Satellite Analyses of Antarctic Katabatic Wind Behavior*

Abstract

Prominent warm signatures of strong, negatively buoyant, katabatic airstreams are present at thermal infrared wavelengths as a result of intense vertical mixing and drift-snow transport within stable boundary layers. These tracers are used to illustrate several aspects of the behavior of katabatic winds in the Ross Sea sector of the Antarctic. The satellite features are compared with surface-based observations whenever possible. Converging surface-wind signatures upslope from Terra Nova Bay are shown to closely follow the observed time-averaged streamlines of drainage airflow. The satellite-observed core of the katabatic airstream descends to sea level via a direct route, but complex three-dimensional trajectories are manifested in marginal regions. Katabatic winds propagating horizontally for hundreds of kilometers over the southwestern Ross Sea do not exhibit the expected influence of the Coriolis force. Katabatic signatures are shown to be climatological features over the Ross Ice Shelf which closely follow surface wind measurements. An approximate proportionality appears to exist between average signature size over the shelf and the magnitude of katabatic mass transport from the plateau.

1. Introduction

The continental-scale surface-wind regime of Antarctica plays a key role in determining the behavior of the atmosphere and ocean in high southern latitudes (e.g., Polar Research Board 1984). The vast size, remoteness, and inhospitable climate of the Antarctic continent coupled with the complexity of the governing physical processes have hindered studies of this phenomenon. Recent advances have come through numerical simulations (Parish and Waight 1987; Parish and Bromwich 1987) and through analyses of data collected by automatic weather stations (Kodama and Wendler 1986; van Meurs and Allison 1986) and specially constructed towers (Ohata et al. 1985).

This paper is intended to demonstrate that imagery collected by polar orbiting meteorological satellites can also be used to analyze the dynamics of polar surface winds. Defense Meteorological Satellite Program (DMSP) images with a spatial resolution of 2.7 km are often available several times a day, and are intermittently complemented by higher resolution National Oceanic and Atmospheric Administration (NOAA) AVHRR (Advanced Very High Resolution Radiometer) data. Discussion is primarily restricted to thermal infrared (TIR) wavelengths (~11 μm) which, for clear skies, display comparatively warm signatures of surface winds as a result of vertical mixing and suspended drift snow. Images often reveal strong spatial variability of surface wind fields, and place observations from widely spaced automatic weather station (AWS) sites in the proper spatial context. In addition, data from logistically inaccessible areas are obtained. The TIR imagery is a valuable tool for the study of katabatic winds because the attendant subidence minimizes obscuration of the surface by dissipating low clouds and fogs.

In the following sections, satellite-observed characteristics of surface winds over both sloping and horizontal ice surfaces are examined. Emphasis is placed upon constraining satellite signature interpretations by in situ observations. A detailed discussion of the physical basis for the warm katabatic signatures is delayed until section 4, which deals with katabatic airflow over the Ross Ice Shelf. For that area, the katabatic signatures are prominent climatological features, and sufficient data are available for a scaling calculation.

2. Winds over sloping ice fields

Satellite imagery has hardly been applied to study the patterns and dynamics of surface airflow over Antarctica. Zhdanov (1977) investigated sudden, localized occurrences of sharply outlined cloud-like features over East Antarctica on visual satellite photographs taken during 1970. By incorporating surface, rawinsonde, and aerial observations, he concluded that these signatures of blowing snow events which are generated by strong, southerly tropospheric winds. Four blowing snow categories were defined which were linked to specific synoptic situations. Zhdanov noted that these signatures could be used to infer surface wind conditions over data-sparse areas, such as the near-coastal ocean regions to the north of the continent.

Kurtz and Bromwich (1983) reported a recurring warm signature on winter TIR satellite images of the plateau to the west of Terra Nova Bay. This signature appears to closely follow the simulated streamlines of surface air drainage (e.g., Parish and Bromwich...
1987). Such regions of converging airstreams experience enhanced surface wind speeds (Parish 1984). Kurtz and Bromwich (1985) presented a sequence of TIR images over 9 days which illustrated the stability of this feature. The warm region contained numerous elongated lineations, suggesting transport of blowing or drifting snow by strong surface winds. Another contributing factor is that strong surface winds thoroughly mix the near-surface layer causing the temperature of the emitting surface to be substantially higher than that in quiescent adjacent areas (Marvill and Jayawerra 1975). The clear skies which allow the surface to be clearly observed on such occasions also favor the development of strong radiation inversions in calm localities.

Figure 1 supports the above explanation. The heavy continuous lines are streamlines of time-averaged air motion over the marginal ice slopes inland from Terra Nova Bay. This analysis (Bromwich et al. 1988) is based upon a detailed airborne photographic survey of sastrugi orientations which was taken on 6 November 1986. Sastrugi are wind-generated features at the snow surface that are parallel to the prevailing wind direction (e.g., Bromwich and Kurtz 1984). The dashed lines are trajectories of surface air motion constructed from a NOAA AVHRR LAC (Local Area Coverage) TIR image for 1706 UTC 18 June 1983 (see section 4 also). As can be expected, there are some differences between the time-averaged (sastrugi-derived) and instantaneous (satellite-derived) motion fields, but the overall inland patterns are very similar.

In the area of complicated coastal topography the satellite image describes how katabatic air reaches sea level. The primary route is down Reeves Glacier, across Nansen Ice Sheet, and out into Terra Nova Bay. Strong katabatic winds were probably blowing across Inexpressible Island and generating the polynya (area of open water) adjacent to the shoreline, as described by Bromwich and Kurtz (1984). However, no wind data are available to confirm this supposition. AWS observations collected since 1984 demonstrate that an intense winter katabatic wind regime is present at Inexpressible Island with speeds averaging 17 m s⁻¹ and episodes of 30 m s⁻¹ occurring at regular intervals (Bromwich 1989a).

Katabatic drainage down the David, O’Kane, and Priestley glaciers is clearly resolved. The former two airflows appear to dissipate just beyond and within the respective glacier valleys. The Priestley Glacier wind leaves the confines of the valley, crosses the Northern Foothills and merges with the airstream from Reeves Glacier as it transits Terra Nova Bay. Such a trajectory requires complex, three dimensional motions to cross such rugged and elevated terrain. Observations during February 1988 from an Italian AWS above the sharp bend in Priestley Glacier show that a strong katabatic (i.e., surface-based) wind blows down this valley most of the time (Bromwich and Parish 1988).

Many of the above features, although clearly present on hard copy TIR images, are difficult to reproduce in journal articles because they are represented by intermediate gray shades. This problem can be solved by enhancing digital images to emphasize features of interest, and by assigning contrasting colors to represent ranges of brightness temperatures. Figure 2 is a false-color, nonlinearly enhanced TIR image produced on the MciDAS facility (Suomi et al. 1983) at the University of Wisconsin–Madison. Processing was designed to bring out the airflow pattern over the polar plateau as well as the details of airflow through the mountains. The plateau signature is particularly difficult to extract because the region’s emissions are dominated by the decrease of temperature associated with the increase in ice surface elevation. This gives rise to isotherm patterns that are parallel to the terrain contours, whereas the signature of interest is oriented almost down the terrain slope. Enhancement table 94C obtained from Satellite Data Services Division of NOAA was used as the basis for preparing figure 2.

The TIR brightness temperature variations in figure 2 can be interpreted in terms of airflow behavior.
Fig. 2. Digitally processed NOAA TIR image for 1227 UTC 29 August 1986 showing surface airflow converging into the Reeves and David glaciers just west of Terra Nova Bay. Latitude in degrees south and longitude in degrees east are given by the negative whole numbers. Black body temperature scale at bottom.

Fig. 4. Same as Fig. 2, but for 1249 UTC 27 August 1986. Katabatic airflow from Terra Nova Bay blowing far out into the Ross Sea is highlighted.
Unfortunately, the anemometer on the Inexpressible Island AWS was not functional at this time. The signature of surface winds converging toward Reeves Glacier is shown by lineations in the northern half of the purple area over the plateau (e.g., around 75°S, 157°E). After the air starts to blow down Reeves Glacier valley (e.g., 74.7°S, 161.0°E), there is ~14°C warming, probably in conjunction with the adiabatic descent of air from 1400 to ~30 m elevation. The region of strong katabatic winds blowing across Nansen Ice Sheet is shown by the red area near 75.0°S, 163.0°E. Horizontal airflow over the sheet is characterized by fairly uniform temperatures along the trajectory (west to east). The north-south temperature gradient across the airstream may be due to stronger winds on the north side of Nansen Ice Sheet, which make the emitting snow surface warmer as a result of more vigorous vertical mixing.

Plateau air converging into David Glacier is shown by the green-yellow signature near 75.3°S, 160.0°E. The air warms ~10°C as it descends ~1000 m from the plateau to the Drygalski Ice Tongue (~75.5°S, 162.6°E). It appears from the 12°C temperature fall (light orange to dark purple) along the tongue that the airstream dissipates within ~28 km. The very cold area (purple-white at 75.3°S, 162.6°E) may be a calm zone between the katabatic jets from Reeves and David glaciers.

The above discussion indicates that TIR brightness temperature variations are consistent with those expected for surface air temperature. Calculations show that thermal radiation is hardly affected by propagation through a clear, cold polar atmosphere (Tanaka et al. 1985), and that the snow surface emissivity is very close to 1 for viewing angles within 30° of the vertical (Dozier and Warren 1982). As a result, the difference between the satellite-observed brightness temperature and the snow surface temperature should be less than 1°C for clear sky conditions during winter. Comparison between the TIR temperature given by figure 2 for the southern end of Inexpressible Island with the simultaneous AWS air temperature (Sievers et al. 1987) demonstrates that the former is ~5°C colder. It is highly unlikely that this difference could be explained as a result of the contrast between air temperature at 3 m height and the snow surface temperature; in the strong wind conditions inferred above this difference should only be a few tenths of a degree. Drift snow influence is probably small or nonexistent because the eastern edge of Nansen Ice Sheet is sharply defined. In addition, temperatures near the top of a drifting snow layer in a stable boundary layer should be higher than those at the snow surface. A reasonable explanation for the 5° discrepancy is the influence of polar stratospheric clouds. Ebert (1988; pers. comm. 1988) found that TIR emission temperatures over the apparently cloudless polar plateau during 1–7 July 1984 were at least 20°C colder than the surface air temperature. She suggested that this discrepancy arose because of the influence of thick polar stratospheric clouds which have been implicated in the formation of the springtime Antarctic ozone hole (Solomon et al. 1987).

3. Katabatic airflow propagation across the southwestern Ross Sea

Until recently, it was generally believed that katabatic winds nearly always dissipate close (10–20 km) to the Antarctic ice slopes (Tauber 1960; Weller 1969). This was explained by analogy with fluid flow as being due to a hydraulic jump where there is an abrupt transition from strong (shooting) to light (tranquil) winds (Ball 1956). A notable exception to this view was advanced by Schwertläger (1958), who inferred that the persistent winds blowing northward across the edge of the Filchner Ice Shelf are sustained by katabatic airflow from elevated terrain located 200 km farther poleward. Documentation that intense winter katabatic winds persistently blow into Terra Nova Bay (Bromwich and Kurtz 1982, 1984; Bromwich 1989a) proves that such airstreams can routinely propagate at least 34 km across flat ice shelves.

Franklin Island is located 150 km offshore from the Transantarctic Mountains in the southwestern Ross Sea. For most of the year winds blow with nearly equal frequency from the S-SE and W–NW sectors (Savage and Stearns 1985). It has been proposed that the latter group is primarily composed of katabatic winds which have traversed some 190 km from the Terra Nova Bay area without the assistance of regional pressure gradients (Kurtz and Bromwich 1985; Bromwich 1986). Because plausible values of the radius of inertia (or alternatively the Rossby radius of deformation) are much smaller than 190 km, the anticyclonic deflection of the Coriolis force must be counterbalanced in order for this highly ageostrophic airflow to reach Franklin Island. As the W and NW winds are usually light (5 m s⁻¹ on average) and the sea ice is relatively warm due to heat conduction from below, TIR images do not generally show a thermal signature of the airstream during winter.

Under atypical circumstances it can be shown that energetic katabatic winds from Terra Nova Bay do reach Franklin Island. In mid April 1984 a maritime depression moved westward toward Ross Island and caused the regional air temperature field to become inverted relative to its usual pattern; the warmest air
FIG. 3. Schematic illustration comparing satellite surface—wind signatures on an AVHRR TIR image for 1738 UTC 22 September 1983 with observed winds and regional sea-level pressure field over the south-western Ross Sea. Isobars (64 = 964 hPa) and surface isotherms in °C are solid and dashed, respectively, and were constructed from AWS observations.

was over the Ross Ice Shelf and the coldest temperatures were found near Terra Nova Bay (Bromwich 1986). This anomalous thermal distribution together with the AWS-observed winds made it possible to follow an intense katabatic surge from Terra Nova Bay, across Franklin Island, and down to the north-western fringes of the Ross Ice Shelf, a distance of about 350 km. Only nominal momentum dissipation was noted and no Coriolis deflection was evident; in fact, it appeared as if the katabatic wind blew straight down the pronounced regional pressure gradient. In the vicinity of Ross Island, the airstream abruptly adjusted to pressure-gradient controlled flow around the maritime cyclone. Hemispheric 500 hPa charts produced by the Australian Bureau of Meteorology indicated that the intense katabatic winds from Terra Nova Bay were accompanied by midtropospheric westerly winds, and their abrupt cessation approximately coincided with the shift to easterly 500 hPa airflow. However, these 500 hPa analyses are suspect because no soundings were available from McMurdo Station during the period. The intense katabatic winds blew uninterrupted for 30 hours.

A similar case occurred in September 1983. Around 0600 UTC 22 September a subsynoptic-scale cyclone (compare Bromwich 1989b) formed just to the southwest of Ross Island. It remained stationary for 9 hours and then started to move slowly northward along the Victoria Land coast. An AVHRR TIR LAC image for 1738 UTC 22 September showed an energetic katabatic surge from Terra Nova Bay just reaching Franklin Island (figure 3). The katabatic airstream with contributions from all glaciers between Priestley and Davis formed a large polynya in Terra Nova Bay and smaller polynyas on the downwind sides of Drygalski Ice Tongue and along the coast to the south. This rare signature of katabatic airflow over the southwestern Ross Sea was probably caused by strong vertical mixing over thick pack ice. At image time, the wind speed on the top of Franklin Island (274 m elevation) was 15 m s⁻¹ and the wind direction was approximately parallel to the eastern boundary of the katabatic signature. The northern part of the airstream appears to have been deflected to the right, until, at Franklin Island, its direction was nearly normal to the weak pressure gradient (i.e., was geostrophic). The small polynya on the south side of Franklin Island verifies that the surface wind direction was northerly. A sequence of 7 DMSP TIR images on 22 and 23 September indicated that the vigorous katabatic surge from Terra Nova Bay across to Franklin Island was associated with upper-level westerly winds. For clarity, the thin high clouds, which showed westerly winds over Terra Nova Bay and areas to the north, have been omitted from figure 3. Only the katabatic airstream from Terra Nova Bay which is sustained by a large mass flux from the continental interior blew far out over the Ross Sea; the other airflows which drain small catchment zones dissipated at the edge of the fast ice. Satellite images and Franklin Island AWS data showed that the pronounced offshore katabatic surge started around 0900 UTC 22 September and continued for 15 hours.

Usually, the satellite-observed offshore trajectory of the katabatic airstream from Terra Nova Bay exhibits the leftward turning of pseudoinertial flow (Kurtz and Bromwich 1985). A digital TIR image from 27 August 1986 has been processed to illustrate this, and is presented in figure 4. An intense katabatic wind probably blew across the Nansen Ice Sheet (green, around 75°S, 163°E) and forced a large polynya in Terra Nova Bay (red and yellow, around 75.2°S, 164°E). A katabatic airflow emerging from David Glacier is shown by the green near 75.4°S, 163°E. This continued along the Drygalski Ice Tongue, forced a polynya off its eastern tip (75.6°S, 165.2°E), and then appears to have merged with the dominant airstream from Reeves Glacier. The combined airstream continued offshore (green), turned slowly leftward, and at least reached 74.5°S, 173°E, some 280 km from Inexpressible Island. The trajectory has an approximate radius of curvature of 280 km. For this to be an inertial trajectory an average speed of 39 m s⁻¹ is required. Although sustained katabatic speeds this...
strong have been measured on rare occasions at Inexpressible Island (Bromwich 1989a), it is improbable that this would be maintained so far offshore. Once again, it appears that simple inferences about the effect of the Coriolis force on such airstreams are invalid.

The above discussions can be rationalized as follows. Usually the dominant airstream from Terra Nova Bay exhibits the leftward turning of pseudoinertial flow as it moves for some distance out over the ice-covered western Ross Sea. It is not yet clear whether this adjustment takes place within the Rossby radius of deformation (Macklin et al. 1988), although this appears to be unlikely. The frequent and light winter katabatic winds affecting Franklin Island are on the southern fringes of the dominant airstream and do not exhibit significant Coriolis effects. The physical basis for this apparent dynamical anomaly has yet to be determined. When upper-level westerly winds are present as in figure 3, the entire katabatic stream may reach Franklin Island, causing substantially stronger-than-normal katabatic winds to be monitored by the AWS. In such situations the katabatic airstream exhibits highly ageostrophic behavior for hundreds of kilometers past the terrain slope, but eventually adjusts to the regional pressure field. The Coriolis deflection must be offset by some force, but the mechanism for this has not been conclusively isolated; one possibility is that surface pressure variations associated with lee waves downstream of the Transantarctic Mountains may inhibit the windfield adjustment (Macklin et al. 1988). In all of the above cases the katabatic airstream must remain negatively buoyant in relation to the environment so that its momentum is confined to near-surface layers (Reynolds 1980).

4. Katabatic winds over the Ross Ice Shelf

In contrast to the Ross Sea pack ice, there is no significant energy source just below the surface of the Ross Ice Shelf. Consequently, winter radiation conditions over this almost flat ice surface favor the development of strong temperature inversions under the clear sky and slack pressure gradients of high pressure areas. Sievers et al. (1986, 1987, 1988) showed that the frequency of light winds (speed <4 m s⁻¹) over the central part of the Ross Ice Shelf (Gill site) averages 56% from March to October. Such conditions provide an ideal background against which to view the warm signature of turbulent katabatic airstreams.

Katabatic signatures emerging from the main glacier valleys which dissect the Transantarctic Mountains are very prominent climatological features on the Ross Ice Shelf (Kurtz and Bromwich 1985; figure 5). Similar features emerge from Kangerdlugssuaq Fjord in southeast Greenland on to the coastal fast ice (Scorer 1988, plate 2). Between April and October in 1984 and 1985, once daily DMSP TIR images of the northwestern Ross Ice Shelf showed these katabatic signatures on 98% of images in which at least one of Byrd, Mulock, and Skelton glaciers was visible. On 51% of images the region was overcast and 17% of days had no satellite coverage. Similar results were obtained by Breckenridge (1985) for June–August 1982. Fifty-eight percent of his TIR photographs contained these same signatures, and on almost all of the remaining images the area was obscured by high and low clouds.

Consistent with figure 5, the most prominent signature in terms of areal extent is typically associated with Byrd Glacier. By comparing the above three signatures for April–October in 1984 and 1985, it was found that the Byrd signature was the largest for 85% of the time compared to 10% for Skelton and 5% for Mulock. About half of these images also included Nimrod and Beardmore glaciers. Evaluation of the images for the most prominent katabatic signature when all five glaciers were visible yielded the following occurrence frequencies: Byrd 87%, Skelton 7%, Mulock 3%, Nimrod 3%, and Beardmore 0%. Parish and Bromwich (1987) have modeled the winter pattern of surface airflow over the sloping ice fields of Antarctica. Air from a huge portion of East Antarctica converges just upslope from Byrd Glacier. Primitive-equation model simulations show that such confluence regions in the boundary layer wind field contain much deeper and faster airstreams and sustain coastal zones of strong, persistent, katabatic winds (Parish 1984). It seems that there may be an approximate proportionality between the time-averaged katabatic mass flux from the glacier and the typical area on the Ross Ice Shelf of the TIR katabatic signature.

These katabatic signatures are consistent with 3-h surface winds recorded by the AWS downwind of Byrd Glacier (data given by Savage et al. 1985). Figure 6 presents a comparison between DMSP TIR images and simultaneous AWS wind data for a six-day period in May 1984. When the AWS is well within the signature, the wind direction is parallel to the orientation of the signature and the speed is high (6 May). The wind speed is low outside the signature domain, but the wind direction is often consistent with signature alignments (e.g., 9 May). When the AWS is close to the edge of the signature, the wind data indicate substantial complexity, e.g., 0727 UTC 10 May. The sharp right turn of the Byrd Glacier signature at 0226 UTC 10 May to adjust to the orientation of the other signatures is remarkable; this probably represents an abrupt transition to directional
FIG. 5. Gray-scale AVHRR TIR image for 1706 UTC 18 June 1983. Katabatic winds blowing from the Skelton (S), Mulock (M), Byrd (B), Nimrod (N) and Beardmore (Bdm) glaciers show up as warm signatures (dark) against the comparatively cold background of the Ross Ice Shelf (I). Katabatic airflow across the recurring polynya (black) in Terra Nova Bay (T) and out over the Ross Sea pack ice (R) is also prominent.
equilibrium with the slack pressure field. Weak ridges covered the area during this period. Figure 6 also shows that the environmental conditions around the AWS exhibit strong spatial variability, and that the satellite information places the temporally detailed AWS observations in the proper spatial setting.

Because these features appear warm on TIR images, they are usually inferred to be foehn winds (Swinthinbank 1973; Breckenridge 1985; D’Aguanno 1986) where the invading air is much warmer than that which is displaced. However, these katabatic signatures exhibit several characteristics in common with the katabatic airstream at Terra Nova Bay which, on average, is negatively buoyant in relation to the surrounding air masses (Bromwich 1989a). In parallel to the findings of section 3, Breckenridge (1985) concluded from a June 1982 case study that low- to mid-tropospheric wind components directed eastward across the Transantarctic Mountains favor the development of prominent katabatic signatures over the Ross Ice Shelf. Furthermore, optimum radiation conditions for the production of cold surface air over the polar plateau appear to encourage enhanced katabatic drainage at Terra Nova Bay (Bromwich 1989a) and the appearance of large TIR katabatic signatures over the northwestern Ross Ice Shelf (Breckenridge 1985).

There is one factor which strongly argues against the foehn-wind origin for these signatures. Foehn air is positively buoyant with respect to the environment and, as a result, some force is required to keep the airstream at the surface. At times, well-defined signatures can extend hundreds of kilometers across the shelf (e.g., Stearns and Wendler 1988, figure 6), and the existence of such restraint over this spatial scale seems highly unlikely. Usually, foehn influence decreases rapidly away from the foot of the upwind mountain obstacle (compare Brinkmann 1974 and Hoinka 1985).

Figure 7 depicts vertical temperature structures that can explain the coexistence of warm katabatic signatures and negatively buoyant katabatic airstreams. Because no direct measurements are available, the stratification has to be inferred. The dashed line is an estimate of the winter average (April-September) temperature profile near Byrd Glacier. Following Schwerdtfeger (1984, p. 83), it is derived from average AWS air temperatures (Sievers et al., 1986, 1987, 1988) and the mean radiosonde temperature profile at McMurdo Station (O'Connor and Bromwich 1988) located 230 km to the north on Ross Island. The strong temperature increase with height is taken to be linear, and the McMurdo temperatures are assumed to apply above 50 m altitude. Data from Plateau Station in the
high interior of East Antarctica show that much stronger and shallower surface inversions are possible when the 32-m wind speed is less than 6 m s\(^{-1}\) (Riordan 1977); inversion strength steadily decreases as the wind speed increases beyond 6 m s\(^{-1}\).

The temperature profile associated with energetic katabatic airflows (like those on 6 May 1984 shown in figure 6) was estimated as follows. D’Aguanno (1986) found for a 9 July 1984 case study that the TIR emission temperature of the katabatic signature emerging from Byrd Glacier was about 10°C higher than that outside the katabatic jet. This difference was used to approximately fix the surface air temperature of the katabatic stream. An inversion strength of 0.7°C (100 m)\(^{-1}\) given by Rusin (1964) for pure katabatic winds at Mirny was adopted; average surface wind speed was 13 m s\(^{-1}\). If the top of the katabatic layer is taken to coincide with the intersection point of the katabatic and ambient temperature profiles (−250 m) then the katabatic layer depth is within the range of values quoted by Rusin (1964). The profiles are arranged so that the vertically averaged temperature of the katabatic layer is less than that of the quiescent surroundings, i.e., the former is negatively buoyant in relation to the latter. A katabatic wind speed profile is also presented in figure 7. This is primarily constructed from a representative value for strong katabatic wind speeds measured by the Byrd Glacier AWS (13 m s\(^{-1}\)) and from Rusin’s (1964) katabatic speed shear.

Warm katabatic signatures appear to arise as follows. Katabatic air probably descends adiabatically from the polar plateau toward the Ross Ice Shelf because initially it is negatively buoyant. If the boundary layer over the ice shelf is strongly stratified as a result of clear skies and weak pressure fields (like the dashed profile in figure 7), the descending air will reach a level of neutral buoyancy that is a few tens of meters above the ice surface; the katabatic airstream can then propagate horizontally. If the radiation inversion can be destroyed by turbulent vertical mixing then a katabatic temperature profile like that in figure 7 can be produced by bringing much warmer and fast-moving air down to the surface. The radiatively cooled snow surface in comparatively calm areas outside the katabatic jet will continue to be much colder, and the warm katabatic thermal signature arises because of the horizontal gradient of snow-surface emission temperatures. These arguments are strengthened by the two case-study flights carried out by Parish and Bromwich (1989) on successive days in November 1987. At 170 m above the flat Nansen Ice Sheet strong katabatic winds and negatively buoyant air temperatures were measured even though simultaneous TIR images showed a warm katabatic signature.

Godin (1977) used DMSP images (both visible and TIR) and 500 hPa synoptic maps to carry out a convincing analysis of an October 1973 episode of katabatic drainage through the Transantarctic Mountains. This was preceded by an extended period of orographic lifting of moist air over the mountains. When the cloud cleared, prominent thermal signatures from Byrd and Nimrod glaciers were present on the shelf. The signatures curved anticyclonically back toward the mountains and were orographically lifted by the Royal Society Range, forming cloud plumes which stretched over the plateau. Godin inferred that these warm signatures reflected the presence of blowing snow, the source for which was the orographic snowfall of the previous several days. The presence of an annual-mean snowfall maximum along the Transantarctic Mountains (Giovinetto and Bentley 1985) probably implies that these precipitation events occur with some frequency. Thus the explanation for the signatures appears to involve both downward turbulent mixing of negatively buoyant air and blowing snow. When there is ample loose snow, the emission may come from near the top of the blowing snow layer; in such situations the airstream effects need not reach the surface. At Mawson in 1961, Streten (1963) on nine occasions between May and October noted overriding katabatic winds at a height of about 1000 m with light winds near the surface, an infrequent occurrence. When the surface supply of loose snow is limited, the thermal emission will come from the turbulently warmed snow surface, probably the most frequent situation.

5. Discussion and conclusions

In the polar regions, satellite information offers the potential of not only high spatial resolutions but also excellent temporal coverage. The latter arises be-
cause satellites in polar orbit pass close to the poles during each circuit of the earth. For a large fraction of the Antarctic, much of this potential will soon be realized as a result of decisions by the National Science Foundation (1988; R. Whritner, pers. comm. 1988) to establish weather-satellite receiving units at McMurdo (started October 1987) and Palmer stations (scheduled for May 1989). Imagery and soundings from both the DMSP and NOAA satellites will be archived several times each day; spatial resolutions of images from the respective satellite systems are 0.6 and 1.1 km. With four satellites in orbit, it is theoretically possible to obtain a 20-min sampling interval. Future satellite analyses of katabatic wind behavior can therefore be much more sophisticated than presented here.

It has been shown that prominent signatures of katabatic surface winds are present at thermal infrared wavelengths under clear sky conditions. It is argued that the vast majority of these warm features actually represent negatively buoyant (i.e., comparatively cold) airstreams. This paradox is explained as follows. Snow surface temperatures in regions with turbulent airstreams and vigorous vertical mixing are significantly higher than those in adjacent areas with light winds. However, at a few tens of meters above the surface, katabatic air is colder than air at corresponding levels outside the katabatic jet. At times suspended drift snow also contributes to the warm katabatic signature. Because the height in the atmosphere at which these proxy indicators occur is not well defined, it is essential that they be calibrated against conventional wind measurements. On the other hand, TIR images repeatedly demonstrate that katabatic windfields are characterized by strong spatial variability, and that the spatially detailed image data are often needed to place the widely spaced conventional observations in the proper context.

A satellite case study of surface airflow converging into the Terra Nova Bay area is shown to closely follow the observed time-averaged streamlines of surface-air motion. Consistent with all previous analyses, the primary route for katabatic mass transport to sea level is down Reeves Glacier. False color, non-linearly enhanced TIR images show that relative black body temperature variations within the surface wind signature follow those expected on the basis of surface wind behavior. Comparison between TIR emission temperatures and surface air temperature measurements suggests the presence of polar stratospheric clouds.

Two examples of katabatic airflow from Terra Nova Bay out into the southwestern Ross Sea are presented. Although AWS observations indicate that katabatic winds from Terra Nova Bay routinely reach Franklin Island some 190 km to the southeast, TIR images do not usually show a katabatic signature because weak vertical mixing does not produce a large thermal contrast with the warm underlying sea ice. In the first case, midtropospheric westerly winds encouraged katabatic drainage down many of the glaciers along the Victoria Land coast. Katabatic airflows from glaciers sustained by small drainage basins dissipated at the fast ice edge. Energetic katabatic winds from Terra Nova Bay blew far out to sea and just reached Franklin Island. Near the island, the airstream made a right turn to blow parallel to the local isobars. In the second case, a false-color TIR image illustrates the more usual circumstances. The dominant katabatic airstream from Reeves Glacier forced a polynya in Terra Nova Bay, turned slowly leftward in a pseudoinertial fashion and at least reached 280 km offshore from Inexpressible Island. For both situations, the expected influence of the Coriolis force was counteracted to a greater or lesser extent. (This topic will be explored in a forthcoming research paper.)

Katabatic signatures are shown to be very prominent climatological features over the northwestern Ross Ice Shelf. On almost all cloud-free images the largest signature emerged from Byrd Glacier which model simulations indicate should drain a very large area of the polar plateau. An approximate proportionality appears to exist between the average signature size on the shelf and the magnitude of katabatic mass transport from the plateau. Changes in signature size are inferred to be due to variations in the radiative production of cold surface air over the plateau.

Acknowledgments. This research was sponsored by the Division of Polar Programs of the National Science Foundation through Grants DPP-8519977 and DPP-8716339. Mr. Will Gould drew the author's attention to the many excellent examples of katabatic wind signatures within the NOAA Satellite Library. Mr. John Pyeatt of the Space Science and Engineering Center at the University of Wisconsin—Madison expended considerable time and effort to process figures 2 and 4. The DMSP images were obtained from the National Snow and Ice Data Center, Campus Box 449, Boulder, CO 80309.

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Volume 10 (1989) monthly 8 pages
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