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Strong wind events in the Antarctic

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[1] We use quality controlled in situ meteorological observations collected at Antarctic research stations over the last 60 years to carry out the first continent-wide investigation into the occurrence, variability, and trend in strong wind events (SWEs). Reanalysis/analysis fields are used to examine the synoptic background in which such events take place. SWEs are a feature of the extended winter season and involve a complex interaction between the downslope buoyancy forcing and the pressure gradient force from synoptic-scale cyclones. Around the coast of East Antarctica the significant majority of SWEs are associated with enhancement of the downslope katabatic flow by the broadscale synoptic circulation, involving a deepening of pressure off the coast and an increase of pressure inland. Orientation of the valleys in relation to the cyclone track is critical in enabling enhancement of the katabatic winds. Casey, Mawson, and Dumont d'Urville stations report the greatest number of winds of storm force and stronger. Interannual variability of SWE numbers is large. Trends in the number of winter strong wind reports are small. The greatest statistically significant increase in wind speed since the 1950s has been at Faraday/Vernadsky and Syowa stations. The largest wind speed increases since 1979 have been at Davis and Mawson stations. Comparison with high-resolution numerical simulations showed that the reanalysis/analysis fields are able to capture the large-scale synoptic features and the associated enhancement of the katabatic flow but underestimated the observed wind speed if it was strongly influenced by local topographical conditions.

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1. Introduction

[2] Strong, persistent and directionally constant near-surface winds are one of the most marked features of the Antarctic climate system and are particularly pronounced around the coast of East Antarctica. These strong winds have been noted at Antarctic coastal stations since the days of the earliest expeditions onto the continent when they proved a great challenge to the overwintering parties. The 1912–1913 expedition led by Douglas Mawson recorded a mean annual average wind speed of 19.4 m s^{-1} and gale force winds on all but one of 203 consecutive winter days [*Mawson*, 1915]. Subsequent investigation has shown that the winds at coastal sites in Adélie Land are not only the strongest in Antarctica, but the strongest on Earth close to sea level [*Parish*, 1988; *Wendler et al.*, 1997; *Parish and Walker*, 2006].

[3] The strong winds in the coastal zone play an important part in the general circulation of high southern latitudes [*Parish and Cassano*, 2001]. They represent a large mass and heat exchange between the Antarctic plateau and the coastal region. They are also important in blowing snow off the continent and onto the ocean or sea ice, and for maintaining ice-free conditions adjacent to the coast via coastal leads and polynyas. Although katabatic winds are a feature of the surface climate of the Antarctic, they interact with the broadscale circulation of high southern latitudes [*Parish*, 1992] and have been linked to the polar vortex [*Simmonds and Law*, 1995].

[4] In the presatellite era, when it was difficult to investigate the broadscale climate of the continent, the strong winds were the subject of many observational and theoretical studies, since instrumentation installed across relatively limited areas could provide great insight into the nature and variability of the wind systems. Such work, carried out especially during the International Geophysical Year (IGY) of 1957/1958, revealed the high directional constancy of the winds and their shallow nature.

[5] From the earliest investigations it was realized that the strong winds were intimately associated with the shape of the Antarctic ice sheet, and that the strongest winds were found in the coastal region at the base of valleys. The winds were linked to extremely cold air on the Antarctic plateau that had cooled as a result of intense radiational heat loss during the winter months and begun to flow down to the coastal region as a result of negative buoyancy. These

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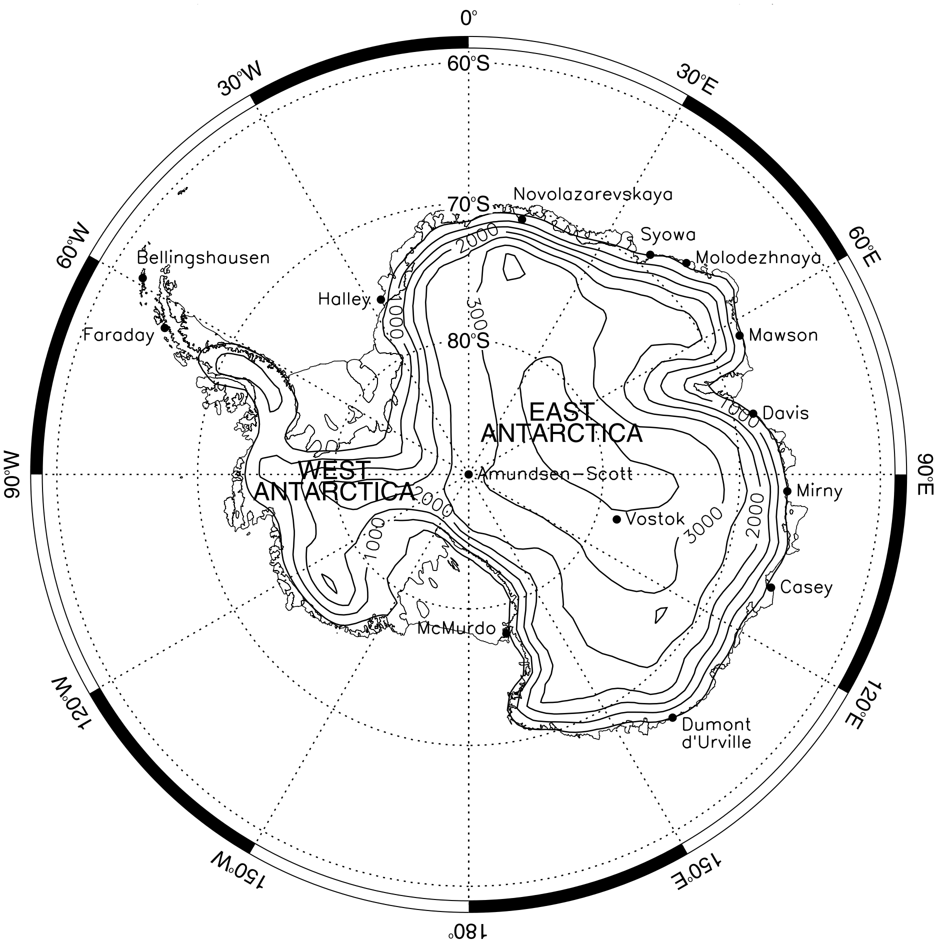

Figure 1. A map of the Antarctic showing the locations of the stations referred to in the text. The contours indicate the orographic height used by ERA-40 (meters).

strong winds have often been referred to as katabatic, however, this term has been used in the literature in a number of different ways [*Parish and Cassano*, 2003]. Sometimes it is used in the sense of any downslope wind, while at other times it is specifically linked to the flow generated by radiational cooling over ice slopes. Studies with diagnostic and numerical weather prediction models have shown that the winds are linked closely to the underlying ice topography and follow the gradient down from the high interior plateau [*Parish and Bromwich*, 1987]. However, it was also recognized that the many synoptic-scale depressions in the Antarctic coastal region could also contribute to strong winds [*Simmonds and Murphy*, 1992; *Murphy and Simmonds*, 1993].

[6] The climatological upper tropospheric flow around the Antarctic is rather zonally symmetric so that most depressions move from west to east in the coastal zone. The large number of depressions here results in the belt of low pressure known as the circumpolar trough. This is a zone of declining synoptic-scale lows that have moved south from midlatitudes, but is also where many lows develop, especially mesoscale systems [*Turner et al.*, 1998]. When the Rossby waves are amplified depressions may be steered into the interior of the continent [*Pook and Cowled*, 1999], however, the high elevation of the Antarctic interior (Figure 1) typically limits the influence of most depressions to the coastal region. Thus, in these areas the near-surface winds are forced by both synoptic forcing and katabatic forcing. Here the synoptic pressure gradient can work to enhance or inhibit the katabatic winds depending on the location of the depressions. Most depressions pass from west to east in the coastal region with the winds being onshore as the depression approaches a location and then offshore once the low has passed to the east. Winds down the valleys therefore tend to be suppressed when a low is to the west of the base of the valley and enhanced when it is to its east. Recently the output from the Antarctic Mesoscale Prediction System (AMPS) [*Powers et al.*, 2003] numerical weather prediction model has been used to examine winds across the Antarctic continent [*Parish and Bromwich*, 2007], which indicated the importance of both synoptic forcing and katabatic forcing to the Antarctic coastal wind regime.

[7] Therefore, strong wind events (SWEs) are often a result of a complex interplay between the katabatic pressure gradient force (PGF) and the broadscale synoptic PGF and that it is difficult to apply any simple classification to the winds observed and that the forcing may change with time.

Table 1. The 10-Min Mean Wind Speeds Associated With the Beaufort Wind Force Levels Used in This Study

Beaufort Wind Force	Wind Speed Range (m s^{-1})
8: gale	17.2–20.7
9: severe gale	20.7–24.5
10: storm	24.5–28.4
11: violent storm	28.4–32.6
12: hurricane force	>32.6

A primary goal of this paper is to examine the role of synoptic-scale weather systems in giving SWEs at the coastal stations.

[8] While there have been many observational [*Turner et al.*, 2001], theoretical [*Ball*, 1960; *Parish and Bromwich*, 1987] and numerical modeling [*Parish and Waight*, 1987; *Gallée et al.*, 1996; *Heinemann*, 1997; *Adams*, 2005] studies of katabatic winds and other SWEs, there has been much less work on the climatology of extreme winds. It is now 50 years since the IGY and a number of stations have operated continuously over this period. Their record of in situ meteorological observations provides an extremely valuable resource with which to investigate the frequency of SWEs and any changes over the last half century. In this paper we examine strong winds in the Antarctic coastal region, with such events being taken as 10-min mean wind speeds above various values on the Beaufort wind scale (see Table 1). The frequency with which observations have been made at the stations has occasionally changed over time, but for consistency we have used only the 6-hourly data.

[9] Most work to date has been concerned with SWEs in the Antarctic coastal region, or on the slopes immediately inland. Wind speeds on the high plateau are much lower than around the coast because of the more gentle topographic slopes (see Figure 1) and the limited occurrence of synoptic-scale weather systems. Yet conditions in the interior of the Antarctic are of great importance because of the precipitation that falls there and how this might change in the future in response to global warming [*Bracegirdle et al.*, 2008]. Most research here on extremes has been concerned with large positive temperature anomalies at the plateau stations as maritime air masses occasionally penetrate far into the interior [*Sinclair*, 1981]. So here we present the first detailed analysis of SWEs at Amundsen-Scott station at the South Pole and Vostok on the plateau of East Antarctica, since these are the only two stations with long meteorological records in the interior.

[10] In section 2 we consider the data available to investigate SWEs and discuss data quality and availability. Section 3 examines the synoptic conditions that give rise to SWEs and we present representative cases involving the interaction of the downslope flow and the broadscale circulation. In section 4 we consider the occurrence, variability and trends in the wind reports. We conclude by summarizing our current knowledge of SWEs and presenting output from a high resolution, limited area atmospheric model. We also discuss possible future work.

2. Data

[11] This study is based on the in situ surface meteorological observations of wind strength, direction, temperature and pressure from stations that are staffed year round and have mostly operated since around the middle of the twentieth century (Table 2). Faraday (now the Ukrainian Vernadsky station) was established in 1947, but some of the data are questionable in the late 1940s, so here we have used the observations from the start of 1950. Most of the stations (Mirny, Davis, Dumont d'Urville, Halley, Mawson, McMurdo, Syowa, Amundsen-Scott and Vostok) were established in the period leading up to the IGY, or during the actual period of the experiment (1957–1958), with Casey established in 1959 and Molodeznaja in 1963. The shortest record we have used, which begins in 1968, is from Bellingshausen Station near the tip of the Antarctic Peninsula. The climate at this northerly station near the polar front is quite different from that at the coastal stations of East Antarctica, but the data from Bellingshausen provides a valuable perspective on SWEs where there is no influence of katabatic flow. We have not used data from stations with shorter records since we are concerned with changes over long periods for which we can investigate significant trends. The locations of the 14 stations used are shown in Figure 1.

[12] Clearly using data from these stations only allows us to examine SWEs under a limited range of conditions across the Antarctic. While Cape Denison (67.1°S, 143°E) is regarded as possibly having the highest mean wind speeds on the continent, it would be inconceivable to build a permanently staffed year-round station at this location because of operational difficulties. In this study we are therefore not going to see the most extreme SWEs found in the Antarctic coastal region. However, stations such as Dumont d'Urville and Mirny experience strong and persistent winds from the interior and are also influenced by many major storms in the circumpolar trough. We therefore feel that the data from the stations examined provide valuable insight into the nature of SWEs which characterize Antarctica and the changes that have taken place in the frequency and magnitude of such events in recent decades.

[13] Since the mid-1980s many automatic weather stations (AWSs) have been installed across the continent [*Stearns and Wendler*, 1988] and the data from these systems have provided a great deal of insight into the nature of katabatic winds [*Wendler et al.*, 1997]. However, there are many challenges in operating AWSs in remote locations, particularly with the measurement of wind speed and

Table 2. Stations and Operating Nations Providing Observations for This Study and the Periods of Data Availability

Station (Operating Nation)	Period of Data Availability
Casey (Australia)	Feb 1959 to Dec 2005
Mirny (Russia)	Feb 1956 to Oct 2006
Davis (Australia)	Mar 1957 to Dec 2005
Dumont D'Urville (France)	April 1956 to Dec 2001
Mawson (Australia)	Mar 1954 to Dec 2005
McMurdo (USA)	Apr 1956 to Feb 2007
Molodeznaja (Russia)	Mar 1963 to Jun 1999
Novolazarevska (Russia)	Feb 1961 to Oct 2006
Syowa (Japan)	Mar 1957 to Dec 2004
Faraday/Vernadsky (UK/Ukraine)	Jan 1950 to Feb 2007
Halley (UK)	Jan 1957 to Dec 2007
Bellingshausen (Russia)	Mar 1968 to Oct 2006
Amundsen-Scott Station (USA)	Feb 1957 to Feb 2007
Vostok (Russia)	Jan 1958 to Oct 2006

Table 3. Highest Observed Wind Speed, With Date of Its Occurrence, and Mean Annual Wind Speed and Percentage of Wind Speeds That Exceed Gale or Storm Force[a]

Station	Highest Observed Wind Speed ($m\ s^{-1}$)	Time/Date	Mean Annual Observed Wind Speed ($m\ s^{-1}$)	Percentage of Observed Winds for Which the Wind Speed Exceeded Gale Force	Mean Number of Observed Winds at Storm Force or Above per Year
Casey	52.4	0600 UT 7 Sep 2003	6.5	10.1	4.5
Mirny	46.3	1800 UT 2 July 1961	11.3	15.1	2.2
Davis	40.1	1800 UT 9 Sep 1969	5.3	2.7	0.3
Dumont D'Urville	58.6	0000 UT 23 May 1957	10.0	14.3	4.3
Mawson	49.9	0600 UT 7 Aug 1971	11.2	16.6	4.6
McMurdo	34.4	1800 UT 26 Sep 1997	5.5	0.7	0.1
Molodeznaja	39.0	0000 UT 20 Oct 1970	10.5	16.4	2.0
Novolazarevska	45.2	0600 UT 14 Aug 1966	9.9	13.2	2.5
Syowa	42.1	1800 UT 11 Sep 1984	6.4	7.8	1.4
Faraday/Vernadsky	28.3	1200 UT 15 Aug 1955	4.2	0.5	0.01
Halley	32.9	0000 UT 9 Oct 1969	6.6	4.1	0.3
Bellingshausen	30.3	1800 UT 23 Apr 1975	7.3	1.7	0.1
Amundsen-Scott Station	20.5	1800 UT 1 Aug 1961	5.4	0.02	0.0
Vostok	24.7	1200 UT 20 Jun 1958	5.1	0.02	0.001

[a]Wind speeds are based on 6-hourly data.

direction during the winter months when the systems cannot be inspected and maintained. Anemometers frequently fail and supply suspect data during the winter so that the time series of observations has many gaps. In this study we have therefore used only wind data from the staffed stations that operate year round.

[14] We have based the study around the surface observations from the Reference Antarctic Data for Environmental Research (READER) database of in situ data created by the Scientific Committee on Antarctic Research [*Turner et al.*, 2004], since the observations have been thoroughly quality controlled and where possible data obtained from the national programs who maintain the stations. We have limited the data used to the period where observations were obtained from the operating agencies and are therefore of a high quality. We have not used data obtained from the Global Telecommunications System, which was sometimes used in the later years of the READER database. This ensures that the data are of the highest quality, which is essential when dealing with extreme events.

[15] European Centre for Medium-range Weather Forecasts (ECMWF) ERA-40 reanalysis and operational analysis data are used to investigate the interaction between the synoptic forcing and the katabatic forcing. The ERA-40 reanalysis [*Uppala et al.*, 2005] fields cover the period 1957–2002 and have a horizontal resolution of ~120 km. For 2002–2006 we employ operational analysis data which has an increased horizontal resolution of ~40 km. These fields will be reasonable on the synoptic scale [*Bromwich et al.*, 2007], but will clearly not be able to resolve realistically the strong winds in the valleys in the coastal region. Our use of the fields is therefore limited to considering the broad-scale pressure field. We only use the fields from 1979 when satellite sounder data became available, since earlier fields have been shown to be of poor quality at high southern latitudes [*Marshall and Harangozo*, 2000].

[16] The output from the University of Melbourne automatic depression tracking scheme [*Murray and Simmonds*, 1991] when applied to the reanalysis/analysis data is used at a number of places in the text. The variability in the number of SWEs is related to changes in cyclone density and the location of the major storm tracks.

3. Nature of Antarctic Strong Wind Events

3.1. East Antarctic Coastal Stations

[17] Many of the coastal stations around East Antarctica have reported strong katabatic winds and these are a pronounced feature of the climate. The mean annual wind speeds are typically higher than for stations on the plateau or the Antarctic Peninsula (Table 3). At 11.3 $m\ s^{-1}$ Mirny has the highest annual mean speed, although Mawson and Molodeznaja have mean speeds of 11.2 $m\ s^{-1}$ and 10.5 $m\ s^{-1}$, respectively. However, the mean annual wind speed can vary considerably over quite short distances. Syowa and Molodeznaja are located only 300 km apart on the coast close to 40°E, yet have mean speeds of 6.4 and 10.5 $m\ s^{-1}$, respectively, which is a result of the locations of the stations in relation to valleys.

[18] The monthly mean wind speeds (Figure 2) all show a minimum in summer, but there are large differences in the annual cycle of the wind. Both Syowa and Molodeznaja have a peak around April/May as the trough off the coast in this sector of the Antarctic deepens at this time of year increasing the pressure gradient in the coastal region. The annual cycles at the other stations are also strongly influenced by changes in the centers of the circumpolar trough just to the north of the coastal region.

[19] Individual SWEs are a result of the combined effects of the katabatic and synoptic-scale PGFs. The importance of katabatic flow at each station can be estimated by considering the location of a station in relation to the "confluence zones" apparent on the streamline map produced by *Parish and Bromwich* [1987]. This field was produced using a model that only considered the buoyancy forcing, so it gives an estimate of the strength of the wind when synoptic forcing is small or absent. Of all the East Antarctic coastal stations Dumont d'Urville is closest to a major confluence zone, which results from the flow down from a large sector of Terre Adélie and George V Land. Mirny and Molodez-

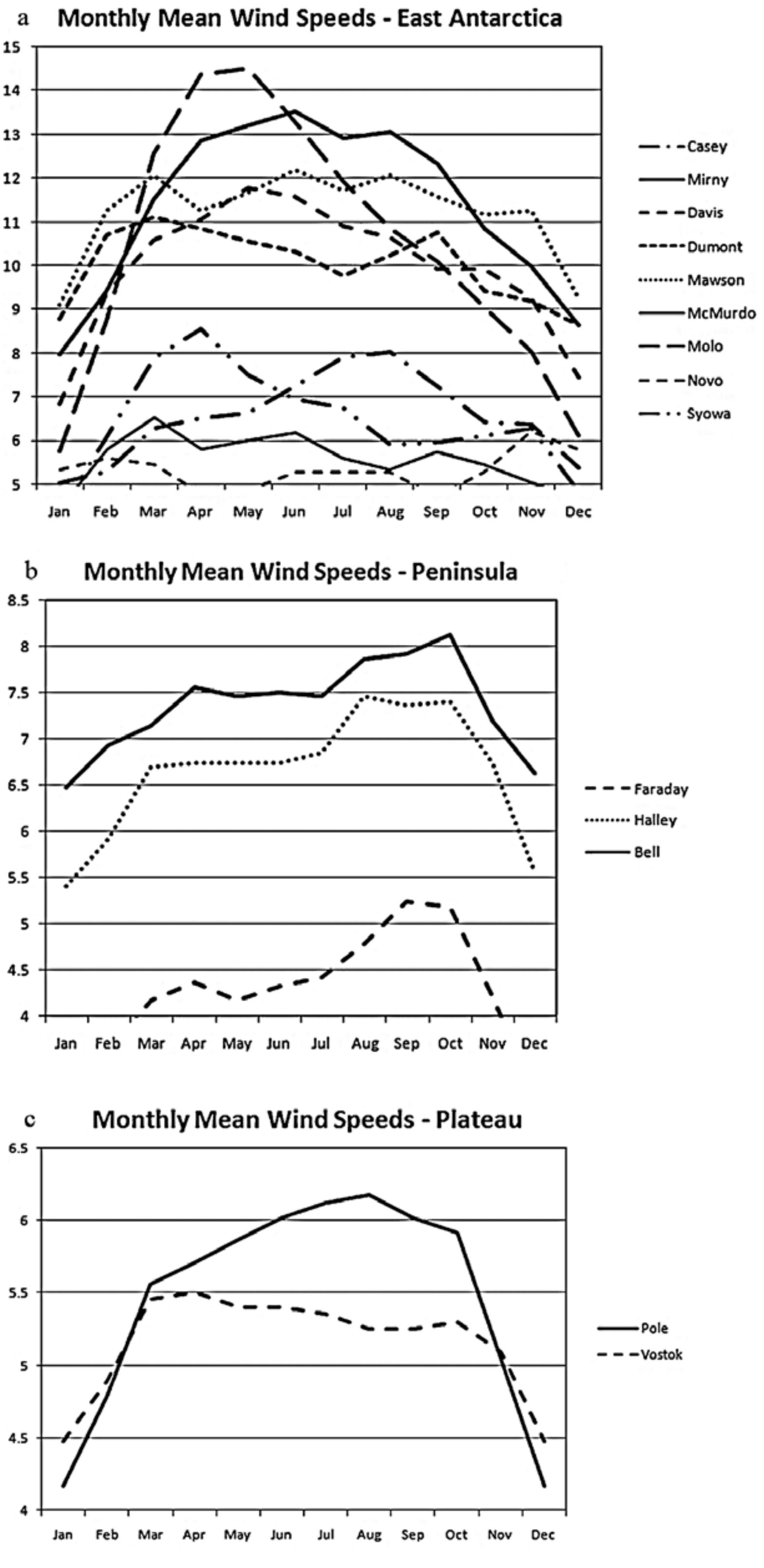

Figure 2. Monthly mean wind speeds (m s^{-1}) at (a) the East Antarctica coastal stations, (b) the Antarctic Peninsula stations, and (c) the plateau stations.

naja are also close to major confluence zones, although the most confluent areas stop some way inland of the stations. Novolazarevskaya, Mawson, Syowa and Davis are all located in regions of more modest confluence than the stations mentioned earlier. However, the model used by Parish and Bromwich to derive their streamline field had a coarse horizontal resolution and so would not represent the role that the local orography around the stations could play

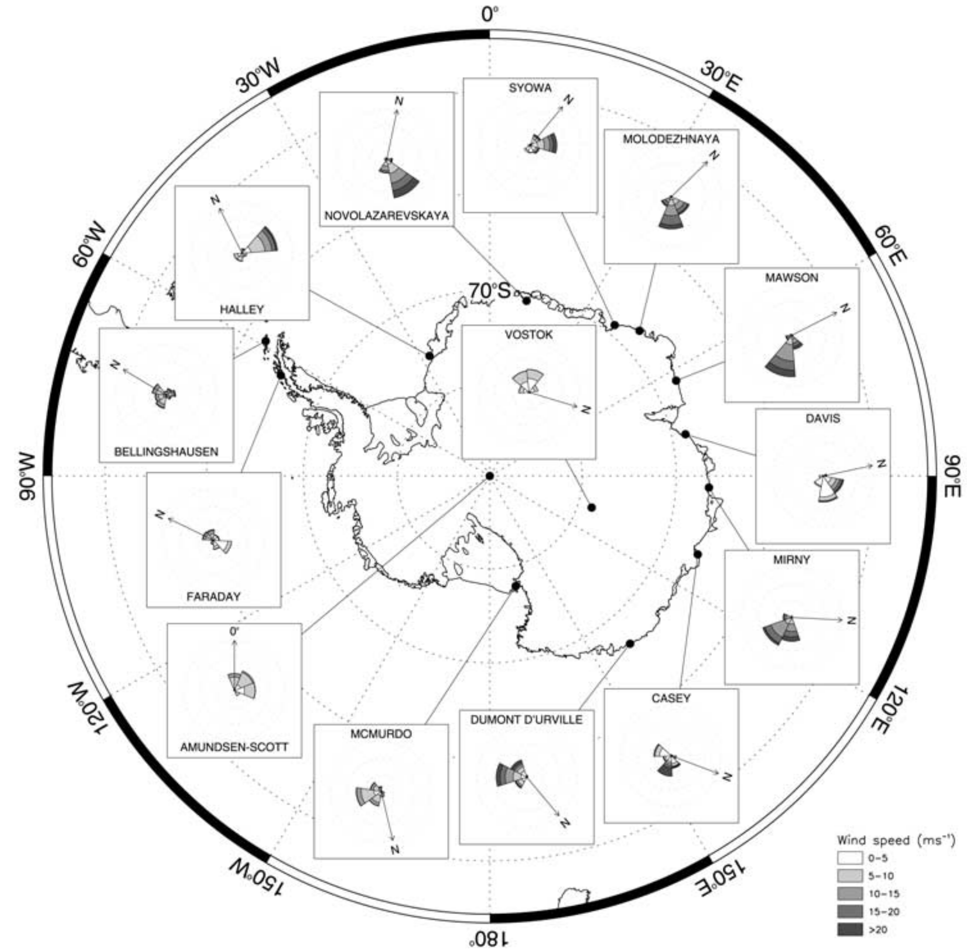

Figure 3a. Winter wind roses for the stations referred to in this study. Each wind rose is oriented so that north (0° for Amundsen-Scott) is aligned with the north (0°) direction at the relevant station (shown as a black dot). The dashed concentric rings on the wind roses show observation frequencies with a 25% interval.

in exposing the stations to the downslope flow or providing a degree of shielding.

[20] For the SWEs of storm force or greater that are considered around the coast of East Antarctica, forcing from the broadscale synoptic flow is found to be important in the majority of the cases examined. This can be seen via the wind roses for all winter season wind reports and the 100 strongest wind observations (Figures 3a and 3b).This is consistent with the study of a SWE in the autumn carried out with a numerical model [*Parish and Cassano*, 2003], which showed that in this case the katabatic component constituted only a small fraction of the total PGF. In addition, the modeling study of *van den Broeke and van Lipzig* [2003a] found that over the gentle inland slopes in July the synoptic-scale PGF could be as important as the katabatic PGF.

[21] With single station data it is not possible to determine the gradient of the pressure field, but we have examined the anomalies from the monthly mean MSLP (mean sea level pressure) in relation to the wind speed. The 1212 reports of storm force winds or stronger for Mawson over 1954–2006 are considered via a scatter diagram of wind speed against MSLP anomaly (Figure 4). This shows a fan-shaped distribution with the highest wind speeds associated with large negative MSLP anomalies and the positive pressure anomalies with lower speeds.

[22] Figure 5 illustrates the synoptic situation when Mawson was reporting a hurricane force wind speed of 37.5 m s^{-1} and a MSLP anomaly of -45 hPa at 0600 GMT 25 July 2004. A deep low was located just to the east of the station and had a central pressure of less than 954 hPa, which explains the extreme pressure gradient and strength of the near-surface winds, with the large-scale PGF enhancing the climatological katabatic wind from the southeast [*Streten*, 1990]. Less intense storms and lows farther to the north are responsible for the SWEs with lower wind speeds.

[23] Figure 4 indicates that there are occasions when there were large positive MSLP anomalies and strong winds at Mawson. The reanalysis/analysis fields show that such events were associated with synoptic situations when a high-pressure ridge built toward the coast from the interior of the continent. Care must be taken when using MSLP data over the high interior of the continent since the values are extrapolated down from the lowest model level, but data in the immediate coastal region will be reliable. Figure 6 shows the analyzed MSLP for 0600 GMT 15 July 1995

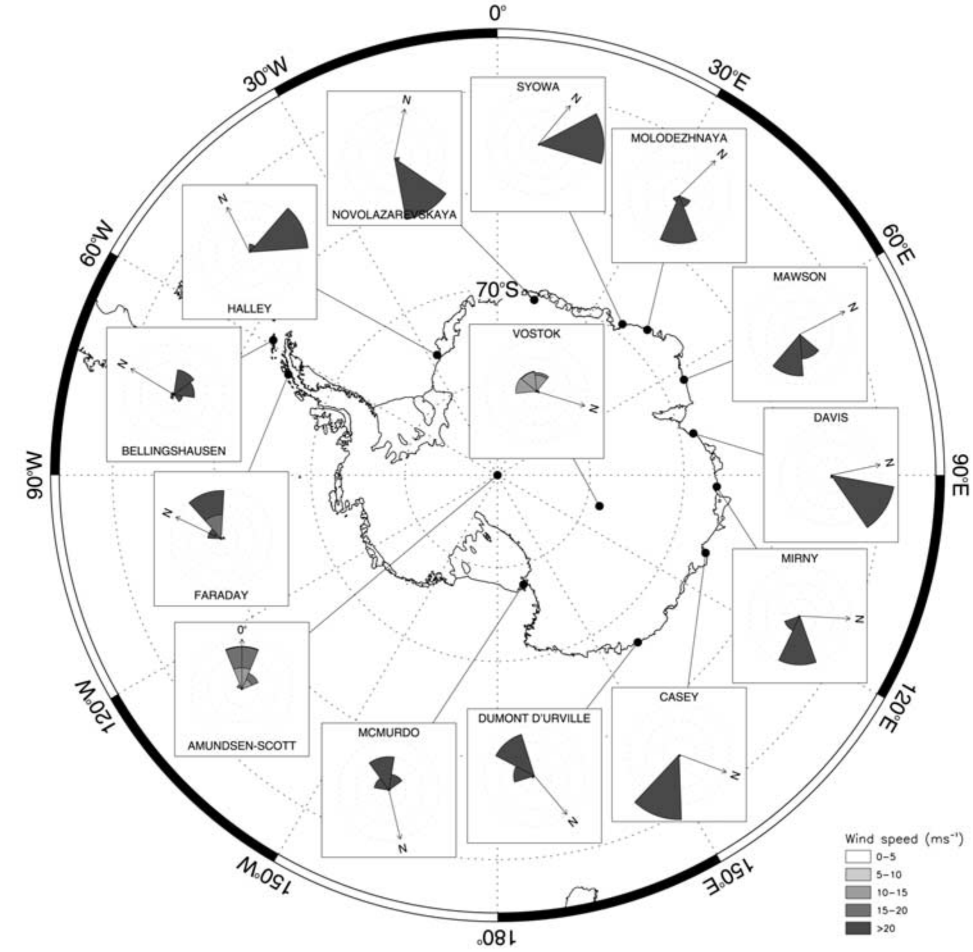

Figure 3b. Wind roses for the 100 strongest winter (JJA) wind events recorded at each of the stations. Each wind rose is oriented so that north (0° for Amundsen-Scott) is aligned with the north (0°) direction at the relevant station (shown as a black dot). The dashed concentric rings on the wind roses show observation frequencies with a 25% interval.

when Mawson had a MSLP anomaly of +17 hPa and a storm force wind speed of 26.7 m s^{-1}. The low to the north in the circumpolar trough was not particularly deep, but the building of the ridge from the interior created a strong pressure gradient that promoted a strong flow in the direction of the climatological wind from the southeast. The case of an extreme wind event at Casey station documented by *Turner et al.* [2001] also involved the establishment of a pronounced ridge over the interior, but in this case the low over the ocean was very deep, which resulted in sustained hurricane force winds of around 51.4 m s^{-1}.

[24] Events in Figure 4 with small positive or negative MSLP anomalies are associated with occasions when a trough of low pressure and a high-pressure ridge occur either side of the station so creating a strong pressure gradient across the station and therefore a strong wind. To enhance the katabatic flow the preferred locations are for the low to be to the northeast and the ridge to the southwest.

[25] Further insight into the SWEs at Mawson can be obtained by examining the in situ wind reports in light of the PGF as determined from the reanalysis fields. Figure 7 shows a scatterplot of the MSLP gradient over Mawson for the period 1979–1998 against the in situ wind speed from the station. There is an almost linear relationship between the pressure gradient and the winds measured at the station, with the winds above ~20 m s^{-1} associated with strong MSLP gradients. However, the linear trend line does not cross the vertical axes at zero. Instead there are a large number of occasions with a small pressure gradient, but with winds of around 10–13 m s^{-1}. Examination of the reanalyzed 700-hPa-height fields indicates that when the MSLP gradient over the station is small the strength of the wind at Mawson is dependent on the synoptic environment over the immediate interior of the continent. When the 700-hPa flow is broadly from the southeast it acts to promote katabatic flow down to the station. Even though the pressure gradient is small on the coast the enhancement over the interior is sufficient to give strong winds in the coastal region. Near-zero wind speeds at Mawson are often associated with a synoptic pattern that gives a west to northwesterly flow over the interior, so suppressing the downslope winds.

[26] Most SWEs at Mawson are associated with positive temperature anomalies at the surface as the low-level

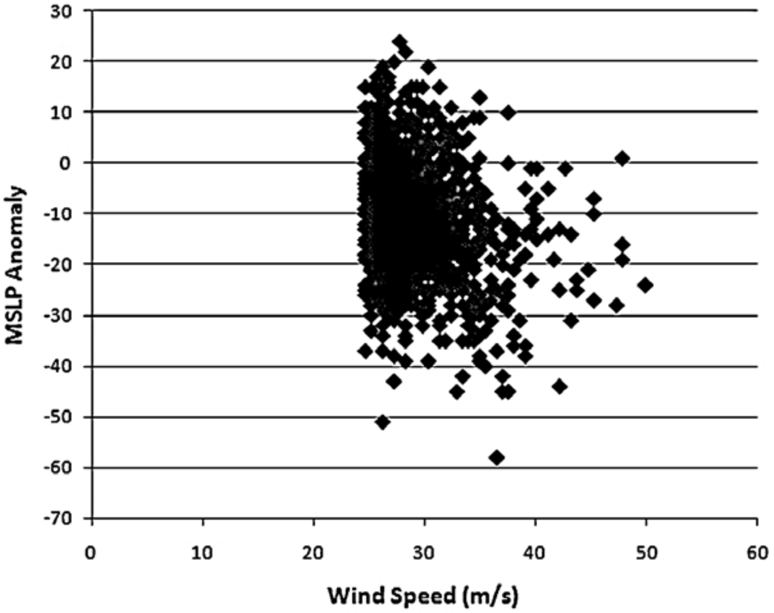

Figure 4. A scatter diagram of all winter season wind speeds (m s^{-1}) of storm force or above measured at Mawson against MSLP anomaly (hPa).

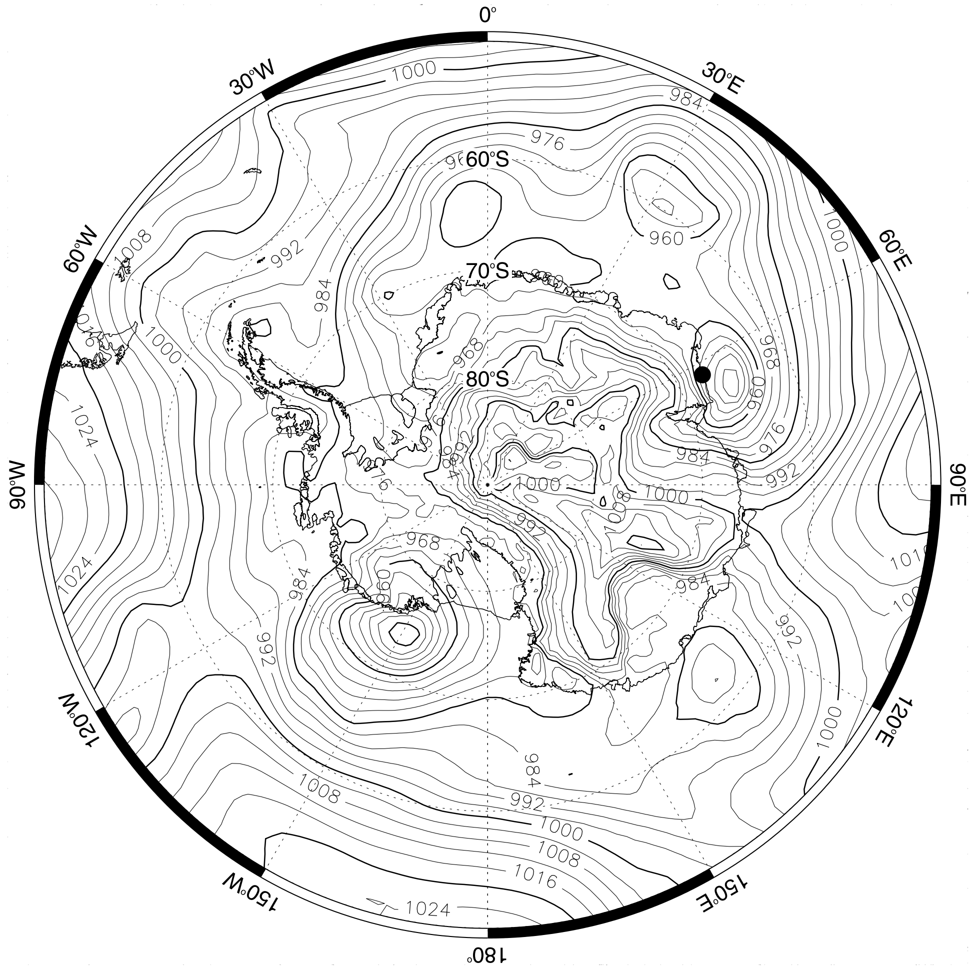

Figure 5. MSLP (hPa) at 0600 GMT 25 July 2004 when Mawson experienced a hurricane force wind speed of 37.5 m s^{-1}. The location of Mawson is shown by a black dot.

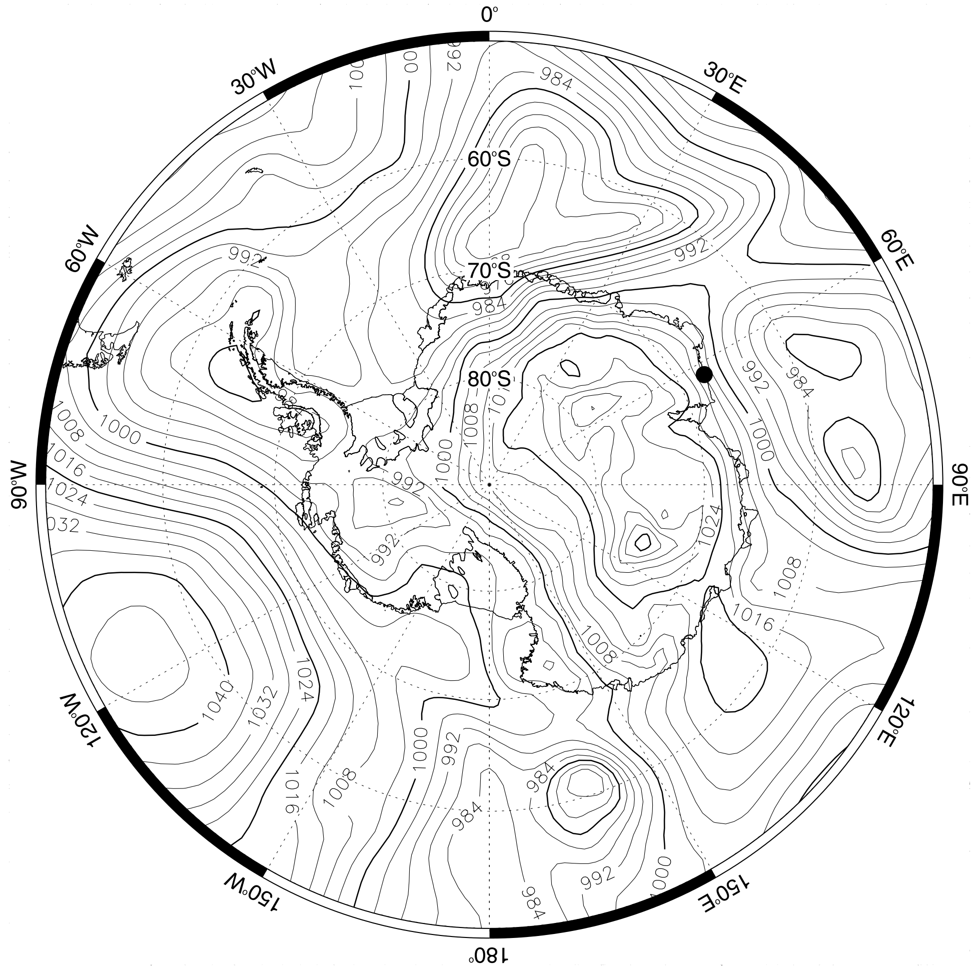

Figure 6. MSLP (hPa) at 0600 GMT 15 July 1995 when Mawson experienced a storm force wind speed of 26.7 m s^{-1}. The location of Mawson is shown by a black dot.

temperature inversion is broken down (Figure 8). As discussed above, the strongest winds are associated with deep depressions just north of the coast, and these result in positive temperature anomalies of about 5°C. The events with negative temperature anomalies are associated with cold air masses coming down from the plateau that have little interaction with relatively mild maritime air masses, and are sufficiently cold that despite the breakdown of the inversion still give negative temperature anomalies.

[27] The other stations around the coast of East Antarctic have broadly the same relationships between temperature and MSLP during SWEs and the broadscale atmospheric circulation. There are minor differences in terms of how storms to the north of the coast enhance or diminish the flow down the valleys depending on the relative locations of the stations with respect to the valley, but Figures 4 and 8 when plotted with data from other stations look essentially the same. However, the environment in the vicinity of McMurdo Station is quite different and warrants being discussed separately.

[28] McMurdo is at a more southerly location than the other East Antarctic stations and its climate is strongly influenced by the presence of the Ross Ice Shelf. This is a region of convergent katabatic flow from the many valleys that drain from the Transantarctic Mountains and Marie Byrd Land [*Bromwich*, 1989] and the wind regime here has been referred to as the Ross Ice Shelf air stream (RAS) [*Parish et al.*, 2006]. The RAS is maintained by the drainage flow off the ice sheets and a persistent cyclonic circulation to the north of the ice shelf. There is often a barrier wind component along the Transantarctic Mountains that can give strong southerly winds at McMurdo. In addition, SWEs can occur as a result of the complex orography around the station that can give rise to barrier winds and mountain waves [*Steinhoff et al.*, 2008]. Synoptic-scale weather systems can also penetrate onto the ice shelf when the upper level steering is from the north, and the whole region of the Ross Ice Shelf and the Ross Sea is characterized by frequent synoptic-scale [*Simmonds et al.*, 2003] and mesoscale [*Bromwich*, 1991] cyclogenesis.

[29] To investigate further the role of anomalies in the broadscale synoptic flow in inducing SWEs we consider the mean MSLP anomaly for all the SWEs that occurred at selected stations during the winter months. As an example, the resulting field for August when there were winds of storm force or greater at Mirny is shown in Figure 9. Mirny experiences winds from the east or southeast on 75% of occasions. However, almost 75% of the winds of storm force or greater arrive from an easterly direction only (Figure 3b). Figure 9 shows that such conditions arise with

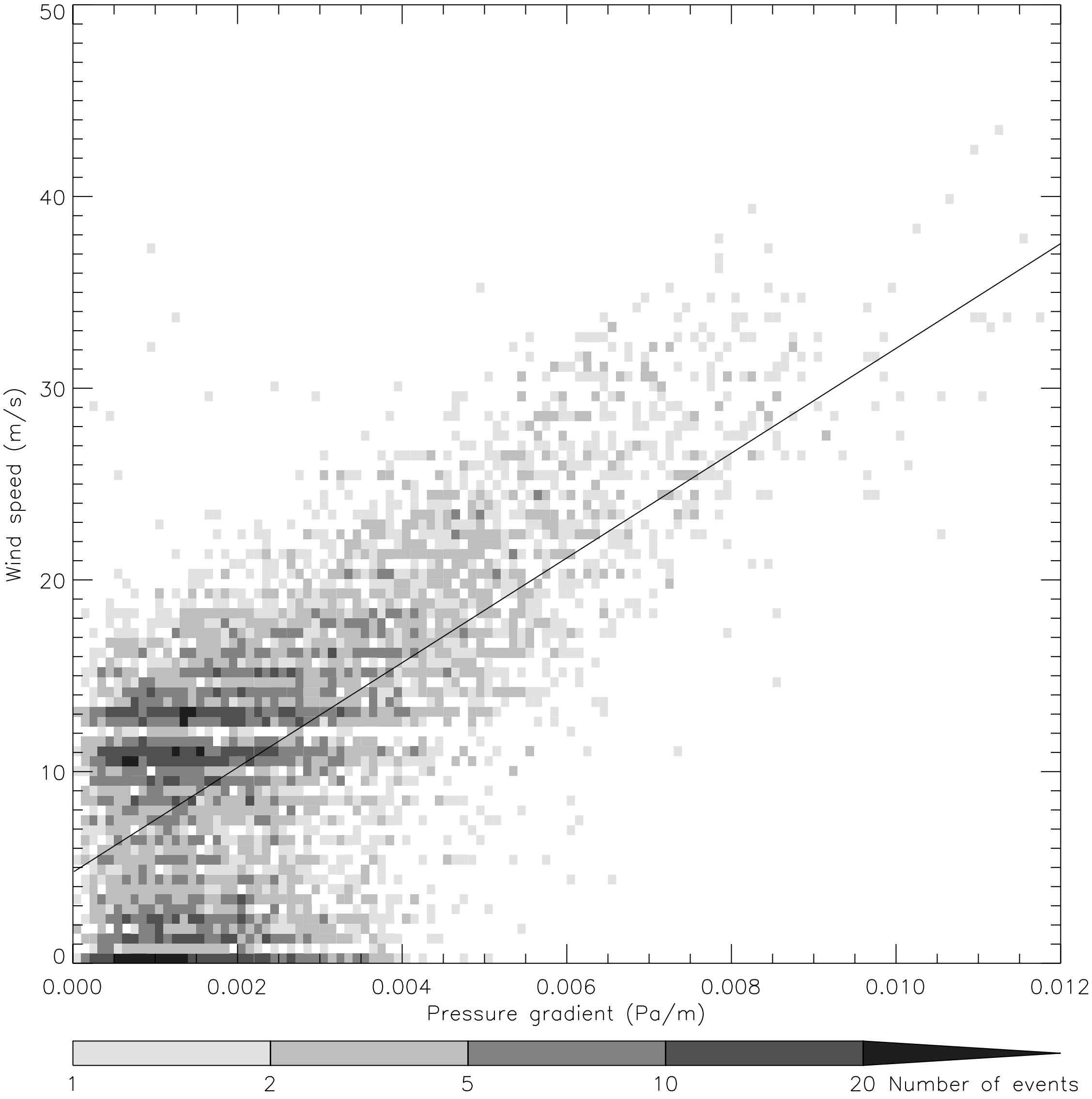

Figure 7. Scatterplot of MSLP gradient (Pa/m) over Mawson station determined from reanalysis data for the period 1979–1998 against the in situ wind speed from the station (m s^{-1}).

a couplet of low pressure to the west and high pressures to the east over the ocean to the north of the station. A further important factor is higher than average pressures over the interior of the continent to the southeast of Mirny, although care must be exercised in using MSLP too far from the coast.

[30] At McMurdo station the strongest winds recorded are associated with synoptic-scale depressions that have penetrated onto the Ross Ice Shelf, with the southerly flow on the western side of the ice shelf enhancing the climatological southerly off-ice shelf flow. A typical example is shown in Figure 10. Here the low tracked onto the ice shelf from the north and introduced mild air with a temperature anomaly of +14.3°C at McMurdo at a time when the station had a southerly storm force wind of 28.3 m s^{-1} and a MSLP anomaly of −42.7 hPa. As with the other coastal stations of East Antarctica, the conditions over the interior of the Antarctic can have a profound effect on the development of SWEs. At McMurdo the SWEs with large positive MSLP anomalies are associated predominantly with occasions when high pressure builds over the interior of the continent and across the station enhancing the gradient to the circumpolar trough. A number of occasions were found of SWEs with large negative temperature anomalies and winds from the north to northeast. At these times the reanalysis/analysis data indicated a southeasterly flow, which is the climatological wind direction, and these events are interpreted as the passage of mesoscale cyclonic disturbances close to the station. The Ross Ice Shelf and Terra Nova Bay regions are where many mesoscale cyclones develop in katabatic outflows of cold air from the interior [*Seefeldt and Cassano*, 2008] and such systems can have a large impact on the conditions at McMurdo.

3.2. Antarctic Peninsula Sector

[31] Bellingshausen and Faraday are maritime stations on the western side of the Antarctic Peninsula. They do not experience persistent katabatic winds, although their cli-

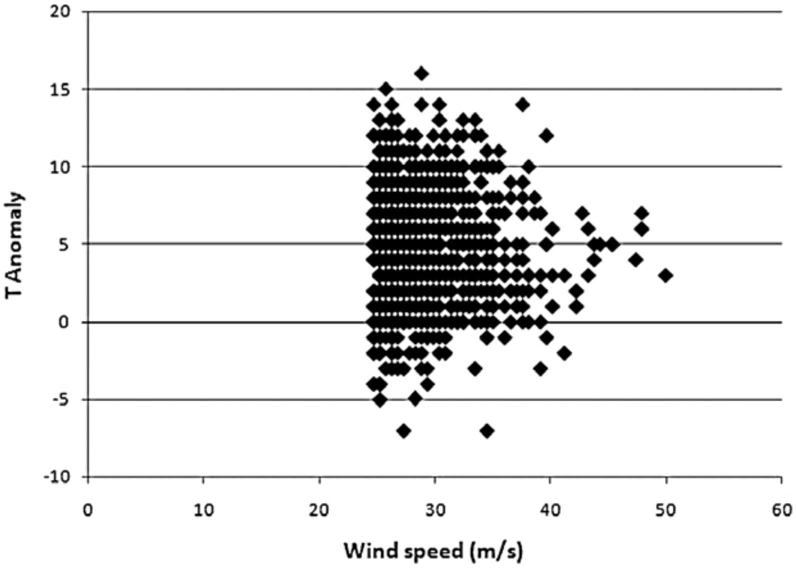

Figure 8. A scatterplot of wind speed (m s^{-1}) against temperature anomaly (°C) measured at Mawson when the wind speed was of storm force or greater.

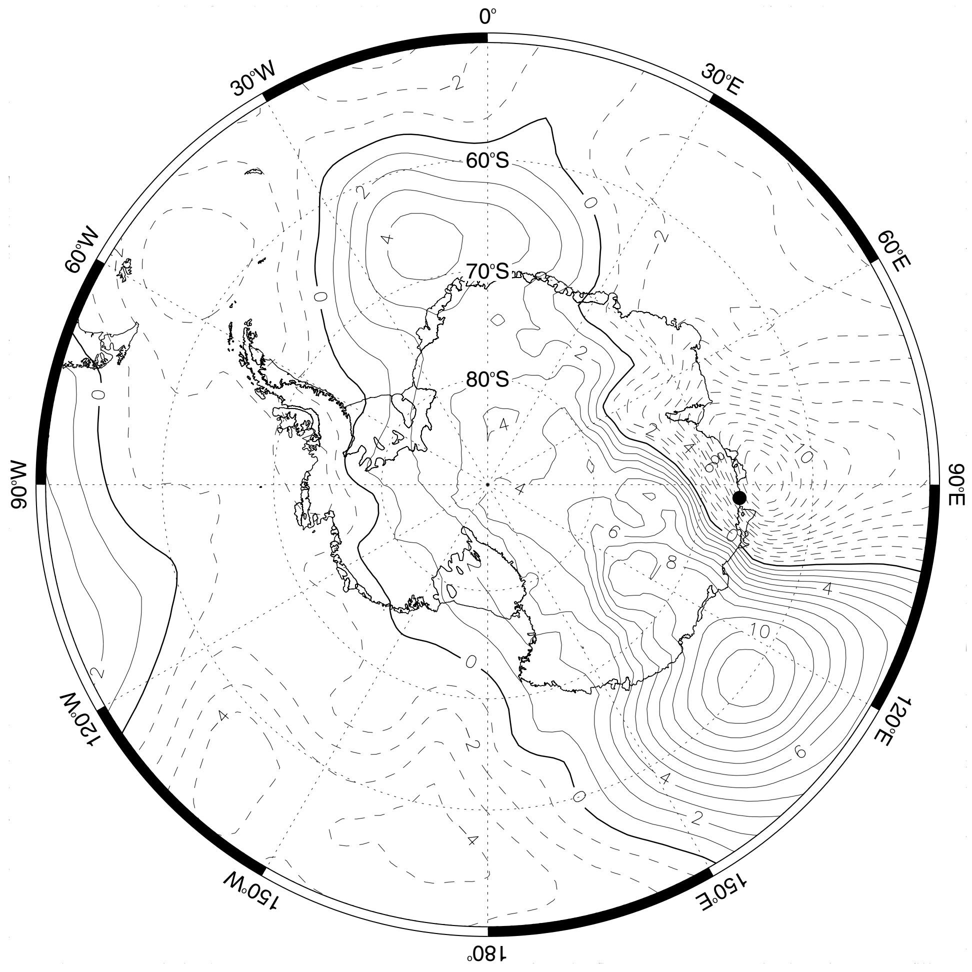

Figure 9. Mean MSLP anomaly (meters) for all occasions at Mirny in August when the wind speed was storm force or greater. The period considered was 1979–2006. The location of Mirny is indicated by the black dot.

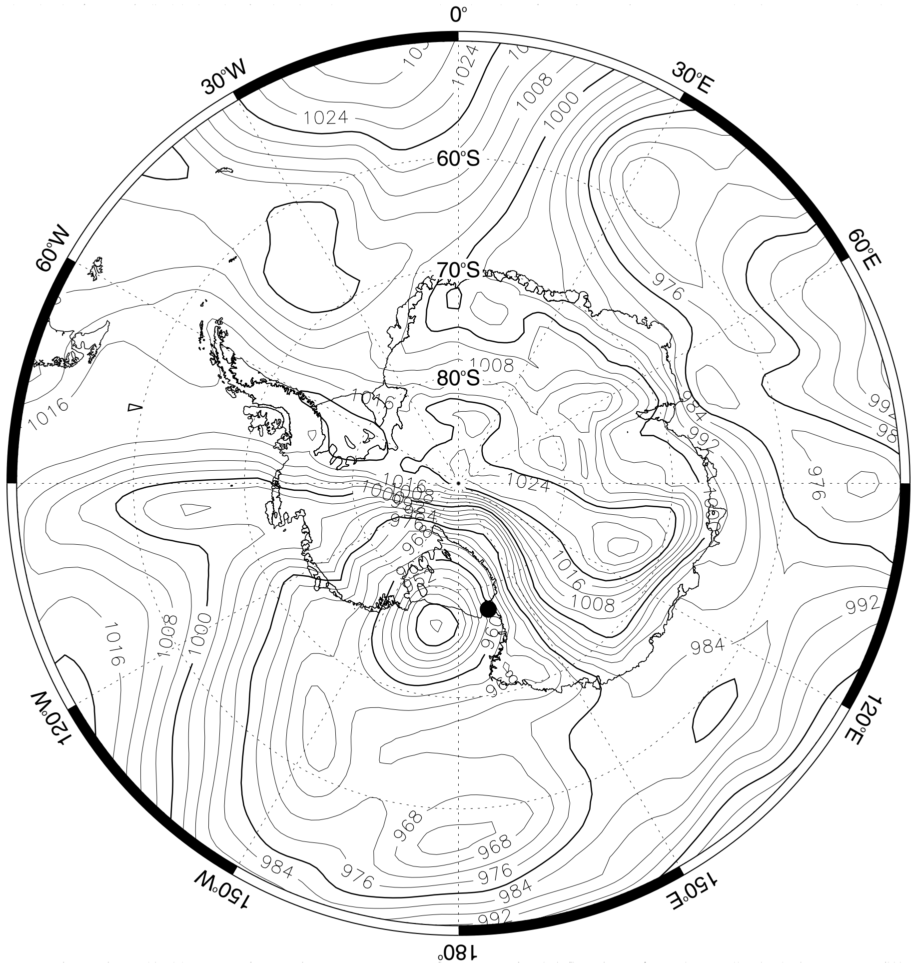

Figure 10. MSLP (hPa) at 0000 GMT 11 June 1984 when McMurdo station experienced a storm force wind speed of 28.3 m s^{-1}. The location of McMurdo is indicated by the black dot.

mates are strongly influenced by the local orography. They are located at the latitude of the circumpolar trough and therefore are frequently under the influence of deep cyclonic systems over the Bellingshausen Sea and passing through the Drake Passage. Halley is to the southeast of the Antarctic Peninsula and is characterized by a much colder continental climate. All three Peninsula stations exhibit a semiannual oscillation in their annual cycle of mean wind speeds (Figure 2b). The SWEs at Faraday usually involve a northeasterly wind with the low being located to the west, where systems often become slow-moving as they come up against the major orographic barrier of the Peninsula. The MSLP at Faraday is usually quite low in such situations. A few SWEs occur when the MSLP is anomalously high, when the station is between a deep low over the Bellingshausen Sea and a large anticyclone over the Weddell Sea to the east of the Peninsula. Occasionally deep lows can be found in the southwestern corner of the Bellingshausen Sea resulting in strong westerlies at Faraday, yet on such occasions the station reports only small MSLP anomalies. Many storms track through the Drake Passage [*Simmonds and Keay*, 2000] and these have a major influence on the winds at Bellingshausen. Most SWEs occur with a easterly or southeasterly wind direction as lows track across the northern Weddell Sea, with a secondary maximum of winds from the north as lows approach the Drake Passage from the west. Around the coast of East Antarctica SWEs are associated with warm temperature anomalies as the temperature inversion is broken down. However, at Bellingshausen many SWEs bring negative temperature anomalies since the strongest winds around a low are often found in the cold, more unstable air arriving from the south.

[32] The climate at Halley is dictated by both broadscale synoptic activity and flow from the interior of Coats Land, although it does not experience the intense downslope flow that dominates the coast of East Antarctica. It has been found that, as on other ice shelves, that there is no coherent katabatic flow signature on the ice shelf on which the station is located [*Renfrew and Anderson*, 2002]. Most SWEs of gale force or greater at Halley occur with easterly flow. The strongest winds are from the east (Figure 11a) when there is a strong pressure gradient between a low over the Weddell Sea and high pressure over the interior. SWEs result in positive temperature anomalies (Figure 11b) as the temperature inversion is broken down.

3.3. Antarctic Plateau Stations

[33] On the high continental interior of Antarctica only Amundsen-Scott station at the South Pole and Vostok in East Antarctica have long climate records, and these both

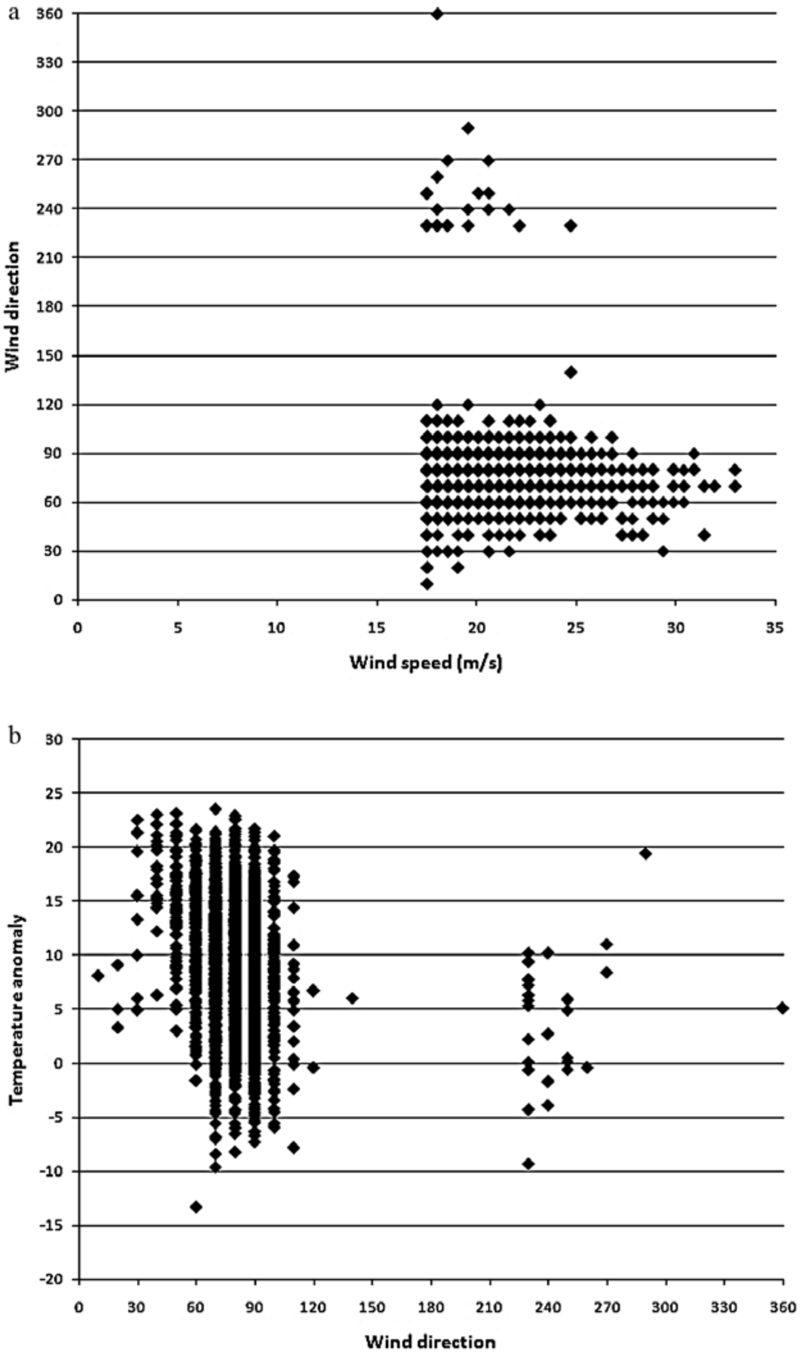

Figure 11. (a) A scatter diagram of all Halley wind speeds (m s^{-1}) and directions (degrees) when the speed is greater than gale force. (b) A scatter diagram of all Halley wind directions (degrees) and temperature anomalies (°C) when the wind speed is greater than gale force.

extend back to the IGY. On this high plateau the wind speeds are dominated by downslope flow and are typically between 4 and 6 m s^{-1}, which is comparable to those at McMurdo. As with the coastal stations, there is a clear minimum in wind speed during the summer (Figure 2c).

[34] At both the plateau sites SWEs are very rare. At Amundsen-Scott station over 85% of the wind direction reports for the year as a whole are between 0° and 90°E (taking 0° as the Greenwich Meridian), since this is the direction from which the downslope flow from the plateau arrives at the station. Winds of gale force or stronger are more backed and come from about 320°E to 50°E. Figure 12 shows the analyzed 500-hPa-height field for 0000 GMT 14 October 2003 when Amundsen-Scott had a station pressure anomaly of +1.1 hPa and a gale force wind speed of 17.5 m s^{-1}. On this occasion there was a low over the eastern Ross Ice Shelf, but significantly, a major high over Dronning Maud Land, which gave strong flow from the direction of the Weddell Sea. All SWEs at Amundsen-Scott involve large, positive temperature anomalies as the surface temperature inversion is eroded and relatively warm air masses are advected south from the coastal region.

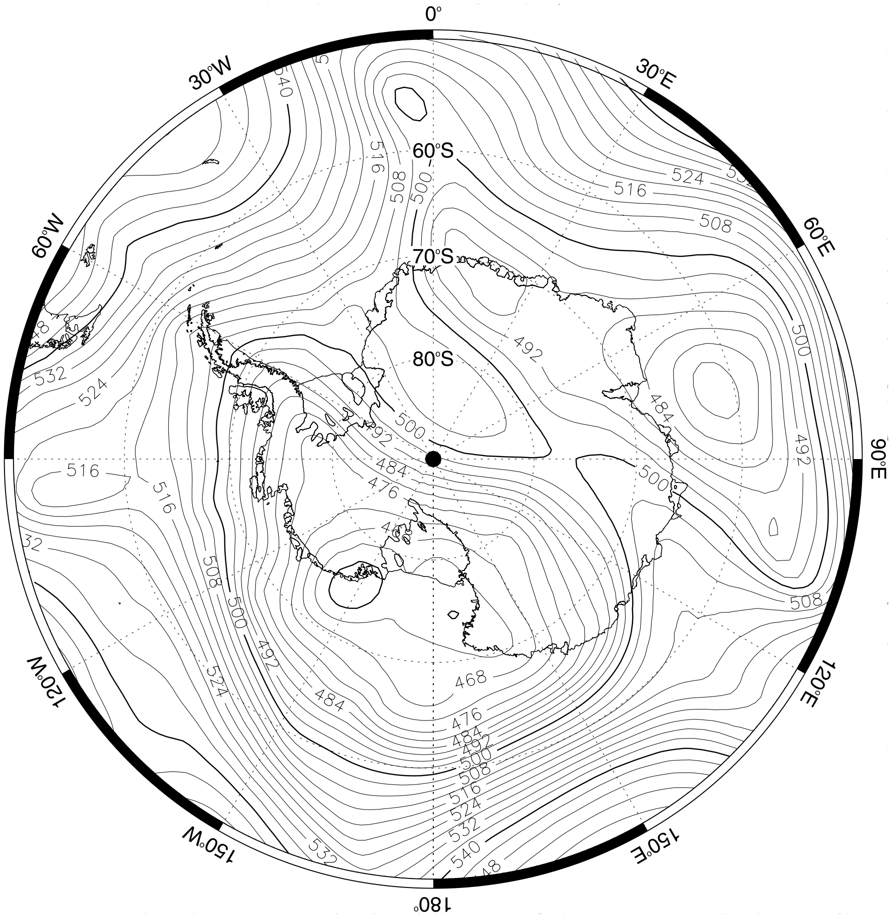

Figure 12. The 500-hPa-height field (decameters) at 0000 GMT 14 October 2003 when Amundsen-Scott experienced a gale force wind speed of 17.5 m s^{-1}. The location of Amundsen-Scott is shown by a black dot.

[35] Winds of gale force or stronger at Vostok are very rare, with only 17 reports since the station was established in 1957. The winds at the station are mainly downslope with directions from south to west, with the SWEs also concentrated in this quadrant and most arriving from the southwest. Figure 13 shows the reanalyzed 500-hPa-height field for 0600 GMT 10 November 1982 when Vostok had a station pressure anomaly of +3.3 hPa and a gale force wind speed of 17.6 m s^{-1}. The event occurred as a result of a ridge of high pressure that had built inland near 30°E directing relatively warm air toward Vostok down the strong pressure gradient that had been established between the ridge and a low in the coastal region.

4. Climatology of Strong Winds

4.1. Mean Occurrence

[36] SWEs are a feature of the extended winter period at all the stations around the coast of East Antarctica, with a clear minimum number of events in summer. There are slight variations in the timing of the peak of activity, as a result of the changes in location of the storm tracks throughout the year. For example, Molodeznya and Syowa, which are close together near to 45°E (Figure 1) both have a peak of strong wind reports in April/May and then fewer strong winds later in the winter. Stations farther to the east all have a peak of strong wind reports in August. The three stations of the Antarctic Peninsula sector all have their SWE peaks in August when the storm activity around the Antarctic is most pronounced. The secondary peak in October coincides with the southward migration and deepening of the circumpolar trough as a result of the semiannual oscillation [*Meehl*, 1991; *Simmonds and Jones*, 1998].

[37] The percentage of winds of storm force or above that occur each year across the Antarctic is highly dependent on location (Table 3). Casey, Mawson and Dumont d'Urville on the coast of East Antarctica have frequent SWEs with storm force winds or greater reported in 4–5% of the observations each year. Mirny, Molodeznaja and Novolazarevskaya have such winds on 2–3% of occasions per year and McMurdo, Syowa and Davis have fewer than 2% reported. There is a broadly linear relationship between mean winter wind speed and the mean number of storm plus wind reports per year, with those stations having lower mean wind speeds receiving fewer strong winds (Figure 14). However, several factors influence the number of strong winds that a location receives, such as its position in relation to the storm tracks and with respect to the valleys that drain

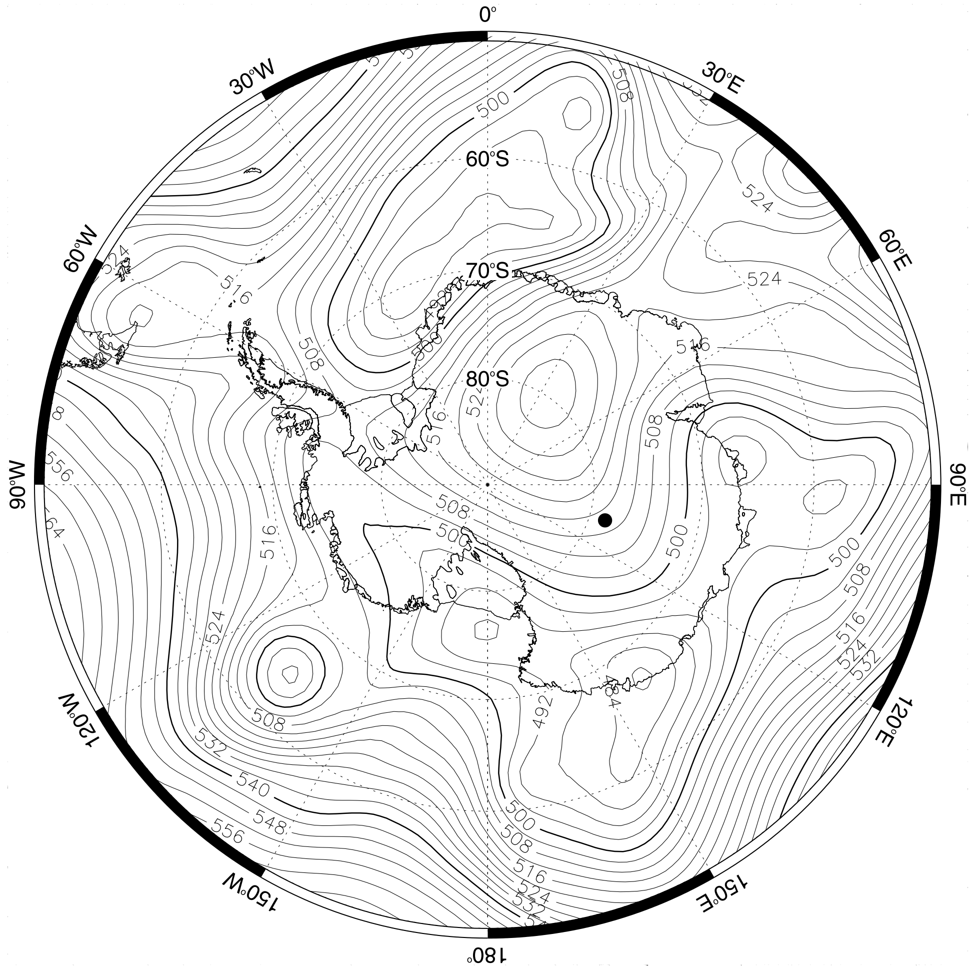

Figure 13. The 500-hPa-height field (decameters) at 0600 GMT 10 November 1982 when Vostok experienced a gale force wind speed of 17.6 m s^{-1}. The location of Vostok is shown by a black dot.

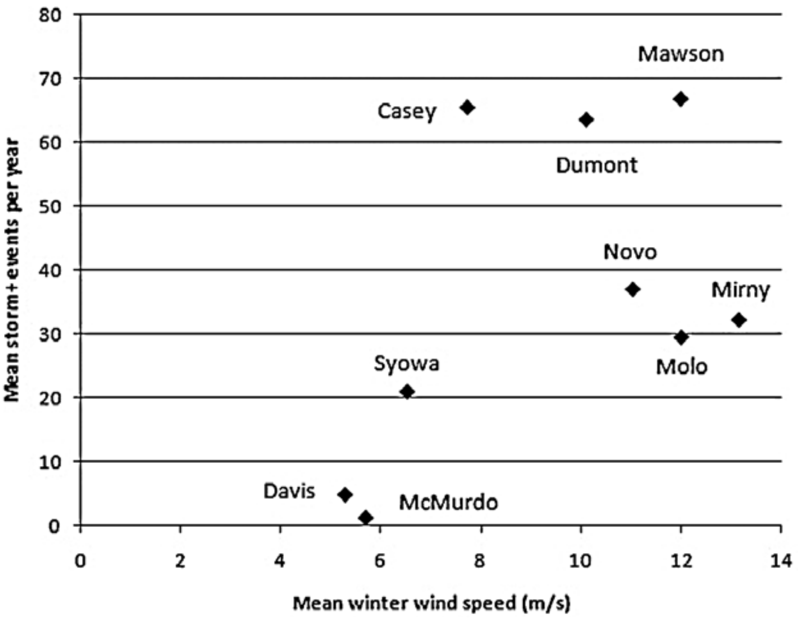

Figure 14. Relationship between mean winter wind speed (m s^{-1}) and the mean number of winds of storm force or greater per year for the nine stations around the coast of East Antarctica.

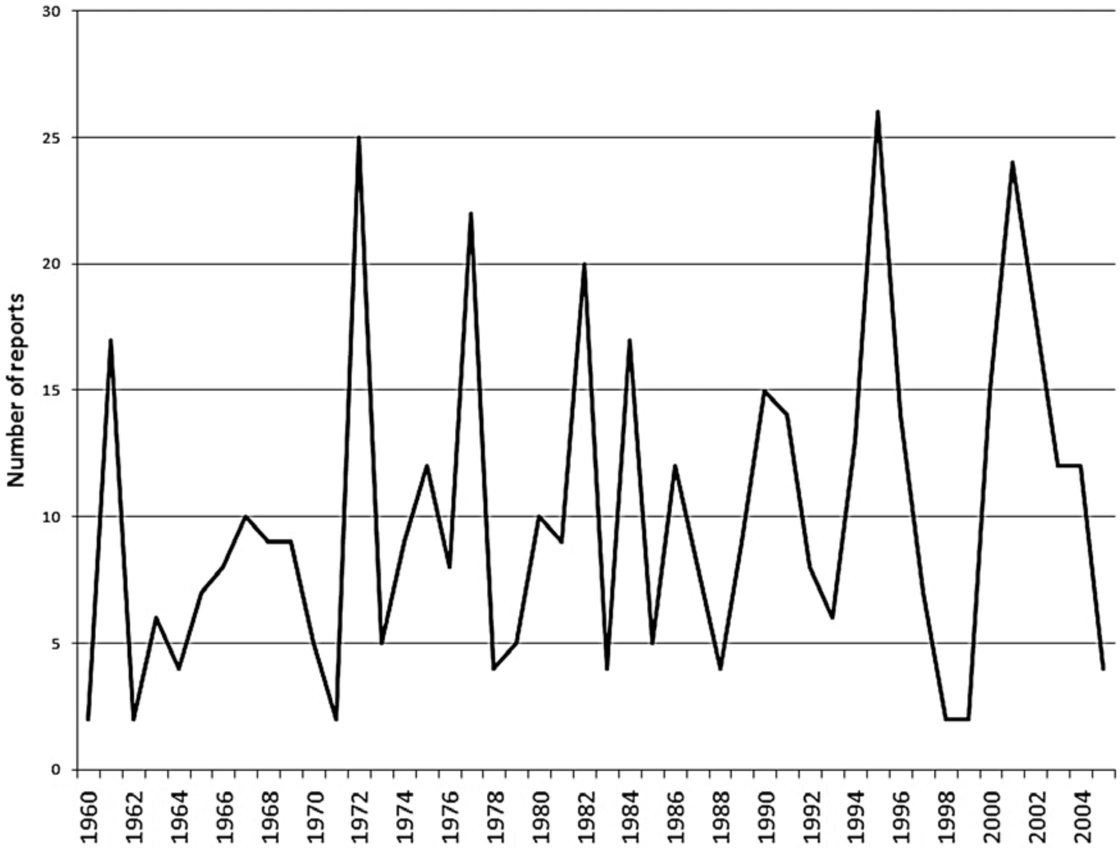

Figure 15. Number of reports of winds of storm force or greater in July at Casey.

cold air from the interior, along with the interactions that can occur between the broadscale flow and katabatic winds at a location.

[38] Figure 14 suggests that the stations around the coast of East Antarctica fall into three general groups. Davis, McMurdo and Syowa all have relatively low mean wind speeds and few SWEs. McMurdo is rather a special case being located well south of the main storm track and removed from many of the deepest depressions. However, the station is on the western side of the Hut Point Peninsula and therefore sheltered from some of the strong winds from the south and southwesterly directions. There are strong barrier winds on the western side of the Ross Ice Shelf, but this flow is often deflected away from McMurdo by Minna Bluff or the blocking effects of Ross Island.

[39] Davis and Syowa are both at locations where the orography of the Antarctic extends northward to their east, so limiting the extent to which storms over the Southern Ocean can enhance the katabatic flow, which is anyway rather weak at these locations [*King and Turner*, 1997, Figure 4.6]. Casey, Dumont d'Urville and Mawson are well placed for depressions in the circumpolar trough to enhance the katabatic flow. At Dumont d'Urville and Mawson these are from the southeast and with storms to the northeast of the stations the broadscale and katabatic PGFs can work together to enhance the flow. Casey is located to the west of Law Dome and the prevailing wind is from that direction. Ninety-three percent of the SWEs come from the east suggesting that this is one of the best placed sites for storms to the north to enhance the prevailing flow: seven of the stations around East Antarctica have most SWEs arriving from the prevailing wind quadrant, with only McMurdo and Mirny having the peak within 45 degrees.

[40] Novolazarevska, Molodeznaja and Mirny all have relatively high mean wind speeds yet relatively few SWEs. Their prevailing wind directions are from the southeast, with the SWEs mostly associated with this wind direction. From our understanding of the synoptic background when SWEs occur (Figure 8), we know that broadscale support from a deep low off the coast is necessary to enhance the flow to storm force or above. The lack of SWEs at these locations considering their high mean wind speed suggests that the local orography is not conducive to the PGF from large lows to the north enhancing the katabatic flow to the extent that occurs at other stations.

4.2. Interannual Variability

[41] The interannual variability in the number of SWEs is large at many of the stations around the Antarctic. For example, at Casey station the number of reports of winds greater than storm force during July varies between 2 and 26 over 1960 to 2005 (Figure 15). Since winds of this strength are linked to synoptic-scale activity off the coast, the number of reports in any one winter month is related to the amplitude and location of the Rossby waves. For example, July 2001 saw many SWEs at Casey as there was an amplified wave number 3 pattern, with the marked upper trough close to 90°E (Figure 16) giving many surface cyclones in the vicinity of the station. This was apparent in the output from the University of Melbourne automatic

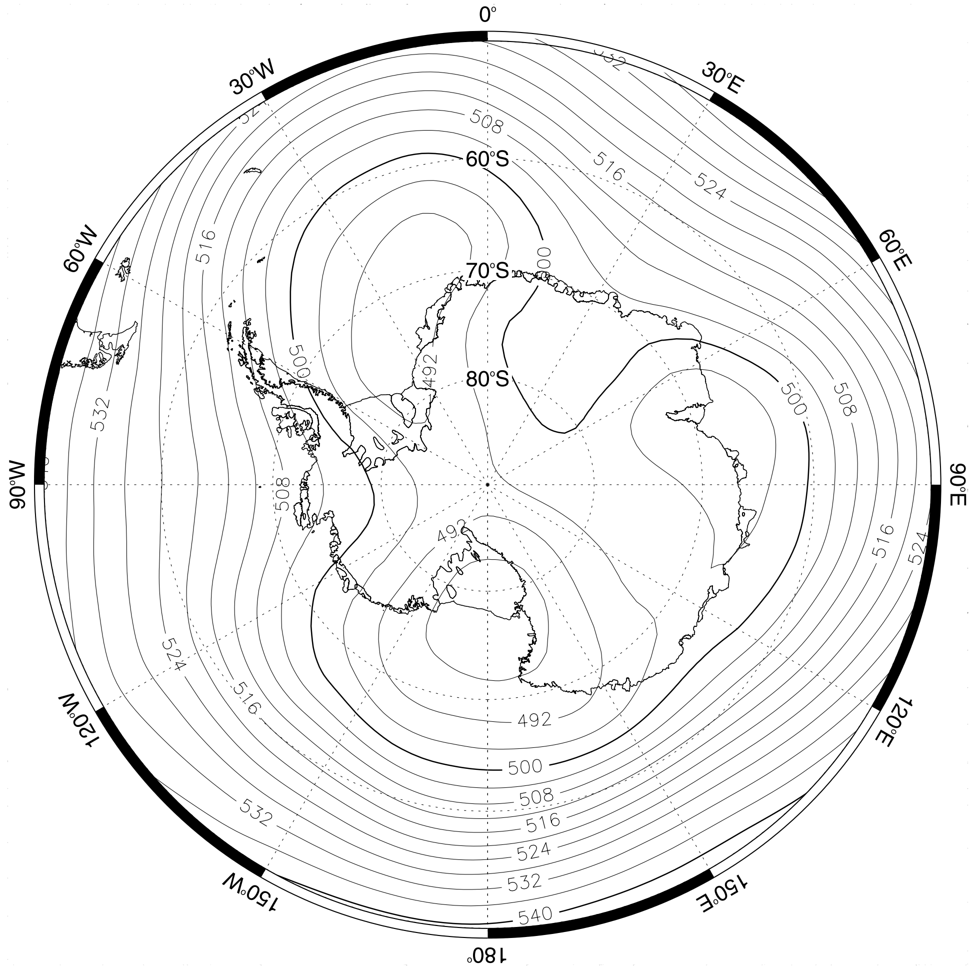

Figure 16. Mean 500-hPa-height field (decameters) for July 2001.

depression tracking scheme, which had a high cyclone density over 100–120° E. Other years with many SWEs, such as 1995, 1982 and 2002, all had an amplified 500-hPa trough across the longitude range 0° to 90°E and a high cyclone density north of the station.

[42] With a marked trough at a particular longitude there will be strong cyclonic activity to the east, but also reduced occurrence of depressions to the west of the location. Therefore, in July 2001 Davis station, which was located to the east of the strong upper trough, had very few SWEs at the time that Casey had one of its windiest months.

[43] The upper level environment varies on a year-to-year basis, with some years having a broad trough across this sector, while others, such as 2001 had a distinct upper center. Years of few SWEs, such as 1999, 1998 and 1988, had an upper flow characterized by ridging from the north in this sector of the continent and therefore fewer deep cyclones.

[44] The points made above regarding the relationship between the number of SWEs in a particular month and the location of nearby upper troughs apply to the other coastal stations, especially around East Antarctica. The local orography and the location of depressions in relation to a station are important factors in controlling the winds at a site, but the Rossby wave activity is the main controlling factor in dictating the interannual variability of SWEs.

[45] The correlation between the number of SWEs at adjacent stations is rather low since the synoptic environment that gives rise to events can be a broadscale upper anomaly or a much more regional perturbation. For example, with Casey and Mirny stations, which are about 700 km apart, July 1982 resulted in a large number of storm force wind reports at both stations since they were both under the influence of a broad upper trough that spanned this sector.

4.3. Trends in the Mean Wind Speeds and the Number of SWEs

[46] Determining the trends in the number of SWEs is hampered by the rather incomplete nature of some of the wind records from the stations, especially in the winter months, when observing conditions can be poor, and also in the early years when instrumentation was not as robust as today. In addition, care must be taken when computing trends from the wind data as instrumentation and the instrument locations will have changed at some of the locations so affecting the wind measurements. As part of the READER project an attempt was made to locate metadata for the Antarctic stations in order to identify possible jumps in the time series resulting from instrumental factors. However, as can be seen on the READER web site (http://www.antarctica.ac.uk/met/READER/metadata/metadata.html), metadata could only be found for a rela-

Table 4. Trends in the Mean Winter Wind Speed for the Period of Data Availability and for 1979–2006[a]

Station	Trend in Winter Wind Speed for the Period of Data Availability[b] ($m\ s^{-1}\ decade^{-1}$)	Period	Trend in Wind Speed for the Period 1979–2006[b] ($m\ s^{-1}\ decade^{-1}$)
Casey	n/a	1989–2005	−0.51 (not sig)
Mirny	−0.26 (<10% sig)	1956–2006	−0.03 (not sig)
Davis	+0.28 (not sig)	1969–2005	+0.66 (<5% sig)
Dumont D'Urville	−0.41 (not sig)	1960–2005	+0.14 (not sig)
Mawson	+0.21 (not sig)	1954–2007	+1.22 (<1% sig)
McMurdo	n/a		n/a
Molodeznaja	+0.23 (not sig)	1963–1998	+0.02 (not sig)
Novolazarevska	+0.01 (not sig)	1963–2006	+0.37 (not sig)
Syowa	+0.28 (<5% sig)	1967–2007	+0.05 (not sig)
Faraday/Vernadsky	+0.22 (<5% sig)	1950–2006	+0.32 (not sig)
Halley	−0.07 (not sig)	1957–2007	−0.58 (<5% sig)
Bellingshausen	+0.03 (not sig)	1968–2007	−0.09 (not sig)
Amundsen-Scott Station	−0.34 (<5% sig)	1957–2007	+0.19 (not sig)
Vostok	−0.19 (not sig)	1958–2006	−0.61 (not sig)

[a] Note that the period of data availability differs occasionally from that of Table 2 if the data record was patchy or incomplete; n/a denotes not available; sig means significant.

[b] Statistically significant trends are indicated in parentheses.

tively small number of stations. Nevertheless, it is clear that the move of Casey station between 1988 and 1989 had a major influence on the wind data, resulting in large trends in wind speed and the number of SWEs at this site. But as they are an artifact of the instrument location trends will only be considered for the post-1989 period.

[47] In this section we will consider changes in the monthly mean wind speeds at the stations in parallel with examining changes in the number of SWEs. To determine trends we will only use data from a particular month if at least 90% of the 6-hourly wind reports are available.

[48] Table 4 summarizes the winter season trends in wind speed from the stations used in this study. Results are presented for the full length of the records, as well as for 1979–2006, for which reliable reanalysis/analysis fields are available and over which changes in atmospheric circulation can be examined. It was not possible to determine wind speed trends for McMurdo since there were 12 years with missing winter wind data during the late 1980s and 1990s.

[49] The most striking change has been an increase in the mean winter wind speed at a number of the stations around the coast of East Antarctica: Mawson, Davis, Molodeznaja and Syowa have all experienced an increase of wind speed in the range 0.2–0.3 $m\ s^{-1}$ $decade^{-1}$, although only the increase at Syowa is statistically significant since the other stations have a large interannual variability in the wind speed.

[50] At Mawson most wind reports are in the sector 90°E–150°E and most SWEs are reported from this direction. Deep synoptic-scale lows in the circumpolar trough enhance the katabatic flow down from the interior of the continent and it is difficult to differentiate "pure" katabatic flow from that with a strong synoptic influence. However, over 1979–2006 the wind speed increased by 1.22 $m\ s^{-1}$ $decade^{-1}$, which is consistent with the changes in MSLP shown in Figure 17. This shows that there has been a trend toward lower pressures off the Amery Ice Shelf with increasing pressures to the west around 45°E. This has resulted in a stronger synoptic PGF along the coast that has enhanced the flow down the valleys feeding toward the coast. This is reflected in the wind speed trends as a function of direction, which show a reduction in the speed from an easterly direction and increases in speeds in the southerly and southeasterly winds. As the wind speeds have increased so there has been a greater number of SWEs, and as can be seen in Table 5, the increase in the number of winds of gale force or greater at Mawson is the largest of any station over 1979–2006.

[51] The change in flow regime to more cyclonic activity off the Amery Ice Shelf is also apparent in the winds at Davis. The in situ observations show that SWEs come from two main wind directions at about 40°E and 70°E with the winds being drawn down the valleys that descend from the promontory to the east of this location. In this area there is a complex interaction between the katabatic flow and storm activity. The winds arriving from about 70°E tend to be associated with lower MSLP values and higher temperatures, suggesting that winds from this direction are more a result of synoptic activity. On the other hand, the winds arriving from about 40°E tend to have more positive MSLP anomalies and colder temperatures suggesting these are more katabatically driven winds. The Davis near-surface winds during the winter have increased by 0.28 $m\ s^{-1}$ $decade^{-1}$ since 1969, although this trend is not statistically significant. However, the trend of 0.66 $m\ s^{-1}$ $decade^{-1}$ over 1979–2006 is significant at less than the 5% level. During this period the winds from the north have decreased, with a strengthening of the winds between northeast and southeast. There has also been an increase in the number of gale reports.

[52] Another region where there has been a change in the atmospheric circulation since 1979 is in the coastal region close to the Greenwich Meridian (Figure 17). Here there has been a trend toward a more cyclonic circulation with the greatest change being a drop of MSLP of around 1 hPa $decade^{-1}$. This has had an impact on the winds at Novolazarevskya station, which is most strongly affected by cyclonic systems to the north and where the majority of SWEs are associated with large negative MSLP anomalies. At this station the winter mean wind speed has increased by 0.37 $m\ s^{-1}$ $decade^{-1}$ since 1979, although this trend is not statistically significant. This station receives its strongest winds from the southeast and since 1979 the mean wind speed from this direction has increased as pressures off the coast have decreased, intensifying the east to southeasterly

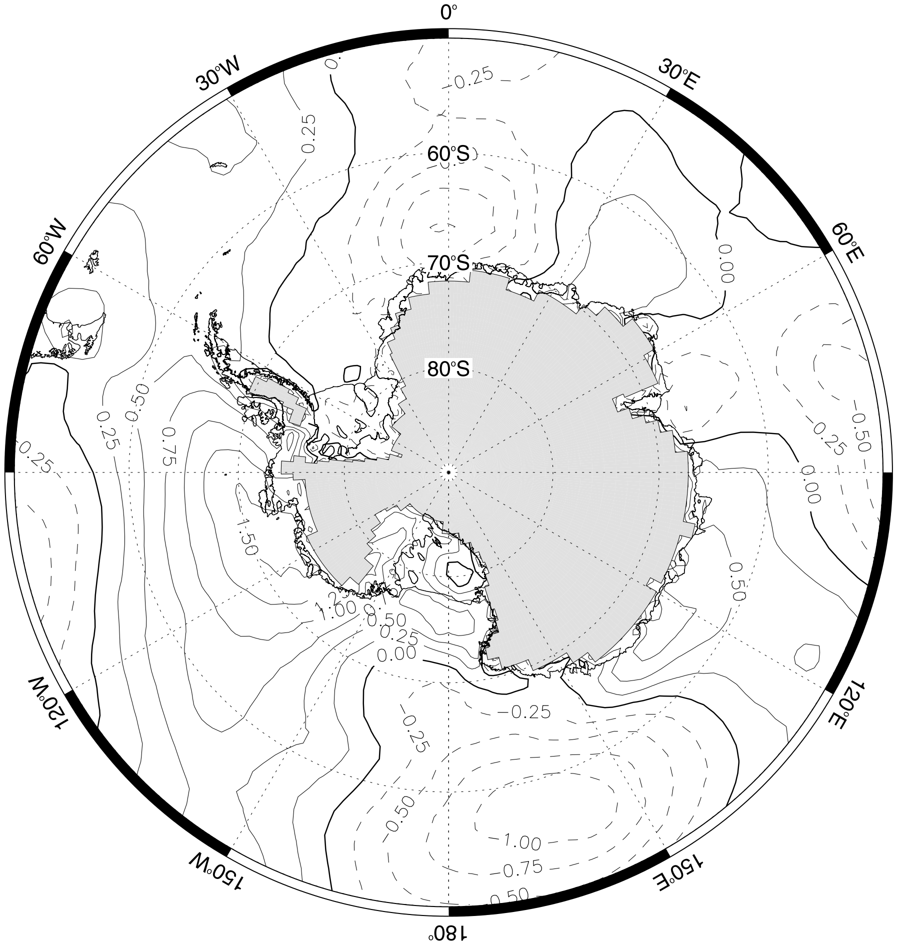

Figure 17. Trend (hPa/decade) in winter season MSLP over 1979–2006. No data are presented if the orographic height is greater than 1000 m.

winds. Since 1979 the number of gale force winds at Novolazarevskya has also increased, although the trend is not statistically significant since the interannual variability in the number of gale reports is large.

[53] Figure 17 suggests that there are a number of areas around the coast of East Antarctica where the trends in MSLP and therefore cyclonic activity have been rather small since 1979 and this is reflected in the small changes

Table 5. Trends in the Number of Winter SWEs of Gale Force or Stronger at Stations for the Period of Data Availability and for 1979–2006[a]

Station	Trend in Number of Winter Gale Force or Stronger SWEs[b] (events/decade)	Period	Trend in Number of Winter Gale Force or Stronger SWEs Over 1979–2006[c] (events/decade)
Casey	n/a	1989–2005	−5.2 (not sig)
Mirny	−5.0 (83.6) (<10% sig)	1956–2006	−5.5 (not sig)
Davis	+1.3 (15.3) (not sig)	1969–2005	+5.2 (not sig)
Dumont D’Urville	−5.8 (57.2) (<5% sig)	1956–2001	+0.3 (not sig)
Mawson	+4.5 (75.9) (not sig)	1954–2007	+22.0 (<1% sig)
McMurdo	n/a		n/a
Molodeznaja	+4.2 (81.5) (not sig)	1963–1998	+0.8 (not sig)
Novolazarevska	+2.7 (67.4) (not sig)	1963–2006	+8.0 (not sig)
Syowa	−0.3 (33.4) (not sig)	1967–2007	−1.7 (not sig)
Faraday/Vernadsky	−0.6 (3.2) (<5% sig)	1950–2006	−0.0 (not sig)
Halley	−0.3 (21.7) (not sig)	1957–2007	−5.3 (<10% sig)
Bellingshausen	−0.5 (10.1) (not sig)	1968–2007	+0.6 (not sig)
Amundsen-Scott Station	n/a	1957–2007	n/a
Vostok	n/a	1958–2006	n/a

[a] Here n/a denotes not available.

[b] The mean number per winter and the statistical significance of the trend is given in parentheses.

[c] The statistical significance is given in parentheses.

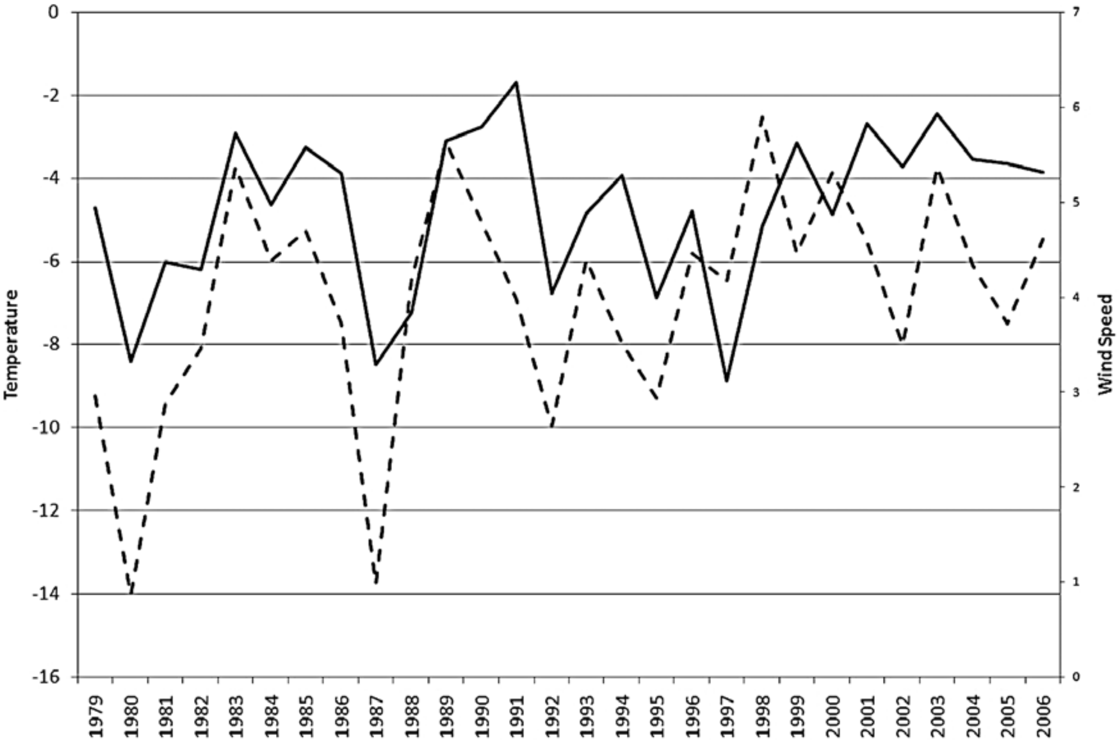

Figure 18. Winter mean temperature (dashed line (°C)) and wind speed (solid line (m s^{-1})) at Faraday/Vernadsky station over 1979–2006.

in the wind speeds at the stations. Mirny is to the west of an area of increasing pressure where there has been a small increase in the northerly component of the wind and no enhancement to the climatological east to southeasterly flow that gives most of the SWEs. Similarly, Syowa and Molodeznaja are both located in areas of little pressure change since 1979 and have both experienced very small changes in mean winter wind speed and the number of gale reports.

[54] Dumont d'Urville experiences frequent and persistent strong winds arriving at the station from a southeasterly direction down the valleys. Winds of storm force or greater are associated with a mean MSLP anomaly of around −4 hPa off the coast, but a large positive pressure anomaly over the Ross Ice Shelf, indicating the importance of pressure anomalies some distance from the stations. As can be seen in Figure 17, the station is on the boundary between positive and negative MSLP trends since 1979. These circulation changes will have led to a slightly more southerly PGF leading to greater flow off the continent. This is reflected in the increase in winter mean wind speed of 0.14 m s^{-1} $decade^{-1}$ and slight increase in the number of gale reports. Examination of the wind speed changes by direction shows that flow from the southeast increased the most.

[55] On the western side of the Antarctic Peninsula the mean winter wind speed at Faraday/Vernadsky has increased in recent decades. Over 1950–2006 it increased at a rate of 0.22 m s^{-1} $decade^{-1}$, which is significant at less than the 5% level. Since 1979 the increase has been larger at 0.32 m s^{-1} $decade^{-1}$, although because of the large interannual variability of the speed this trend is not statistically significant. Most winds at the station are from the north or northwest since the station is to the east of the Amundsen Sea Low and the climatological trough over the Amundsen-Bellingshausen Sea extending eastward from that center. There is a close relationship (a correlation coefficient of 0.63) between the winter mean wind speed and surface temperature (Figure 18) with higher wind speeds (essentially stronger northerly winds) associated with increased advection of mild air and higher temperatures. From 1979 until the late 1990s the mean wind speeds were quite variable with a number of winters with low speeds, such as 1987, when temperatures were cold. However, since 1998 winters have repeatedly had stronger wind speeds with consequent higher temperatures. Figure 17 indicates that since 1979 surface pressures have tended to be higher across the Amundsen Bellingshausen Sea, but importantly pressures have decreased at the base of the Antarctic Peninsula. Examination of the wind speed and MSLP data for Faraday/Vernadsky shows that throughout the period 1979–2006, low-pressure values during winter have always been associated with strong winds from the north to northwest. However, the wind speeds associated with winters with positive pressure anomalies have been increasing. Examination of the mean winter MSLP reanalysis/analysis fields over this period suggest that during the 1980s and early 1990s ridging over the southern Antarctic Peninsula gave a southerly component to the winds and inhibited the climatological northwesterlies, resulting in lower wind speeds. However, since the early 1990s MSLP has decreased over the southern Antarctic Peninsula (Figure 17), allowing the northwesterlies to be established even when pressures are relatively high at the latitude of the circumpolar trough.

[56] Elsewhere in the Antarctic Peninsula region wind speeds have generally decreased since 1979. At its location near the tip of the Antarctic Peninsula Bellingshausen

station was less influenced by the ridging from the southern peninsula area in the early part of the record, and speeds have dropped by a small amount since 1979 as pressures have risen to the west of the Antarctic Peninsula.

[57] Halley has also experienced a drop in wind speed of -0.58 m s^{-1} $decade^{-1}$ over this period, which is statistically significant at less than the 5% level. Winds at Halley are a result of both conditions over the interior of the continent and the synoptic environment over the Weddell Sea. Dronning Maud Land provides one of the sources of air masses that reach Halley after descending from the plateau and being deflected toward the west. There are no long time series of in situ observations with which to investigate temperature changes across Dronning Maud land in recent decades. *Comiso* [2000] used satellite data to examine trends in annual mean temperature over the interior for the period 1978–1999 and found slight warming just inland of the coast of the eastern Weddell Sea and cooling at high elevations. With the data available it is not possible to determine if there have been changes in the air reaching Halley from the interior. However, the MSLP changes shown in Figure 17 indicate that there has been little change in pressure over the Weddell Sea since 1979, although pressures near the Greenwich Meridian have dropped near one of the climatological centers in the circumpolar trough. Such a change in circulation will have tended to decrease the easterly winds along the coast of Coats Land, which is consistent with the Halley wind observations, which show the greatest decrease in speed in the winds from between the northeast and southeast.

[58] On the plateau the two stations show contrasting changes in the mean wind speed since 1979, with winds at Vostok decreasing slightly and those at Amundsen Scott increasing, although neither trend is significant. Determining the reasons for circulation changes and changes in the in situ observations on the plateau is not easy since the reanalysis/analysis fields for this region are unlikely to be reliable owing to the lack of assimilated observations and high altitude of the plateau. In addition, changes in instrumentation that may result in spurious jumps in the data are more difficult to detect than at coastal sites owing to the generally very low wind speeds. However, at Vostok the reduction in wind speed has a clear winter peak and the greatest decrease has been with winds down the slope from Dome A. This suggests that the katabatic flow has reduced in recent decades, although it is not possible to determine whether this is a result of warmer temperatures in the area of Dome A or changes in the circulation on the plateau.

[59] At the South Pole, there has been an increase in wind speed throughout the year, but with the largest increase in late autumn. The greatest increase in speed has been in directions other than down the slope from the plateau, which spans 0°–90°E. This suggests that there has been greater variability in the air masses arriving at the South Pole and a reduction in katabatic flow, although there is little data with which to confirm this.

5. Discussion

[60] Strong wind events are one of the most characteristic features of the Antarctic climate system and are particularly pronounced around the coast of East Antarctica during the extended winter period. Earlier studies have shown that the winds are caused by contributions from both the PGF resulting from radiational cooling of air on the slopes of the Antarctic continent and the PGF due to synoptic-scale low-pressure systems north of the Antarctic coast. Around the coast of East Antarctica there is a minimum in the number of SWEs in summer, which is consistent with the reduction of katabatic forcing over December to February, as shown by *Parish and Cassano* [2003].

[61] Examination of the mean MSLP anomalies associated with SWEs at the coastal stations has shown that enhancement of the katabatic flow down the valleys is critically dependent on the location of storms relative to the valleys. The relative contribution of katabatic and synoptic-scale pressure forcing to SWEs varies considerably around the continent and depends on the location of the storm tracks. Stations such as Mawson and Dumont d'Urville have exposed locations on the coast where storms passing from west to east over the Southern Ocean can enhance the local flow, resulting in many SWEs at the stations. In contrast the relatively sheltered locations of Davis and Syowa, on the eastern side of embayments, means that enhancement of the prevailing downslope flow at these stations is unlikely unless the depressions are located at relatively southerly locations close to the embayments.

[62] SWEs at coastal stations are strongly influenced by the local orography, which around much of Antarctica is characterized by large and rapidly varying gradients in elevation. Although the horizontal resolution of the reanalysis/analysis data is sufficient to capture the large-scale synoptic forcing, it severely smoothes the coastal orography and does not resolve complex local features along the coastal margins (see Figure 1), therefore underestimating the strength of katabatic winds and the influence of local topography on the formation of SWEs. The coarse resolution also results in the misrepresentation of the fine-scale interaction between the katabatic and the synoptic winds, as well as failure to capture localized low-level wind jets driven by abrupt changes in surface drag and heat flux [*Orr et al.*, 2005] at the vicinity of the sea ice edge and over coastal leads and polynyas, and at the coastal margins in general. To quantify the impact this has on the simulation of SWEs, the three coastal SWE cases shown in Figures 5, 6, and 10 were simulated using the atmosphere-only Met Office Unified Model (UM) version 6.1 with a horizontal resolution of 0.11° (approximately 12 km) and 38 vertical levels, using a nested limited-area domain of 700 × 542 points centered over the Antarctic. UM 6.1 solves non-hydrostatic, deep-atmosphere dynamics using a semi-implicit, semi-Lagrangian numerical scheme on a horizontal latitude-longitude grid and a terrain following hybrid-height vertical coordinate with Charney-Philips staggering [*Davies et al.*, 2005]. The effects of unresolved processes are calculated by a comprehensive set of physical parameterization schemes. In limited area mode the model uses a rotated coordinate pole to achieve uniform resolution. The limited area model was one-way nested inside a global version of the model with a horizontal resolution of approximately 40 km and 50 vertical levels. The model was initialized by ECMWF reanalysis/analysis and daily high-resolution Bootstrap sea ice concentrations [*Comiso*,

1999] and GHRSST sea surface temperatures [*Reynolds et al.*, 2007] to realistically represent the surface forcing.

[63] The SWEs presented in Figures 5 and 6 for Mawson and Figure 10 for McMurdo were simulated; the first and second were initialized at 0000 GMT 24 July 2004 and 0000 GMT 14 July 1995, respectively, and computed using a 30-h integration, and the third was initialized at 0000 GMT 10 June 1984 and computed using a 24-h integration. Figure 19 compares the simulated MSLP and 10-m wind with the equivalent reanalysis/analysis fields. In all three cases the UM simulates appreciably stronger katabatic winds and stronger winds at the stations. Figures 19a and 19b show that the UM simulated 10-m wind speed at Mawson at 0600 GMT 15 July 1995 is approximately 18 m s^{-1} and the analysis wind speed is 16 m s^{-1}, both of which are significantly less than the observed value of 26.7 m s^{-1}. The valley to the east of Mawson is better resolved with the UM simulation, which shows much stronger winds being funneled into the valley and exiting as a gap jet. This turns sharply to the left owing to the Coriolis force and forms a barrier jet which reaches Mawson. This feature is almost completely missed by the analysis. However, both the UM simulation and analysis agree that the synoptic forcing is relatively weak, with the low to the north of Mawson having a UM simulated central low pressure of 976 hPa and an analyzed pressure of 980 hPa. It is likely therefore that a horizontal resolution of 12 km is unable to properly resolve the formation of the barrier jet which appears to be the dominant contributor to the SWE, resulting in the underestimation of the observed wind speed [*Hunt et al.*, 2004]. Figures 19c and 19d show that the UM simulated 10 m wind speed at Mawson at 0600 GMT 25 July 2004 of approximately 24 m s^{-1} and the reanalysis wind speed of approximately 22 m s^{-1} both are significantly weaker that the observed value of 37.5 m s^{-1}. Although the UM simulation again shows a much stronger gap flow which turns into a barrier flow, the forcing is dominated by the very deep low situated slightly to the northeast of Mawson which acts to enhance the katabatic flow. The UM simulated minimum pressure of 936 hPa and the reanalysis minimum pressure of 944 hPa are both associated with very strong southeasterly flow at Mawson. Figures 19e and 19f show that the UM simulated 10-m wind speed at McMurdo at 0000 GMT 11 June 1984 is approximately 20 m s^{-1} and the reanalysis wind speed is approximately 16 m s^{-1}, both of which are lower than the observed wind speed of 28.3 m s^{-1}. The UM simulation and reanalysis agree that the SWE is dominated by synoptic forcing over the Ross Ice Shelf, although the UM simulation is better able to resolve the enhancement of southerly flow on the western side of the ice shelf as a barrier jet forms parallel to the steep coastal margin and which reaches McMurdo. The UM simulated central low pressure of 940 hPa and the analyzed pressure of 936 hPa are similar, however, the UM simulated low is situated farther south and so delivering stronger winds to McMurdo. The three cases suggest that the reanalysis/analysis fields are able to capture the large-scale synoptic features and the associated enhancement of the katabatic flow, but underestimate the observed wind speed if it is strongly influenced by local topographical conditions. Higher-resolution simulations using UM 6.1 are planned, which will help understand further the importance of local topographic forcing.

[64] The number of SWEs occurring at a location in a particular winter is strongly dependent on the amplitude and location of the Rossby waves around the Antarctic, since there will be more depressions to the east of an upper-level trough. Although climatologically there is a mean wave number 3 pattern around the continent, on an interannual basis there will be large variations in the Rossby wave pattern. There is therefore no significant correlation between the number of SWEs at adjacent stations in individual years. For example, Syowa and Molodeznaja are only 300 km apart yet on a year to year basis the number of events are very different because Syowa is strongly affected by cyclones to the north while the number of events at Molodeznaja is relatively unrelated to MSLP values nearby.

[65] The Antarctic climate system is affected by tropical atmospheric and oceanic variability and in particular the El Niño-Southern Oscillation (ENSO), although the high-low latitude links can vary with time [*Turner*, 2004]. Investigations using the reanalysis data sets have shown that the most robust high-low latitude atmospheric links are in the sector from the Antarctic Peninsula to the Ross Ice Shelf [*Yuan and Martinson*, 2001]. On average, there is more storm activity in the Amundsen-Bellingshausen Sea during La Niña events than during the El Niño phase, so SWEs are more common on the Antarctic Peninsula during La Niña conditions. In the Ross Sea area there are some indications of consistent changes in atmospheric circulation at different stages of ENSO [*Bertler et al.*, 2004], although decadal time scale shifts in the teleconnection have been noted [*Cullather et al.*, 1996], which complicate the investigation of the role of ENSO in modulating SWEs in the Ross Sea area. With the large gaps in the McMurdo in situ record it is therefore not possible at the moment to establish robust links between tropical variability and SWEs in this sector. There are no links between ENSO and variability of the wind field around the coast of East Antarctic.

[66] One of the most marked changes in the Antarctic climate system in recent decades has been the shift of the Southern Annular Mode (SAM) into more positive conditions [*Marshall*, 2003]. This has resulted in a decrease (increase) in MSLP over the Antarctic (Southern Ocean) with a consequent increase in the westerly winds over the Southern Ocean. The greatest change in the SAM has been during the summer and autumn with the shift being linked to cooling around the coast of East Antarctica [*Thompson and Solomon*, 2002]. During the winter there has been a smaller shift of the SAM into more positive conditions, and it is estimated that at Vostok this has resulted in a cooling of about 0.5°–1.0°C over 1957–2004 [*Marshall*, 2007]. This will have led to a small increase in the downslope buoyancy forcing, although the horizontal extent of this change cannot be estimated with the in situ data alone. However, *van den Broeke and van Lipzig* [2003b] used the output of a regional atmospheric climate model run over 1980–1993 to examine the impact of changes in the SAM on the winter season temperature and wind fields across the Antarctic. They found that the July surface potential temperature perturbation between positive and negative SAM polarity years was rather small across most of East Antarctica, but with values

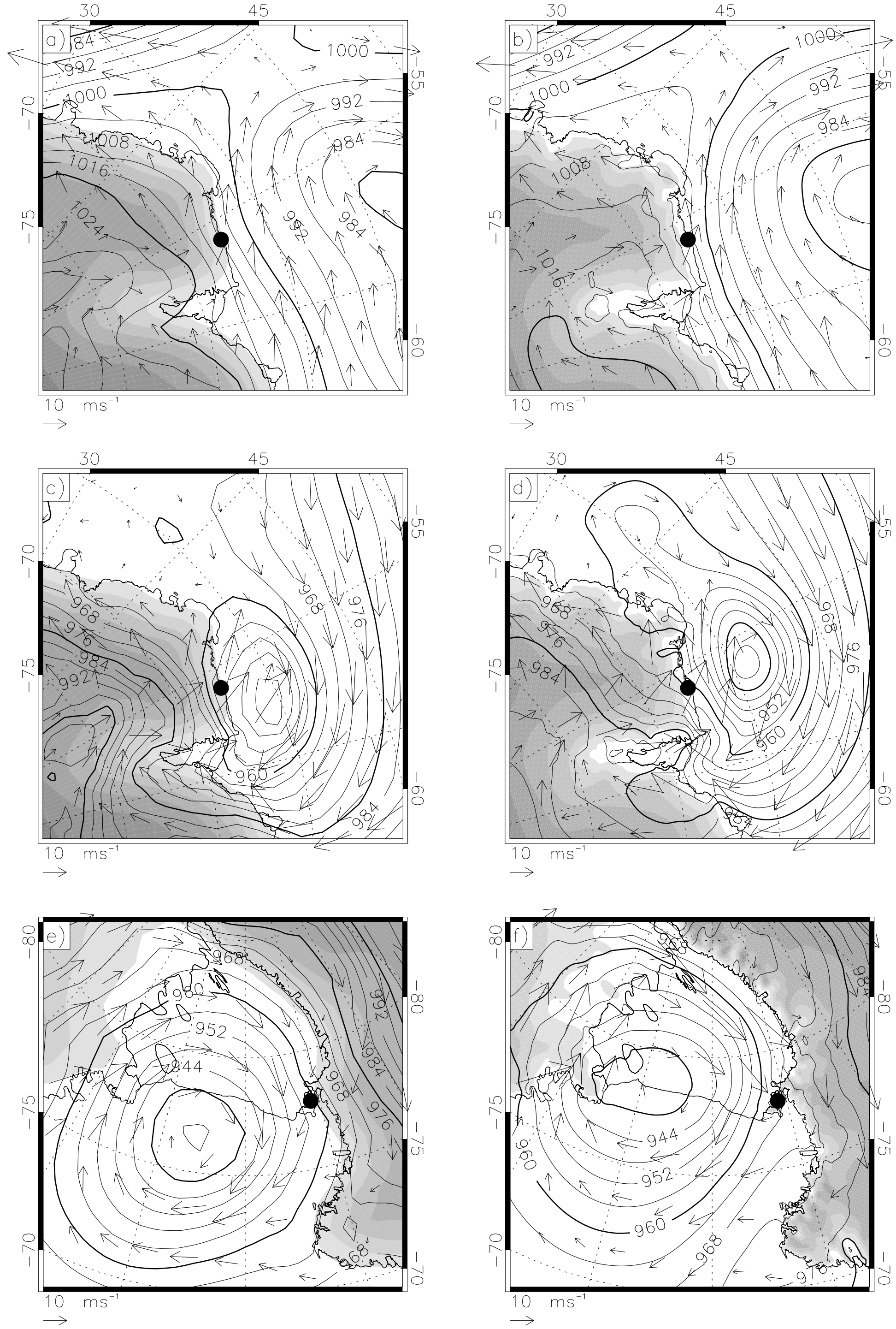

Figure 19. Comparison of reanalysis/analysis and UM 6.1 simulated 10-m wind (shown as wind vectors (m s^{-1})) and MSLP (shown as contours (hPa)) for (a and b) Mawson at 0600 GMT 15 July 1995, (c and d) Mawson at 0600 GMT 25 July 2004, and (e and f) McMurdo at 0000 GMT 11 June 1984. The UM 6.1 data are computed at 12-km horizontal resolution and initialized at 0000 GMT 14 July 1995 (T + 30 h) (Figure 19b), 0000 GMT 24 July 2004 (T + 30 h) (Figure 19d), and 0000 GMT 10 June 1984 (T + 24 h) (Figure 19f). Figures 19a, 19c, and 19e show the reanalysis/analysis fields. The ERA40 10-m wind speed data have been interpolated to the UM 6.1 12-km horizontal resolution grid. Only vectors from every twentieth grid point are displayed. The shaded contours depict mean orography height and have an interval of 500 m.

in excess of 2°C around the Amery Ice Shelf, suggesting that changes in the SAM may have influenced the wind field in this area. However, quantifying the relative contributions of changes in the SAM and MSLP on the wind field north of the coast is not possible at present.

[67] Predicting how the winds across the Antarctic will alter over the next century is not easy, but coupled climate models can provide a broadscale indication of how conditions may change under different greenhouse gas emission scenarios. If greenhouse gas concentrations double over the next century then it is predicted that surface temperatures across the Antarctic will increase by several degrees [*Bracegirdle et al.*, 2008]. This would potentially reduce the pool of cold air that feeds the katabatic wind system, resulting in an expected weakening of the katabatic winds reaching the coastal region. However, the Bracegirdle et al. study found that the IPCC models when run over the next 100 years suggested almost a zero change in wind speed across the continent. This may be a result of changes in synoptic activity over the Southern Ocean since, as discussed earlier, the winds in the coastal region are a result of both katabatic forcing and synoptic forcing. As climate models are improved through better simulation of boundary layer processes and run with higher horizontal resolution it should be possible to generate better predictions of how the Antarctic wind field will evolve.

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