use of simple diagnostic equations of motion and available information on terrain slope and the temperature inversion strength over the continent, it is possible to estimate the mean surface winds over the gentle slopes in the interior. A reasonable picture of the time-averaged winter flow regime over much of East Antarctica can be generated.

The pattern of streamlines shows regions of converging drainage currents, implying abnormally large supply pools of cold air available to downslope stretches. It is proposed that such conditions enable katabatic winds to become much stronger and more persistent than normally found. Observations have shown anomalously intense katabatic winds are found at the Cape Denison-Port Martin and Terra Nova Bay areas, each located downslope of cold air convergence zones in the interior.

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