Instrumented Aircraft Observations of the Katabatic Wind Regime Near Terra Nova Bay*

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ABSTRACT

Two aircraft missions to sample the boundary layer dynamics associated with the intense katabatic wind regime at Terra Nova Bay, Antarctica were flown on successive days in early November 1987. Light winds averaging 5 m s^{-1} were monitored at the 170 m flight level over the interior of the ice sheet. Dramatic acceleration of the airflow and abrupt 5°–7°C cooling were encountered on both days near the head of Reeves Glacier just upslope from where the terrain steepens considerably. These results suggest that much of the airflow convergence which sustains the coastal katabatic winds is forced by localized topographic channeling into Reeves Glacier, and that the descending airstream is negatively buoyant. The horizontally propagating katabatic winds were followed for 250 km directly offshore and for 200 km southward parallel to the Victoria Land coast; the airstream momentum gradually decreased along both flight paths.

In conjunction with the descent of negatively buoyant air down Reeves Glacier and horizontal flow across Nansen Ice Sheet, thermal infrared satellite images showed a warm katabatic signature along the trajectory. This paradox is explained by vigorous vertical mixing within the katabatic layer which makes the temperature of the emitting snow surface beneath the katabatic jet much warmer than that for adjacent light-wind areas. Thermal images often suggest that katabatic winds propagate for hundreds of kilometers beyond the slope break; this interpretation is strongly supported by the offshore aircraft data.

Primitive-equation model simulations for the aircraft flight level reproduced the light, nearly frictionless, contour-parallel winds seen in the interior. The model also reproduced the abrupt airflow acceleration near the head of Reeves Glacier. Maximum speeds within the steeply-sloping glacier valley are underestimated, however, and it appears that a much finer grid spacing than 32 km is required to accurately simulate katabatic drainage through the complex coastal mountains.

1. Introduction

Katabatic winds are among the most spectacular meteorological phenomena of the Antarctic continent. Surface winds in excess of 50 m s^{-1} occur with some frequency over the steeply sloping coastal perimeter of the continent giving rise to spectacular displays of cloud formations associated with hydraulic jump phenomena (Ball 1957). The existence of these strong, persistent drainage flows has been known from the time of the earliest expeditions onto the face of the continent nearly 80 years ago. The extreme strength of the katabatic winds experienced by the Mawson expedition to Cape Denison along the coast of Adelie Land (see Fig. 1) in 1911–14 offered striking testimony to the importance of the drainage flows on the climate of the Antarctic coastal environs and has served as an impetus for continuing studies of Antarctic slope flows. There is a strong interplay between the thermal field and underlying ice terrain in establishing the katabatic wind. Prolonged periods of strong radiational cooling over the sloping ice surface enable a production of cold, negatively buoyant air in the lowest levels of the atmosphere. The cooling of the ice slopes leads to the development of a pressure gradient force directed down the fall line. This terrain-induced pressure gradient force has been called the "sloped-inversion" force (Mahrt and Schwerdtfeger 1970) to emphasize the topographic–thermodynamic association. Antarctic slope flows can generally be classified into two regimes based on the steepness of the local terrain slope. Drainage flows over the gently sloping interior ice fields are quasi-geostrophic (Parish and Waight 1987) with only weak to moderate wind speeds and flow directions at large angles from the fall line. The resulting katabatic flows over the near-coastal sections of Antarctica where ice slopes display a dramatic increase reflect the enhanced sloped-inversion force and are more intense and more closely aligned with the fall line. Modeling results

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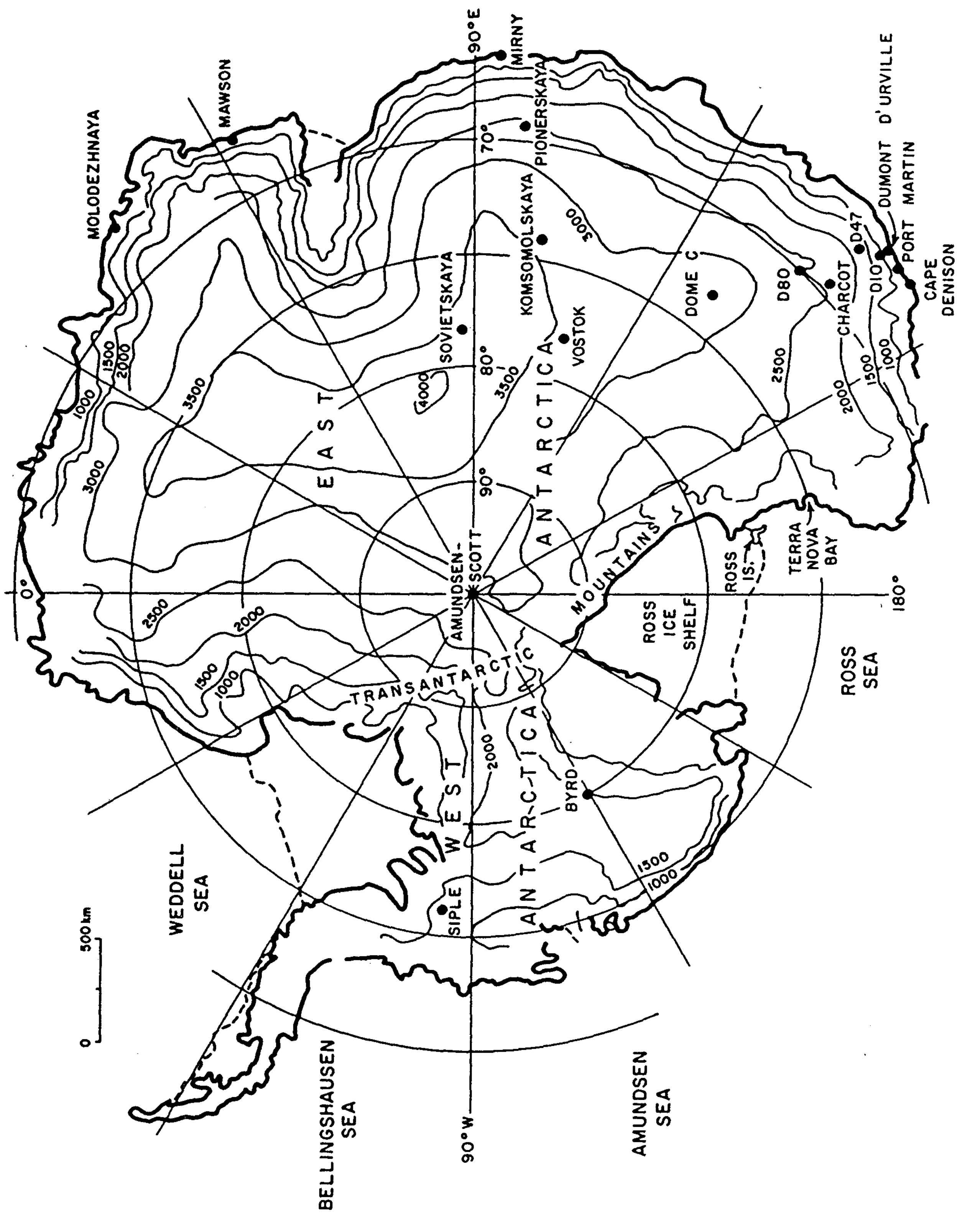

FIG. 1. The Antarctic continent and selected geographical features and scientific stations. Height contours in m.

(Parish and Waight 1987) suggest the coastal drainage flows are nearly antitriptic as the friction force is considerably greater than the Coriolis force.

Although the strongest katabatic flows are associated with the near-coastal environment, the roots of the drainage winds can often be traced deep into the continental interior. As noted in Parish and Bromwich (1987), the surface wind pattern over the Antarctic interior is highly irregular. In certain sections of the interior cold air becomes channeled into narrow zones focused on the coastline. Such "confluence zones" represent regions of enhanced supplies of negatively buoyant air which enable coastal katabatic winds to become anomalously strong and persistent. Numerical experiments by Parish (1984) verify the potential importance of the interior windfield on the coastal wind regime and suggest confluence zones can lead to a katabatic wind intensification of 50%–100%. The surface streamline map of Parish and Bromwich (1987, see Fig. 2) clearly reveals a number of confluence zones with the flow convergence most striking upslope of Adelie Land. Mather and Miller (1967) note that the katabatic winds at Cape Denison along the coast of Adelie Land are approximately 75% stronger than found elsewhere about the continental perimeter.

Terra Nova Bay is another region seemingly affected by flow convergence in the interior. Observations suggest that the katabatic regime in the vicinity of Terra Nova Bay is highly anomalous with intense, persistent drainage flow for nearly nine months of the year. The site has relevance in the history of Antarctic exploration. Scott's Northern Party was forced to spend the winter of 1912 on Inexpressible Island which is downwind from the foot of Reeves Glacier and adjacent to Terra Nova Bay; journals kept by party members included extensive meteorological data which were reexamined by Bromwich and Kurtz (1982, 1984) in order to quantify the katabatic winds at Terra Nova Bay. Observations of the intense katabatic winds near Inexpressible Island made by members of that early expedition served as the only database for over 70 years. Surface wind data collected between 1984 and 1987 by an automatic weather station (AWS) located on Inexpressible Island show that the katabatic wind speed averages 17 m s^{-1} for the fall months of February to April with speeds mostly varying between 10 and 30 m s^{-1} (Bromwich 1989). Currently a comprehensive study of the katabatic regime at Terra Nova Bay is underway. Four new AWS units were established during the 1987/88 field season about the Reeves Glacier and an equal number were deployed a year earlier by the Italians who have established an Antarctic base in Terra Nova Bay. In addition to the data obtained from the AWS platforms, satellite imagery has offered valuable information as to the spatial extent of the katabatic winds. Thermal infrared images clearly show the flow is able to maintain its identity for hundreds of kilometers past the edge of the ice slope. This finding is in direct contrast with conclusions reached from earlier studies (Tauber 1960; Weller 1969) and offers testimony as to the magnitude of the cold air transport provided by katabatic winds. More recently, documentation of Terra Nova Bay katabatic winds has been obtained from data collected during a series of instrumented LC-130 flights in the lower boundary layer over Reeves Glacier and the interior confluence zone during November of 1987. The purpose of this paper is to report on the katabatic wind measurements from the recent flights and integrate the observations within the conceptual framework of the confluence zone-forced Terra Nova Bay katabatic wind regime.

2. LC-130 flight strategy

For the last decade or so Antarctic scientists have had access to an LC-130 instrumented aircraft for meteorological research. Details of the data system are found in Renard and Foster (1978); an itemization of the onboard instrumentation is given in Gosink (1982). Recently a portable data acquisition and real-time display system was designed and built for the National Science Foundation's Division of Polar Programs by the Cloud and Aerosol Research Group at the University of Washington to be used on the LC-130. In the study of katabatic winds near Terra Nova Bay, a total of 18 data channels of meteorological and navigational parameters were recorded at 1-s intervals on high density magnetic tape.

Three instrumented LC-130 flights were conducted during November 1987. Two of the missions focused on boundary layer measurements of the katabatic stream and the third was to photograph the sastrugi patterns well into the interior of the continent to delineate the time-averaged windfield and hence the confluence zone; sastrugi are aeolian-forced features at the snow surface which are aligned parallel to the prevailing wind direction. Results of the last flight will be presented in a separate article. With the confluence zone construct in mind, flight paths for the two low-level missions were designed to capture the mechanisms at work in forcing the strong katabatic winds in the Terra Nova Bay region. In-flight refinement of the paths was made periodically to more appropriately sample the katabatic wind. Data were collected within the katabatic layer over a broad area from the confluence zone in the interior of the continent down Reeves Glacier in the steeply sloping coastal region and extending some considerable distance offshore. In addition, several soundings were taken to depict the vertical temperature structure at selected locations. Owing to the rate of ascent and inherent problems with the inertial navigation system-derived winds during turns, the vertical profiles of the motion components are considered suspect and will not be presented. With the exception of soundings, a flight level of approximately 170 m above ground level was maintained although local terrain

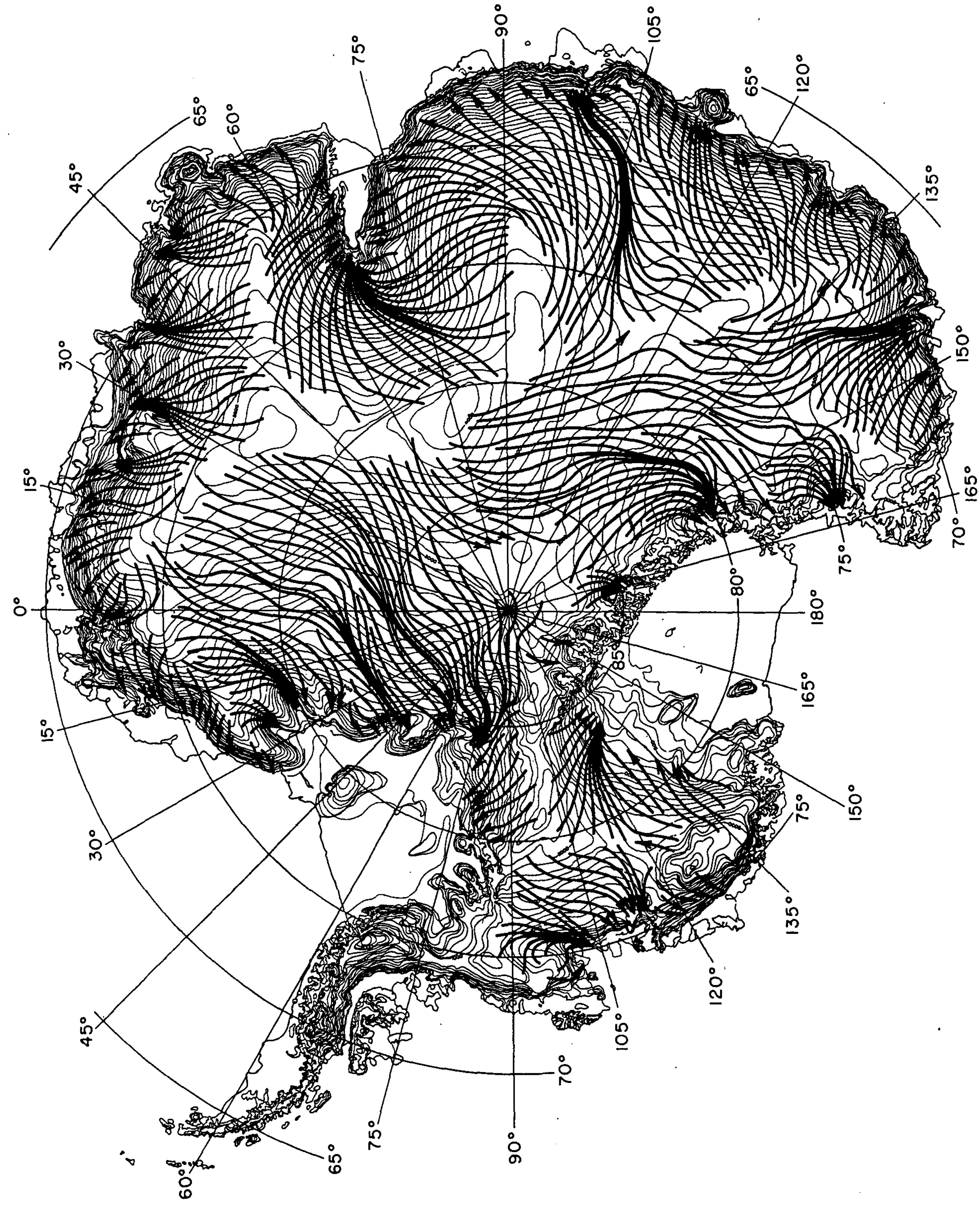

FIG. 2. Time-averaged near-surface wintertime streamlines of cold air drainage over Antarctica [after Parish and Bromwich 1987].

undulations and/or turbulence at times introduced variations on the order of 20 m or so. Atmospheric visibility was unrestricted in all case study flights. The choice of late October–early November as the time to study katabatic winds was made for logistical reasons. McMurdo Station, the Ross Island base for flight operations, opens for summer field season activities about the middle of October. The LC-130 aircraft is not available for scientific research in Antarctica before the end of October. The flights were conducted as early in

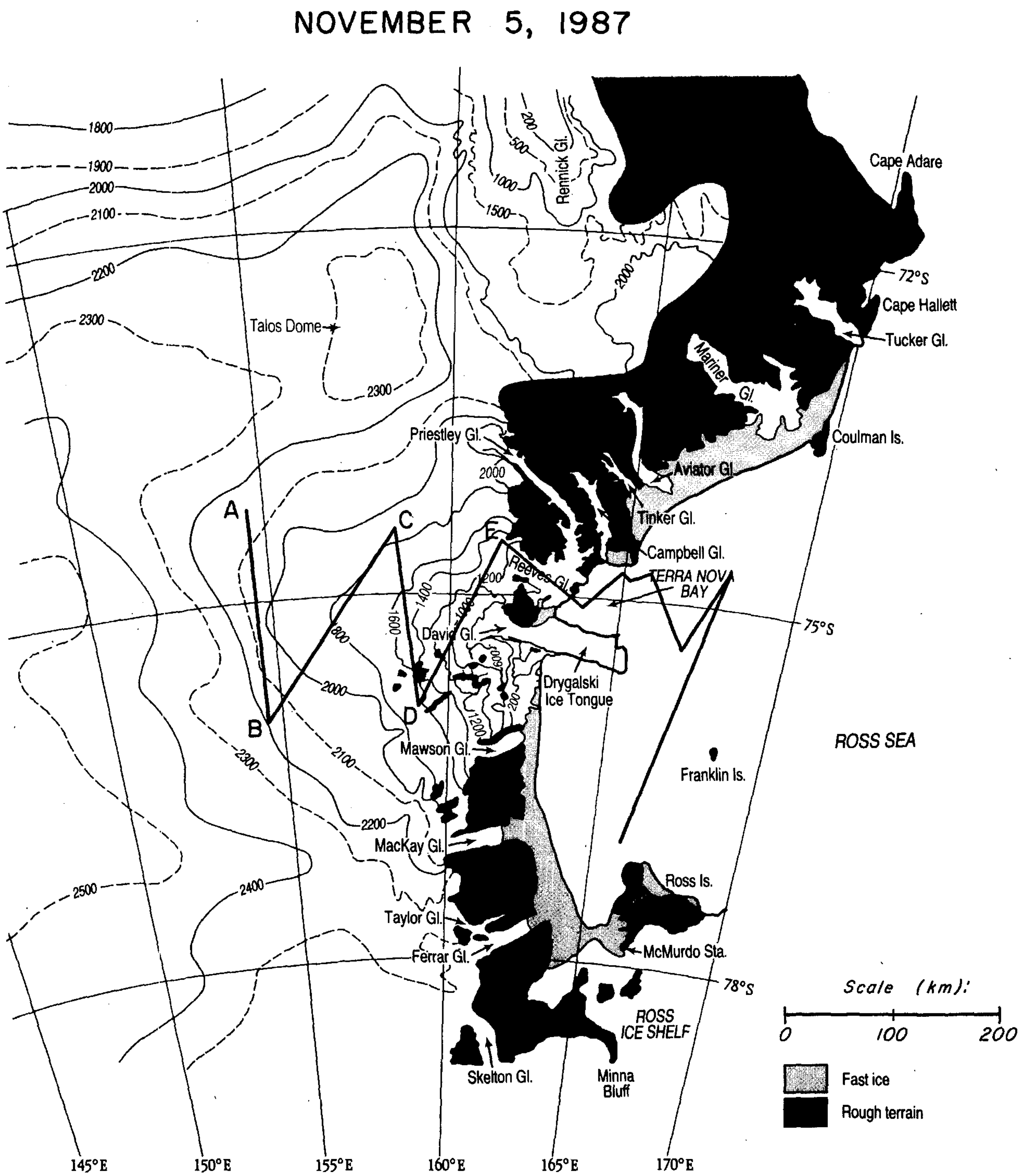

FIG. 3. LC-130 flight tracks in the Terra Nova Bay region for (a) 5 November 1987 case study and (b) 6 November 1987 case study.

the austral spring as possible to ensure that the katabatic winds would still be active. The flight paths for the two katabatic wind case studies are illustrated in Fig. 3.

Actual decisions to launch a case study flight were made based on the inferred intensity of the katabatic wind at Terra Nova Bay. The AWS situated on Inex-

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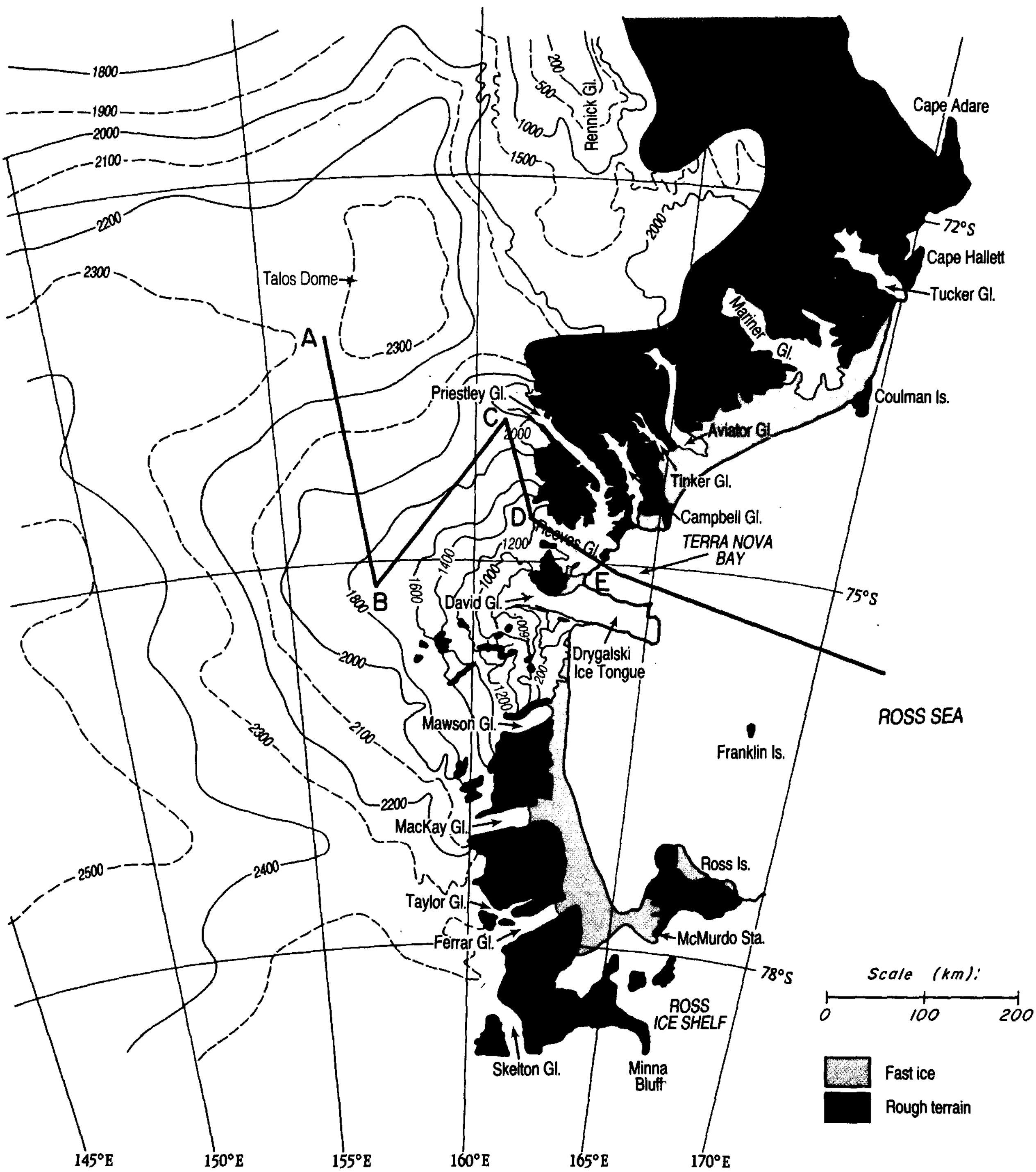


FIG. 3. (*Continued*)

pressible Island had been destroyed during the course of prolonged exposure to high intensity winds during the Antarctic winter season and thus could not be used as guidance, but certain proxy methods of estimating the katabatic wind were available. During periods of pronounced drainage flow off the continental ice dome, a characteristic infrared signature is seen in the glaciers along the Transantarctic Mountains. These thermal images of drainage flow show up as dark (warm) features which can often be followed for hundreds of kilometers over pack ice or ice shelves (Kurtz and Bromwich 1985; Stearns and Wendler 1988). Representative thermal infrared images for the case study flights are presented in Fig. 4. Katabatic drainage leaves a characteristic thermal signature with sharply defined lateral boundaries even after the airstream leaves Reeves Glacier (R) and crosses the flat Nansen Ice Sheet to reach Terra Nova Bay (T). The offshore presence of katabatic winds can be inferred from the large warm area which extends beyond Terra Nova Bay; in Fig. 4a and 4c this region tends to merge into the comparatively warm pack ice over the western Ross Sea, but on the original images these two zones are distinct. Simultaneous visible images show that this bay warmth is not primarily due to open water or thin ice as most of the surface is covered by sea ice which thickens to the east, and only

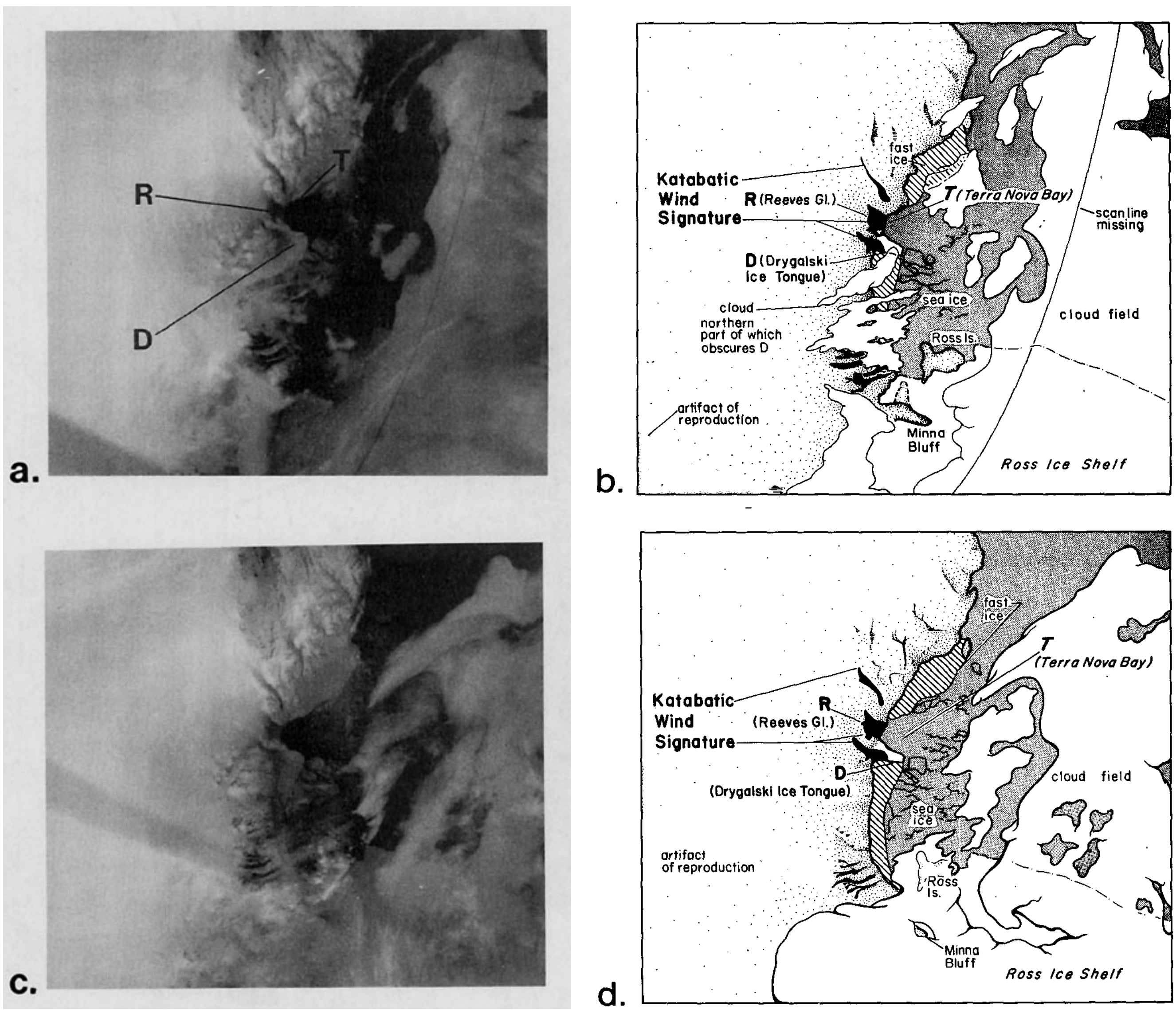


FIG. 4. NOAA AVHRR thermal infrared imagery of the katabatic wind regime near Terra Nova Bay. (a) 5 November 1987 at 0833 UTC (2033 LT). (b) Explanation sketch for image in panel (a). (c) 6 November 1987 at 0641 UTC (1841 LT). (d) Explanation sketch for image in panel (c). Image data were processed by Robert Whritner of the Antarctic Research Center at Scripps Institution of Oceanography from HRPT transmissions recorded by U.S. Navy personnel at McMurdo Station.

a narrow polynya (area of open water surrounded by ice) is present along the western shore. A reasonable explanation is that strong vertical mixing within the katabatic layer causes the surface temperature to be much warmer than that in adjacent light-wind areas. Wind information can usually be obtained from thermal images of the interior of the continent. Often a thermal convergence pattern can be seen directly upslope from Reeves Glacier (Kurtz and Bromwich 1983), although this is not evident in Fig. 4a and 4c due to the low interior wind speeds which are discussed below. Significant warming is shown by the imagery as the flow moves down the glacier, presumably due to the adiabatic compression of the air during descent. The fact that the katabatic thermal signature shows up warmer than the surrounding environment is paradoxical and has been alluded to by several authors, including Kurtz and Bromwich (1985), since katabatic winds are generally considered to be of the bora-type drainage flows that are denser than the air which is replaced. Despite appearance to the contrary, the katabatic wind must be negatively buoyant. The clear topographic channeling and long spatial extent on many thermal images can only indicate a negatively buoyant phenomenon. This topic will be addressed in more detail later.

Additional confirmation of well-defined katabatic winds at Terra Nova Bay is provided by the occurrence of northwesterly winds detected by the AWS situated atop Franklin Island some 200 km from Inexpressible Island. The katabatic streams issuing from the Reeves and David glaciers are able to maintain their identity for extended distances and reach Franklin Island with some frequency (Kurtz and Bromwich 1985; Bromwich 1986). Bromwich (1986) has shown the wind directions at Franklin Island have a bimodal distribution with major components from either the south, the direction of prevailing synoptically forced winds, or from the northwest, associated with the strong katabatic outflow in the vicinity of Terra Nova Bay. The Franklin Island AWS was functioning throughout the case study period and provided invaluable confirmatory information on the katabatic winds. For each case study flight, both satellite and the Franklin Island AWS observations offered positive indication as to the occurrence of katabatic winds near Terra Nova Bay.

3. Katabatic wind case studies

a. 5 November 1987

The initial Terra Nova Bay case study flight occurred on 5 November; the data were collected over a 3-hour period commencing at 2000 LT (12 hours ahead of UTC). As illustrated in Fig. 3a, the flight track followed a zigzag pattern covering the interior confluence zone, down along Reeves Glacier to Terra Nova Bay and then southward to the terminus of the katabatic stream. To illustrate the variation of the basic state parameters throughout the course of the flight, a series of time sections of 10-s averages of state variables has been prepared (Fig. 5). End points of the respective legs are indicated by tick marks at the top and bottom of the time sections; the times that soundings were taken are indicated by the breaks in the individual traces. The temperature and potential temperature profiles are shown in Fig. 5a. Over the interior region at a height of approximately 170 m above ground level (points A to E) cold temperatures ranging from 240 K over the highest terrain to near 255 K over lower portions of the continent are found. Potential temperatures show smaller variations and over most of the interior average approximately 270 K. The boundary layer thickness over interior sections of Antarctica is generally quite shallow owing to the stable conditions and low wind speeds. It was expected that the nearly constant 170 m flight level would be near the top of the boundary layer over the continental interior. There is a strong indication, however, that the topographically induced processes still play a major role at this height. For example, small-scale variations in the temperatures can be related to the changes in the underlying terrain height. This is illustrated by the temperature trace between, for example, points D and E in Fig. 5a. As is shown on the flight track in Fig. 3a, the terrain height between D and E decreases sharply for the first half of the leg and then increases by approximately the same amount during the second half. The temperature profile over the leg is a mirror image of the terrain height variations with the temperature increasing as the underlying terrain height decreases. Little variation in potential temperature is seen in the interior of the continent from point A to E, which implies a near-adiabatic alongslope temperature gradient, a feature which has been documented in previous observational and numerical studies of the katabatic wind. Alongslope temperature profiles have been discussed by a number of authors including Wendler and Kodama (1985) and Kodama and Wendler (1986) who note that superadiabatic profiles are found along the slope of Adelie Land in East Antarctica for approximately 10 months of the year. Parish and Waight (1987) show that near-adiabatic profiles appear in numerical simulations of the katabatic wind and are a result of the strong modification of the thermal pattern in the lower atmosphere which occurs during the katabatic wind evolution. This temperature pattern suggests the influences of the underlying surface are significant at the flight level. Wind information collected during the various legs supports this notion.

The time traces of wind speed and wind direction are also illustrated in Fig. 5. In the continental interior (points A to E), wind speeds (Fig. 5b) are generally light to moderate and average approximately 6 m s^{-1}. The observed wind directions (Fig. 5c) are closely related to the orientation of the underlying terrain slope. Near the top of the boundary layer over the interior of

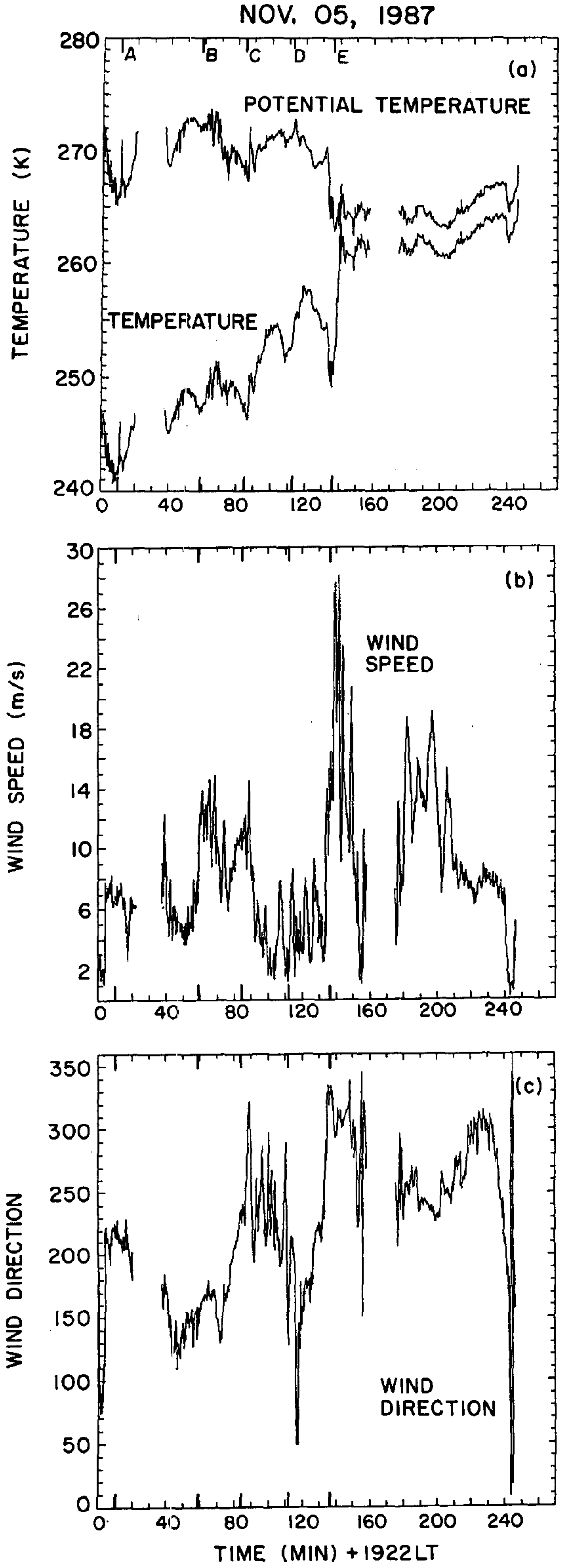
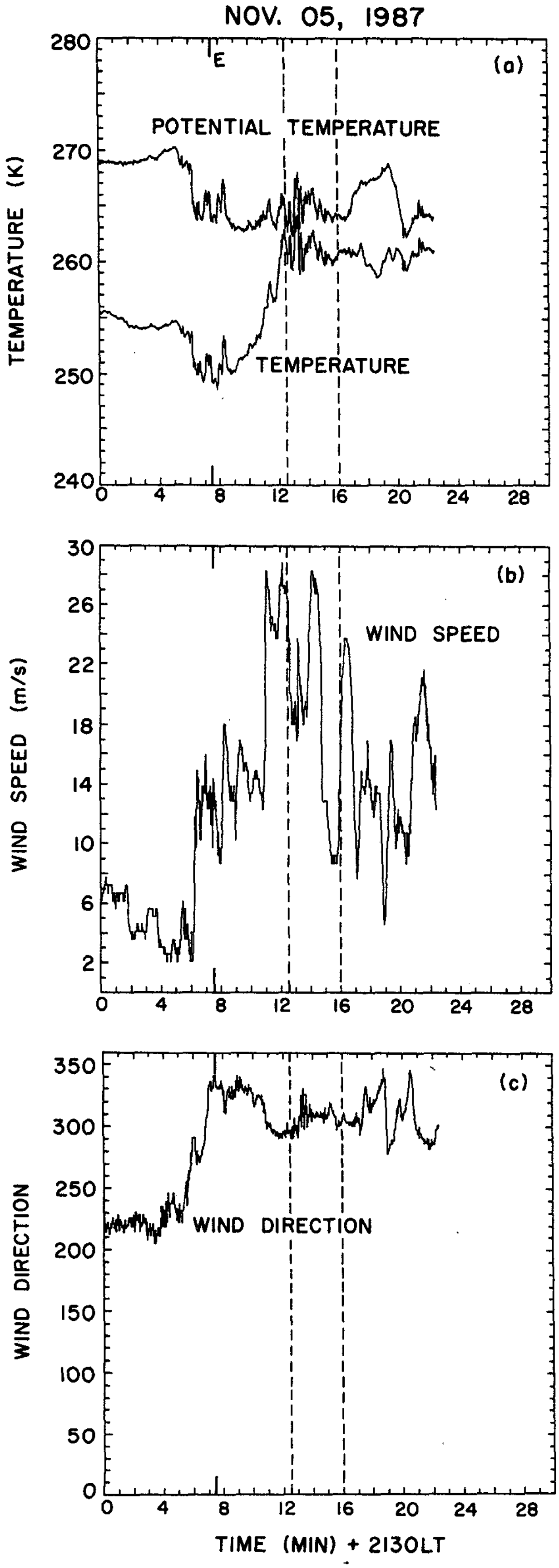


FIG. 5. Time sections of (a) temperature and potential temperature, (b) wind speed, and (c) wind direction averaged over 10-s intervals for the 5 November 1987 case study. End points of flight legs in Fig. 3 denoted by labeled tick marks along time axis.

the continent, the friction force should be quite small. This assertion is in contrast to the inferences of Manins and Sawford (1979) who suggest that the interfacial stress at the top of the katabatic layer is a dominant retarding force on the katabatic flow. No strong wind shear was found at the top of the interior drainage flow and in fact vertical soundings suggest a gradual transition to very weak winds aloft. For katabatic wind situations in which the friction force is small and in absence of synoptic forcing, the flow should nearly parallel the underlying terrain contours with highest terrain to the left, a negative thermal wind such as discussed by Lettau and Schwerdtfeger (1967). As a consequence, the confluence zone pattern in Fig. 2 which is representative of the near surface layer must be shifted to correspond to a wind regime oriented in a more height contour-parallel direction. It is to be expected that winds are shifted some 30° or so in a counterclockwise sense from those near the surface. An example of the topo-dynamic forcing of the wind can be seen in the leg A–B in Fig. 5c. By inspecting Fig. 3a, the downslope direction of the underlying ice terrain varies from approximately 310° at A to 230° or so at B. The wind directions corresponding to this leg change from 220° at A to 150° at B, generally 90° from the fall line and totally compatible with the concepts discussed above. Similar changes can be seen along the remaining three interior flight legs, underscoring the dominance of terrain-induced processes in forcing the boundary layer wind field over the interior. The observed wind directions are therefore consistent with the confluence zone simulation of Fig. 2 inland of Terra Nova Bay.

Point E marks the start of the flight path down Reeves Glacier and abrupt changes occur in both temperature and wind. Unmistakable signatures in both temperature and wind indicate the presence of strong katabatic flow. Time traces (one second values) of the state parameters associated with the descent are shown in Fig. 6. In Reeves Glacier the ice terrain drops sharply over a 50 km distance from approximately 1200 m at the head to near sea level at the foot. Ice from Reeves and Priestley glaciers merges to form Nansen Ice Sheet, which is nearly flat and has an elevation of about 30 m. Inexpressible Island, situated on the eastern side of Nansen Ice Sheet, is about 34 km from the terminal ice slopes of Reeves Glacier. Katabatic winds that reach Inexpressible Island, therefore, must have traveled some 34 km over flat ice terrain with presumably little dissipation. The flight track crossed the head of Reeves Glacier, proceeded along the northern edge of the glacier valley, traversed Nansen Ice Sheet and passed just south of Inexpressible Island. Fig. 6a shows the tem-



perature and potential temperature traces associated with this flight path. Reference point E is shown for comparison with Fig. 3a. A strong increase in the temperature is seen during the descent down the glacier, presumably due to the attendant adiabatic compression of the airstream as it reaches lower elevations. Note, however, that the potential temperatures display an abrupt decrease corresponding to a point at the head of Reeves Glacier, indicating that while the katabatic stream along and beyond Reeves Glacier is between 10°–15° warmer than found at elevated regions upslope in the interior, the air is potentially colder and hence is negatively buoyant. The cold air must originate from below the 170 m flight level and its presence is indicative of strong mixing in the lower atmosphere. The wind speed trace (Fig. 6b) underscores this point. A sharp increase of the wind from 3 m s^{-1} to 12 m s^{-1} accompanies the drop in potential temperature. This suggests that cold air near the surface is mixed upward by convergence associated with the dramatic acceleration of the katabatic winds. This sudden onset actually occurs before point E in Fig. 3a is reached and corresponds to the point the aircraft enters the catchment at the head of Reeves Glacier. From point E, the flight track continues down the northern half of the glacier, transits Nansen Ice Sheet and passes just south of Inexpressible Island. The strongest katabatic winds measured were near 30 m s^{-1} and occurred both in the lowest reaches of Reeves Glacier and out over Nansen Ice Sheet. It is unclear if these sharp increases in katabatic wind speed represent just localized changes because the height of the aircraft above the terrain varied from 150 m to 300 m. These aircraft height oscillations were due to rapid changes in the elevation of the underlying terrain and to moderate turbulence encountered during course of the flight leg. As shown by Fig. 6c, the wind directions during the passage down and beyond the glacier were consistently from the northwest and along the orientation of the glacier fall line.

b. 6 November 1987

The second case study of katabatic winds in the vicinity of Terra Nova Bay took place the following day. Again, satellite imagery and AWS data from Franklin Island confirmed the existence of katabatic winds issuing from Reeves Glacier. The flight commenced at 2100 LT and the track, illustrated in Fig. 3b, follows an abbreviated zigzag pattern similar to that of the previous day over the interior and down the center of Reeves Glacier, continuing in a southeastward direction past Inexpressible Island for several hundred ki-

FIG. 6. Time sections of (a) temperature and potential temperature, (b) wind speed, and (c) wind direction at 1-s intervals down Reeves Glacier and across Nansen Ice Sheet for the 5 November 1987 case study. Dashed lines indicate position of the foot of Reeves Glacier and Inexpressible Island, respectively, and enclose Nansen Ice Sheet.

lometers out to sea. Time sections of 10-s average values of the temperature and wind parameters along the flight path are illustrated in Fig. 7. Again, reference points from Fig. 3b are indicated by tick marks along the time axis. Over the interior of the continent (points A–D), the temperatures (see Fig. 7a) range between 248 K and 255 K and show a similar relationship to the height of the underlying terrain as seen in the 5 November case. The initial leg stretches from point A, situated over ice terrain at a height of 2300 m, to point B, which lies over terrain some 1700 m above sea level. The temperature trace for this leg is a mirror image of the underlying terrain height and shows warmer temperatures at the lower elevations. The corresponding potential temperature profile shows little variation over the interior which suggests the temperature changes may be explained by adiabatic compression as the flow moves to lower elevations. The wind speeds (Fig. 7b) from A to D are quite light (averaging 5 m s^{-1}); there is a suggestion that the wind speeds may be enhanced directly upslope of the head of Reeves Glacier. Local maxima in the interior wind speeds are found midway between points A–B and B–C. Wind directions are compatible with the confluence zone concept discussed earlier and show a clear relationship with the underlying terrain orientation. For example, from point A to point B, the direction of the fall line changes from near 360° at A to approximately 250° at B. The wind directions at the 170 m flight level show a consistent pattern of backing from a direction of 290° at A to near 150° at B, which is congruous with expected behavior of terrain-induced geostrophic winds. A similar coherent wind–topography relationship can be found along the leg B–C. This strong coupling of the wind to the terrain offers additional testimony to the Parish and Bromwich (1987) near-surface simulation of time-averaged katabatic winds over the Antarctic continent and especially of the confluence feature situated in the interior upslope from Reeves Glacier.

As seen in the previous example, abrupt changes in wind and temperature occur near the head of Reeves Glacier. Figure 8 is an expanded look at the flight path and temperature and wind information plotted at one second intervals. The flight track (see Fig. 3b) passes near the head of Reeves Glacier, descends to Nansen Ice Sheet and crosses the coast to the south of Inexpressible Island. A sharp break in the temperature and potential temperature traces (Fig. 8a) is apparent at the 15-minute mark, indicating the aircraft had encountered a significantly colder temperature regime. The temperature drop at this sharp interface appears to be 5°–7°C. This point corresponds to the initial jump in the wind speed (Fig. 8b) and again is suggestive of upward turbulent mixing of the cold surface air. Wind speeds averaged 20 m s^{-1} through the course of the descent of Reeves Glacier with peak winds attaining speeds near 30 m s^{-1}. Speed variations near the foot of Reeves Glacier are associated with marked changes

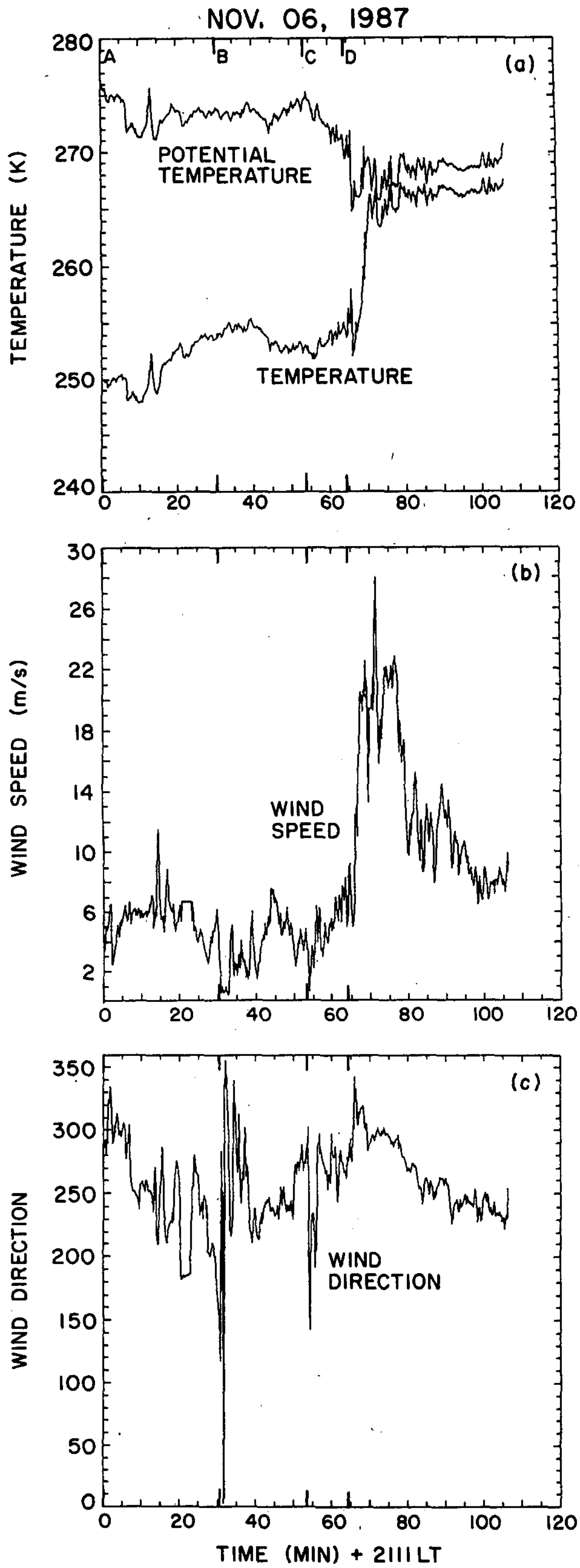


FIG. 7. As in Fig. 5 except for 6 November 1987 case study.

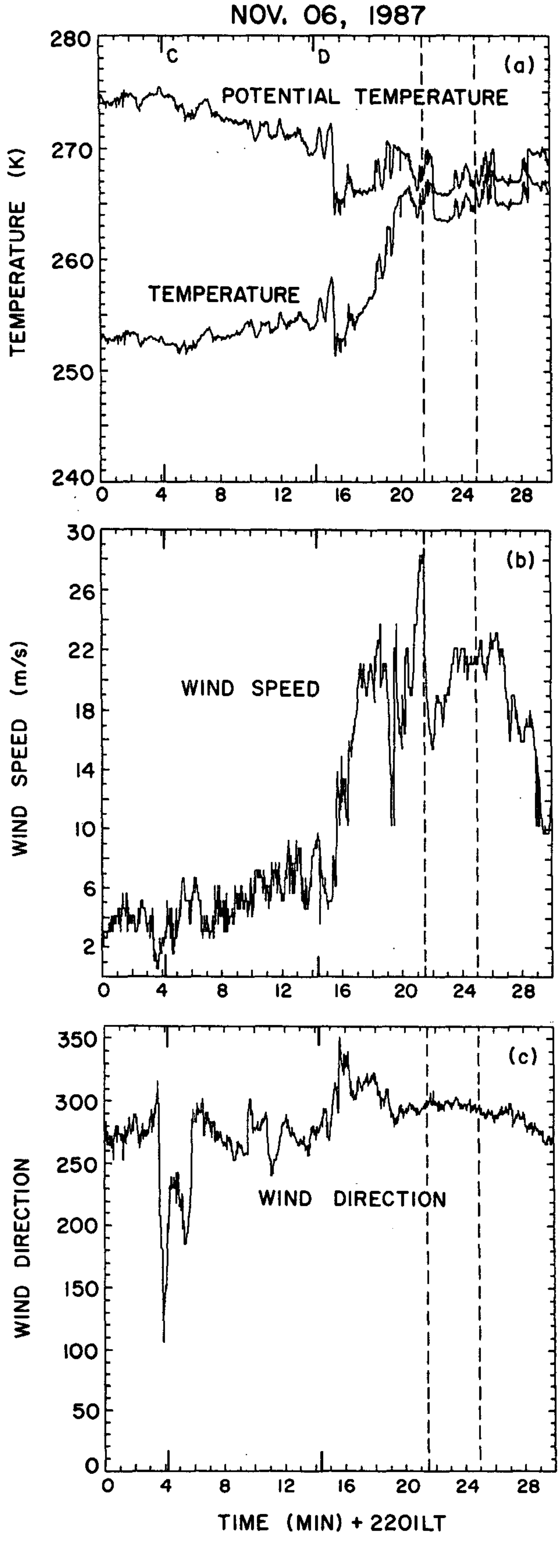


FIG. 8. As in Fig. 6 except for 6 November 1987 case study.

in the terrain clearance of the aircraft. Wind directions (Fig. 8c) are from 300° within and beyond the confines of the glacier. It is interesting that the strong katabatic winds commenced with such abruptness; in a distance of slightly over 10 km wind speeds increased from 5 m s^{-1} to over 20 m s^{-1}. This dramatic change occurs at approximately the 1200 m contour at the head of the Reeves Glacier and is consistent with the thermal signature and onset of the katabatic wind seen in the 5 November case study. Furthermore, these changes approximately coincide with the upwind edge of the katabatic thermal signatures shown in Fig. 4a and 4c. There appears to be no suggestion that strong katabatic winds are found in the interior above approximately the 1500 m contour.

The dramatic suddenness with which the strong katabatic regime becomes established was unexpected and deserves comment. Although the terrain slopes show a significant increase in the vicinity of Reeves Glacier, the strong winds do not seem to be linked exclusively to the topography. Rather, the location of the initial katabatic wind signatures at the head of the glacier seems to be more relevant. The confluence zones depicted in Fig. 2 suggest the nature of the interior wind field upslope of Terra Nova Bay is significantly different from that observed upslope from the Adelie Land coast. The Terra Nova Bay confluence zone appears strongest at the head of Reeves Glacier and little evidence of a converging wind field can be seen above the 2000 m contour. By contrast, the Adelie Land confluence zone can be traced much farther into the interior. It is probably not surprising, therefore, that strong katabatic winds have been reported deep into the interior of Adelie Land some 400 km from the coast (see Parish 1981) whereas the strong katabatic winds near Terra Nova Bay seem focused within the confines of Reeves Glacier. The steep mountains immediately north of the Reeves Glacier entrance cause the approaching westerly airstream to pile up and be deflected into the head of the glacier (Bromwich et al. 1988). The resulting convergence allows a local strengthening of the airstream only in the vicinity of Reeves Glacier, and the transport to 170 m altitude of air that came from the surface contributes to the associated potential temperature decrease. A similar confluence zone can be seen in Fig. 2 near Byrd Glacier; satellite imagery often reveals a katabatic signature near Byrd Glacier similar to that observed near Terra Nova Bay (Kurtz and Bromwich 1985; D'Aguanno 1986).

4. Model simulations of the Terra Nova Bay katabatic winds

Numerical simulations have been conducted in order to depict the confluence zone in the continental interior and evolution of the katabatic wind regime in the vicinity of the Terra Nova Bay region (Parish 1987; Bromwich et al. 1988). Previous emphasis has been placed on the wind and temperature fields in the lowest levels of the atmosphere, especially the association of the confluence zone with the katabatic wind intensity. Here the results of the model simulations in the upper portion of the boundary layer will be compared with the LC-130 instrumented observations. The numerical model used is the three-dimensional version of the primitive equation model discussed in the katabatic wind study of Parish and Waight (1987). The model is written in terrain-following sigma coordinates and incorporates 10 vertical levels which are staggered to allow the highest resolution in the boundary layer. Prognostic equations in the model include the horizontal motion components, temperature, the surface energy budget and pressure. Explicit representation of the longwave radiative processes in the atmosphere is incorporated in the model to provide a realistic numerical treatment of the forcing of katabatic winds. The ice topography for the Terra Nova Bay region was obtained from the detailed and accurate Antarctic contour map of Drewry (1983) and digitized to a 32-km grid spacing. This resolves the large scale interior structure, but individual glacier outlets and irregular mountainous topography are not explicitly represented. The results are therefore considered representative of the broadscale structure upslope from Reeves Glacier but cannot be expected to provide fine-scale information over the very complex terrain to the north and southwest as well as depict the drainage flow down narrow glaciers such as the Priestley Glacier. The model simulations have been initialized about a state of rest to isolate the terrain-induced drainage flows; model equations are integrated for a 12-hour period by which time the katabatic winds are well developed and have reached a near steady state.

Katabatic wind development is rapid in the model simulations. Within four hours from the start of the model integration, significant drainage flows appear in the lowest levels along Reeves Glacier. Most of the adjustment of the katabatic winds is complete by eight hours and relatively minor changes take place during the final few hours of model integration. As discussed in Parish (1987), the streamlines of cold air drainage upslope from Terra Nova Bay in the lowest levels agree closely with the large scale time-averaged streamlines shown in Parish and Bromwich (1987). The streamline analysis shows the confluence zone to be a prominent feature and suggests that a significant interior area drains through a narrow glacier outlet. Significant changes are found in the upper portion of the katabatic layer. Results are presented for the third sigma level corresponding to a height of 175 m above the ice terrain which closely corresponds to the flight level of the LC-130. Figure 9 illustrates the streamlines of cold air drainage after the 12-hour simulation for the third level. Note that the streamlines closely follow the orientation of the terrain contours and the confluence feature, prominent at the lower levels, becomes less well defined. The contour-parallel orientation of the streamlines suggests that the terrain-induced pressure gradient force is still active at the 175 m level and that the frictional force is small. The solid arrows in Fig. 9 represent average wind directions for points along the flight legs for both case studies. The aircraft measurements of wind direction and the orientation of the model streamlines agree relatively well.

The wind speeds at the level corresponding to the flight paths are shown in Fig. 10. The flight tracks are superimposed for reference. The strongest katabatic winds are found near the coastal slopes adjacent to Terra Nova Bay. Wind speeds in excess of 16 m s^{-1} stretch from the 1200 m contour line to a point some 60 km past the ice slope. Wind speeds near the surface are greater than 20 m s^{-1} at a position corresponding to the terminal slopes near the Reeves Glacier; the wind maximum can be seen extending over into the David Glacier. Note that only moderate wind speeds are simulated in the interior of the continent; the strong katabatic winds are not depicted until just upslope of the Reeves Glacier. These two model characteristics are in agreement with the data collected during the case study flights. The model simulations fail to capture the intensity of the acceleration down the Reeves Glacier; observations of the katabatic wind for both case studies revealed localized maxima in excess of 25 m s^{-1}. The terrain-induced channeling of the flow discussed in section 3b may be responsible for significant acceleration of the katabatic flow down the steep glacial slopes which is not simulated by the grid scale of the terrain used in this model simulation.

5. Summary

Data from the LC-130 instrumented aircraft flights have provided a unique look at one of the most intense katabatic regimes found in Antarctica. Winds at the 170 m flight level are strongly controlled by topography; wind data from both flights are consistent with the confluence zone paradigm. The strong confluence feature in the aircraft-derived wind field and as revealed in Fig. 2 is directed at the head of Reeves Glacier and therefore local enhancement of the katabatic wind is seen along the glacier although not apparent above approximately the 1500 m contour. Three-dimensional numerical simulations of the Terra Nova Bay region (Parish 1987) show the core of strong katabatic winds to be situated along Reeves Glacier with wind speeds in excess of 20 m s^{-1}. Near surface winds of less than 10 m s^{-1} were simulated in the interior of the continent above approximately the 1500 m contour line, consistent with data collected from each flight. It appears that the strong katabatic winds become established only over the steep coastal sections of the Terra Nova Bay

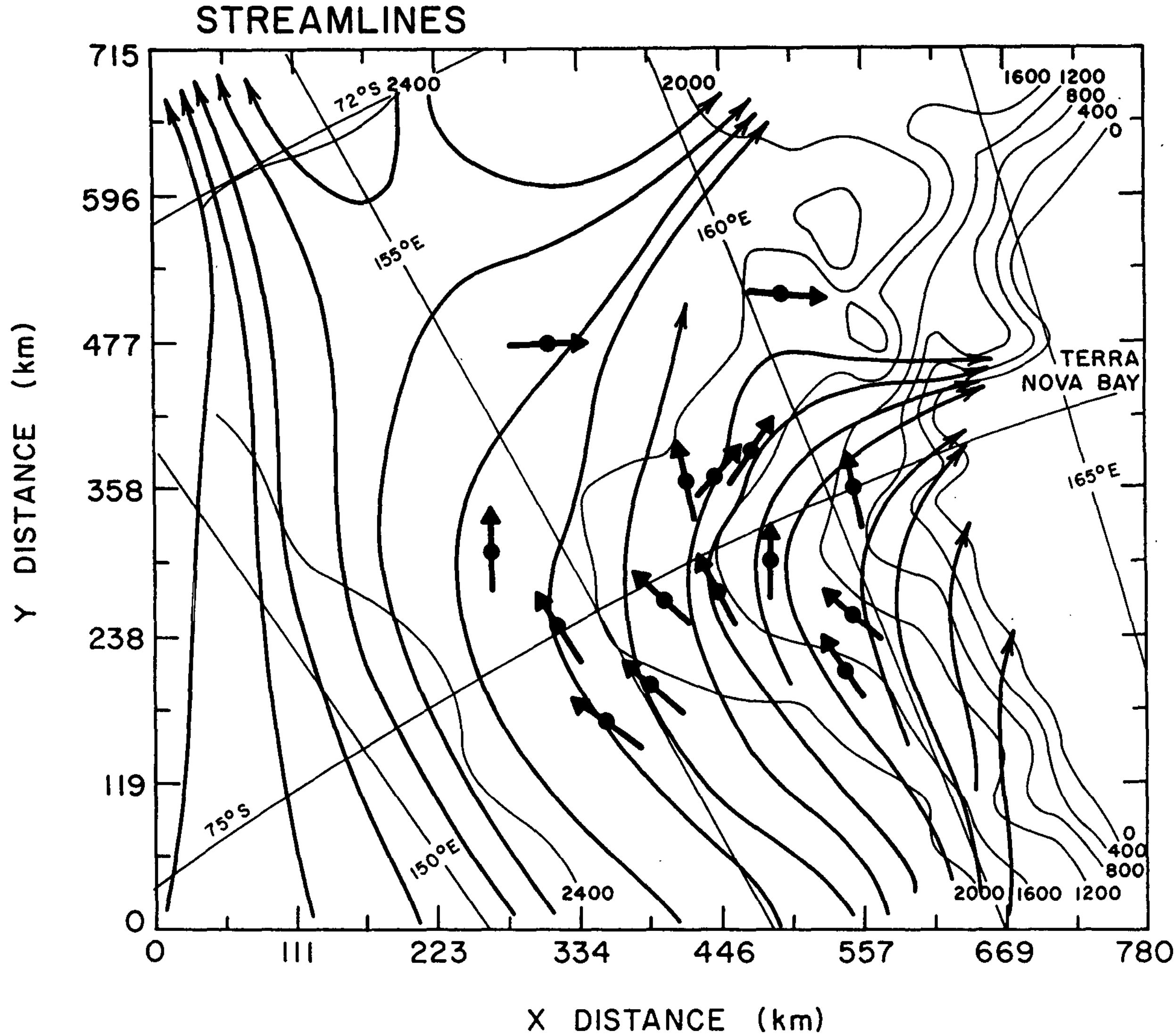


FIG. 9. Model streamlines at 175 m above ice terrain after 12-h integration. Bold arrows indicate aircraft-derived wind direction measurements.

region and encompass Reeves Glacier, but the strong katabatic winds are able to maintain their identity at significant distances from the edge of the continental ice slope. The offshore extent of the katabatic flow has been tracked at least 200 km southward and over 250 km eastward from the end of the ice slopes at Reeves Glacier, offering strong confirmation for the substantial offshore katabatic longevity which is often shown by infrared satellite imagery. The observed offshore behavior of the katabatic airflow will be examined in detail in another paper.

Dramatic decreases in temperature and potential temperature of over 5 K accompany the initial increase in wind speed as the aircraft enters the katabatic stream. The source of the cold air must be from the near-surface layer; the increased levels of turbulence associated with the strong katabatic wind act to effectively mix the atmosphere and thereby transport radiatively cooled air upward. The time sections of temperature traces also show the katabatic stream near the coast to be significantly warmer than air found at the same level in the interior of the continent owing primarily to adiabatic compression as the flow descends the steep ice slopes along the continental periphery. The katabatic winds, however, are shown to be significantly potentially colder than air at corresponding levels above the ice terrain in the interior of the continent. This strongly supports the notion that katabatic winds represent a negatively buoyant flow throughout the descent of the terminal ice slopes near the coast; yet they are accompanied by simultaneous satellite observations of a warm thermal-infrared katabatic signature. It is probable that the satellite-observed thermal contrast is due to strong vertical mixing within the katabatic layer; this brings

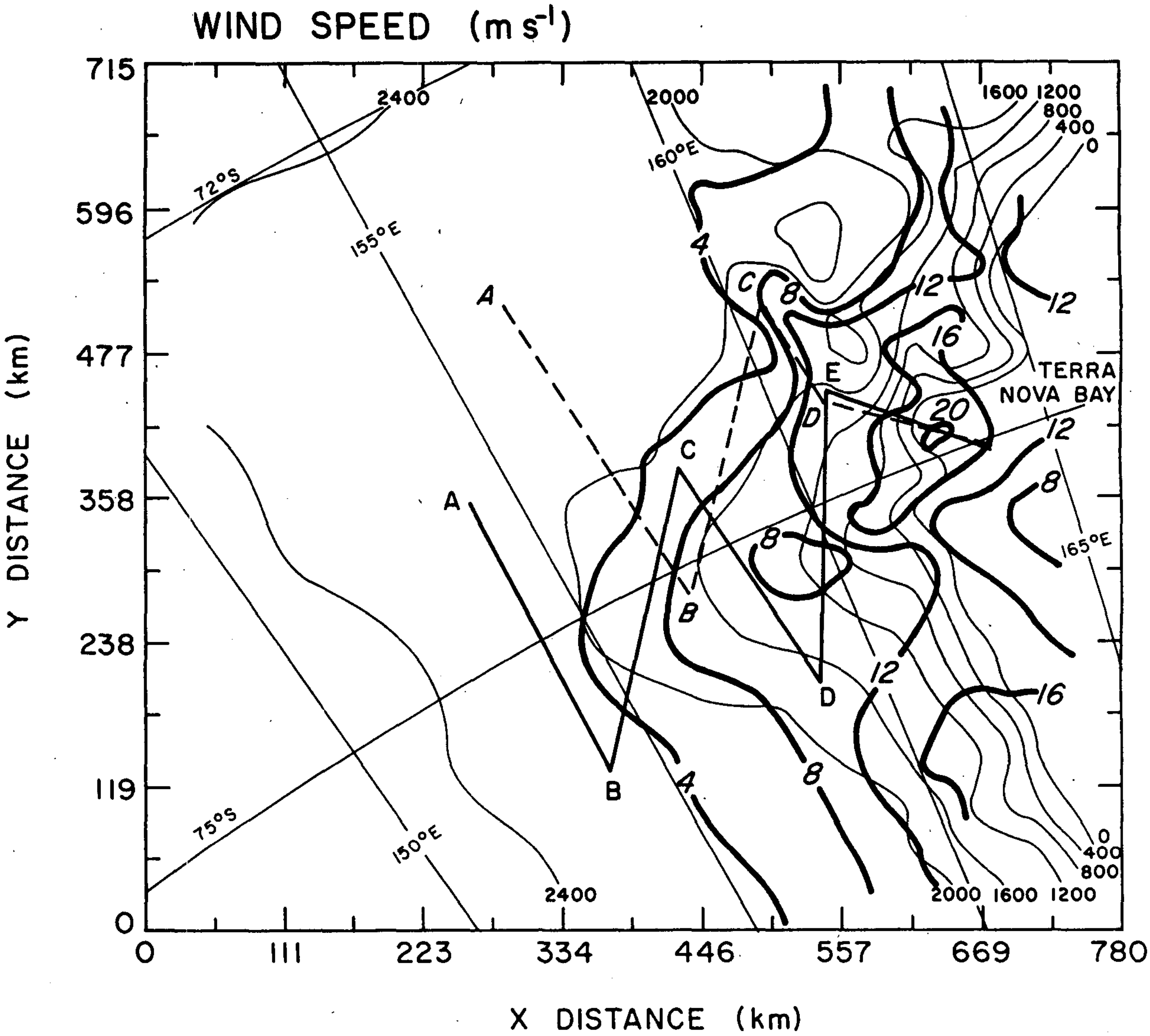


FIG. 10. Model wind speeds (m s^{-1}) at 175 m above ice terrain after 12-h integration. LC-130 flight tracks indicated by solid and dashed lines.

warmer air from higher levels down to the surface and makes the temperature of the emitting snow surface substantially higher than that in light wind areas outside the katabatic jet (Kurtz and Bromwich 1985). It would be difficult to interpret the pronounced channeling of katabatic flow by topography as revealed by satellite imagery and especially the anomalous persistence of katabatic streams for hundreds of kilometers beyond the edge of the ice slope if the flows were of a positively buoyant nature.

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