An Extraordinary Katabatic Wind Regime at Terra Nova Bay, Antarctica*

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ABSTRACT

Three years of automatic weather station observations for the months of February to April show that intense katabatic winds persistently blow across the western shore of Terra Nova Bay. The data demonstrate that the anomalously strong katabatic winds of Adelie Land are not unique, and thus strongly support the proposition that most of the cold boundary layer air from the ice sheet crosses the coastline in a small number of narrow zones. Furthermore the observations prove that katabatic winds can routinely blow for substantial distances across flat terrain in marked contrast to the abrupt dissipation previously monitored just offshore from East Antarctica. Winter wind conditions onset suddenly in mid-February and are characterized by negligible directional variations and by speeds mostly ranging between 10 and 30 m s^{-1}.

Katabatic winds at Terra Nova Bay both affect and are affected by the regional atmospheric circulation. This katabatic airflow is a time-averaged source of cold boundary layer air for the western Ross Sea. Maximum thermal contrast with the regional temperature field occurs between January and June. Temperature observations suggest that the katabatic winds at Inexpressible Island are primarily of the boratype throughout the year. Strong southerly geostrophic winds over the western Ross Sea appear to suppress the katabatic outflow during winter while weak zonal pressure gradients coincide with intensified katabatic drainage. This relationship is suggested to arise because clouds modulate the radiative production of cold surface air over the interior of the ice sheet.

1. Introduction

Recent work has produced a new description of the surface air drainage over the sloping ice fields of Antarctica. Near-surface winds under the influence of gravity, friction and the Earth's rotation do not blow radially and uniformly away from the highest parts of the ice sheet, but rather converge into several regions about the continent (Parish and Bromwich 1987). These interior confluence regions provide large reservoirs of cold, negatively buoyant air to sustain strong, persistent katabatic winds over the steep coastal ice slopes. Simulations of katabatic confluence zones with a three-dimensional primitive equation model (Parish 1984) have shown that the depth of the boundary layer increases and wind speed is substantially enhanced along the confluence axis. It has been proposed that these features are responsible for the majority of the boundary layer transport of air across the Antarctic coastline (Parish and Bromwich 1986).

The annual mean surface wind speed at the East Antarctic coastal sites of Cape Denison (142.7°E) and Port Martin (141.3°E) is 18.5 m s^{-1}, the highest wind speed near sea level anywhere on Earth (Loewe 1974). Loewe's examination of eight mechanisms proposed to explain the strength of these katabatic winds lead to the conclusion that this outstanding 60-year old problem in Antarctic meteorology was unsolved as of 1974. Recent work on two of these mechanisms, the temperature gradient along the snow surface and the airflow acceleration induced by blowing snow, has been conducted by Kodama and Wendler (1986) and Kodama et al. (1985). Parish (1981) proposed that the primary cause of persistent strong katabatic winds between 140° and 144°E is the anomalously large supply of cold air set up by converging air currents in the continental interior. Schwerdtfeger (1984) has called the resulting katabatic airstream "extraordinary" to underscore the extreme nature of the winds.

Figure 2 of Parish and Bromwich (1987) shows that a convergence zone of drainage streamlines is also present on the plateau to the west of Terra Nova Bay, and thus intense katabatic winds should be present over downwind coastal areas. Until recently, the only records of katabatic winds at Terra Nova Bay were the writings of Raymond E. Priestley, who, along with five other members of Scott's Northern Party, was stranded and lived in a snow cave on Inexpressible Island (Fig. 1) during the winter of 1912. Examination of these noninstrumental data (Bromwich and Kurtz 1982, 1984) revealed that the katabatic winds are of similar strength and persistence to those at Cape Denison and Port Martin. These winds are responsible for the formation and maintenance of a large polynya (open water area surrounded by ice) in the bay.

* Contribution 640 of Byrd Polar Research Center.

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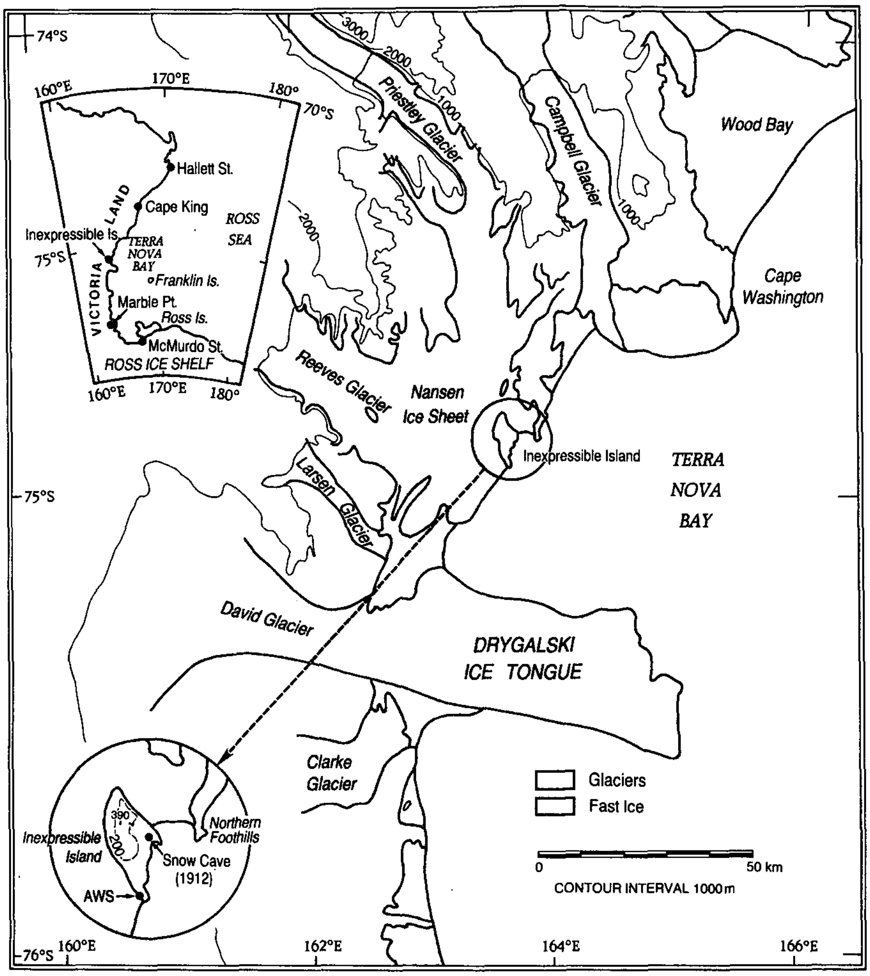

FIG. 1. Location map with local inset for Inexpressible Island and regional inset for western Ross Sea.

This note presents an analysis of automatic weather station (AWS) observations of this intense katabatic airflow collected between 1984 and 1987. Through a combination of electronic, logistic and mechanical difficulties, reliable wind data are only available for the months of February to April. A recurring problem has been the inability of freely rotating anemometers to withstand the intense mechanical stress exerted by the turbulent, high momentum airstream. Section 2 describes the wind conditions at Inexpressible Island, and section 3 relates the Terra Nova Bay environment to regional temperature and pressure gradient fields.

2. Katabatic winds at Inexpressible Island

a. Data

An AWS was set up on the southern tip of Inexpressible Island on 4 February 1984 (Stearns 1986), and has operated intermittently since then. Air temperature and vector wind are measured at 3 m above the surface, and atmospheric pressure at 1 m height. The platform broadcasts a data message every 200 s, with an update occurring every 10 minutes (Stearns and Wendler 1988). NOAA polar orbiting meteorological satellites record the transmissions when the satellites are above the AWS's horizon. With two satellites in orbit, a nearly continuous data stream, with a 10-minute sampling interval, can often be obtained. Gaps of several hours duration intermittently appear in the time series.

Data tapes containing all AWS transmissions were obtained from Professor Stearns at the University of Wisconsin–Madison. Datasets intended to approximate standard synoptic observations were derived at three hour intervals (0000 UTC, 0300 UTC, etc.). Transmissions closest in time to the specified hour were sought within ±2 hour window; generally, less than 3% of the observations differed by more than one hour from the nominal time. Instantaneous temperature and pressure readings from the selected transmission were utilized as the three-hourly values. Each selected transmission contained five instantaneous vector winds covering the previous 40 minutes. These readings were vector-averaged to yield a representative wind direction and wind speed.

The Inexpressible Island AWS collected observations of all variables from 4 February to 19 April in 1984, and pressure and temperature readings from 29 January 1985 until 26 June 1987. The wind speed sensor operated from 29 January to 10 May in 1985 when it started to malfunction; after this, spurious light winds and extended calm periods were recorded. Highly questionable speed readings were frequently noted until mid-September 1985 when the sensor failed completely. In contrast to Sievers et al. (1986) only wind data from 29 January to 9 May in 1985 are considered to be reliable. The wind record resumed on 15 February 1987 and lasted until 29 April 1987 when the propeller of the Belfort anemometer probably blew off in winds of around 43 m s^{-1}.

b. Gross wind conditions

Table 1 gives a monthly summary of all available surface wind observations. Average wind speeds are much higher than those at "ordinary" coastal locations influenced by katabatic winds (Streten 1968), and comparable to those recorded at Port Martin (Parish 1982). Strongest speeds are similar to those found at other East Antarctic coastal sites (Schwerdtfeger 1970), regardless of whether or not there is pronounced katabatic influence. Directional constancy is defined as the ratio of the magnitude of the vector average wind to the mean speed. Values near 1 mean that surface winds are almost always katabatic and blow from the direction of Reeves Glacier; only at Cape Denison are directional constancies this high (Parish 1982).

The interannual variability appears to be small. In 1987 wind speeds were measured at 1.5 m rather than the 3 m height used previously. The slightly lower 1987 speeds are likely to arise primarily because of the lower measurement height. Assuming a logarithmic wind speed profile with a roughness length of 0.1 mm (Budd et al. 1966) shows that the height difference accounts for a 7% speed decrease, or about 64% of the observed change between 1987 and the other years. Estimated wind speeds at 3 m are also given for 1987 and are used to construct the 3-year average. The AWS results are very similar to the conditions monitored in 1912,

TABLE 1. Monthly surface winds measured by AWS at the southern end of Inexpressible Island.

Month(s)	Resultant wind (m s^{-1})		Mean speed (m s^{-1})	Directional constancy	Maximum sustained speed (m s^{-1})	Maximum gust (m s^{-1})
1984						
4–29 Feb	295°	13.7	14.1	0.97	30	36
Mar	295°	18.1	18.3	0.99	36	41
1–19 Apr	304°	16.6	17.0	0.98	31	35
1985						
Feb	300°	15.9	16.9	0.94	40	45
Mar	304°	18.5	18.7	0.99	33	40
Apr†	301°	17.4	17.5	0.99	38	43
*1987**						
15–28 Feb	285°	13.5 (14.5)	14.0 (15.0)	0.96	29 (31)	34
Mar	289°	15.9 (17.0)	16.3 (17.5)	0.98	33 (35)	40
1–29 Apr	292°	15.6 (16.7)	15.6 (16.7)	0.99	35 (38)	43
*1984–87***						
Feb	294°	14.6	15.3	0.95	40	45
Mar	296°	17.8	18.2	0.98	36	41
Apr	299°	16.8	17.1	0.98	38	43
1912@						
Feb–Sep	293°	15.0	~16.7	~0.9	~35	?

† Corrected for 18° clockwise wind direction shift detected in mid April 1985. Probably due to metal fatigue of the AWS tower, which was found lying on the ground when the site was again visited in February 1987.

* Values in brackets are estimated speeds at 3 m height, which are taken to be 1.07 times the measured speeds at 1.5 m.

** Based upon estimated 3 m wind speeds for 1987.

@ Derived from noninstrumental historical observations by Bromwich and Kurtz (1982, 1984). These data describe the topographically undisturbed airflow near Inexpressible Island.

and indicate that this site is exposed to intense, unidirectional katabatic winds each and every year.

Observations of strong, sustained katabatic winds at Inexpressible Island prove that such airstreams can blow *at least* 34 km beyond the slope break. This contrasts with the abrupt katabatic dissipation (within 10–20 km) observed immediately beyond the East Antarctic coastal slopes near Mirny (Tauber 1960) and Mawson (Weller 1969). Kurtz and Bromwich (1985) present evidence from thermal infrared satellite images that katabatic airstreams can propagate for distances of 100 km or more across the flat terrain of the Ross Ice Shelf. This occurs even though the downslope buoyancy force no longer acts on the airflow and surface friction dissipates its momentum.

Bromwich (1985) studied the interaction between the katabatic airstream and Inexpressible Island to determine whether the island significantly affects the flow monitored by the AWS. The main mass of the island is oriented for about 7.5 km almost normal to the direction of the approaching wind. The obstacle height exceeds 150 m over this distance and attains a maximum value of ~350 m. The AWS is located about 3 km south of the southern end of the obstruction. Based upon the 60° difference between the predominant winter wind direction observed by the AWS (300°) and at the snow cave site in 1912 (240°), it was proposed that the greater winter stability may result in the air being deflected southward around the main bulk of Inexpressible Island, possibly leading to unrepresentative measurements of the approaching katabatic airstream.

For the following reasons it is now believed that this conjecture is incorrect. If it is assumed that the katabatic airflow generates a polynya in Terra Nova Bay by continuing to advect newly formed ice offshore (Bromwich and Kurtz 1984), then the satellite observed configuration of the polynya can be used as a proxy indicator of the offshore location of the airstream. Figure 2 summarizes the polynya configurations seen on DMSP (Defense Meteorological Satellite Program) thermal infrared satellite images during April 1984; images were available once a day and had a spatial resolution of 2.7 km. The bay was divided into grid squares of ~60 km^2, and whenever a polynya was observed, it was noted whether or not each grid square lay partly or completely (≥50%) within the polynya. The 90% isopleth means that 90% or more of the time a polynya was observed, part or all of it occupied the region enclosed between the coastline and isopleth. A similar pattern was obtained for all months between April and October in 1984 and 1985. It can be seen that the AWS site is just to the north of the most frequent location for the polynya. This result is interpreted to mean that during winter the core of the katabatic jet passes to the south of Inexpressible Island on most occasions, and that the elevated part of the island is on the northern fringes of the airstream. It seems that the

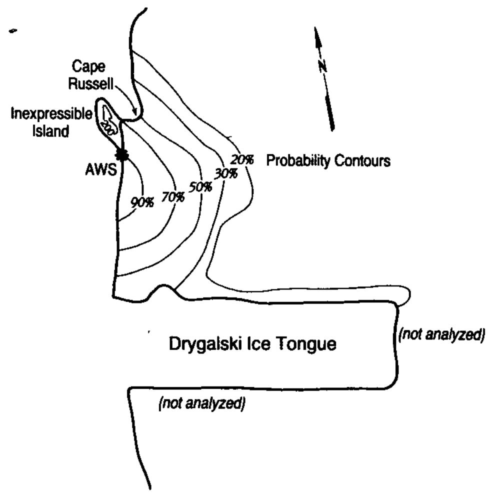

FIG. 2. Domain diagram of the Terra Nova Bay polynya for April 1984. See text for explanation of probability isopleths.

deflection of stably stratified air by Inexpressible Island may have only a small effect upon AWS wind measurements.

c. Seasonal variations

AWS data for February provide some idea of wind conditions during late summer. A pronounced diurnal speed cycle is present with a maximum at 0600 LT and a minimum at 1900 LT. The highest wind speeds coincide with the lowest air temperatures, but the temperature maximum precedes the speed minimum by 4 hours. Average daily ranges are 3.4 m s^{-1} and 3.6°C. Similar wind conditions were found at Cape Denison and Port Martin (Mather and Miller 1967).

Priestley (1962, p. 135) noted that in mid-February 1912 "a gale sprang up that lasted the entire winter." He continued "we did not have twenty-four hours' consecutive calm from then on until September 30." AWS wind data presented in Fig. 3 suggest that this abrupt winter onset takes place each year. February 1987 results are omitted because no observations were collected during the first half of the month. Slight differences between 1984 and 1985 are evident with a slower, more systematic speed increase in 1985, although winter wind conditions are established by 15 February in both years. This abrupt commencement is probably caused by the rapid radiatively forced cooling of surface air over the polar plateau (Schwerdtfeger 1984, pp. 26–27) which quickly establishes the boundary layer stratification required for sustained cold air drainage.

Once winter wind conditions are established (15 February and later) speeds are high and fairly consistent. Speeds are continuously less than 10 m s^{-1} or continuously stronger than 29 m s^{-1} for short intervals, generally 12 hours or less. During one sequence in 1984

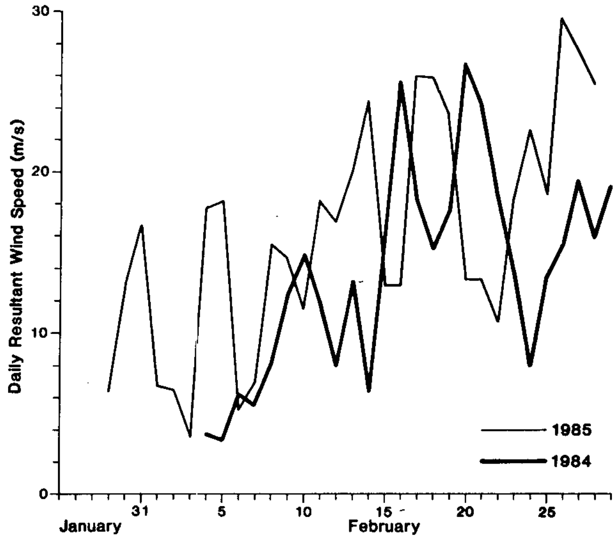

FIG. 3. Onset of winter wind conditions at Inexpressible Island.

the speed was continuously stronger than 9 m s^{-1} for 17 consecutive days!

3. Regional context

a. Air temperature

The average monthly surface air temperatures measured at Inexpressible Island are given in Table 2. All available AWS data between 1984 and 1987 have been used. Also listed is the temperature contrast between Inexpressible Island and McMurdo Station on Ross Island (column A). Monthly temperatures given for McMurdo in the *Antarctic Journal of the U.S.* (National Science Foundation, 1984, 1985, 1986, 1987) have been subtracted from Inexpressible Island AWS values for the same months; when McMurdo values were unavailable they were estimated from AWS observations at Marble Point. Inexpressible Island is colder than McMurdo in 6 of 12 months. On a seasonal basis, Inexpressible Island is colder than McMurdo during winter (March to October) by 1.1°C but 0.4°C warmer in summer (November to February). This amounts to a winter reversal of the normal poleward decrease of air temperature at sea level. McMurdo Station is about 300 km closer to the South Pole than Terra Nova Bay.

The climatological temperature contrast (column B) between McMurdo and the vicinity of Terra Nova Bay has been estimated as half the climatological temperature difference between McMurdo and Hallett stations (Schwerdtfeger 1970). Terra Nova Bay is half way between these sites. Addition of columns A and B yields an estimate of the climatological temperature difference between Inexpressible Island (representing the katabatic airstream) and the adjacent regional temperature environment.

Column C demonstrates that the katabatic airstream shows up as a time-averaged source of cold air in relation to the regional temperature field. The temperature contrast is 1.6°C for the year as a whole and 2.0°C during winter, but it decreases to 0.9°C in summer. The katabatic airflow is thermally well-defined between January and June. Maximum thermal contrast of 5.9°C occurs in April; it was in large part for this reason that Bromwich (1986) was able for a mid-April

TABLE 2. Surface air temperatures (°C) at Inexpressible Island in relation to the regional temperature field.

Month	Average monthly air temperature at Inexpressible Island (I.I.)	Number of months of data	A Temperature contrast (I.I.- McMurdo)	B Climatological temperature contrast McMurdo vs Terra Nova Bay vicinity	C Estimate of climatological contrast between I.I. and regional temperature field (A + B)
Jan	−1.7	2	−0.1	−1.2	−1.3
Feb	−10.6	4	+0.7	−2.6	−1.9
Mar	−18.1	4	−1.3	−4.2	−5.5
Apr	−23.5	4	−4.2	−1.7	−5.9
May	−24.0	3	−3.5	−0.7	−4.2
Jun	−24.0	3	−1.8	−0.2	−2.0
Jul	−26.6	2	+2.2	+0.5	+2.7
Aug	−26.2	2	+1.5	−0.6	+0.9
Sep	−27.1	2	+0.8	+0.2	+1.0
Oct	−20.0	2	−2.1	−0.8	−2.9
Nov	−10.4	2	+0.1	−0.4	−0.3
Dec	−3.0	2	+1.1	−1.1	0.0
Annual	−18.0		−0.6	−1.0	−1.6
Mar–Oct	−23.7		−1.1	−0.9	−2.0
Nov–Feb	−6.3		+0.4	−1.3	−0.9

1984 case to trace the Reeves Glacier airstream over 350 km down onto the Ross Ice Shelf.

The relative coldness of the katabatic winds at Inexpressible Island suggests that they are primarily of the boratype (Bromwich and Kurtz 1984; Stearns and Wendler 1988). Under such circumstances the air that arrives at the bottom of the slope is negatively buoyant in relation to the ambient stratification, and this descent does not require any synoptic support (Schwerdtfeger 1970).

During July to September, the average temperature at Inexpressible Island is 1.5°C warmer than the regional temperature field. This could suggest the frequent presence of foehn-type katabatic winds (Stearns and Wendler 1988). However, the surface temperature difference between the katabatic jet and the surroundings need not indicate that the entire katabatic layer is positively buoyant. Aircraft and satellite observations, which will be reported in a subsequent paper, showed that during early November 1987, comparatively warm surface air temperatures over the Nansen Ice Sheet coexisted with a strong katabatic airstream from Reeves Glacier, which overall was denser than the environment. This is most probably a consequence of strong, vertical mixing within the katabatic layer. It is concluded that the results in Table 2 are not inconsistent with the year-round presence of boratype katabatic winds.

b. Pressure gradient influence

The relationship between katabatic winds and the synoptic scale pressure field has been studied extensively, but with mixed results. For example, Ball (1960) concluded that eastward passage of a transient maritime cyclone along the East Antarctic coast is associated with reduced katabatic winds ahead of the storm and intensified winds behind it. Some observational evidence qualitatively supports this theoretical result (Streten 1968). However, Loewe (1974) found that at Port Martin winds tend to be stronger with falling (implying cyclonic approach) rather than rising pressure, with the strongest winds occurring with the largest average pressure falls. Such conflicting findings may be attributable to large uncertainties in the spatial and temporal characteristics of the synoptic pressure gradient force.

To test whether the synoptic scale pressure field modulates the katabatic outflow at Terra Nova Bay, winter katabatic wind speeds every three hours were compared with simultaneous values of the regional pressure gradient. This gradient was approximated from sea level pressure readings at Marble Point, Inexpressible Island and Franklin Island (see Fig. 1). Thus, the gradient is actually evaluated at the center of the triangle formed by the three stations, a point out over the Ross Sea about 120 km to the SSE of Inexpressible Island. Prior to 1987 it was not possible to construct a regional pressure gradient centered on Terra Nova Bay. In January 1987 the Italian Antarctic Expedition set up an AWS at Cape King (Fig. 1) about 180 km to the NNE of Inexpressible Island. The 1987 set of pressure readings from Cape King was not available at the time of writing, but will be used in the future to refine the analyses presented here.

Only the zonal component of pressure gradient was found to be consistently and significantly correlated with the katabatic wind speed. Low katabatic speeds were associated with strong southerly geostrophic winds, and high speeds accompanied weak zonal pressure gradients (Fig. 4). Linear regression of katabatic speed against zonal pressure gradient produced correlation coefficients of 0.36, 0.42, and 0.63 for 15 February to 19 April in 1984, 1985, and 1987, respectively. This means that between 13% and 40% of the three-hourly katabatic wind speed variance was associated with pressure gradient changes.

The meridional pressure gradient components displayed a variable linkage with the katabatic speeds at Inexpressible Island. The variables were uncorrelated in 1984 ($r = 0.02$), but exhibited significant negative correlations for 1985 and 1987 ($r = -0.33$ and -0.43, respectively). For the latter periods strong westerly geostrophic winds and strong katabatic winds coincided, while weak meridional gradients were associated with light katabatic winds.

There are at least two possible explanations for the consistent association between zonal pressure gradients and katabatic winds at Inexpressible Island. Schwerdtfeger (1984, p. 109) suggests that strong pressure gradients over the ocean, which are oriented normal to the coast, promote intense mixing of milder maritime air and cold continental air, leading to rapid momentum dissipation of katabatic airstreams. Alternatively, strong zonal gradients normal to the Victoria Land coast between Inexpressible Island and Marble Point could tend to be linked with the close approach of cyclonic centers. Extension of the associated cloud shields over the polar plateau inland of Terra Nova Bay would tend to disrupt the winter-time production of cold air by substantially reducing the net long wave radiation loss from the surface; as a result the discharge rate of cold air across the coastline will probably decrease. If slack gradient conditions are linked with clear skies over the plateau, katabatic outflow could be enhanced.

4. Summary

Persistent technical problems have confined reliable katabatic wind observations at Inexpressible Island to the months of February to April. Vigorous efforts have been undertaken by Professor Stearns to resolve these difficulties, and substantial progress toward their solution has been achieved. At the time this report was prepared only the historical records from Scott's Northern Party were available to describe wind conditions between May and September.

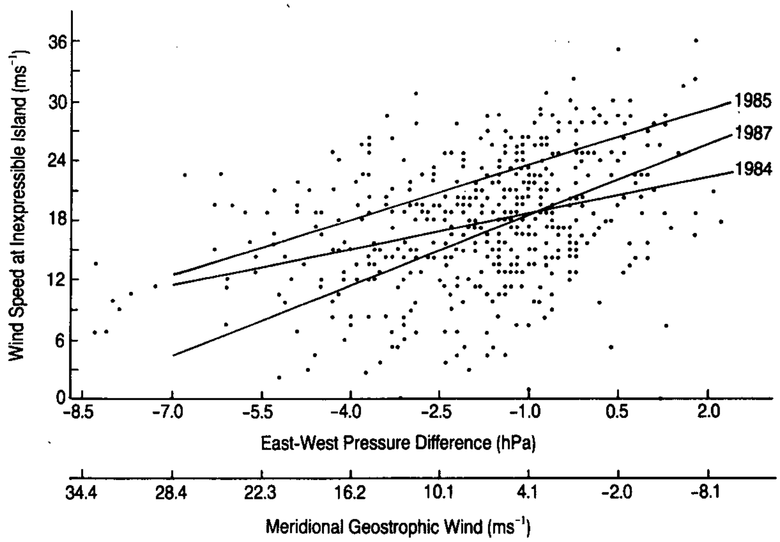

FIG. 4. Synoptic modulation of the katabatic airflow. Data for each year span the interval 15 February to 19 April. Dots represent individual three-hourly observations for 1984. Straight lines are a linear least squares fit to the data for each year.

Around mid-February each year the intense winter wind regime onsets abruptly, and then is maintained with little interannual variability at monthly time scales. Wind speeds are very similar to those monitored at Port Martin, while directional constancies more closely mirror Cape Denison conditions. Whereas these two Adelie Land sites are located at the foot of the coastal ice slopes, Inexpressible Island lies 34 km beyond the slope break. Observations of intense winds at the island prove that katabatic airstreams can propagate for substantial distances across flat terrain, in contrast to the abrupt dissipation typically observed offshore from East Antarctica. The katabatic wind records analyzed here provide strong confirmation for the Antarctic surface windfield diagnosis of Parish and Bromwich (1987).

Katabatic winds from Terra Nova Bay are a time-averaged source of cold boundary layer air for the western Ross Sea. Thermal contrast with the ambient temperature field is most marked between January and June. Bromwich (1987) has shown that these cold winds played a major role in forming and maintaining a mesoscale storm complex that produced adverse weather conditions at McMurdo Station for two days in February 1984. Katabatic winds at Inexpressible Island appear to be of the boratype throughout the year.

The pressure field over the western Ross Sea regulates the katabatic wind strength at Inexpressible Island. Strong southerly geostrophic winds are associated with weak katabatic winds, and slack pressure gradients accompany intensified katabatic airflow. It is suggested that this winter katabatic modulation could result from the influence of clouds on the radiative production of cold air over the plateau.

A comprehensive study of the kinematics and dynamics of the Reeves Glacier katabatic airstream is being conducted in association with the Italian Antarctic Expedition. When data from the array of eight AWSs in and around Terra Nova Bay become available, many of the above findings will be examined in much greater depth.

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