

A re-examination of the winds of Adélie Land, Antarctica

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(Manuscript received June 2005; revised October 2005)

Records of the surface wind at the coast of Adélie Land, Antarctica between 140°E and 144°E show an annual mean wind speed of approximately 20 m s⁻¹. The intensity of this wind regime remains unsurpassed for stations at sea level. The low-level winds are thought to be primarily katabatic, having their origin over the continental interior. Surface winds display an extremely high directional constancy value of near 1.0, implying that the air flow is essentially unidirectional. Wind speeds show a seasonal bias. The intensity of the mean winds during the winter period from June through August is 60 per cent stronger than those observed during the short summertime period of December through February. Confluent channelling of the drainage flows off the ice sheets upwind from Adélie Land has been proposed as the reason for the intense wind conditions at this section of coastal Antarctica. Streamline convergence in the interior of the continent ensures an ample supply of negatively buoyant air that enables the coastal wind regime to be so persistent.

Analyses of the original hourly data series collected by Mawson's party at Cape Denison and subsequent records from automatic weather stations along Adélie Land have been completed. Gridded model output from real-time mesoscale simulations of the Antarctic atmosphere and high southern latitudes using a modified version of the Fifth-generation Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (Polar MM5) from the one-year period November 2001 to October 2002 have also been analysed to investigate the mean structure and extent of the strong wind zone. Detailed simulations with Polar MM5 have been conducted during April 2002 to investigate the modulation of the Adélie Land winds due to cyclones to the north of the coastline. Some thoughts as to the uniqueness of the Adélie Land winds are offered.

Introduction

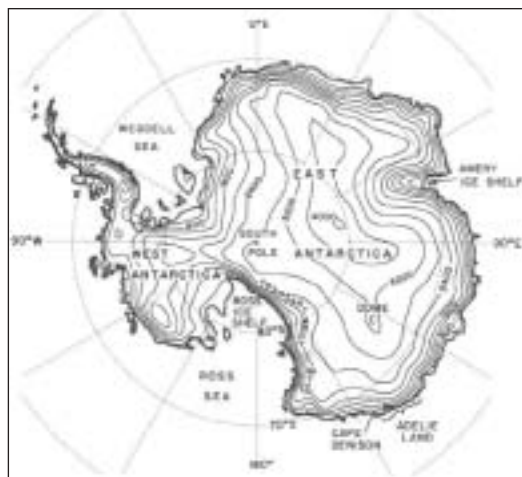
It has been nearly a century since the Australasian Antarctic Expedition (hereafter, AAE) under the leadership of Sir Douglas Mawson first set foot on the Antarctic continent. The party arrived at what would

become the base station of Cape Denison (67°S, 142.7°E; see Fig. 1) in January 1912. For the next two years, party members maintained a record of weather observations, the first extensive meteorological log for a station on the main body of the Antarctic ice sheets. The wind was the outstanding feature of the Adélie Land climate. Phenomenally high wind speeds were experienced throughout the course of the expe-

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Fig. 1 The Antarctic continent. Terrain contours in metres.



dition, especially during the nine months of winter conditions from March through November. For the 683-day period, the mean wind speed was an astounding 19.8 m s^{-1} . Winds were characterised by their extraordinary constancy, both in terms of intensity and direction. Nearly all winds in excess of 10 m s^{-1} , which amounted to nearly 90 per cent of all observations, were from either the south or south-southeast direction. The meteorologist for the expedition, C.T. Madigan, has published hourly values and extensive summaries of the meteorological measurements (Madigan 1929).

After the return of the party in 1913, questions surfaced regarding the intensity of the wind and the quality of the measurements. Tests and extensive recalibrations were conducted with the anemometer upon its return and all wind speeds were corrected prior to publication of the results. Loewe (1972) has offered that the corrections applied may have been too severe and that the actual winds were closer to the original values. He was especially concerned that the high intensity winds were reduced by a factor that was not warranted. Testimony of the extreme wind conditions as described in Mawson's popular account of the expedition, *The Home of the Blizzard* (Mawson 1915), only reaffirms the contention by Madigan that the Cape Denison wind regime is the most intense ever experienced at sea level.

Numerous theories have been offered as to why the wind conditions along Adélie Land are so severe (Ball 1957; Mather and Miller 1967; Loewe 1974; Parish 1981; Parish and Wendler 1991; Wendler et al.

1993). Prior to the mid-1970s, the terrain contours to the south of Adélie Land were not known with sufficient accuracy to permit assessment of patterns of air drainage off the interior of the continent. It had been repeatedly suggested that the Adélie Land winds must be of topographic origin to account for their intensity and persistence. Now that the contours of the ice terrain have been mapped, estimates of the near-surface flows over the continent have been possible (e.g. Parish and Bromwich 1987). There is no question that streamlines of the near-surface wind field display a convergent behaviour upwind from Adélie Land, thereby providing an enhanced source of negatively buoyant air from the continental interior.

During the past decade, two important advances have been made that add additional information on the Adélie Land wind regime. First, automatic weather stations (AWS) have been installed at the historic sites of Cape Denison and Port Martin. Initially deployed during January 1990, both sites have been plagued by recurring instrument failures owing to the extreme wind conditions. A relatively complete year-long record at Cape Denison is available for 1995 (Keller et al. 1997), however, supplemented with available data from other years. Second, real-time numerical weather simulations have been conducted for the Antarctic in support of operational programs during the past five years or so. For this study, output from a version of the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5) that has been used to support the US Antarctic Program will be used. A number of physical parametrisation schemes, such as those representing radiative exchanges and cloud microphysics, required modification for use in the polar regions (Bromwich et al. 2001; Cassano et al. 2001; Guo et al. 2003; Bromwich et al. 2005). Beginning in September 2000, the Antarctic Mesoscale Prediction System (AMPS), based on the 'Polar' MM5, began producing numerical forecasts using a triple-nested grid of 90, 30 and 10 km horizontal resolution that is centred over the Ross Island region. The 30 km domain provides sufficient horizontal resolution to capture detailed topographic forcing over nearly the entire continent including the region encompassing Adélie Land (Powers et al. 2003). Analyses shown here are taken from the 30 km horizontal resolution grid for the one-year period from November 2001 through October 2002. This period was chosen in order to maintain a consistent grid structure; configuration of the nested grids in AMPS changed in November 2002. In addition, 10 km resolution simulations using Polar MM5 centred over Adélie Land region were conducted daily for the month of April 2002.

This paper will focus on analyses incorporating the new AWS data with the complete meteorological record from the AAE that has been recently digitised. In addition, analyses from the gridded AMPS output and high resolution Polar MM5 simulations will be used to address details regarding the vertical profiles and spatial extent of the strong wind zone near Adélie Land and to examine the modulation of the wind regime to transient cyclones in the coastal margin.

The Cape Denison wind record

Table 1 shows the mean monthly wind statistics at Cape Denison for the two-year period February 1912 through December 1913. These calculations have been made based on the reanalysis of the hourly values that have been digitised from Madigan (1929). The record is remarkably complete given the extreme wind events and difficulties in maintaining the wind sensing equipment. The largest gap in the data record at Cape Denison is from mid-February to the end of March 1913, following damage to the anemometer. Party meteorologists by this time were quite skilled at visual estimates of wind speeds and hence the records from this period, while based solely on visual estimates, should not be construed as unreliable (Madigan 1929). No attempt was made to fill in for other missing values of the hourly records. Details of the corrections Madigan applied are provided in the original publication, thereby permitting determination of the original values from the anemometer charts. Given the concerns expressed by Loewe (1972), the

original uncorrected data record for wind speeds has been provided in Table 1 as well. As a means of comparison, the wind statistics for the AWS at Cape Denison for 1995 are included in Table 1.

For the entire two-year period at Cape Denison, the mean wind speed was 19.8 m s^{-1} for the corrected record published by Madigan (1929). The original wind record suggests a wind regime slightly more intense with a mean speed of 22.2 m s^{-1} . Note that the original record compares favourably to the 1995 record from the AWS that was situated near the position of the original anemometer and offers support to Loewe's concern regarding the applied corrections to the original record. It is unfortunate that little 1995 AWS data was available from May, which is one of the windiest months at Adélie Land. In all likelihood, the mean AWS winds from 1995 would have been higher had complete measurements been available for May. This provides yet another suggestion that the uncorrected AAE records are consistent with the latest observations.

For the 683-day record, daily resultant wind averages show that 50 per cent of the days had a mean vector wind speed in excess of 20 m s^{-1} and less than 13 per cent of all days experienced a mean wind less than 10 m s^{-1} . The windiest month was July 1913 with a resultant wind speed of 24.2 m s^{-1} (27.6 m s^{-1} from the original anemometer readings). During that month, seven days experienced a mean vector wind in excess of 30 m s^{-1} and each day had a mean wind in excess of 10 m s^{-1} . The highest mean wind speed over a 24 h period was 36.0 m s^{-1} (42.1 m s^{-1} from the original record) on 16 August 1913. Note that such a wind

Table 1. Mean monthly wind statistics at Cape Denison from the Australasian Antarctic Expedition 1911-14 and from an automatic weather station. V represents the mean wind speeds in m s^{-1} , V_r the vector resultant wind speed, dd the wind direction and q is the wind constancy (defined as the ratio of V/V_r). Corrected data are from published data from Madigan (1929); original data are taken from the expedition without anemometer correction.

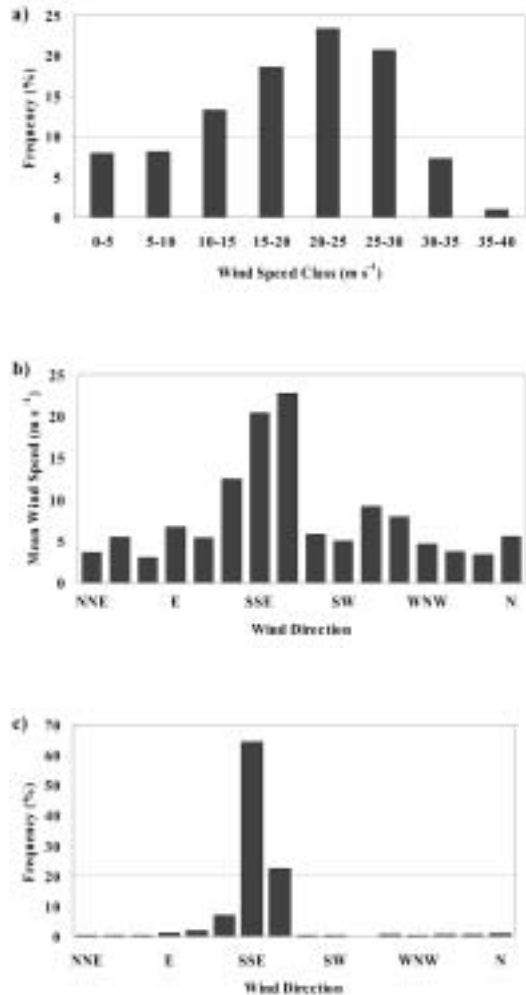
	<i>Corrected</i>				<i>Original</i>			<i>AWS (1995)</i>			
	V	V_r	dd	q	V	V_r	q	V	V_r	dd	q
Jan	12.6	11.9	152	0.94	13.3	12.7	0.96	15.2	14.4	157	0.94
Feb	14.8	14.0	157	0.95	16.9	16.3	0.96	18.6	17.9	162	0.96
Mar	20.7	20.1	163	0.97	24.1	23.4	0.97	27.2	26.5	160	0.98
Apr	21.0	20.5	166	0.98	23.6	23.1	0.98	24.4	23.9	162	0.98
May	23.5	23.1	159	0.98	26.7	26.3	0.99				
Jun	21.9	20.9	162	0.95	24.7	23.7	0.96	27.7	26.8	159	0.97
Jul	23.6	22.9	163	0.97	26.8	26.1	0.97	26.1	24.8	167	0.95
Aug	21.7	20.8	160	0.96	24.4	23.6	0.96	25.1	23.8	159	0.95
Sep	18.8	17.6	164	0.93	21.0	19.8	0.94	25.5	24.9	165	0.98
Oct	21.5	20.7	165	0.96	24.2	22.8	0.94	24.8	24.4	166	0.98
Nov	16.6	15.9	161	0.96	18.2	17.7	0.97	17.6	17.0	164	0.96
Dec	15.0	14.1	157	0.94	17.5	16.8	0.96	11.7	10.8	150	0.92
YR	19.8	19.0	162	0.96	22.2	21.3	0.96	21.7	20.9	162	0.96

speed is above the threshold for winds within a tropical storm to be classified as a hurricane. The highest hourly wind speed was 41.6 m s^{-1} (48.9 m s^{-1} from the original record) on 24 March 1912. Recognising that this measurement represents an average over an hour-long period makes this even more impressive. Instantaneous values of the extreme winds can only be estimated but from the discussion found in Mawson (1915) speeds in excess of 75 m s^{-1} were experienced. The maximum wind speed (representing a 10-minute average) recorded from the high wind speed sensors deployed as part of the AWS instrumentation at Cape Denison in 1995 was in excess of 57 m s^{-1} .

Nearly continuous hourly records are available from February 1912 through January 1913. From that yearly record, statistics have been generated as to the frequency of strong wind events. Figure 2 illustrates the frequency distribution of wind speed events. Over 60 per cent of all hourly reports for wind speeds fall within the 15–30 m s^{-1} class (Fig. 2(a)). A directional bias in wind speeds exists (Fig. 2(b)) with the strongest winds from the S or SSE direction; average wind speeds from either S or SSE are in excess of 20 m s^{-1} . It is extremely uncommon for wind speeds exceeding 10 m s^{-1} to occur from any direction other than between SE and S. The frequency of wind directions (Fig. 2(c)) shows the strong bias from the south and south-southeast directions; over 85 per cent of all observations are from these two directions. The gradient of the ice terrain as specified from Madigan (1929) indicates a rise ‘about 1500 feet in the first 5 miles, after it is much more gentle, reaching 4000 ft in about 50 miles’. The orientation of the fall line appears to be nearly along a line from south to north. The resultant wind direction is 161° , which is roughly 20° to the left of the fall line of the ice terrain. Descriptions from the AAE suggest that the wind can often be characterised as steady state. Ball (1960) has examined katabatic winds from a momentum equation standpoint, arguing that winds can be considered to be a balance between the horizontal pressure gradient force (PGF), Coriolis force and friction forces. From that model, it can be seen that steady solutions exist for winds of comparable strength of those at Cape Denison given conditions discussed by Madigan (1929). For the entire period, the directional constancy value (a ratio of the vector average speed to the mean wind speed) is 0.96. This indicates the unidirectional nature of the wind at Cape Denison and is among the most persistent wind regimes on earth.

A pronounced seasonal variation can be seen in Table 1 such that during the brief summer period from December through February the wind speeds are roughly 60 per cent of the average wind speed

Fig. 2 (a) Frequency of winds by wind speed class, (b) mean wind speeds by wind direction, (c) frequency of wind directions for Cape Denison hourly winds February 1912–January 1913.



during the midwinter season from June through August. This behaviour is characteristic of katabatic winds that tend to be stronger during the coldest part of the year. Directional constancy values decrease only slightly during the summer period for the two-year record and thus flows retain their unidirectional nature. This deviation angle of the wind from the fall line is $5\text{--}10^\circ$ higher during the summer period, probably in response to the decrease in the downslope-directed PGF.

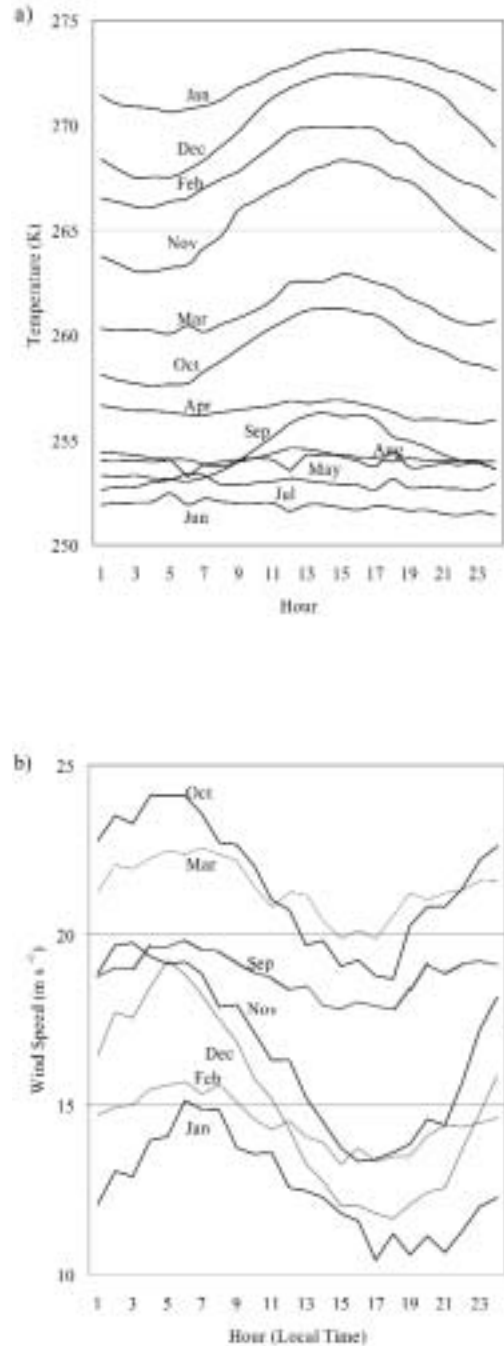
It is well known that there is also a diurnal period in the wind speed during the summer period at Adélie Land that follows the solar insolation cycle (see also Kodama et al. 1989). Figure 3 illustrates the mean diurnal cycle of temperature and wind taken from the historical record at Cape Denison. From the mean monthly hourly temperature trends (Fig. 3(a)), a diurnal cycle can be seen for about seven months from September through March. Wind speeds (Fig. 3(b)) follow the temperature cycle and a diurnal signal is seen for those same months. A maximum wind speed occurs during the early morning hours, as would be expected given the diurnal heating cycle. The maximum diurnal difference in wind speed for the two-year period is 7.6 m s^{-1} in December. It is likely that the increase during this period is katabatic in nature given the obvious link between wind speed and the diurnal temperature cycle. Wind speeds from the 1995 AWS (not shown) are again slightly stronger than corresponding measurements from the AAE although the amplitude of the diurnal cycle of the wind is comparable.

Wind direction and directional constancy values also display a diurnal trend from both the AAE record and the 1995 AWS data. Observations of wind direction show a backing of approximately 10° from the early morning hours to the middle of the afternoon; winds are directed in a more contour-parallel sense during the warmest parts of the day. Constancy values are lowest during the afternoon hours, yet remain nearly 0.90 suggesting that the predominantly unidirectional wind regime can continue even during the warmest times of the year. During such relatively warm times, the katabatic forcing is at a minimum and thus the background PGF must also be directed mostly down the fall line of the terrain. Only minor differences are present between the historical record and the 1995 AWS statistics regarding directional constancy.

Numerical simulations of the Adélie Land winds

Given the extreme wind events at Cape Denison, it is appropriate to inquire as to the uniqueness of the region. Are there other regions about the Antarctic continent that could rival the Adélie Land region in terms of the wind intensity? The spatial coverage for which observations exist over the continent unfortunately remains sparse. AWS have helped increase the data volume over the continent and provide input to initialise numerical forecast models, but the available observational record remains meagre as compared to the middle latitudes. The emergence of relatively

Fig. 3 Diurnal cycle of (a) temperature (K), (b) wind speed (m s^{-1}) at Cape Denison based on hourly values from February 1912 – December 1913. Wind speeds shown for only February and March 1912-1913, September – December 1912-1913 and January 1913.



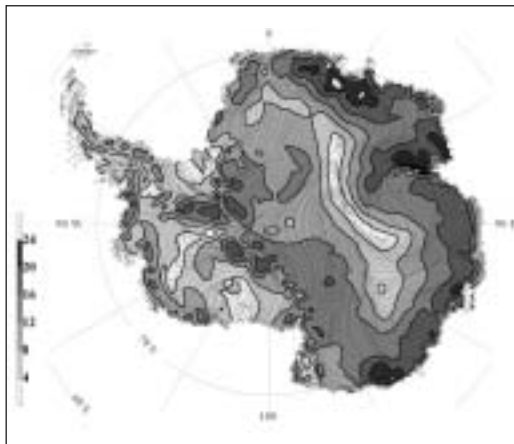
high-resolution numerical weather prediction models provides an alternate means of inferring a dynamically consistent meteorological output set over the continent. Here the 30 km resolution gridded AMPS output is used to infer the wind characteristics over the entire continent.

Figure 4 illustrates the mean streamlines and vector wind speeds for the period November 2001 through October 2002 based on the six-hourly output values from AMPS at $\sigma = 0.9844$, corresponding to a level about 100 m above the surface. This height is near the maximum in the low-level winds over Antarctica. Streamlines display a predominant diffluent drainage pattern off the high plateau of East Antarctica. The confluence of streamlines upwind from Adélie Land that feeds the strong wind region can be identified. The zone of maximum wind speeds associated with the Adélie Land region from the AMPS simulations can be seen to extend approximately 300 km into the interior of the continent with local maxima in excess of 24 m s^{-1} situated at the coast and also 100 km inland. Analysis of the AMPS archive from other years provides nearly the identical wind speed pattern and so the results presented here are considered representative of most years.

From this analysis other high wind speed regions can be identified, such as near the Lambert Glacier at 72°S , 65°E and the broad region just inland from Princess Ragnhild coast at 72°S , 30°E , that are comparable to Adélie Land. A string of AWS that has been deployed and operated by the Australian Antarctic Division Glaciology Program are situated about the 60°E meridian just to the east of the high wind region depicted in Fig. 4; data from those sites are in good agreement with the AMPS output. It is not known to the authors if observational evidence exists at the Princess Ragnhild coast to support the model analysis in Fig. 4. As is the case for the Adélie Land winds, streamline confluence occurs upwind from both sites and can be seen in the earlier Parish and Bromwich (1987) simulation. If such simulations are representative, it can be stated that the Adélie Land wind regime may share the claim as the windiest site on earth near sea level with a couple of other special Antarctic locations.

From the original expedition, only hints as to the vertical structure and extent of the strong winds were possible. AMPS analyses provide insight as to the vertical structure of the wind regime at Adélie Land to address issues such as the level of the maximum winds and depth of the strong wind layer. In addition, analyses can depict differences between the Adélie Land wind and other wind regimes about the continental rim of East Antarctica. Figure 5 illustrates vertical profiles of wind speed, wind direction, potential

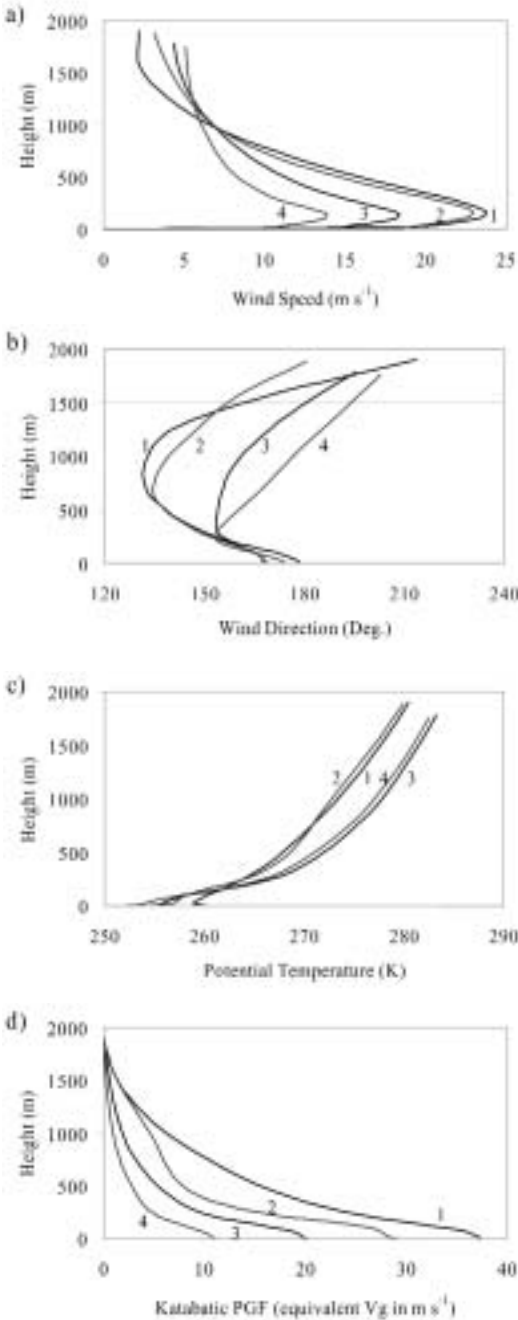
Fig. 4 Mean vector wind speeds (m s^{-1}) and streamlines from AMPS 30 km resolution archive at $\sigma = 0.9841$ (approximately 100 m above the surface) for the annual period November 2001 – October 2002.



temperature and the katabatic component of the PGF along a line commencing at Cape Denison and progressing upslope along the confluence channel at latitudes 68° , 70° and 72°S for the annual period November 2001–October 2002. From Fig. 4 it can be seen that the strong wind region of Adélie Land extends to approximately 70°S . Calculation of the katabatic component of the PGF follows from the method described in Parish and Cassano (2003). Key parameters in this calculation include the terrain slope and the potential temperature deficit, a measure of the radiational cooling of the ambient environment that can be estimated from the potential temperature profile. For each profile, a well-defined low-level jet is seen in the wind that is typical of katabatic or other terrain-induced wind maxima. The layer of strong winds is confined primarily within the lowest 500 m with the maximum wind speeds found near the coast at approximately 100–200 m above the surface. By 70°S , maximum wind speeds have dropped below 20 m s^{-1} and inland beyond this point wind speeds are representative of ‘ordinary’ katabatic-type flows. Wind directions in each case show an expected backing with height, consistent with effects of friction. Above the terrain-induced flows, wind directions display a veering with height to the predominantly westerly flow found in the mid-troposphere above the maximum height shown in the profiles of Fig. 5.

Mean profiles of potential temperature in the lower atmosphere display a pronounced increase over the lowest several hundred metres, depicting the radiative

Fig. 5 Vertical profiles of (a) wind speed (m s^{-1}), (b) wind direction, (c) potential temperature (K), (d) the katabatic component of the horizontal pressure gradient force expressed in terms of the geostrophic wind (m s^{-1}) for four points commencing at Cape Denison and heading inland along the confluence zone. Profile 1 refers to Cape Denison at 67°S , 143°E , profile 2 to 68°S , 143°E , profile 3 to 70°S , 145°E , profile 4 to 72°S , 147°E .

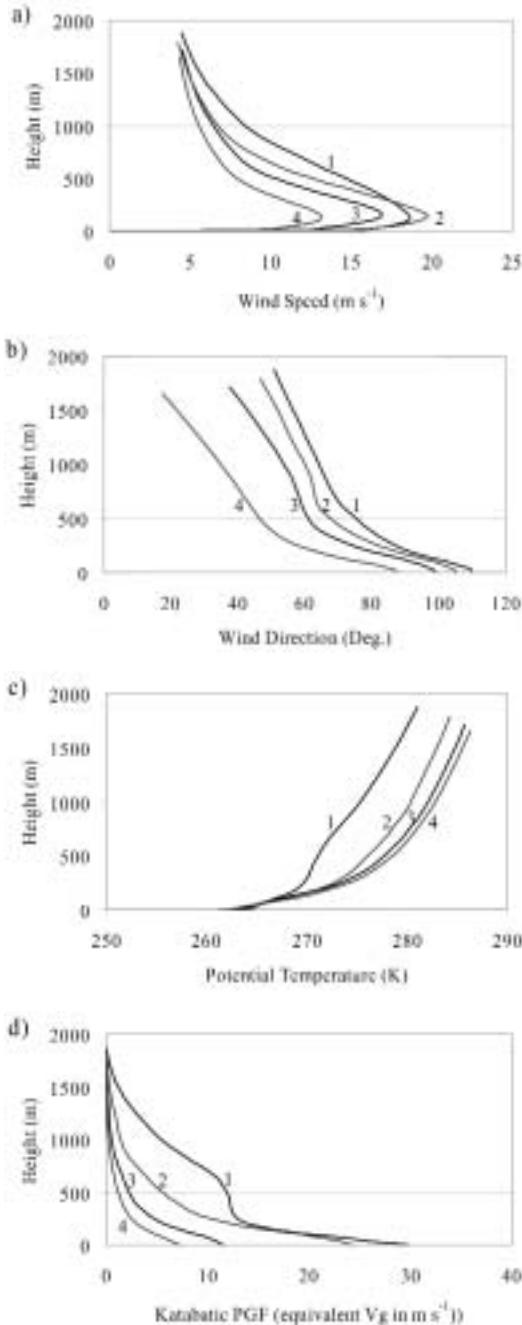


cooling of the lower atmosphere over the ice slopes. This diabatic cooling is responsible for the katabatic component of the PGF, which by definition is directed down the terrain gradient with the greatest magnitude at the surface equivalent to a geostrophic wind of nearly 40 m s^{-1} at the grid-point nearest Cape Denison. The katabatic PGF decreases rapidly with height and by 500 m or so is less than half that at the surface. The large magnitude of the katabatic forcing strongly suggests that the flows of Adélie Land are primarily katabatic. Note that the wind speeds above 250 m are in reasonable agreement with geostrophic values. The total PGF is not a standard output variable from the AMPS archive and so direct comparison of the katabatic component to the total PGF is not possible. Other modelling studies using Polar MM5, such as those shown later in which the PGF is output, confirms that the katabatic component at Adélie Land is a significant fraction of the total PGF. Note that the surface values of potential temperature decrease inland from approximately 260 K at the coast to 252 K at an elevation of 2100 m , implying that the air over the interior is negatively buoyant even when averaged over the entire year.

Recognising the relative uniqueness of the wind regime at Adélie Land, it is appropriate to examine differences in the vertical profiles with other locations about the continent that are positioned outside of a confluence zone. As an example, Fig. 6 shows the wind speed, potential temperature and katabatic PGF profiles along the 90°E meridian, extending from the coast to points at 68° , 70° and 72°S . This section of coastline is near the manned station Mirnyj, a site prone to katabatic winds off the continental interior though less intense than Adélie Land. As can be seen in Fig. 2, streamlines of the near-surface wind over this section of Antarctica display a diffluent behaviour. Wind speed profiles suggest a maximum wind near 20 m s^{-1} at a similar level to the maximum wind speeds at Adélie Land. Potential temperature profiles along 90°E depict a strong increase in the lowest few hundred metres, similar to that seen in the Adélie Land profiles although not as prominent. Note that the change in the surface potential temperature from approximately 264 K near the coast to 262 K at an elevation of 2500 m is considerably smaller than seen at Adélie Land, implying that the negative buoyancy is less pronounced along 90°E . Despite being situated at nearly the same latitude as Cape Denison, the coastal grid-point along 90°E is approximately 5° warmer than found at Adélie Land.

Differences between the two sites are also apparent in terms of the katabatic PGF, which is a maximum at the coastal site along 90°E with an equivalent geostrophic wind value of about 29 m s^{-1} as compared

Fig. 6 Vertical profiles of (a) wind speed (m s^{-1}), (b) wind direction, (c) potential temperature (K), (d) the katabatic component of the horizontal pressure gradient force expressed in terms of the geostrophic wind (m s^{-1}) for four points along 90°E commencing at the coast and heading inland. Profile 1 refers to 67°S , 90°E , profile 2 to 68°S , 90°E , profile 3 to 70°S , 90°E , profile 4 to 72°S , 90°E .



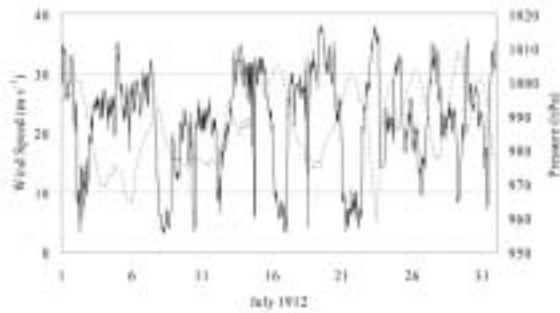
to near 38 m s^{-1} for the Cape Denison grid-point. Note that the values of the katabatic PGF, and the depth through which it acts, are greater inland from the Adélie Land coast as well. The differences in potential temperature profiles, attendant differences in the magnitudes of the katabatic forcing and the vertical extent through which it acts are logical byproducts of the confluent nature of the drainage flows upwind from Cape Denison that enhance the supply of negatively buoyant air available to downslope stretches.

Synoptic modulation of the Adélie Land winds

Given the strong topographic influence displayed in the wind records and the sensitivity of wind speed to seasonal and diurnal thermal forcing, it is logical to conclude that the wind regime at Adélie Land can be explained primarily by katabatic processes. The correlation between wind and temperature for the entire 22 months of data from the AAE is -0.53 . The relatively large negative correlation is not unexpected given the prominent annual cycle and the link between katabatic winds and diabatic cooling of the terrain slopes. Wind and pressure data from individual months, however, clearly show that wind speed is also related to the passage of cyclonic storms. An example, for July 1912, is shown in Fig. 7. Peaks in the wind speed trace are associated with periods of low or falling pressure. Correlation coefficients between wind speed and pressure and wind speed and temperature for this month are -0.35 and -0.01 , respectively. This implies that in the absence of seasonal or diurnal trends that wind speeds can vary as the synoptic setting changes. Similar results were seen from the 1995 AWS record (i.e. Parish and Cassano 2003). Madigan (1929) acknowledged the steadiness of the wind at Adélie Land regardless of the pressure, although noting that 'extra violent winds followed low barometers'.

It is appropriate to inquire as to how transient synoptic-scale cyclones along the coastal margin interact with the katabatic forcing of the winds. To address this issue, daily numerical simulations were conducted with Polar MM5 for the month of April 2002 centred over the Adélie Land region using a two-way nest of outer and inner grid resolutions of 30 and 10 km, respectively. AMPS 90 km output was used to initialise Polar MM5; AMPS runs were not available for 7-8 April and thus no simulations were conducted for those two days. Modification to the Polar MM5 source code was made to allow for output of the actual PGF. Calculation of the katabatic PGF was then made following Parish and Cassano (2003) so as to

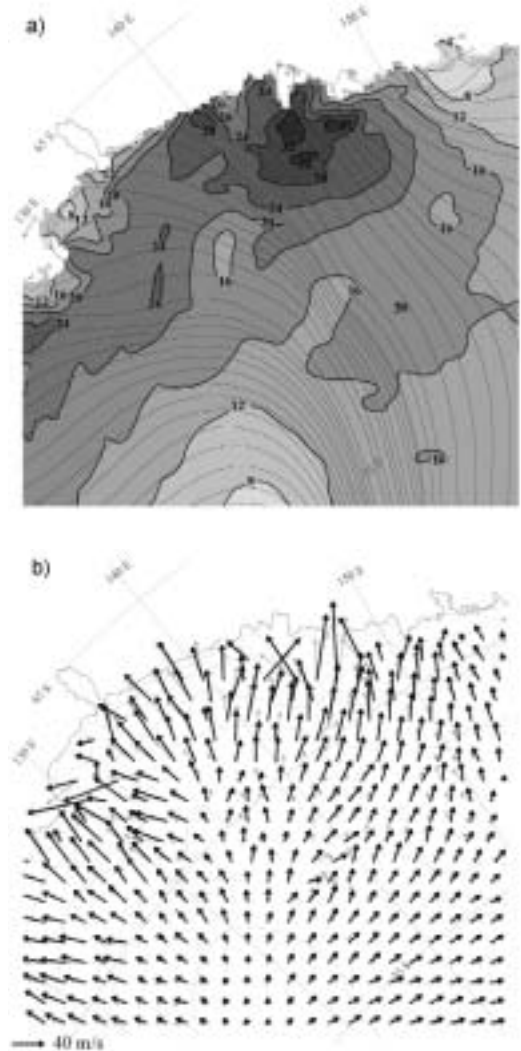
Fig. 7 Time series of wind speed (solid line, units in m s^{-1}) and pressure (dashed line, units in hPa) at 1 h intervals from Cape Denison record July 1912.



isolate the ambient PGF, presumably reflecting the influence of the background environment. As noted by Parish and Cassano (2003), this ambient PGF over the ice sheets can be considerably different from that found over the ocean. As stable air is forced against the Antarctic ice sheets, blocking occurs. Subsequent adjustment of both wind and pressure fields results in a net pressure gradient force that is directed downslope, similar to that occurring for the katabatic force. The mean monthly wind speeds, streamlines, and pressure gradient force vectors for both the total and katabatic components for the April 2002 simulations at $\sigma = 0.9841$, corresponding to a height of approximately 100 m above the surface, are depicted in Fig. 8. A zone of high wind speeds inland from and encompassing the Cape Denison region can be seen (Fig. 8(a)) with highest wind speeds in excess of 30 m s^{-1} . Streamlines suggest the confluent channelling of drainage flow from the interior into the strong wind zone; note the marked diffuence east of the 140°E meridian. Note that the katabatic component represents a significant fraction of the total PGF for vectors shown in Fig. 8(b). It is also worth noting that even for grid-points in which the katabatic component does not comprise the largest component to the PGF, the direction of the total PGF is still directed nearly downslope. This is a reflection of the strong control that the topography plays in the forcing of Antarctic winds through adjustment processes such as discussed in Parish and Cassano (2003).

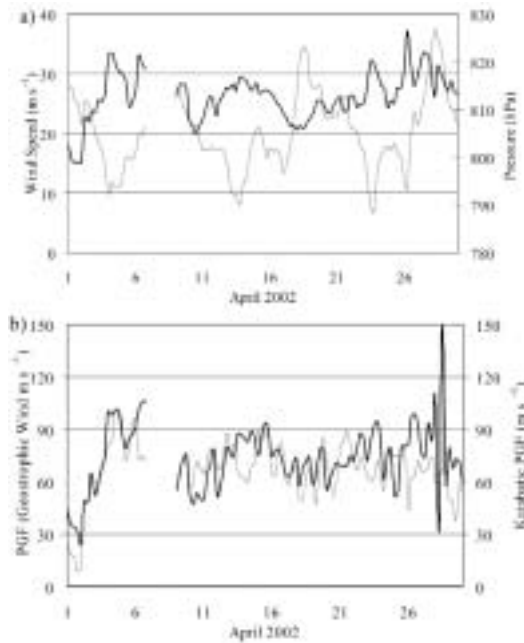
On shorter time-scales, the ratio of the katabatic forcing to the total PGF can vary. Figure 9 depicts a time series composite of wind speed and pressure (Fig. 9(a)), the total PGF from AMPS and the katabatic component of the PGF (Fig. 9(b)) at the lowest sigma level at six-hourly increments just upslope

Fig. 8 April 2002 Polar MM5 simulations of the monthly mean (a) wind speed (m s^{-1}) and streamlines and (b) vectors of the total PGF (bold) and katabatic component of the PGF (thin) expressed in terms of geostrophic wind magnitudes (m s^{-1}) at $\sigma = 0.9841$ corresponding to approximately 100 m above the surface.



from the coast of Adélie Land at 69°S , 143°E for April 2002. Model output suggests that the wind displays changes related to passing cyclones. Similar to that shown for the historical record in Fig. 7, increasing wind speeds typically are found during periods of low or falling pressure. Individual cyclone events can

Fig. 9 Time series of (a) wind speed (solid line, m s^{-1}) and pressure (thin line, hPa), (b) the horizontal pressure gradient force in terms of the geostrophic wind (solid line, m s^{-1}) and the katabatic component of the pressure gradient force in terms of the geostrophic wind (m s^{-1}) at $\sigma = 0.9981$ (about 13 m above the surface) at grid-point 69°S , 143°E from the Polar MM5 simulations for April 2002.

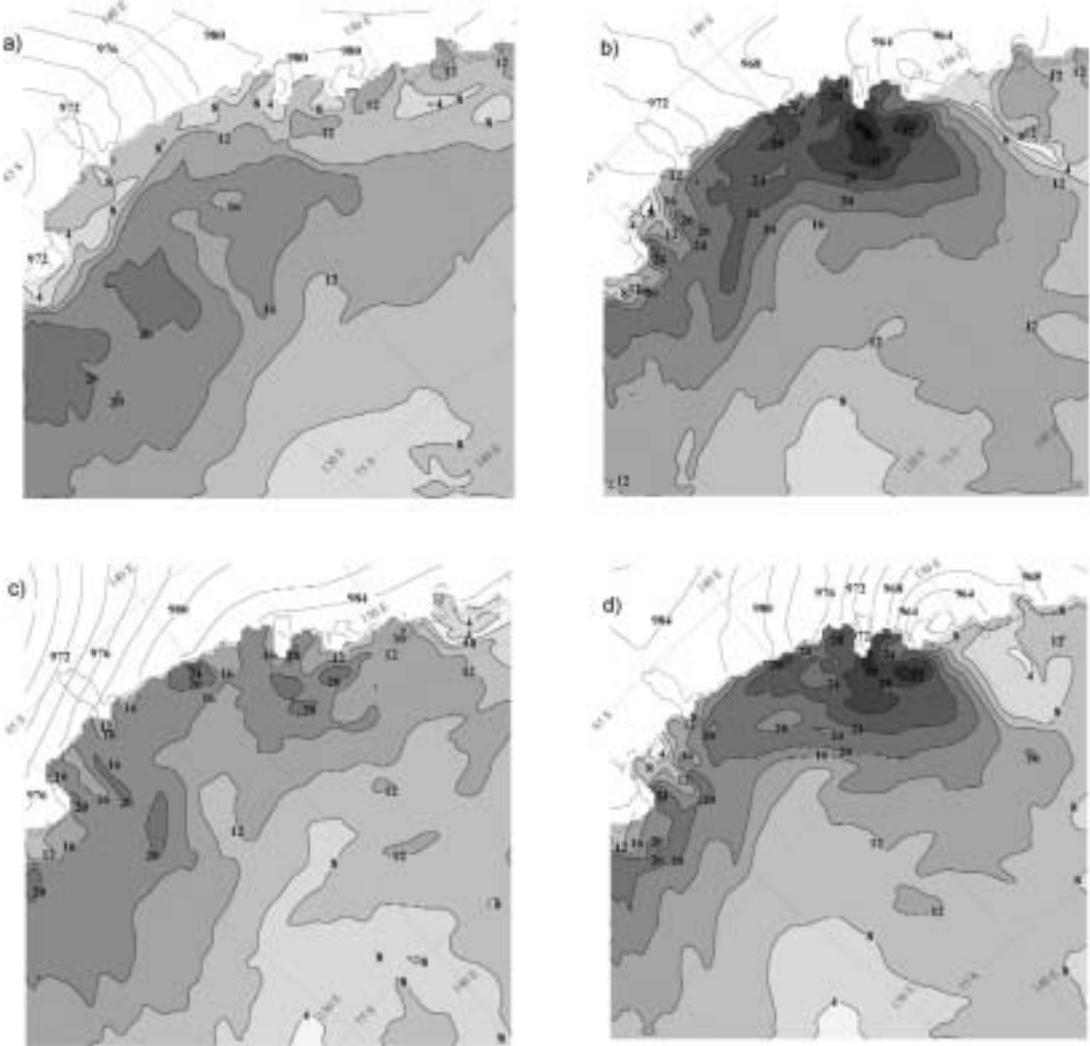


be seen on 4, 13, 17, 24 and 26 April and there appears a noticeable wind speed increase on all days but the 17th. The total PGF tracks with the wind speeds near the Adélie Land coast, as would be expected. As in Fig. 8(b), results from this near-coastal grid-point show that a significant percentage of the total PGF throughout the month is made up by the katabatic component. It is also apparent that the katabatic PGF can change in response to the evolving synoptic environment. For example, the significant decrease in pressure during the first five days in April is accompanied by an increase in the katabatic component of the PGF at this grid-point. Transport of cold, negatively buoyant air from the interior toward the steep coastal slopes is the only means by which the katabatic PGF can increase at a coastal grid-point. This occurs frequently during the summer months where temperature and wind speed show a significant negative correlation. This also suggests that although the net forcing can be explained by katabatic processes, the synoptic situation is responsible for helping

establish the favourable drainage pattern off the high interior. Close inspection of Fig. 9 reveals that the total PGF at this grid-point can increase while the katabatic component decreases, such as during the 13 and 26 April events. Typically, the katabatic component makes up in excess of 90 per cent of the total PGF. This ratio decreases during the aforementioned events, but even at its weakest relative strength the katabatic component still contributes more than half of the total PGF at this particular grid location. It can be concluded that the net forcing at the Adélie Land coast within the confluence zone throughout the month is primarily katabatic.

Two examples of synoptic modulation of the low-level wind regime can be seen in the 1-4 and 9-13 April cases. Figure 10 depicts composite pictures for each case, illustrating the mean wind speeds at $\sigma = 0.9841$ (approximately 100 m) over the continental ice sheets of Adélie Land with an analysis of the surface pressure field over the ocean to the north of the coastline. No analysis of the pressure field is attempted over the ice terrain owing to uncertainties in reducing surface pressures to sea level. Figure 10(a) depicts conditions on 1 April 2002 at which time wind speeds are at a minimum; Fig. 10(b) is for 4 April 2002 at the time of maximum wind speeds over Adélie Land. Figures 10(c) and 10(d) refer to minimum wind conditions on 9 April 2002 and maximum winds on 13 April 2002, respectively. There are common features in each of these two cases. From Fig. 9, surface pressures at the grid-point corresponding to 69°S , 143°E decrease in excess of 20 hPa during each of the approximately four-day periods. Minimum wind speeds (Figs 10(a),(c)) occur with a synoptic environment over the ocean favouring a northerly geostrophic wind at the surface; higher pressures are situated to the east. In each case an intensifying cyclone was situated to the east of Adélie Land near 125°E . It appears in both cases that cyclones slowly progressed toward the east, reaching 140°E before heading north as they approached Cape Denison. Secondary cyclone development occurred to the east of Adélie Land at approximately 150°E . As a result of the synoptic situation, an intense PGF in the near coastal vicinity became established. Maximum winds for both cases occur under conditions in which a tight PGF supporting a southerly geostrophic flow was present in the offshore environment. This north-south orientation of the isobars associated with a depression to the east of Cape Denison was repeated on the 17, 23 and 26 April cases as well. The region just offshore near 150°E appears to be a favoured location for cyclone formation. Results from the simulations suggest that the airflow from Adélie Land may play a role in the development and movement of these cyclones. The implication is that the cold air provided

Fig. 10 Polar MM5 simulations of wind speed (shaded, units in m s^{-1}) over the Antarctic continent and pressure (solid lines offshore, units in hPa) at $\sigma = 0.9841$ from (a) 0000 UTC 2 April, (b) 0600 UTC 4 April, (c) 0000 UTC 10 April, (d) 0000 UTC 14 April 2002. Minimum winds are represented by cases (a) and (c); maximum winds represented by cases (b) and (d).



by the continental outflow may play a role in cyclogenesis and a positive feedback between the Adélie Land winds and the synoptic environment may be present (see also King and Turner 1997).

Summary and conclusions

The Adélie Land coast is home to the most extreme wind conditions ever measured at a site near sea level. To enhance our understanding of the wind characteristics of this region, original data collected by the

Mawson expedition to Cape Denison have been digitised and reanalysed. Some concern has been expressed that the corrections applied to the original wind speed records were unwarranted. Comparison with an AWS deployed at nearly the same location some 80 years later has confirmed that the uncorrected wind records are not excessive. Rather, the AWS records show that the mean wind speeds monitored from 1995 are very similar to those taken from the original records. Cape Denison winds are negatively correlated with both temperature and pressure. On an annual basis, the strongest winds should show a

strong correlation with temperature since pronounced annual and diurnal cycles in wind speed follow the solar insolation cycle. Strongest winds at Cape Denison are found during periods of low or falling pressures that suggest synoptic activity in the highly baroclinic zone to the north of the continent plays a role in forcing the wind.

Little evidence is available from the original expedition regarding the spatial organisation of the wind. Sledging treks were undertaken during the summer period of the initial field season and provide the only observational record away from the Cape Denison base station. Results from operational weather forecasting models such as AMPS provide a dynamically consistent output set that has helped expand an understanding of the extent of the strong wind regime at Adélie Land. Evidence from AMPS suggests that the zone of strong winds extends south and east of the coast for at least 300 km. Modelling work confirms the confluence of cold air from the Antarctic interior that feeds the winds at Cape Denison. In addition, estimates as to the vertical extent of the strong wind zone can be inferred. It seems clear from the mean annual averages obtained from the AMPS archive that the strong wind layer is confined within the lowest kilometre with the strongest winds between 100-200 m above the surface.

Simulations have been performed with AMPS to better understand the forcing mechanisms that drive the strong winds of Adélie Land. Tendencies such as the horizontal pressure gradient force were output and resolved into katabatic and ambient synoptic components. The katabatic component is the dominant component of the PGF within the Adélie Land confluence zone for the month of April 2002. This is not to imply that synoptic settings cannot impact the wind conditions. Maximum wind speeds for April 2002 occurred under a similar synoptic setting with lower pressure to the east and a significant east-west gradient of pressure just offshore. In some cases, the ambient synoptic pattern enhances cold air advection from the interior. In other cases, the synoptic forcing simply reinforces the PGF and acts in a downslope direction similar to katabatic forcing. This process occurs whenever a component of the wind is directed against the Antarctic continent and is a result of the adjustment of the wind and pressure gradients adjacent to the elevated terrain that is similar to the forcing of barrier winds (e.g. Schwerdtfeger 1975; Parish 1983).

There also seems to be a clear relationship between the favoured location of cyclones in the coastal environment near 150°E and the outflow from Adélie Land. This relationship will be explored in future work, yet it is apparent that some feedback exists between the Antarctic drainage flow and cyclo-

genesis in the near coastal regions that has been suggested previously (e.g. Carrasco et al. 1997).

Acknowledgments

Automatic weather station data were provided by the Antarctic Meteorological Research Center at the University of Wisconsin and by the Australian Antarctic Division Glaciology Program. This research was supported in part by the US National Science Foundation grant OPP-0229337.

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