Satellite Observations of Katabatic-Wind Propagation for Great Distances across the Ross Ice Shelf †

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ABSTRACT

Five winter months (April–August 1988) of thermal infrared satellite images were examined to investigate the occurrence of dark (warm) signatures across the Ross Ice Shelf in the Antarctic continent. These features are inferred to be generated by katabatic winds that descend from southern Marie Byrd Land and then blow horizontally across the ice shelf. Significant mass is added to this airstream by katabatic winds blowing from the major glaciers that flow through the Transantarctic Mountains from East Antarctica. These negatively buoyant katabatic winds can reach the northwestern edge of the shelf, a horizontal propagation distance of up to 1000 km, 14% of the time. Where the airstream crosses from the ice shelf to the ice-covered Ross Sea, a prominent coastal polynya is formed. Because the downslope buoyancy force is near zero over the Ross Ice Shelf, the northwestward propagation of this katabatic air mass requires pressure gradient support. The study shows that the extended horizontal propagation of this atmospheric density current occurred in conjunction with the passage of synoptic cyclones over the southern Amundsen Sea. These cyclones can strengthen the pressure gradient in the interior of West Antarctica and make the pressure field favorable for northwestward movement of the katabatic winds from West Antarctica across the ice shelf in a geostrophic direction. The glacier winds from East Antarctica are further accelerated by the synoptic pressure gradient, usually undergo abrupt adjustment beyond the exit to the glacier valley, and merge into the mountain-parallel katabatic air mass.

1. Introduction

Advanced Very High-Resolution Radiometer (AVHRR) images from the National Oceanic and Atmospheric Administration (NOAA) satellites have been routinely collected at McMurdo Station (Fig. 1) in the Antarctic continent since October 1987 (Anonymous 1988; Van Woert et al. 1992). One of the major features that can be seen at thermal infrared wavelengths during winter are dark (warm) signatures that extend from southern Marie Byrd Land to the northwest edge of Ross Ice Shelf, with an orientation almost parallel to the Transantarctic Mountains (Figs. 2a–c). The thermal infrared brightness temperatures indicate that these dark features are revealing warm air immediately above the ice surface. Swithinbank (1973), Breckenridge (1985), and D'Aguanno (1986), studying the same types of features over the ice shelf but coming from the glaciers that dissect the Transantarctic Mountains, suggested that the dark signatures are due to foehn winds. Cold air compressively warms as it descends from the high plateau to the ice shelf. With the foehn-wind explanation, the air mass that arrives at the foot of the valley should be warmer than the air mass that it displaces. Usually because of their positive buoyancy, foehn winds do not propagate far beyond the end of terrain slope (e.g., Hoinka 1985). The hundreds of kilometers that these features can extend across the horizontal ice shelf suggest that another mechanism is active.

Bromwich (1989a) inferred that such warm signatures are actually generated by comparatively cold airflows. That dark signatures are associated with negatively buoyant airflows is explained as follows. Cold air that descends from the plateau usually starts out very cold. Adiabatic compression heats the air so that it reaches a level of neutral buoyancy at a few tens of meters above the ice shelf. Then the airstream propagates horizontally, and the associated turbulence ver-

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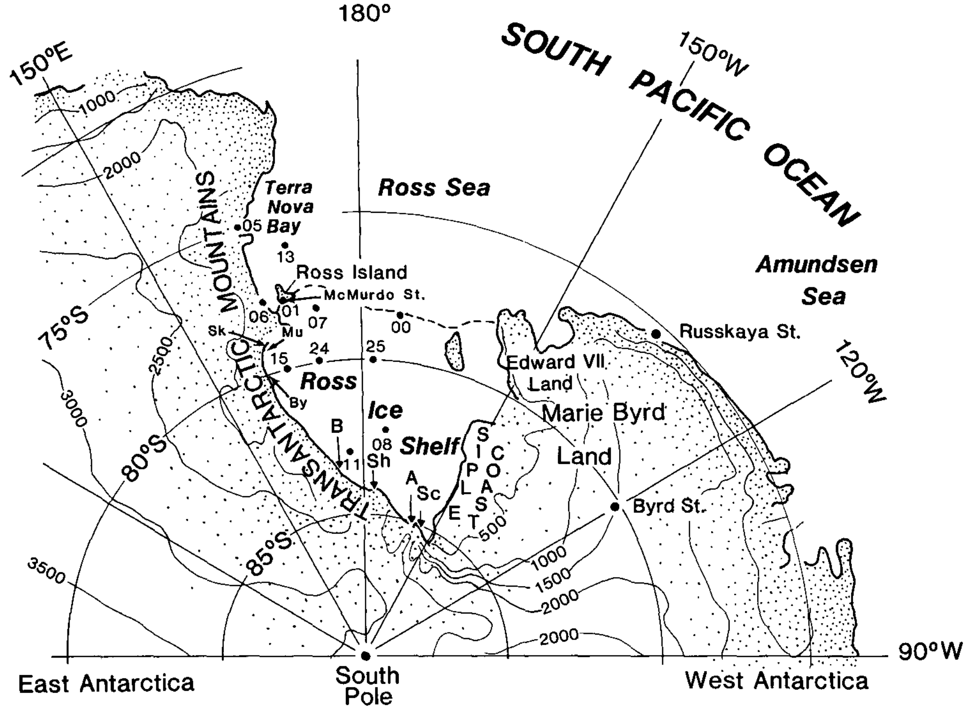

FIG. 1. Location map of the Ross Ice Shelf and surrounding areas. The dots with associated numbers are AWS sites. Near Siple Coast, B, Sh, A, and Sc, respectively, denote Beardmore, Shackleton, Amundsen, and Scott glaciers. Farther to the north Sk, Mu, and By locate Skelton, Mulock, and Byrd glaciers. Thin lines are elevation contours in meters.

tically mixes the underlying layer, which initially has a strong surface temperature inversion (Fig. 3). Transport of warmer air from aloft heats the ice surface, but higher up the airstream is significantly colder than the surroundings. Confirmation of this conjecture was obtained from two case-study flights above the flat Nansen Ice Sheet during November 1987 when warm thermal infrared satellite signatures coexisted with negatively buoyant air at the 175-m flight level (Parish and Bromwich 1989). Therefore, the dark signatures captured by thermal infrared satellite images qualitatively reflect the extension of negatively buoyant katabatic airflows across the ice shelf.

Parish and Bromwich (1987) modeled the near-surface airflow over the Antarctic continent using the simple steady-state model of Ball (1960). They found that the surface winds inland of the Ross Ice Shelf area converge toward Siple Coast and the Byrd Glacier area (Fig. 4). Such convergence features in the continental interior allow the downstream katabatic winds to become intensified and more persistent by providing an enhanced supply of negatively buoyant air to the coastal slopes. The location and orientation of the dark features across the Ross Ice Shelf suggest that their origin can be tied to the enhanced katabatic airflow that descends from Marie Byrd Land through Siple Coast (Carrasco and Bromwich 1993). As noted by Bromwich (1989b), studies of the time-dependent behavior of such features indicate that the katabatic airflow from the Byrd Glacier area adds significant mass to the airstream. Horizontal propagation of katabatic winds for hundreds of kilometers beyond the foot of the terrain slope at Siple Coast contrasts sharply with the typically abrupt dissipation that characterizes most of the katabatic winds blowing beyond the East Antarctic coastal slopes (Weller 1969; Schwerdtfeger 1970).

Bromwich (1989a) provided evidence for the Ross Sea sector that katabatic-wind propagation beyond the slope break is proportional to the upstream boundary-layer mass flux. The gentleness of the terrain slopes of southern Marie Byrd Land implies less acceleration of the surface winds that converge toward Siple Coast in comparison to those that converge into areas of steepening terrain like Byrd Glacier. This is in general agreement with the results obtained by Parish and Bromwich (1991) who used a three-dimensional numerical model to simulate the directions and speeds of winter surface winds over the Antarctic continent; however, the 100-km grid spacing is not ideal for resolving the smaller-scale convergence that feeds into Byrd Glacier. Thus, it would be expected that the horizontal extension across the Ross Ice Shelf of katabatic airflow from southern Marie Byrd Land would typically be less than that of the winds coming from Byrd, Mu-

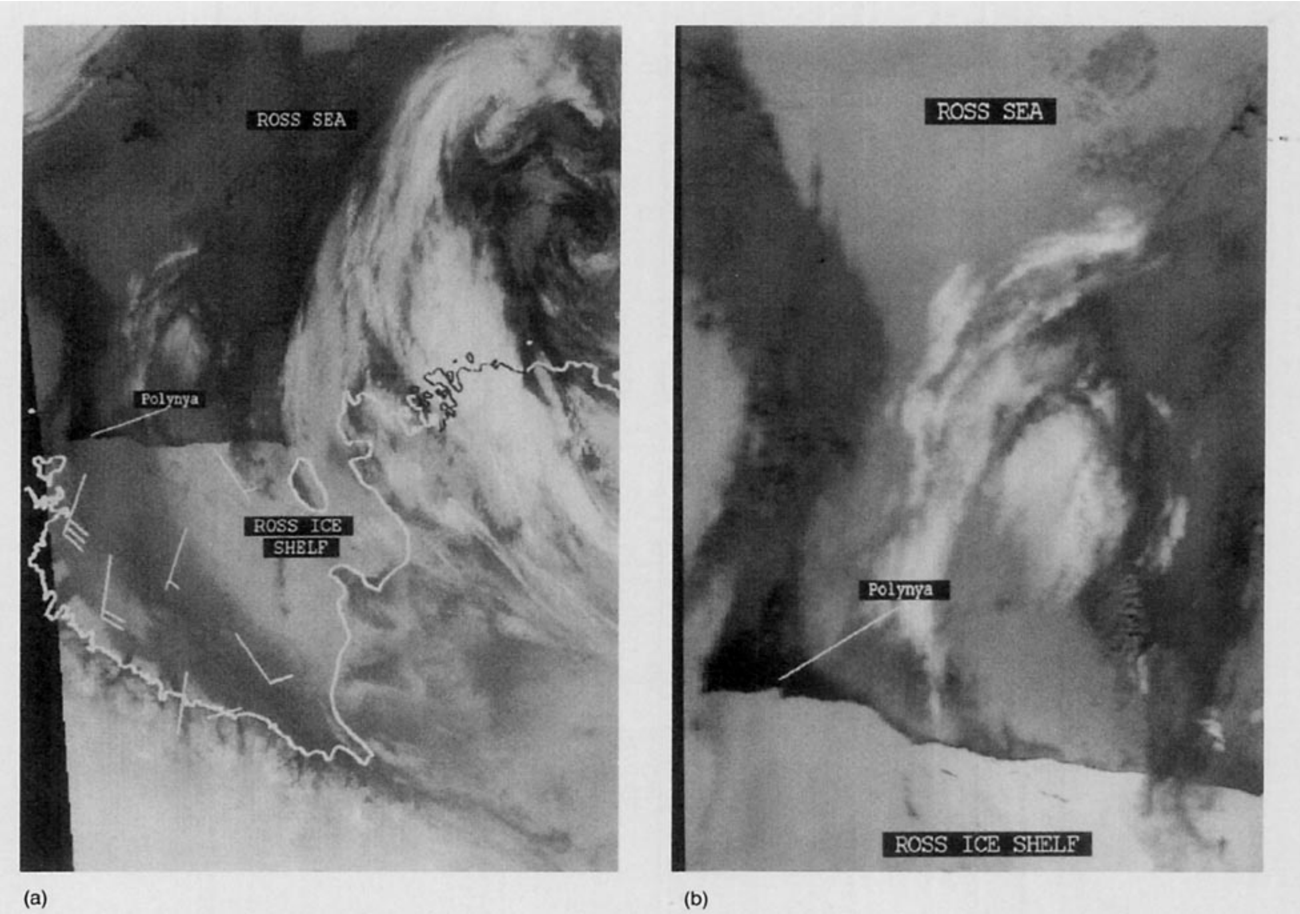

FIG. 2. (a) Thermal infrared imagery from the *NOAA-9* satellite at 0253 UTC 23 April 1988 showing the dark (warm) katabatic-wind signature across the Ross Ice Shelf. Simultaneous AWS winds are plotted using conventional notation (long barb = 5 m s^{-1}). (b) Close-up of (a) detailing the katabatic wind-forced polynya and the associated clear slot through the low-cloud field farther north.

lock, and Skelton glaciers. Thermal infrared satellite images reveal that the extension of the former at times greatly exceeds that of the latter and indicate that another mechanism is required to assist the former katabatic airflow in its northwest propagation.

Carrasco and Bromwich (1993), studying examples of this phenomenon for the period June–August 1988, found that the common synoptic pattern was the presence of synoptic cyclones crossing the southern Amundsen Sea. The position of these cyclones produced a pressure distribution whereby the cyclonic orientation of the isobars was almost parallel to the Transantarctic Mountains. Under this circumstance, the negatively buoyant katabatic winds that arrive at the foot of the Marie Byrd Land slope find a favorable pressure distribution for their northwestward propagation along the isobars and subsequent warming of the air immediately above the ice-shelf surface. The pressure field also generates enhanced katabatic winds down the main glacier valleys through the Transantarctic Mountains by the gap-wind mechanism. These winds rapidly adjust to geostrophic orientation beyond the valley exit and merge into the katabatic airstream from Marie Byrd Land as it moves northwestward parallel to the Transantarctic Mountains. As outlined above, the atmospheric density current also receives significant mass from the enhanced katabatic winds blowing from the Byrd Glacier area.

This article describes the results obtained by examining 277 thermal infrared satellite images, which spanned five Antarctic winter months (April–August 1988), to determine the occurrence frequency of dark signatures far across the Ross Ice Shelf. This period includes the interval from which Carrasco and Bromwich (1993) extracted their case studies (June–August 1988). Here the emphasis is placed on the mesoscale and synoptic-scale environments associated with this phenomenon.

2. Satellite analysis

All available infrared satellite images were examined in order to study the presence of dark signatures at the southeastern corner of the Ross Ice Shelf and those

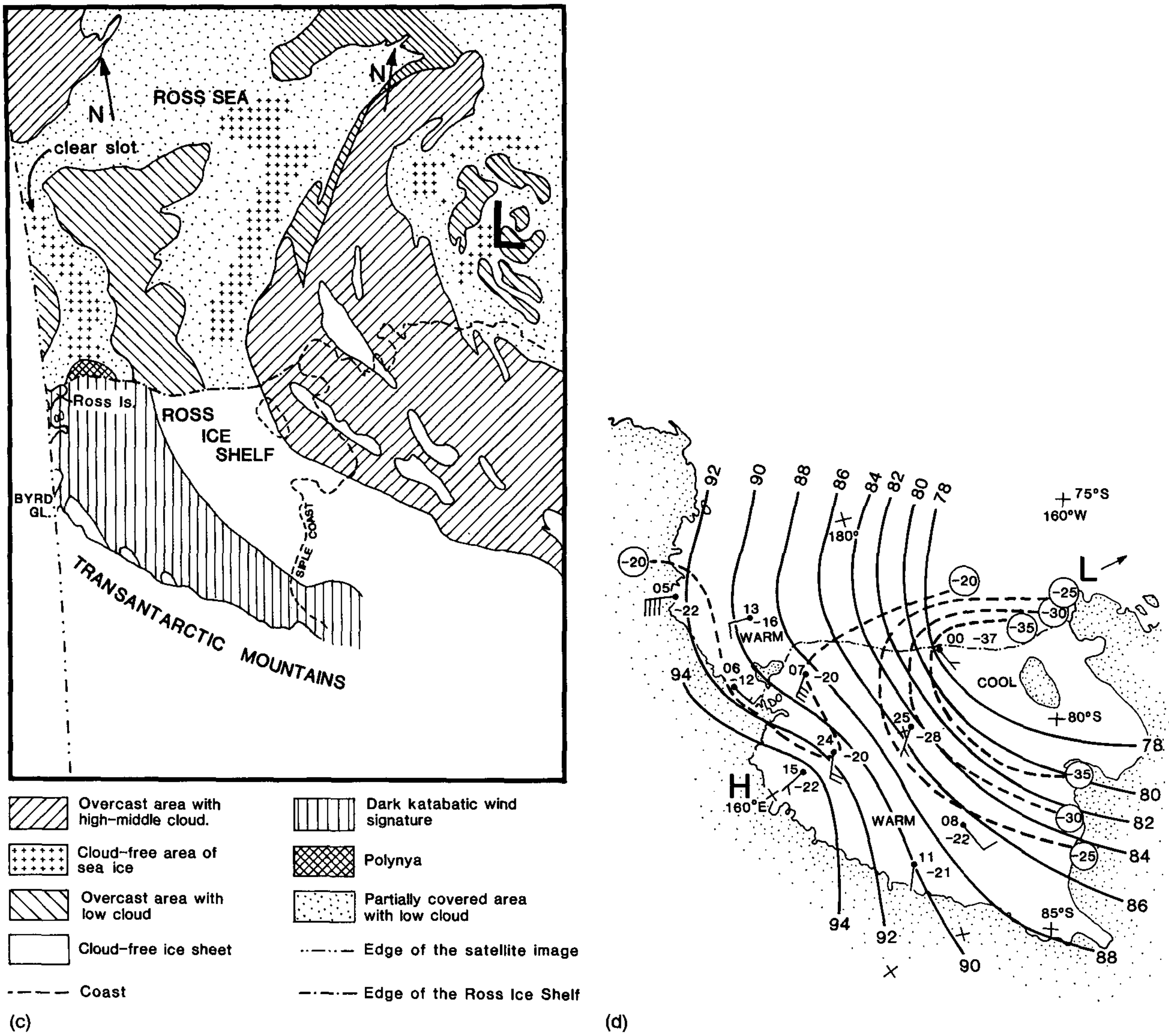

FIG. 2. (c) Schematic of (a) emphasizing the main features. (d) Regional concurrent analysis of sea level isobars (hPa, solid 78 = 978) and surface isotherms (°C, dashed) from AWS observations. Air temperatures (°C, negative numbers) are given for each AWS site.

with a northwestward projection. The AVHRR data collected at McMurdo Station were obtained from the Antarctic Research Center at Scripps Institution of Oceanography and processed at a spatial resolution of 2.2 km on a SUN 4/110 workstation using the TeraScan software package supplied by SeaSpace. To evaluate the presence of dark signatures across the ice shelf, it was considered that all those dark features extending to the north-northwest of automatic weather stations (AWS) 08 and 11 (Fig. 1) were counted as a northwestward propagation of the katabatic winds; otherwise, they were considered as being present just around the Siple Coast area. For approximately one-third of the study period (Table 1) the Ross Ice Shelf was overcast or the satellite information was not available. It was found that during 14% of the total period (corresponding to 22 days, which hereafter will be called *signature days*), dark signatures extended to the north of AWS 11 and 08. Considering only the days for which the presence of surface-wind signatures could be evaluated (hereafter called *analyzable days*), the above percentage rises to 21% of these days. Dark signatures just around Siple Coast area were found to be a frequent phenomenon, being observed on 65% of the entire period and 92% of the analyzable days. The high frequency of dark signatures on the southeastern corner of the shelf reveals the typical horizontal distance that the katabatic winds propagate onto the Ross Ice Shelf from Marie Byrd Land (mean = 170 ± 10 km). On the other hand, the occasional presence (around 14%) of these features across the entire ice shelf reveals the horizontal distance that the katabatic winds can cover

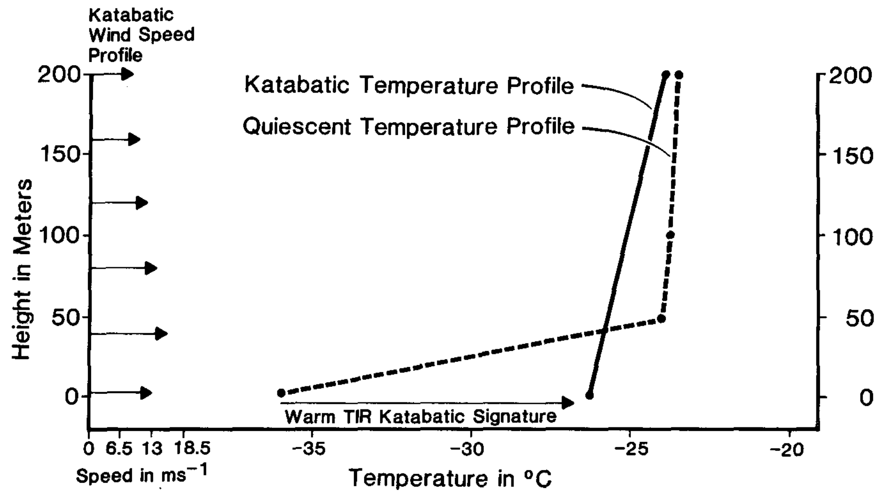

FIG. 3. Schematic winter illustration for the Ross Ice Shelf near Byrd Glacier of how warm, thermal infrared (TIR) satellite signatures can reveal the presence of negatively buoyant katabatic airstreams (from Bromwich 1989a).

(>1000 km) when they have the appropriate synoptic-scale support.

Also, it was noted that dark signatures extending from the main glaciers that dissect the Transantarctic Mountains on the southern half of the Ross Ice Shelf (Beardmore, Shackleton, Amundsen, and Scott glaciers in Fig. 1) were more prominent in conjunction with a northwestward projection of the dark signature from Siple Coast. In fact, it was not generally possible to separate the katabatic contribution from Scott and Amundsen glaciers from that originating in southern Marie Byrd Land. The greater signature prominence suggests that on signature days, the katabatic winds descending from the high plateau through the above four glaciers are intensified. Another area where katabatic flow from East Antarctica always makes a major contribution to the mountain-parallel airflow is that around Byrd Glacier. The satellite images also revealed

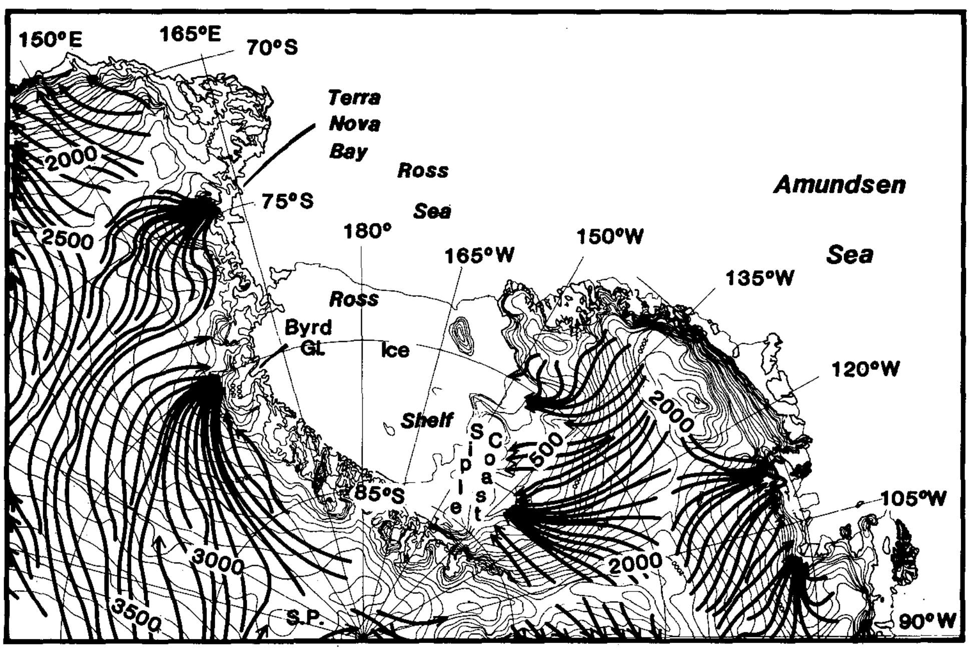

FIG. 4. Time-averaged near-surface wintertime streamlines of surface airflow over the sloping ice fields surrounding the Ross Ice Shelf (after Parish and Bromwich 1987). Thin lines are elevation contours in meters.

TABLE 1. Satellite surface-wind signatures across the Ross Ice Shelf during April–August 1988 (277 AVHRR images).

Percentage of days (total = 153) that were overcast or without data. The remaining days are called *analyzable.*	30%
Percentage of total days with surface-wind signatures at foot of Marie Byrd Land slope.	65%
Percentage of analyzable days with surface-wind signature at foot of Marie Byrd Land slope.	92%
Percentage of total days with surface-wind signature all the way across the Ross Ice Shelf (called *signature* days).	14%
Percentage of analyzable days that are signature days.	21%
Percentage of signature days with katabatic-wind signatures coming from East Antarctica.	100%

Note: Analyzable days are those for which, in the opinion of the analyst, the ice-surface conditions over almost all of the western half of the Ross Ice Shelf can be determined on one or more thermal infrared satellite images. Thin, nonobscuring cloud cover may be present on such days.

the frequent presence of a polynya (area of open water/thin ice surrounded by sea ice) along the northern edge of the Ross Ice Shelf mainly on its western side. This polynya is a conspicuous feature on passive microwave images of Antarctic sea ice (compare Zwally et al. 1983). When a dark signature was observed across the entire ice shelf, a more prominent polynya was present along the edge of the ice shelf (Figs. 2a–c) (see also Carrasco and Bromwich 1993). This suggests that the katabatic winds coming from the Siple Coast area, in conjunction with those from Byrd, Skelton, and Mulock glaciers, can enlarge the polynya. The associated synoptic-scale circulation described below matches that found by Zwally et al. (1985) to be associated with a dramatic expansion of this polynya.

The surface-wind signature is illustrated by Fig. 2a, which is a thermal infrared satellite image at 0253 UTC 23 April 1988. It shows a katabatic signature extending horizontally for about 1000 km from southern Marie Byrd Land to the northwestern edge of the Ross Ice Shelf. This image is from the middle of a 5-day period (21–25 April) with a similar signature across much of the Ross Ice Shelf. The signature propagated from south of AWS 08 at 1114 UTC 20 April to near AWS 24 by 1051 UTC 21 April, demonstrating that the signature originated from the West Antarctic area. Note that the orientation of the dark signature in Fig. 2a almost parallels the Transantarctic Mountains and that the signature broadens to the north as it crosses the ice shelf. The latter probably arises because katabatic winds, blowing from the glaciers that pass through the Transantarctic Mountains, progressively add mass to the katabatic airstream as it moves northward. Earlier satellite images (not reproduced) showed that katabatic airflow from East Antarctica, particularly from around Byrd Glacier, contributed significantly to the airflow over the Ross Ice Shelf both prior to and after the dark signature propagated to the northwest between 20 and 21 April. A polynya (Figs. 2a,b) can be seen along the northwestern edge of the ice shelf that seems to be created by the winds coming from West Antarctica along with those coming from East Antarctica (Bromwich 1992). The continued presence of the dry katabatic air mass to the north of the polynya is shown in Fig. 2b by the dry slot that cuts through the low-cloud field.

The simultaneous AWS surface winds over the Ross Ice Shelf (Fig. 2a) are not very useful for confirming the nature of the satellite signature because most sites are located at the edge of or outside the signature domain. Only AWS 08, 07, and 24 are well inside the katabatic-wind signature, and only at AWS 08 is the wind direction parallel to the edge of the signature. The wind at the second site, which is just to the south of the polynya, is 15 m s^{-1} in a offshore direction but is undoubtedly influenced by the adjacent high terrain of Ross Island and the Transantarctic Mountains. At AWS 24, the observed wind direction cuts across the orientation of the signature and may represent the adjustment of the enhanced katabatic airstream from the Byrd Glacier area into the broader northward-directed katabatic air mass. The average wind speed on 23 April (6 m s^{-1}) at the site nearest Byrd Glacier (AWS 15) was the lowest of the 5-day period (average = 12 m s^{-1}); this may suggest a less important contribution from this glacier at image time, although high spatial variability characterizes this airflow (Bromwich 1989a). In general, the AWS winds within or to the south of the southern part of the signature are consistent with mass addition by katabatic winds blowing from the Transantarctic Mountains.

The image in Fig. 2a shows a dissipating synoptic cyclone over the southern Amundsen Sea with an associated frontal system over Marie Byrd Land. The pressure field over the Ross Ice Shelf is cyclonic (Fig. 2d), and the main signature is parallel to the isobars. On the southern side of the signature, significant ageostrophic motion is exhibited by the observed winds and the satellite signatures as the katabatic winds adjust to a geostrophic orientation within a few tens of kilometers beyond the foot of the terrain slope. In the vicinity of Byrd Glacier and farther north, substantial ageostrophic motion is present for hundreds of kilometers over the flat ice shelf in association with the enhanced katabatic drainage from that area. The main features accompanying the presence of the dark signature described above were observed on other signature days [see case studies presented by Carrasco and Bromwich (1993)]. This indicates that the northward propagation of the negatively buoyant airstream generally along the isobars occurred in conjunction with the passage of a synoptic storm across the southern Amundsen Sea.

3. Synoptic analysis

To investigate the broad-scale conditions under which the katabatic airflow can propagate toward the northwest, the hemispheric synoptic charts produced by the Australian Bureau of Meteorology were reviewed. Figures 5a and 5b are the averages of the synoptic analyses for the five winter months and for the signature days, respectively. They were obtained by evaluating the Australian sea level pressure charts for 0000 UTC, with corrections for the AWS pressure observations in the Ross Sea–Ross Ice Shelf area. The average pressure was found for an array of grid points at intervals of 10° of latitude and longitude. It can be seen in Fig. 5a that the mean winter position of the synoptic cyclone is slightly to the northeast of the Ross Ice Shelf [compare with Fig. 18 on pp. 281 of Schwerdtfeger (1970)]. On the other hand, Fig. 5b shows that the mean location of the synoptic cyclone for the signature days is slightly to the north of Russkaya Station, revealing a northeastward displacement and an intensification with respect to the 5-month average. This pattern (Fig. 5b), dominated by the synoptic cyclone centered over the southern Amundsen Sea, results in a well-defined cyclonic circulation over the Ross Ice Shelf and Marie Byrd Land with the isobars running almost parallel to the Transantarctic Mountains. The average fields are statistically different at better than the 95% confidence level (using a two-tailed t test) over southern Amundsen Sea, where the synoptic cyclone was located on signature days.

The 500-hPa analyses produced by the Australian

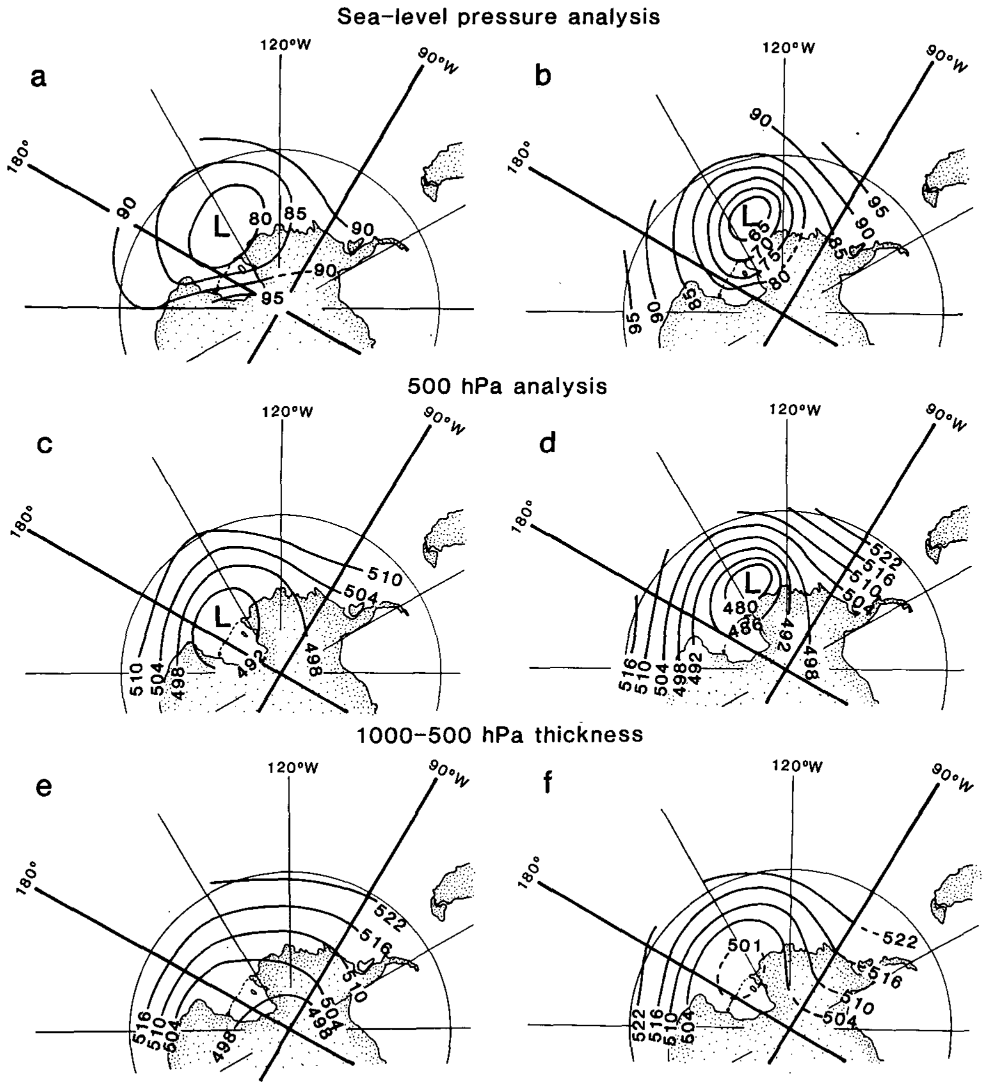

FIG. 5. (a) The mean sea level pressure field for the five winter months obtained from evaluation of the daily surface analyses at 0000 UTC produced by the Australian Bureau of Meteorology. (b) Same as (a), but for the days with dark signatures across the Ross Ice Shelf. (c) The mean 500-hPa geopotential height for the five winter months. (d) Same as (c), but for the signature days. (e) The mean 1000–500-hPa thickness for the five winter months derived from the mean surface and 500-hPa analyses. (f) Same as (e), but for signature days.

Bureau of Meteorology were examined in a similar fashion. Figures 5c and 5d correspond to the 500-hPa average field for the five winter months and for signature days, respectively. It can be seen that the midtropospheric vortex, which is located over the Ross Ice Shelf during the five winter months [Fig. 5c; see also Fig. 20 on pp. 283 of Schwerdtfeger (1970)], is displaced to the northeast of its mean winter position to be located slightly to the north of Russkaya Station (Fig. 5d). Once again, the position and intensification of the vortex for signature days give a well-defined midtropospheric cyclonic circulation over Marie Byrd Land and the Ross Ice Shelf. The 500-hPa average fields were found to be statistically different at better than the 95% confidence level over the southern Amundsen Sea. The near coincidence for signature days of the synoptic cyclones (Figs. 5b,d) at the surface and 500 hPa reveals the (equivalent?) barotropic environment in which the northwestward extension of the katabatic winds took place.

The 1000–500-hPa geopotential thicknesses for the five winter months (Fig. 5e) and for signature days (Fig. 5f) were obtained from the sea level pressure and 500-hPa analyses described above. Although the averages did not differ significantly, a cold trough extending northeastward from the Ross Ice Shelf is indicated by the 1000–500-hPa thickness analyses for signature days (Fig. 5f); a warm ridge extends southward over the eastern side of Marie Byrd Land. The shortage of appropriate data over the interior of the continent limits the accuracy with which the thickness ridge can be analyzed. It can be noted that the meridional 1000–500-hPa thickness configuration for signature days (Fig. 5f) contrasts with the almost-zonal flow pattern of the thermal winds shown by Fig. 5e. The thermal trough and ridge are, respectively, associated with the synoptic-scale equatorward advection of cold air and the poleward advection of warm, probably moist air. The presence of the warm satellite signatures in the cold trough strengthens the contention that they are associated with cold katabatic drainage. Typically fronts lie along the thickness gradient between the cold trough and the warm ridge.

Evaluation of the synoptic analyses along with the results obtained from the satellite examination indicate that for 82% of the signature days, the synoptic analysis resolved the presence of a synoptic storm over the southern Amundsen Sea (Table 2). In general, these synoptic storms appeared to be in a dissipating state, which is in agreement with the barotropic conditions derived from the synoptic analyses for signature days (Figs. 5b,d).

4. AWS analysis

To analyze the mesoscale environment associated with the presence of dark signatures across the ice shelf, surface weather observations collected by the network of AWS on the Ross Ice Shelf were examined. Air pressures, air temperatures, wind speeds, and wind directions from selected stations (Keller et al. 1989) were examined in order to evaluate the behavior of these parameters for signature days in comparison to the respective monthly averages. First, to study the pressure variation over the northeastern Ross Ice Shelf, the pressure data recorded by AWS 00 and Russkaya Station were evaluated. Data for the latter station were obtained directly from the Australian surface charts. Mean pressures for each day were utilized. For 77% of signature days, the pressure recorded by one or both stations was lower than the respective monthly average (Table 2). Also, the mean pressure over the northeastern Ross Ice Shelf for all signature days was significantly smaller (at the 95% confidence level using a two-tailed t test) than the 5-month average. Finally, for 68% of signature days, the decrease of pressure in this area was accompanied by the passage of synoptic storms over the southern Amundsen Sea.

TABLE 2. Surface environment on signature days.

Percentage of signature days with a synoptic storm over the southern Amundsen Sea.	82%
Percentage of signature days with warmer temperatures at the southeastern corner of the Ross Ice Shelf.	82%
Percentage of signature days with reduced pressure over the northeastern Ross Ice Shelf.	77%
Percentage of signature days with reduced pressure and a synoptic storm over the southern Amundsen Sea.	68%
Percentage of signature days with warmer temperatures and reduced pressure.	73%
Percentage of signature days with warmer temperatures, reduced pressure, and the presence of a synoptic storm over the southern Amundsen Sea.	68%

Second, to study the air-temperature behavior over the southeast part of the ice shelf, daily average air temperatures measured by AWS 08 and 11 were calculated. These stations were selected because they are the closest to Siple Coast and can be affected by katabatic airflow coming from West Antarctica. The result for signature days was that in 82% (Table 2) of the cases, the air temperature at one or both stations was warmer than the respective monthly average. This confirms the warm characteristics of the air immediately above the ice surface in association with katabatic-wind signatures. Although the mean temperature for signature days at AWS 08 was not statistically different from the 5-month average, the same parameter was significantly different at better than the 95% confidence level for AWS 11 and for the composite of AWS 08, 11, and 25. Also, it was found that for 73% of signature days, the pressures recorded by AWS 00 and/or Russkaya Station were lower than the monthly average, and the temperatures measured by AWS 08 and/or AWS 11 were above average. Integrating the satellite, synoptic, and AWS analyses, the results indicate that 68% of signature days were associated with warmer temperatures around AWS 08 and 11, lower pressure over the northeastern Ross Ice Shelf, and the presence of a synoptic storm passing over the southern Amundsen Sea.

Third, to analyze the wind behavior on the southeastern corner of the Ross Ice Shelf, the wind data recorded by AWS 08 were studied. The daily mean behavior of the wind for each signature day was compared with its respective monthly average. For 80% of signature days, the daily mean wind speed was above average. Also, the average wind speed for all signature days was 3.1 m s^{-1} stronger than the 5-month average (3.9 m s^{-1}). This difference is statistically significant (95% confidence level), as is the same difference for the north–south (meridional) component of the wind. Moreover, although the difference between the mean direction for signature days (165°) and for the 5-month period (177°) was not statistically different, the directional constancy for signature days was 0.91, compared with 0.71 for the 5 months. These results indicate that the momentum required to mix the katabatic layer and raise the air temperature near the ice surface was present.

The winds at AWS 11 did not reveal a significant difference of speed for signature days with respect to the 5-month average. However, the vector-average direction for signature days was found to point more toward Beardmore Glacier. This again suggests that propagation of the katabatic wind from southern Marie Byrd Land far across the Ross Ice Shelf is accompanied by an intensification of the katabatic airflow from that part of East Antarctica adjacent to Siple Coast.

The AWS analysis described above indicates that northwestward propagation of the katabatic wind is likely to occur when the pressure field over the northeastern Ross Ice Shelf is below average. This is associated with the passage of synoptic-scale storms over the southern Amundsen Sea. The warm characteristics of the ice surface and the air immediately above it, linked to katabatic drainage observed on infrared satellite images, are confirmed by the AWS temperature analysis. The low-level warming occurs with higher wind speeds that are due to pressure gradient–supported katabatic winds.

5. Discussion

The preceding analyses can be summarized as follows. Katabatic winds over the southeastern corner of the shelf are a frequent phenomenon being observed on almost all satellite images for which the presence of dark signatures could be evaluated. A similarly high frequency of katabatic-wind signatures was found previously to be characteristic of the Ross Ice Shelf near Byrd Glacier (Bromwich 1989a). These features are situated downwind of confluence regions in the near-surface winds over the sloping ice fields, which results in intensified and more persistent katabatic winds at the coast (Fig. 4). The synoptic and mesoscale analyses show that when the isobars are cyclonic over Marie Byrd Land and the Ross Ice Shelf (Fig. 5b), the katabatic winds from West Antarctica can propagate northward along the isobars and merge with the drainage flows from East Antarctica. The combined negatively buoyant airstream can propagate horizontally at least to the edge of the Ross Ice Shelf, a distance of 1000 km, and sometimes much farther to the north. These favorable synoptic conditions were associated with the passage of synoptic storms over the southern Amundsen Sea. The cold trough suggested by the 1000–500-hPa thickness analysis for signature days (Fig. 5f) confirms the assumption that the dark signatures observed on infrared satellite images are an effect of cold drainage that goes down onto the shelf and that the warming of the airflow occurs by vertically mixing highly stratified air adjacent to the ice surface (Fig. 3). According to the AWS and synoptic analyses, the occurrence frequency of katabatic airflow far across the ice shelf, obtained from evaluations of satellite imagery for April–August 1988, could be higher than 14% but probably does not exceed 21%. This is suggested by the fact that warmer temperatures over the southeastern ice shelf, along with lower air pressures and the passage of a synoptic storm across the southern Amundsen Sea, were also found on days for which the presence of dark signatures could not be determined because the Ross Ice Shelf was overcast or the satellite information was not available.

The intensified synoptic pressure gradient force over Marie Byrd Land on signature days does not appear to enhance the katabatic winds crossing Siple Coast because this force acts primarily at right angles to the downslope buoyancy force that drives the drainage airflow. Furthermore, frontal cloud, which usually covers parts of Marie Byrd Land on signature days, would tend to reduce the stratification of the near-surface air, thus decreasing the downslope buoyancy force. Inspection of Ball's (1960) analysis suggests that isobars parallel to terrain contours do not lead to enhanced airflow convergence but may slightly alter the orientation of the resulting airstream. The katabatic winds crossing Siple Coast are inferred to be negatively buoyant in relation to the boundary layer over the Ross Ice Shelf apart from the lowest few tens of meters of very cold, radiatively cooled air near the ice surface. The katabatic winds propagate across the shelf for extended distances parallel to the regional isobars with apparently well-defined lateral boundaries (compare the sharp lateral edges to the katabatically warmed area in Fig. 2a). Examples of negatively buoyant boundary-layer jets propagating horizontally for hundreds of kilometers without synoptic pressure-gradient support are known (e.g., Parish and Schwerdtfeger 1977; Clarke 1988) but exhibit the expected inertial turning.

The katabatic winds that blow down from East Antarctica on signature days are probably accelerated down the local pressure gradients that are oriented along the axis of the glacier valleys (compare Overland 1984) passing through the Transantarctic Mountains (i.e., they form gap winds that emerge from sloping valleys). Beyond the exit to the valleys, rapid adjustment to geostrophic conditions takes place over the nearly flat ice shelf, and the katabatic winds merge into the mountain-parallel flow that originates farther to the south. Downwind of the Byrd Glacier area, ageostrophic katabatic flow for hundreds of kilometers over flat terrain is associated with the large mass flux issuing from the ice sheet.

Clearly the present qualitative analysis of infrared satellite imagery can not quantitatively define the relative importance of the katabatic airflows from West and East Antarctica to the mountain-parallel airstream studied here, but it does originate from West Antarctica. One case was found previously where it appeared that the mountain-parallel air mass was entirely supplied by katabatic drainage from East Antarctica (Bromwich 1992). For the foreseeable future, the observational systems are unlikely to be able to resolve such questions. Regional numerical modeling of surface airflow will be used to explore this phenomenon in the near future.

Finally, some indications of the broader-scale impact of the mountain-parallel airstream can be provided. Basically, the formation of low-level cold-air outbreaks from the Ross Sea sector has been described. Fitch and Carleton (1991) investigated the formation of mesoscale cyclones over the Southern Ocean from 100°E eastward to 80°W and to the south of 50°S during some of the months studied here: April, June, and August, as well as October, 1988. They concentrated on "active" days, which were defined as the the central day of a series having a high frequency of formation of mesoscale cyclones in their entire study area during each month. The formations were concentrated to the north and northwest of the Ross Sea. The composite fields of sea level pressure, 500-hPa height, and 1000–500-hPa thickness for their active days were very similar to the average fields shown in Fig. 5 for signature days. This strongly suggests (as generally surmised by Fitch and Carleton) that mesoscale cyclones frequently form in the present cold low-level airstream as it is advected northward across the sea ice and over the open ocean beyond; in-depth comparisons of the individual events are needed to substantiate this conjecture.

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