THE KATABATIC WIND REGIME AT ADELIE LAND, ANTARCTICA

THOMAS R. PARISH

Department of Atmospheric Science, P.O. Box 3038, University Station, University of Wyoming, Laramie, WY 82071, USA

AND

GERD WENDLER

Geophysical Institute, University of Alaska, Fairbanks, AK 99775, USA

Received 16 November 1989
Revised 6 March 1990

ABSTRACT

The coastal sections of Adelie Land in East Antarctica experience the strongest and most persistent slope (katabatic) winds recorded about the continental periphery. The area was first explored during Mawson's 1911–14 Australasian Antarctic Expedition; the annual average surface wind speed at the base camp of Cape Denison was approximately 20 m s^{-1} during the course of the 2-year stay in Antarctica. Field traverses conducted by the Mawson group and the subsequent establishment of additional bases and more recent deployment of automatic weather stations suggest that the zone of extreme katabatic winds is not confined to the Cape Denison site, but rather, extends several hundred kilometres inland from the coast and at least 60 km west along the coast. Numerical simulations of the Adelie Land katabatic wind regime have been conducted using a primitive equation three-dimensional model. Results confirm the extreme wind conditions over the Adelie Land region and strongly suggest that the confluence of cold air drainage currents from the interior towards Adelie Land is responsible for the anomalous katabatic wind intensity.

KEY WORDS Katabatic winds Antarctica

INTRODUCTION

During the austral spring of 1911, the Australasian Antarctic Expedition under the direction of Douglas Mawson set out for the southernmost continent. Upon reaching Commonwealth Bay along the Adelie Land coast of East Antarctica in January of 1912, the base camp of Cape Denison (see Figure 1) was established. This station was to serve as home base for the expedition members over the next two winter seasons. Extremely strong and persistent winds from an almost unchanging direction with accompanying blizzard-like conditions were encountered throughout the year and almost continually during the period from mid-February through to mid-November. Vivid descriptions of the weather and attendant conditions may be found in the popular account of the expedition, *The Home of the Blizzard* (Mawson, 1915) as well as the summary article by Loewe (1972).

The intense surface winds recorded during the 2-year stay at Cape Denison were far in excess of any previously recorded (see Table I; Madigan, 1929). The mean wind speed of 19·1 m s^{-1} remains the highest yearly average wind speed for a station near sea level, including other manned stations in Antarctica. Mather and Miller (1967) estimate the Cape Denison winds to be at least 75 per cent stronger than other coastal stations fully exposed to the katabatic wind from the elevated Antarctic hinterland. The winds along the Adelie Land coast were clearly of a katabatic nature; the direction of the flow was nearly down the fall line in a

0899–8418/91/010097–11$05.50

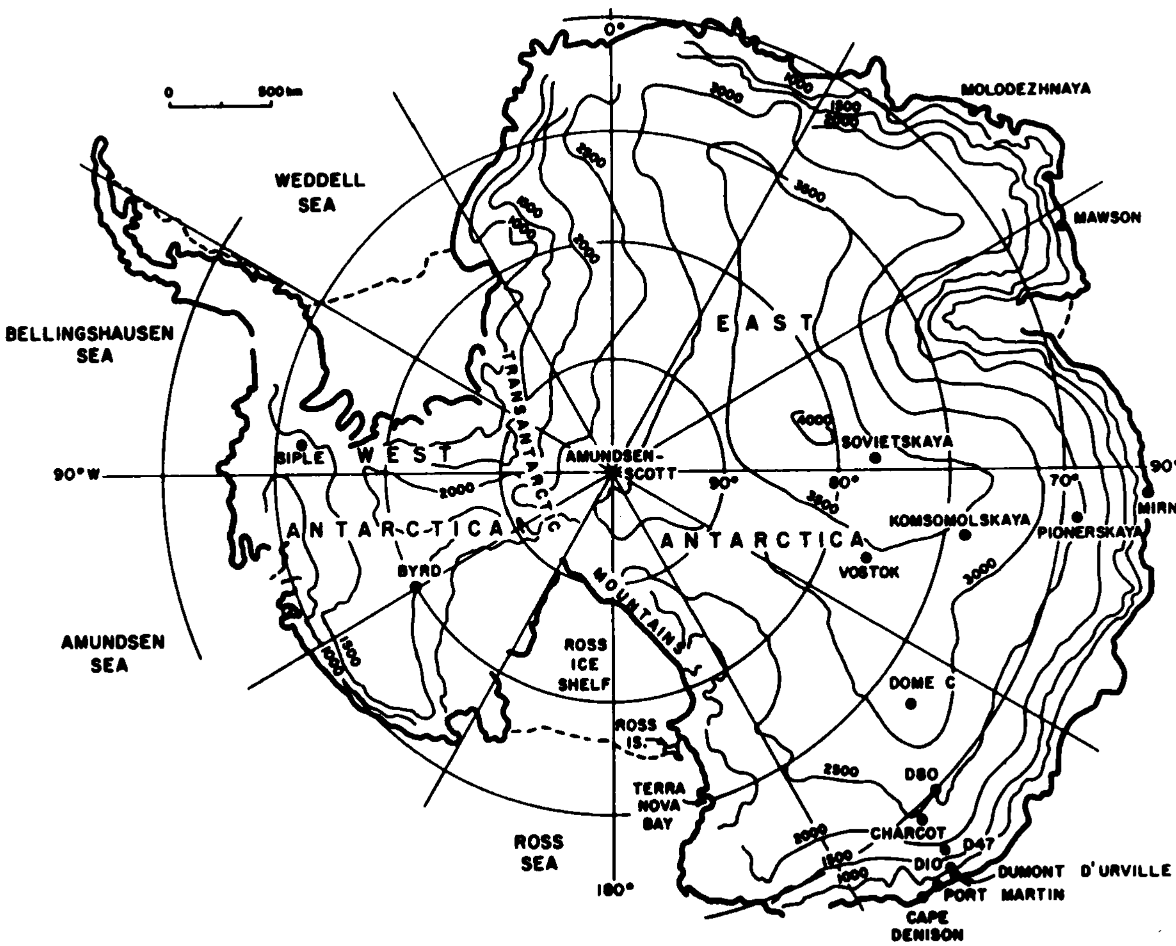

Figure 1. The Antarctic continent with selected geographical features and stations. Contour elevation given in metres

Table I. Mean monthly resultant wind statistics for Cape Denison, 1912–1913. Notation V_r refers to resultant wind speed, *dd* is the direction of the wind in degrees, *q* is the directional constancy and angle refers to the estimated angle of the wind from the fall line of the terrain in degrees

Month	V_r ($m\,s^{-1}$)	*dd*	*q*	Angle
Jan.	12·9	151	0·95	30
Feb.	13·0	154	0·82	25
Mar.	20·3	164	0·97	15
Apr.	19·9	165	0·98	15
May	23·0	159	0·98	20
Jun.	20·5	163	0·96	15
Jul.	22·6	163	0·97	15
Aug.	20·9	160	0·95	20
Sep.	17·3	164	0·94	15
Oct.	20·6	164	0·97	15
Nov.	17·3	160	0·95	20
Dec.	16·7	158	0·96	20
Total	19·0	161	0·97	20

markedly persistent fashion. The mean monthly wind direction at Cape Denison was south-south-east for all but 2 months of the 2-year record.

AREAL EXTENT OF THE STRONG KATABATIC WINDS

During the summer months of 1912–1913, Mawson's group conducted four major traverses from the base camp of Cape Denison. Three of the traverses covered territory in the interior of the continent to the east, south, and west of Cape Denison; a fourth expedition travelled along the coastline in an eastward direction. The tracks of each of the traverses can be found in Madigan (1929) or Parish (1981). During each party's stay in the field, meteorological records were maintained. The data set remains unique since it represents the only register of surface wind observations in the adjacent sectors of the immediate vicinity concurrent with those made at Cape Denison. From these data it may be possible to delineate regions of high katabatic wind potential in Adelie Land. However, caution must be exercised when using this data as the sole basis for judgement. The data records themselves are extremely short; most traverses were of a duration less than 2 months during the mid-summer period. Furthermore, the summertime observing period covers the warmest 2 months of the year when the katabatic winds are often poorly defined and occur somewhat less frequently; well-organized storms of synoptic origin may mask themselves as katabatic events and make generalizations difficult.

Mather and Miller (1967) and Parish (1981) have re-examined the available wind observations; the traverse routes have been divided into 50–100-km segments and wind average applied to each segment. Ratios of the mean wind speed over each leg were compared with the corresponding wind average at Cape Denison. Results of the wind-speed analyses suggest that the zone of strong katabatic winds is not confined to the local environment surrounding Cape Denison, but extends approximately 150 km west and at least 250 km to the south. Winds encountered by both the southern and western traverse party were closely correlated with those measured at the base camp. The wind record along the eastward treks is somewhat inconsistent and confusing. The zone of strong katabatic winds appears to extend only a short distance in an eastward direction. Ratios of wind speed in the field to that at Cape Denison obtained from both the east-coast party and the far-east party show an abrupt decrease away from the base camp; wind speeds roughly half those measured at Cape Denison are the general rule. However, zones of extremely intense winds were encountered and were especially pronounced along the far-east traverse into the interior. These strong wind episodes could be the result of either strong synoptic forcing or localized regions of pronounced katabatic winds; this topic will be alluded to later.

Additional information on the extent of the zone of intense katabatic winds in Adelie Land can be inferred from two sources: manned stations established in the years following Mawson's expedition and the more recent data obtained from automatic weather stations in the surrounding areas. In February of 1950 the French established the station of Port Martin, some 60 km to the west of Cape Denison. Meteorological data were collected for 2 years (Boujon, 1954; Prudhomme and Le Quino, 1954; Le Quino, 1956); results again suggest that the strong winds are not restricted to the Cape Denison region. The mean annual wind speed at Port Martin for the 2-year period was 17·9 m s^{-1}, slightly less than previously measured at Cape Denison but still anomalous. The wind reached hurricane force (32 m s^{-1}) on an average of 122 days for each of the 2 years for which data were collected. The Port Martin wind record offers confirmatory evidence that the extreme katabatic wind speeds stretch at least 60 km to the west of Cape Denison.

A third manned station, Dumont d'Urville, was established approximately 65 km west of Port Martin during the mid-1950s and has since been operational. The station is situated on an island some 5 km from the terminus of the ice slopes on the mainland. Dumont d'Urville is the only station for which long-term climatological data are available. The mean annual wind speed is 10·5 m s^{-1}, about half that measured at Cape Denison and Port Martin. Mather and Miller (1967) have noted that the exposure of the wind sensor on an island some distance from the steep coastal ice escarpment may be responsible in part for the more moderate winds. However, the available wind data suggest that the area of strong katabatic winds does not envelop the entire coastline of Adelie Land. This appears to be in contrast to the wind data collected by the western traverse party of the Australasian Antarctic Expedition, which suggest that the strong wind zone extends further west. The annual course of the wind speed for the three stations is plotted in Figure 2. Note that during the brief summer period of December and January, wind speeds at the three stations are fairly similar; marked differences in katabatic wind intensity can be seen between Dumont d'Urville and the other two stations during the remaining non-summer months. The uniform summertime wind speeds observed at all three stations may help explain the wind data collected during the western traverse party.

In 1980, installation of a series of automatic weather stations (AWS) stretching over 1000 km from Dumont d'Urville at the coast of Adelie Land to Dome C in the deep interior of Antarctica was conducted as part of a joint USA–French katabatic wind experiment (Wendler and Poggi, 1980; Poggi *et al.*, 1982). Detailed results of the experiment may be found in Wendler and Kodama (1984), Sorbjan *et al.* (1986), Wendler *et al.* (1988), Ishikawa *et al.* (1988) and Kodama *et al.* (1989). Six stations (D-10, D-17, D-47, D-57, D-80, Dome C) were deployed (see Figure 1); five have operated for extended periods of time up to 9 years, while one (D-17) has a data record of only 7 months. In addition to providing insight into the downslope evolution of the katabatic wind (Wendler *et al.*, 1983), the string of AWS serves as a check on the westward extent of the strong katabatic wind zone near Adelie Land.

In Figure 3, the mean annual wind speed measured by the AWS versus distance from the coast is plotted. The wind speed at Dome C is among the lowest for all inland stations of Antarctica (Wendler and Kodama, 1984). Dome C rests atop one of the major ridges in the interior of Antarctica and the local terrain is nearly flat. In the absence of terrain slopes, no katabatic flow can develop despite the presence of strong temperature inversions. Wind speeds steadily increase downslope from Dome C in response to increasingly steep terrain slopes. The maximum wind speed is observed between D-47 (105 km from shore, elevation 1560 m) and D-17 (12 km from shore, elevation 900 m). Note that the strongest annual wind speeds are slightly greater than those recorded at Dumont d'Urville, but are significantly less than those recorded at Cape Denison and Port Martin. With the exception of Dome C, all stations display extraordinarily high values of directional constancy of approximately 0·90. This suggests an essentially unidirectional wind regime, presumably due to topographic forcing.

The AWS data offers confirmatory evidence that the intense katabatic winds of Adelie Land do not stretch more than approximately 100 km west of Cape Denison. Possible causes for the intense wind regime

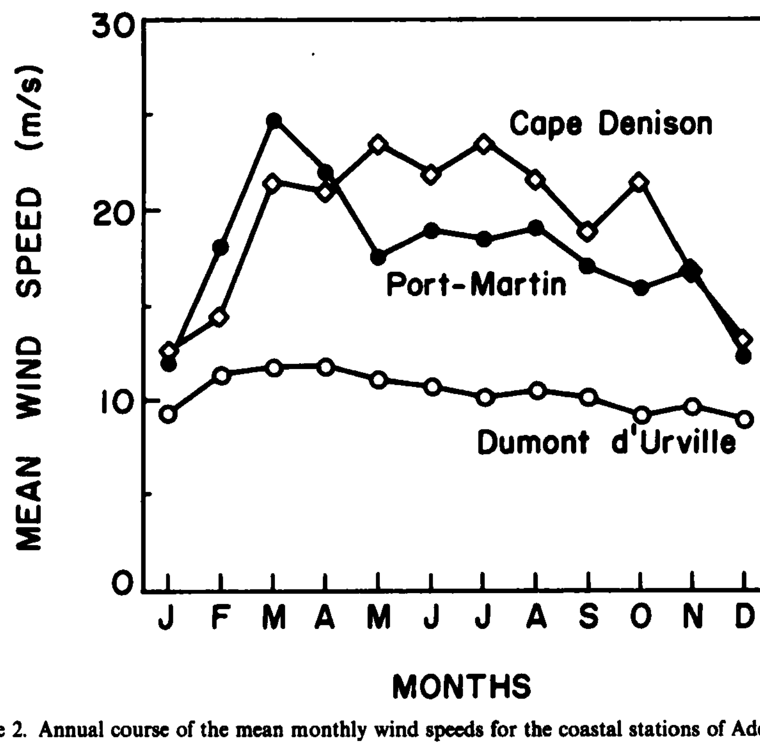

Figure 2. Annual course of the mean monthly wind speeds for the coastal stations of Adelie Land

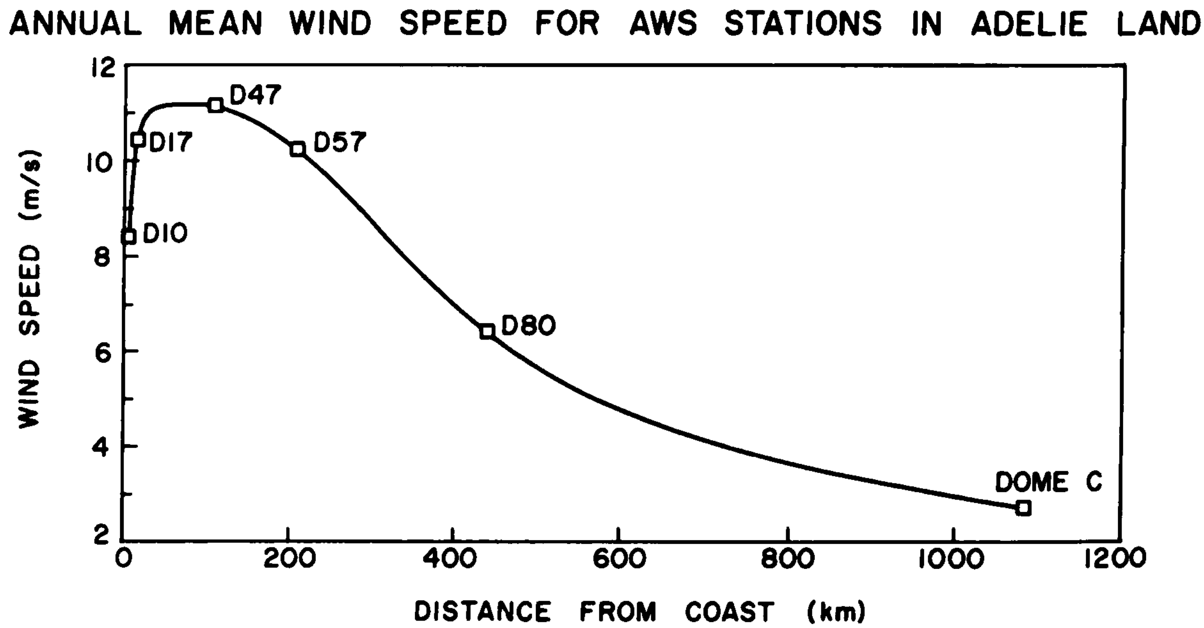

Figure 3. Mean surface wind profile from AWS array from coast to Dome C

encompassing Cape Denison and Port Martin have been discussed by Mather and Miller (1967) and Loewe (1974). Parish (1981) has attributed the extreme katabatic nature of this region to a channelling of drainage flow directly upslope from the Adelie Land coast. This 'confluence zone' results in an enhanced supply of cold, negatively buoyant air that enables the coastal katabatic winds to become stronger and more persistent. This confluence feature is well depicted in the large-scale simulation of time-averaged streamlines of drainage flows over Antarctica (Parish and Bromwich, 1987).

MODELLING THE ADELIE LAND KATABATIC WINDS

There is evidence that suggests that the strong katabatic wind regime encompassing Cape Denison is not a localized phenomenon but rather extends a considerable distance into the interior to the south of the station and some distance west. Previous work has suggested that the low-level confluence of cold, negatively buoyant air from the interior of the continent is the singular factor in shaping the anomalous katabatic winds of Adelie Land. Numerical simulations have been conducted as a means of checking the validity of inferences proposed in the previous section.

The model used is a three-dimensional, hydrostatic, primitive equation system adapted from Anthes and Warner (1978). The model is written in terrain-following sigma coordinates; prognostic equations include the horizontal equations of motion, temperature, and continuity. Details of the equation system can be found in Parish and Waight (1987). The numerical simulations carried out in this study incorporate a bulk treatment of the planetary boundary layer in which the entire planetary boundary layer is represented by a single layer. No explicit representation of the turbulent fluxes of heat and momentum is attempted within the boundary layer; rather, fluxes are related to surface conditions and the temperature and wind within the bulk layer. The boundary layer height is held constant at approximately 125 m, corresponding to the height above ground level of the first sigma level in the model.

A bulk approach is suitable for well-mixed boundary layers and has been used extensively in atmospheric modelling applications. The primary advantage of such a boundary layer treatment is that the computer resources required for the simulations are significantly reduced. Mixed-layer assumptions have been used in previous studies of Antarctic winds (Ball, 1957, 1960). The approach is appropriate for strong katabatic wind regimes since the vigorous turbulent exchanges in the lower atmosphere associated with the intense winds often result in a well-mixed katabatic layer. The form of the momentum flux in the lowest layer used in the model calculations follows that of Ball (1960). The frictional drag coefficient was set at $5{\cdot}5 \times 10^{-6}$ based on comparisons with a two-dimensional version of the model incorporating a high-resolution boundary layer parameterization (Pickett, 1989).

To simulate the cooling effects of turbulent and radiative fluxes in the lowest layer of the bulk model, a series of comparisons were made between the high-resolution two-dimensional model and the bulk model. Inspection of the time evolution of the net cooling of the katabatic layer produced by the high-resolution model (see figure 8 in Parish and Waight, 1987) reveals that near-steady conditions prevail approximately 6-h from the start of the model integration. The net cooling of the entire katabatic layer ranges from 60 W m^{-2} over the interior ice slopes to near 100 W m^{-2} in the coastal vicinity. The turbulent heat transport arising primarily from the strong mixing processes associated with the katabatic wind is the dominant cooling effect in the lower atmosphere over all but the most gentle terrain slopes. For simplicity, a constant surface-cooling rate was imposed in the bulk model. As a starting point, cooling rates were prescribed based on the results of the high-resolution model. Tests were conducted to check the sensitivity of the wind speeds produced by the bulk model with various cooling rates. Results indicate that the intensity of katabatic winds in the bulk version are not overly sensitive to variations in the cooling rate. In the simulation to be presented, cooling rates ranging from approximately 120 W m^{-2} near the coast to 70 W m^{-2} over the gently sloping interior were used. These values are somewhat larger than corresponding values from the high-resolution model; the coarse resolution in the lower atmosphere may necessitate anomalously large cooling rates to simulate the horizontal pressure gradient force and hence the katabatic wind regime.

The model simulation for the Adelie Land region encompasses a 51 × 51 model domain with a grid spacing of 20 km. Height values of the Adelie Land terrain were obtained from a digitized version of the detailed map of Drewry (1983). The topographic representation of the Adelie Land topography used in the model is shown in Figure 4(a). The simulation emphasizes the terrain-driven slope flows; effects of synoptic forcing are not included. The model is initialized about a state of rest in which the geostrophic wind components in the free atmosphere are set to zero. The initial temperature profile was taken from the sounding shown in Schwerdtfeger (1984; see his figure 6); the temperature profile is assumed to be representative of non-katabatic spells in which the low-level inversion has been disrupted by passing cyclonic disturbances and attendant enhanced downward longwave radiation from thick clouds. It should be pointed out that the initial temperature structure is only of secondary concern; variation of the initial atmospheric stability results in minor changes in the time evolution of the katabatic wind. The model equations were integrated for a period of 12-h, by which time near steady-conditions prevail.

Figure 4(b) illustrates the streamline pattern of the modelled drainage flow in the lowest sigma layer after the 12-h integration period. Note that a marked confluence of the katabatic wind streamlines extends some 300 km from the interior of Adelie Land to near Commonwealth Bay. The position and orientation of this modelled confluence zone agrees well with that shown in Parish and Bromwich (1987). As discussed in Parish (1984), the confluence of negatively buoyant air in the interior of the continent provides a large supply of cold air available downslope. Persistent katabatic flow requires replenishment of negatively buoyant air; as noted by Lettau and Schwerdtfeger (1967), even moderate katabatic winds rapidly exhaust upwind reservoirs of radiatively cooled air. This confluence zone enables the katabatic winds along the axis of confluence and downwind to the coast to become significantly enhanced. This suggests that it is impossible to infer katabatic wind characteristics based solely on local terrain slopes. It is essential that the katabatic regime be viewed in a larger context; the pattern of upwind drainage currents is critical.

Results of the katabatic wind speeds in the lowest level of the model after the 12-h integration are shown in Figure 4(c). The coupling between the katabatic wind speeds and the confluence zone is evident upon comparison of Figures 4(b) and 4(c). The strongest winds in excess of 24 m s^{-1} are found along the axis of confluence in the vicinity of Cape Denison and extending south-eastward into the interior of the continent. Note that the zone of strong winds is not localized about the coastal region but stretches inland nearly 300 km. Some observational evidence in support of an extended domain of strong katabatic winds can be found in the southern party traverse log during the summer of 1912–1913. The path of the traverse nearly

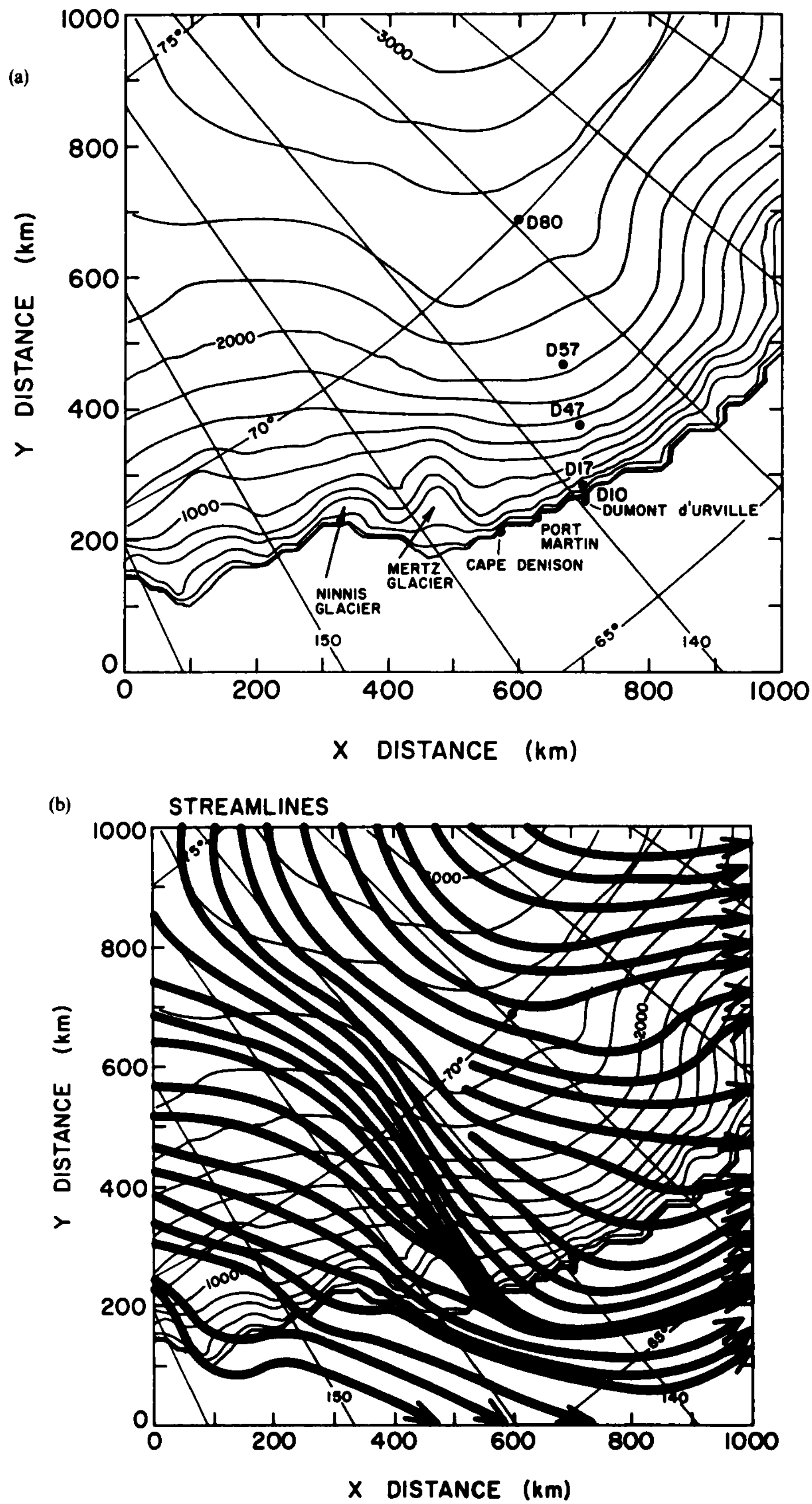

Figure 4. (a) Terrain representation, (b) 12-h model results of streamlines, (c) and wind speed (ms^{-1}) for Adelie Land katabatic wind simulation

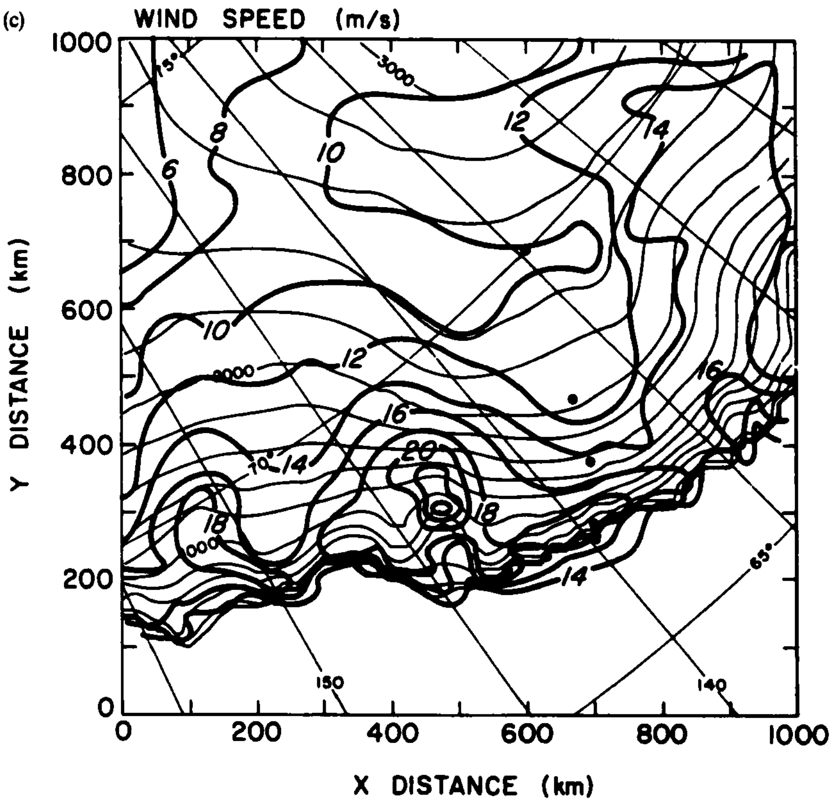

Fig. 4(c)

followed the orientation of the confluence axis and passed through the simulated strong katabatic wind zone in Figure 4(c). Katabatic winds comparable with those monitored at Cape Denison were experienced by members of the southern party until the group was some 400 km from the base station (Mather and Miller, 1967). The simulated wind speeds therefore appear to confirm the anomalous katabatic wind regime in the Adelie Land region.

To more closely examine the details of the numerical simulation, the 12-h results over a section of the model domain centered on the Cape Denison area have been isolated. The nested grid consists of 21 points in each horizontal direction. The topographic representation and locations of pertinent geographical features including traverse routes from the Australasian Antarctic Expedition are shown in Figure 5(a). Figure 5(b) depicts the 12-h streamline patterns over the nested grid. Again, the outstanding feature is the pronounced confluence of the drainage streamlines commencing some 300 km from the coast. The orientation of the confluence zone suggests that a broad area in the interior of Adelie Land effectively drains through a very narrow region. The corresponding 12-h pattern of wind speed is shown in Figure 5(c). Note that the zone of strong katabatic winds closely follows the axis of confluence and that the intense katabatic winds can be traced well over 200 km into the interior from the coast. It can be seen clearly that the strongest winds do not necessarily correspond to the steepest terrain slopes. Note that the inland wind maximum occurs in an area of rather modest terrain slopes of roughly 5×10^{-3}, a value more representative of the deep Antarctic interior. This again emphasizes the importance of upwind drainage features in understanding characteristics of the katabatic wind regime and underscores the difficulty in assessing the katabatic wind potential from only local terrain slope information.

Careful inspection of the detailed streamline map (Figure 5(b)) shows a secondary confluence feature situated midway between the Mertz and Ninnis glaciers. The corresponding wind speeds in Figure 5(c) support this confluence feature; wind speeds in excess of $20\,\mathrm{m\,s^{-1}}$ are simulated along this secondary

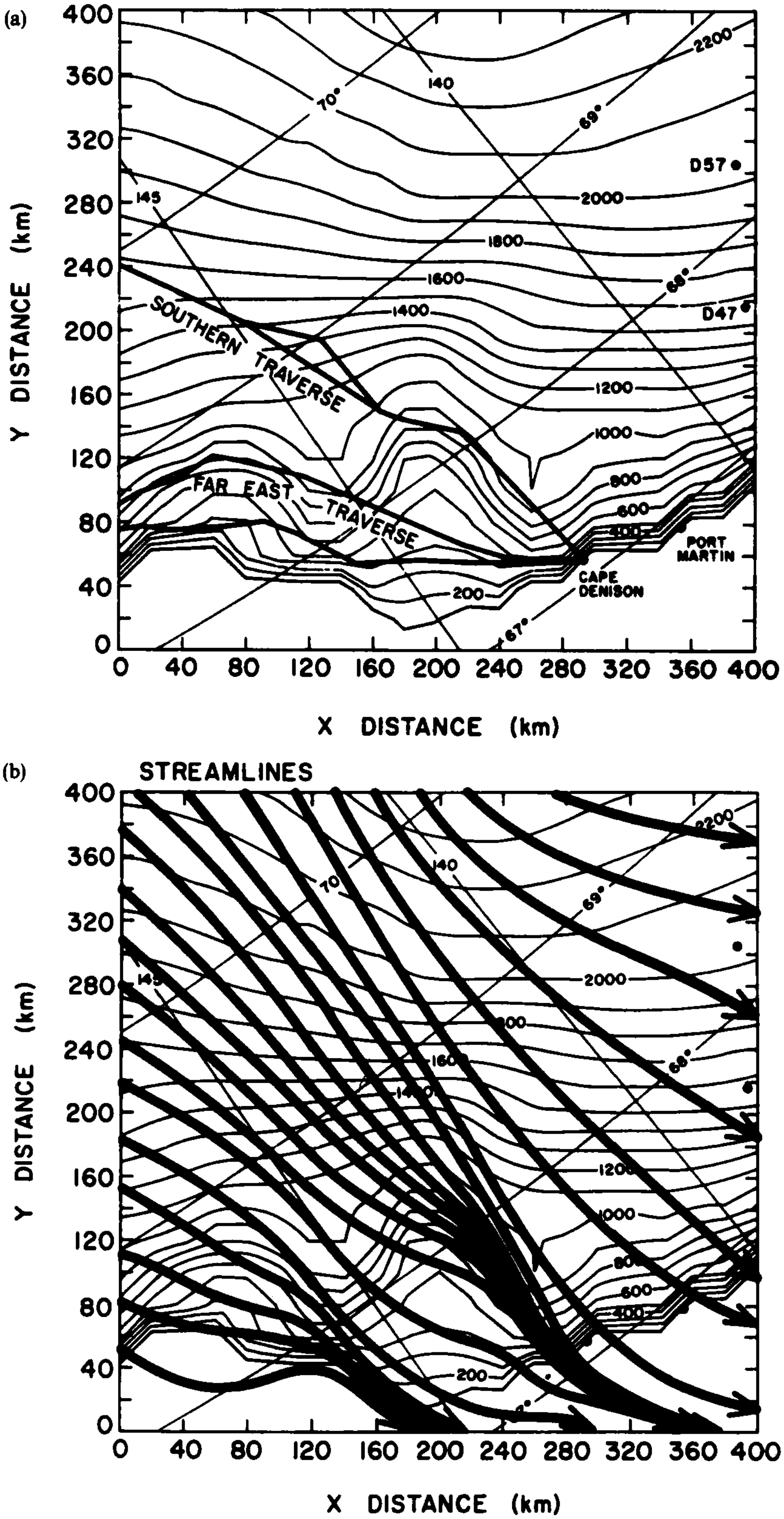

Figure 5. As in Figure 4, except for fine-scale view of model results near Cape Denison and Port Martin

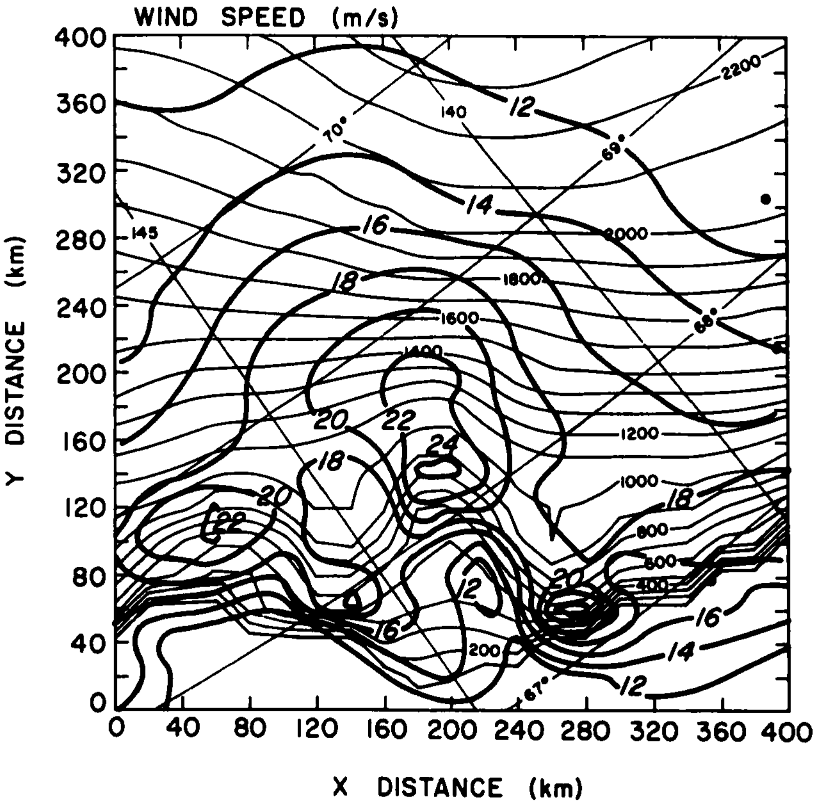

Fig. 5(c)

confluence axis. It is difficult to find observational evidence to support this aspect of the numerical simulation. The only observational record is from the far-east traverse of the Australasian Antarctic Expedition. As noted by Mather and Miller (1967), the katabatic wind information obtained during this trek is somewhat inconsistent. However, during both the outbound and return legs, periods of intense katabatic winds were encountered near the simulated zones of strongest katabatic winds. It is difficult to assess the utility of these data; synoptic influences may play a major role in forcing strong winds during the summer. On the other hand, it is probable that the intense katabatic winds of Adelie Land are not unique to the near-coastal Antarctic environment. The large-scale streamline map of Parish and Bromwich (1987) show a number of confluence zones about the continental periphery; the katabatic wind potential along most of these confluence features is quite high.

CONCLUSIONS

The strength and persistence of the surface wind in the Adelie Land sector is unequalled anywhere on the surface of the Earth, including other parts of Antarctica. Previous work has clearly illustrated the katabatic nature of the surface wind regime. Numerical simulations of the Adelie Land katabatic winds have been conducted to depict the forcing of the strong drainage flows and to infer causal mechanisms. Results confirm the existence of an anomalously intense surface wind regime along the coast of Adelie Land and extending at least several hundred kilometres into the interior south of the coastline. Parish (1981) has proposed that the confluence of drainage streamlines in the interior of the continent upwind from Cape Denison provides an enhanced supply of negatively buoyant air necessary for supporting the intense katabatic wind regime. Model results seemingly confirm this conceptual picture. A confluence zone is clearly depicted over a broad interior area of Adelie Land directed towards the coastal sections encompassing Cape Denison and Port Martin. The zone of strongest katabatic winds is directed along the axis of confluence. Wind speeds in excess of 24 m s^{-1} by 12 h into the model simulation are comparable to wind speeds measured at Cape Denison by the original expedition members. In addition, the pattern of strong winds is in general agreement with traverse observations made in the early part of the century. It can be concluded that the confluence of cold, negatively buoyant air in the interior of the continent provides the large-scale support for the generation and maintenance of the strong katabatic wind regime in coastal Adelie Land.

ACKNOWLEDGEMENTS

This study was supported by the National Science Foundation through Grant DPP-8714828. We wish to thank the participants of the US Antarctic Research Program and Expeditions Polaires Francaises for their support.

REFERENCES

Anthes, R. A. and Warner, T. T. 1978. 'Development of hydrodynamic models suitable for air pollution and other mesometeorological studies', *Mon. Wea. Rev.*, **106**, 1045–1078.

Ball, F. K. 1957. 'The katabatic winds of Adelie Land and King George V Land', *Tellus*, **9**, 201–208.

Ball, F. K. 1960. 'Winds on the ice slopes of Antarctica', in *Antarctic Meteorology, Proceedings of the Symposium in Melbourne, 1959*, Pergamon, New York, pp. 9–16.

Boujon, H. 1954. 'Les observations meteorologiques de Port-Martin en Terre Adelie. Fasc. I. Conditions atmospheriques en surface et en altitude du 14 Fevrier 1950 au 14 Janvier 1951. Releves quotidiens et commentaires', *Exped. Pol. Franc., Resultats Scientifiques, Serie S 5*, 167 pp.

Drewry, D. J. 1983. 'The surface of the Antarctic ice sheet', in Drewry, D. J. (ed.) *Antarctica: Glaciological and Geophysical Folio*, sheet 2, Scott Polar Research Institute, Cambridge.

Ishikawa, N., Kodama, Y. and Wendler, G. 1988. 'Climatological features of Adelie Land during the austral summer season, *Pure Appl. Geophys.*, in press.

Kodama, Y., Wendler, G. and Ishikawa, N. 1989. 'On the diurnal variation of the boundary layer in summer in Adelie Land, Eastern Antarctica', *J. Appl. Meteorol.*, **28**, 16–24.

Le Quino, R. 1956. 'Les observations meteorologiques de Port-Martin en Terre Adelie. Fasc. IV. Conditions atmospheriques en surface et en altitude du Fevrier 1950 au Janvier 1952. Resultats quotidiens et complementaires', *Exped. Pol. Franc., Resultats Scientifiques. Serie S 5*, 97 pp.

Lettau, H. H. and Schwerdtfeger, W. 1967. 'Dynamics of the surface-wind regime over the interior of Antarctica', *Antarct. J. U.S.*, **2**, 155–158.

Loewe, F. 1972. 'The land of the storms', *Weather*, **27**, 110–121.

Loewe, F. 1974. 'Considerations concerning the winds of Adelie Land', *Z. Gletscherkd. Glazialgeol.*, **10**, 189–197.

Madigan, C. T. 1929. 'Australasian Antarctic Expedition 1911–14', *Scientific Reports, Ser. B. IV.* Tabulated and reduced records of the Cape Denison station, Adelie Land, 287 pp.

Mather, K. B. and Miller, G. S. 1967. 'The problem of the katabatic winds on the coast of Terre Adelie', *Polar Record*, **13**, 425–432.

Mawson, D. 1915. *The Home of the Blizzard*, Heinemann, London.

Parish, T. R. 1981. 'The katabatic winds of Cape Denison and Port Martin', *Polar Record*, **20**, 525–532.

Parish, T. R. 1984. 'A numerical study of strong katabatic winds over Antarctica', *Mon. Wea. Rev.*, **112**, 545–554.

Parish, T. R. and Bromwich, D. H. 1987. 'The surface windfield over the Antarctic ice sheets', *Nature*, **328**, 51–54.

Parish, T. R. and Waight, K. T. 1987. 'The forcing of Antarctic katabatic winds', *Mon. Wea. Rev.*, **115**, 2214–2226.

Pickett, J. L. 1989. *A mixed-layer model of katabatic winds.* M.S. thesis, University of Wyoming, Laramie, WY.

Poggi, A., Delaunay, D., Hallot, H. and Wendler, G. 1982. 'Atmosphere–Ice–Ocean interactions in the Antarctic', in *Proceedings of the Argos users conference*, Paris, 20–21 April. Sponsored by the WMO and the French Space Agency, pp. 103–111.

Prudhomme, A. and Le Quino, R. 1954. Les observations meteorologiques de Port-Martin en Terre Adelie. Fasc. II. Conditions atmospheriques en surface du ler Janvier 1951 au 20 Janvier 1952. Releves quotidiens. Analyse critique', *Exp. Pol. Franc., Resultats Scientifiques, Serie S 5*, 179 pp.

Schwerdtfeger, W. 1984. '*Weather and Climate of the Antarctic*', Elsevier, New York, 261 pp.

Sorbjan, Z., Kodama, Y. and Wendler, G. 1986. 'Observational study of the atmospheric boundary layer over Antarctica', *J. Clim. Appl. Meteorol.*, **25**, 641–651.

Wendler, G. and Kodama, Y. 1984. 'On the climate of Dome C, Antarctica in relation to its geographical setting', *J. Climatol.*, **4**, 495–508.

Wendler, G. and Poggi, A. 1980. 'Measurements of the katabatic wind in Antarctica', *Antarc. J. U.S.*, **15**, 193–195.

Wendler, G., Kodama, Y. and Poggi, A. 1983. 'Katabatic wind in Adelie Land', *Antarct. J. U.S.*, **18**, 201–203.

Wendler, G., Ishikawa, N. and Kodama, Y. 1988. 'On the heat balance of the icy slope of Adelie Land, Eastern Antarctica', *J. Clim. Appl. Meteorol.*, **27**, 52–65.