Dominant Regimes of the Ross Ice Shelf Surface Wind Field during Austral Autumn 2005

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ABSTRACT

An analysis of the surface wind field across the Ross Ice Shelf, Antarctica, is conducted for austral autumn 2005. The airflow is divided into dominant wind regimes identifying similar wind patterns and the associated typical atmospheric forcing. The results of previous research and a seasonal analysis of the recently expanded network of automatic weather stations in the Ross Ice Shelf region are used to define the dominant wind regimes. Events composing each wind regime are identified by matching wind speed and wind direction observations at several automatic weather station sites for durations of at least 10 h. The four different dominant wind regimes are barrier wind, strong katabatic, weak katabatic, and light wind. Each wind regime is studied through the use of wind rose plots and sea level pressure fields from the Antarctic Mesoscale Prediction System. The sea level pressure fields are used to characterize the forcing of the surface wind field by synoptic pressure gradients. The four dominant wind regimes result in classifying less than 50% of the total hours for austral autumn 2005. The results indicate that previous studies of the Ross Ice Shelf surface wind field, focusing on katabatic winds and barrier winds, represent less than one-half of the observed winds. This study provides a better understanding of the composition of the surface wind field in Antarctica and more insight into the characteristics of the Ross Ice Shelf airstream.

1. Introduction

The Ross Ice Shelf in Antarctica is the location of a dynamic and dramatic surface wind field. Katabatic winds, barrier winds, and winds associated with the passage of cyclones and mesocyclones all play a role in shaping the surface wind field. Because of limited spatial and temporal observations, a complete description of the surface wind field has been limited. An expanded array of automatic weather stations (AWS), installed in 2004 and 2005, is providing a better understanding of the surface wind field across the Ross Ice Shelf. Through the use of wind rose analyses, and by defining dominant wind regimes for the region, a more thorough understanding of the different components of the surface wind field is sought.

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The Ross Ice Shelf is a nearly flat permanent ice shelf that extends over 900 km from south to north and over 900 km from west to east, at its extremes (Fig. 1). The Ross Sea lies to the north of the Ross Ice Shelf. The Transantarctic Mountains, with elevations from 2000 m to peaks over 4000 m, borders the Ross Ice Shelf to the west and south and runs the entire length of the Ross Ice Shelf and Ross Sea. Several prominent glaciers, including Skelton, Mulock, Byrd, and Beardmore, are located in the Transantarctic Mountains along the Ross Ice Shelf. These glacier valleys provide the only major breaks in this barrier. The Siple Coast, bordering the Ross Ice Shelf to the east, has a more gradual ascent to the West Antarctic plateau. Ross Island, White Island, Black Island, and Minna Bluff make up the complex topography of the northwest Ross Ice Shelf.

Past studies of katabatic winds provide the primary characterization of the surface wind field across the Ross Ice Shelf. Parish and Bromwich (1987) perform a study of the characteristics of the surface wind field

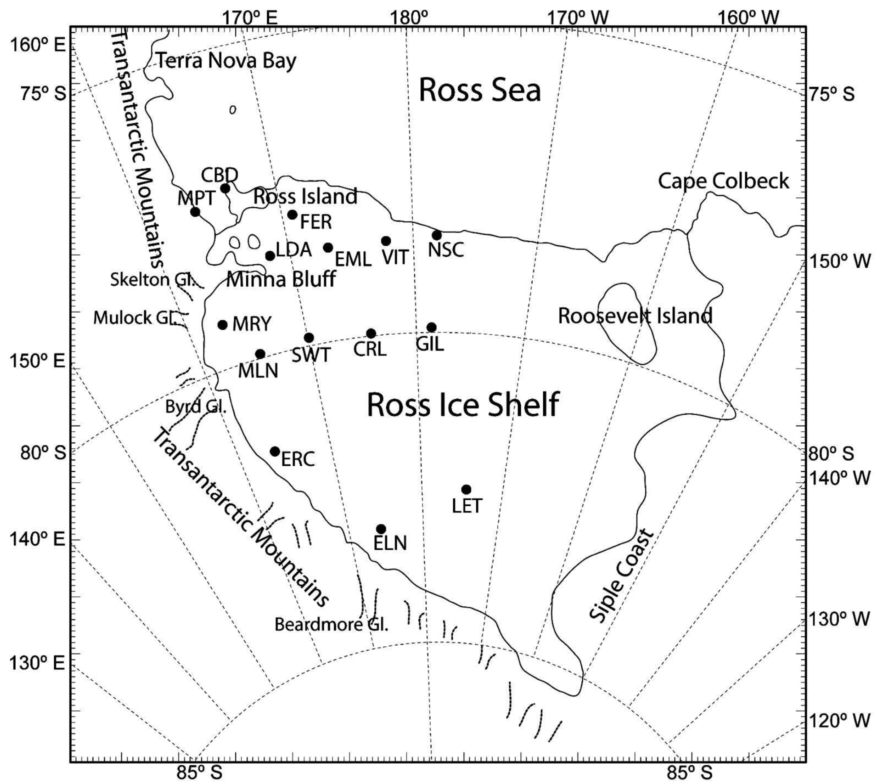

FIG. 1. The Ross Ice Shelf region with locations of the UWAAWS. See Table 1 for a listing of AWS site names corresponding to the indicated AWS site IDs.

over the entire Antarctic continent using a high-resolution terrain dataset. The Parish and Bromwich study concludes that intense katabatic winds occur in confluence zones where cold, dense air draining from a large area of the polar plateau converges and drains off the continent. The Siple Coast, Byrd Glacier, and Terra Nova Bay regions are locations of pronounced katabatic drainage in the Ross Ice Shelf region. Thermal infrared satellite imagery has been used to study the characteristics of katabatic winds. A classic thermal infrared satellite image indicating the katabatic flow through the glaciers in the Transantarctic Mountains and down the Siple Coast is shown in King and Turner (1997, their Fig. 6.6). Bromwich (1989) analyzed katabatic winds near Terra Nova Bay and over the western Ross Ice Shelf using thermal infrared satellite imagery. Warm thermal infrared katabatic signatures were found to be prominent climatological features at these locations. The study includes cases of katabatic winds extending up to 200 km from Terra Nova Bay. Breckenridge et al. (1993) provides a study on the characteristics of katabatic winds along the western Ross Ice Shelf based on the identification of events on infrared satellite imagery. A synoptic-scale low pressure region over the eastern Ross Ice Shelf was also found to contribute to katabatic activity. AWS data were used in the study of katabatic winds in these studies. The AWS wind observations are at a nominal height of 3.9 m indicating that the observations are only a small representation of the katabatic winds, as the wind will be stronger above the friction layer. Bromwich et al. (1992) and Carrasco and Bromwich (1993) study the propagation of katabatic winds across the Ross Ice Shelf. In these studies a corresponding synoptic or mesoscale cyclone is found to aid in katabatic winds traversing such large distances. Numerical simulations on the propagation of the katabatic winds across the Ross Ice Shelf are described by Bromwich et al. (1994).

Studies involving barrier winds in Antarctica are not as prevalent. An initial description of barrier winds in Antarctica is provided by Schwerdtfeger (1975). The study describes the characteristics and formation of barrier winds in the Weddell Sea Antarctic region resulting from the influence of the Antarctic Peninsula. Barrier winds on the Ross Ice Shelf, caused by the propagation of cold and stable air against the Transantarctic Mountains, are described by Schwerdtfeger (1984). O'Connor et al. (1994) describes the results of a 2-yr climatological study of barrier winds on the Ross Ice Shelf. Two different forcing mechanisms were found to result in the formation of barrier winds. The first is the passage of a mesocyclone across the northwestern Ross Ice Shelf. The second type is associated with synoptic-scale cyclones passing through the Ross Sea and Ross Ice Shelf regions from the north and east.

The region surrounding Antarctica is often described as one of the most active cyclogenetic regions in the world. King and Turner (1997) provide a climatology and description of the synoptic-scale cyclones and mesocyclones in the Antarctic region. The thermal contrast between the cold continental air in the interior and the relatively warm maritime air masses adjacent to the continent is attributed to the high density of cyclones and cyclogenesis. Climatology studies of mesocyclones in the greater Ross Ice Shelf region, including the Ross Sea, are provided by Carrasco and Bromwich (1994) and Carrasco et al. (2003).

In recent years an emphasis has been placed on the northward transport of atmospheric mass in the Ross Ice Shelf region. Parish and Bromwich (1998) present an analysis of a 1988 event that resulted in a large decrease in observed pressure over the entire continent. The atmospheric mass transport associated with this pressure change is attributed to the katabatic flow from the Antarctic plateau, through the Ross Ice Shelf corridor, which was enhanced by the presence of a strong cyclone in the eastern Ross Sea. The Antarctic science community has given the name Ross Ice Shelf airstream (RAS) to this southerly flow across the Ross Ice Shelf. Parish et al. (2006) provide a description of the characteristics of the RAS based on an analysis of output from a 30-km horizontal-resolution real-time atmospheric model run over Antarctica.

The purpose of this study is to gain a more thorough understanding of the characteristics of the surface wind field across the Ross Ice Shelf. The surface wind field across the Ross Ice Shelf is composed of katabatic winds that propagate across the Ross Ice Shelf after flowing through glacier valleys in the Transantarctic Mountains and across the Siple Coast, barrier winds along the Transantarctic Mountains, and the airflow associated with the passage of cyclones and mesocyclones. The previous studies listed above focused primarily on the individual aspects of the Ross Ice Shelf airflow, including katabatic winds, barrier winds, and the effects of the passage of cyclones and mesocyclones. This study aims to build a more comprehensive understanding of the role that these individual wind patterns play in shaping the surface wind field over the Ross Ice Shelf and their relationships to the RAS.

Austral autumn 2005 is used in this study to gain an understanding of the wind field in the Ross Ice Shelf region. An extensive study over several years, or over even a single year, is not possible because of the discontinuous operation of the AWS in the harsh Antarctic environment. The autumn 2005 season is being used, as it includes the observations from recently installed AWS and there are valid observations from nearly all of the AWS sites. This represents the most comprehensive collection of in situ meteorological data for the Ross Ice Shelf.

A seasonal analysis of austral autumn 2005 indicates that a selective process of analyzing the AWS data is necessary in order to gain a more complete understanding of the surface wind field and the corresponding forcing. The dominant wind regimes identified in this study are defined based on the characteristics of the wind field described in the previous research discussed above. The dominant wind regimes represent the primary features of the Ross Ice Shelf wind field and they provide an objective method to classify different wind patterns. This methodology is similar to Zaremba and Carroll (1999), which identified three frequent wind regimes to analyze the major flow features of the lower Sacramento Valley. The four dominant wind regimes used in this study are barrier wind, strong katabatic, weak katabatic, and light wind. The dominant wind regimes require matching wind speed and wind direction observations at several AWS sites and for durations of at least 10 h. The combination of these restrictions results in the selection of slightly less than half of the observations from austral autumn 2005. However, given the limited spatial and historical observations in the region, this method develops an initial understanding of the composition of the primary wind patterns for the Ross Ice Shelf.

Section 2 provides a description of the data collection from the AWS observations, the method used in defining the dominant wind regimes, and the use of wind rose analyses. A seasonal analysis for austral autumn 2005 is presented in section 3. A description of the dominant wind regimes through wind rose plots and analyses of the forcing mechanisms is covered in section 4. The final section provides conclusions and a summary of the results.

2. Data and method

The University of Wisconsin Antarctic Automatic Weather Station (UWAAWS) program provides continuous data measurements of basic meteorological variables at locations throughout Antarctica (Stearns et al. 1993). Figure 1 shows the location of selected UWAAWS sites on and surrounding the Ross Ice Shelf. Table 1 lists the AWS sites used in this study. The Ross Ice Shelf region has been central to the

TABLE 1. Name, identifier (ID), latitude, longitude, and elevation for the UWAAWS sites on the Ross Ice Shelf.

Name	ID	Lat (°)	Lon (°)	Elev (m)
Cape Bird	CBD	77.217S	166.439E	38
Carolyn	CRL	79.964S	175.842E	52
Elaine	ELN	83.111S	174.316E	59
Emilia	EML	78.502S	173.121E	52
Eric	ERC	81.504S	163.940E	45
Ferrell	FER	77.871S	170.819E	46
Gill	GIL	79.922S	178.586W	54
Lettau	LET	82.518S	174.452W	55
Linda	LDA	78.451S	168.394E	43
Marble Point	MPT	77.439S	163.754E	108
Marilyn	MLN	79.954S	165.130E	64
Mary	MRY	79.303S	162.968E	58
Nascent	NSC	78.100S	178.500W	30
Schwerdtfeger	SWT	79.867S	170.142E	54
Vito	VTO	78.501S	177.753E	50

UWAAWS program since the early years. However, a dense network of AWS sites has been limited to the Ross Island region in the northwest corner of the Ross Ice Shelf. Marilyn, Schwerdtfeger, Gill, Elaine, and Lettau AWS are the only sites on the Ross Ice Shelf with an extended observation record. These sites were installed between 1984 and 1993. With the recent installations of Emilia and Vito in 2004, and Carolyn, Eric, Mary, and Nascent during the 2004–05 field season, a reasonable network of surface observations has now been established across the Ross Ice Shelf. This expanded network provides the first opportunity to comprehensively study the surface wind field across the Ross Ice Shelf from an in situ observational perspective.

Each AWS measures wind speed, wind direction, temperature, and atmospheric pressure. The wind speed, wind direction, and temperature are measured at the top of the tower, at a nominal height of 3.9 m. Station atmospheric pressure is measured at the electronics enclosure, at a nominal height of 1.5 m. The heights of the sensors change because of snow accumulation at the site. Oftentimes the AWS unit or specific sensors may fail in the harsh Antarctic environment, which limits the data collected from a specific site. Measurements from the sensors are made every 10 min and are transmitted via the Argos data collection system and processed at the University of Wisconsin. A semiautomated quality control process is applied to the AWS 10-min data. Hourly observations are created using the closest valid observation within 10 min of the hour from the quality control processing.

The surface observations provided by the UWAAWS program are the sole source of in situ measurements available to characterize the wind field across the Ross Ice Shelf. There are no regular atmospheric observations above the surface of the Ross Ice Shelf, and the upper air observations from McMurdo Station have little value to this study because of the extreme local topographic influences on the low-level winds in the northwest Ross Ice Shelf region (Seefeldt et al. 2003). As such, the observations from 15 AWS in operation during the austral autumn 2005 season are used in this study. The AWS observations must be relied upon to gain a sense of the airflow based on actual measurements.

Wind roses created from hourly AWS observations are used as the primary representation of the surface wind field (e.g., Fig. 2). The wind direction is divided into 16 separate and equal sectors (petals). The length of each petal of the wind rose indicates the frequency of the wind direction in that sector. The frequencies in the wind rose plots are calculated based on the number of available observations. Each circle around the center of the wind rose indicates a frequency increment of 5%. The shading and petal width indicate the wind speed. The plotted wind speed values are less than 1.9, 2.0–5.9, 6.0–9.9, and greater than 10.0 m s^{-1}, from black to light gray and thin to thick. Multiple wind rose plots are placed on a map of the Ross Ice Shelf at the location of the AWS sites to provide a spatial representation of the wind field. All plotted AWS wind roses are based on observations representing over 95% of the total hours, except for the wind roses for Nascent and Mary AWS, which are based on approximately 75% of the total hours.

Defined dominant wind regimes are used to gain an increased understanding of the surface wind field. By separating the flow into different regimes this type of analysis provides the opportunity to identify and understand the different forcing mechanisms associated with common wind patterns. Initially, a seasonal wind rose analysis of the surface wind field is presented. Using the results of the seasonal analysis, along with the results from the previous research discussed in the introduction, the airflow is divided into dominant wind regimes. The dominant wind regimes require matching wind speed and wind direction observations at several AWS sites in order to ensure that an event is represented over the region and not just a specific AWS site. Observations matching the wind regime criteria must do so for at least 10 h with minimal nonmatching observations (approximately one nonmatching observation for every 5 matching hourly observations) in order to qualify as a regime event. This matching requirement is used in order to select continuous events driven by well-defined forcing. Table 2 provides a summary of the

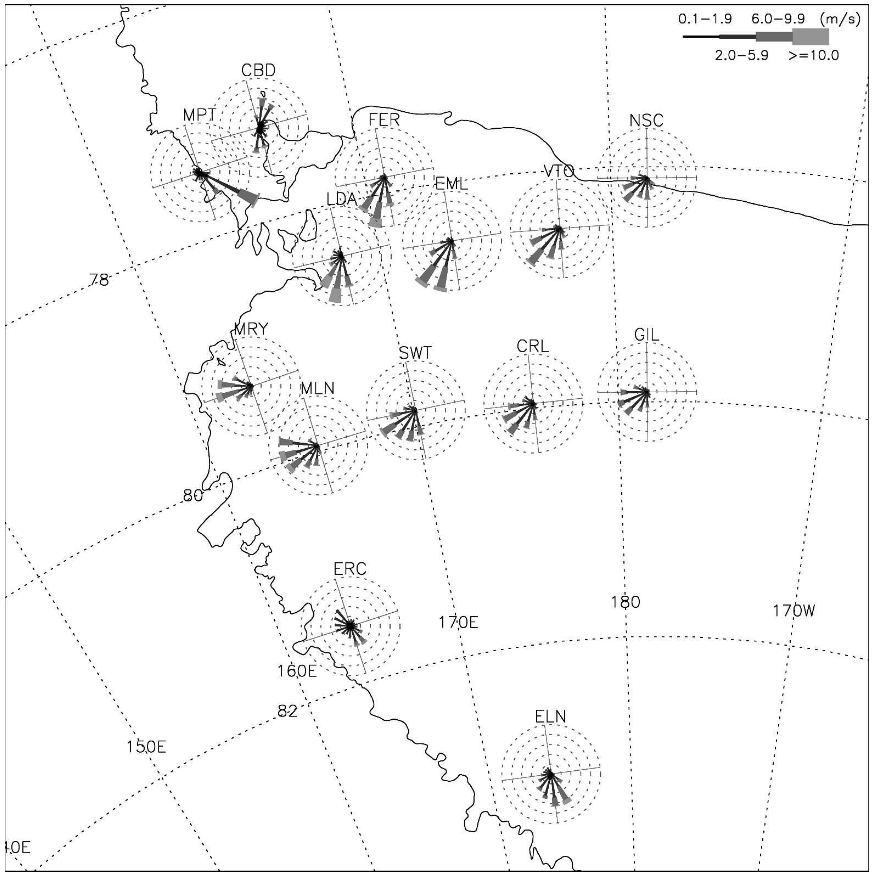

FIG. 2. Wind rose plots for austral autumn 2005 for the Ross Ice Shelf region. The length of each petal indicates the frequency. Each circle around the center indicates a frequency increment of 5%.

selection criteria for the different dominant wind regimes.

Sea level pressure fields from the Antarctic Mesoscale Prediction System (AMPS) are used in this study to gain a more complete understanding of the regional synoptic-scale forcing. AMPS uses a version of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale

TABLE 2. Selection criteria for the four dominant wind regimes. An observation is considered to be valid if it meets the specified number of criteria—barrier: 6 of 7, strong katabatic: 4 of 4, weak katabatic: 4 of 5, and light wind: 4 of 5.

	Barrier		Strong katabatic		Weak katabatic		Light wind	
AWS site	Wind direction (°)	Wind speed (m s^{-1})	Wind direction (°)	Wind speed (m s^{-1})	Wind direction (°)	Wind speed (m s^{-1})	Wind direction (°)	Wind speed (m s^{-1})
Carolyn							—	≤3.9
Elaine	169–213	—						
Emilia	169–236	—					—	≤3.9
Ferrell	169–236	—						
Gill	169–236	—					—	≤3.9
Linda	169–236	≥5.0						
Marilyn			236–304	≥5.0	236–304	1.0–4.9		
Mary					236–326			
Schwerdtfeger			214–304	≥5.0	236–304	1.0–4.9	—	≤3.9
Vito	169–236	—					—	≤3.9

Model that has been modified for use in the polar regions, referred to as the Polar MM5. Bromwich et al. (2001) and Cassano et al. (2001) provide a detailed description of the Polar MM5 model and an evaluation of simulations over the Greenland ice sheet. The version of AMPS used in this study consists of 6 model domains with resolutions of 90, 30, 10, and 3.3 km. Powers et al. (2003) and Bromwich et al. (2005) provide a detailed description of the configuration and operation of AMPS. Guo et al. (2003) indicate that the Polar MM5 is reasonably accurate over the Antarctic continent on the synoptic scale. Bromwich et al. (2005) calculated correlation coefficients greater than or equal to 0.95 between the AMPS 30-km domain surface pressure and observations at manned and automatic weather stations over a 2-yr period. Based on these results the AMPS sea level pressure field is used with reasonable confidence across the Ross Ice Shelf and Ross Sea.

The sea level pressure fields from the 30-km domain are used to characterize the forcing of the surface wind field by synoptic pressure gradients. Sea level pressure forecasts valid from 12 to 21 h after the model initialization time, at 3-h intervals, will be used to represent the state of the atmosphere. For example, the 3-h forecasts from 12 to 21 h from the 0000 UTC 11 March 2005 model run are used to represent the 1200–2100 UTC 11 March 2005 conditions. Using 12–21 h forecasts allows the model 12 h to adjust from the coarse resolution initial fields to the higher-resolution AMPS grids and topography. This is similar to the methodology in Guo et al. (2003) and Bromwich et al. (2005).

3. Seasonal analysis—Austral autumn 2005

Figure 2 is a wind rose plot for the Ross Ice Shelf region for austral autumn (February–April) 2005. Nearest to the Transantarctic Mountains at approximately 80°S is Marilyn AWS. At this site the wind is most prevalent from the west with winds frequently over 10 m s^{-1}. This pattern is typically associated with katabatic winds flowing down Byrd Glacier, immediately to the west, (Fig. 1) and propagating across the Ross Ice Shelf (Carrasco and Bromwich 1993). Approximately 25% of the observations at this site show winds from the south-southwest. A south-southwest wind typically represents a strong barrier wind along the Transantarctic Mountains or the passage of a mesocyclone moving northward across the Ross Ice Shelf. Wind observations at Marilyn AWS rarely, if ever, occur from the easterly direction. Moving from west to east across 80°S, the prevalence of westerly winds decrease while southerly flow becomes more common. The wind speeds decrease from west to east along 80°S. The frequency and intensity of katabatic initiated flow is expected to decrease with increasing distance from the Transantarctic Mountains and Byrd Glacier. Flows that originate as katabatic winds on the east Antarctic ice sheet lose their katabatic forcing over the flat ice shelf, and thus friction acts to decrease the wind speed with increasing distance from the glacial valleys. The individual sea level pressure plots for the entire season (not shown) indicate that the eastern AWS sites are more influenced by the passages of mesocyclones over the Ross Ice Shelf. This results in more frequent winds from directions other than southerly to westerly.

The influence of the complex topography of the northwest Ross Ice Shelf region is apparent in looking at the line of AWS extending to the east from Minna Bluff (Linda, Emilia, Vito, and Nascent AWS). The wind direction at Linda AWS is primarily confined to a 68° sector to the south and west, with a frequency over 60%. Linda AWS is located just to the east of the tip of Minna Bluff, a narrow ridge with elevations greater than 800 m. This ridge acts as a barrier that deflects nearly all southerly wind to the east (Seefeldt et al. 2003). Linda AWS is located in the deflected air resulting in frequent occurrences of southwesterly winds. It appears there is a funnel-like effect as the air flows past the barrier resulting in the highest frequency of winds for the Ross Ice Shelf AWS with speeds greater than 10 m s^{-1}. The influence of the regional topography plays less of a role farther to the east at Emilia, Vito, and Nascent AWS. The winds at Nascent AWS, on the edge of the Ross Ice Shelf, indicate a pattern expected with the frequent passage of cyclones to the north of the Ross Ice Shelf resulting in no clearly dominant wind direction at this site.

The winds at the sites closest to the Transantarctic Mountains (Mary, Eric, and Elaine AWS) are strongly influenced by the nearby topography. Mary AWS, located near the base of Skelton and Mulock Glaciers, has frequent westerly and northwesterly winds. It is likely that such winds are down-glacier katabatic flow propagating across the ice shelf. Eric AWS is not located near a glacier with prevalent katabatic flow and therefore experiences primarily flow parallel to the barrier, either from the northwest or southeast. The strongest winds are from the southeast. A study of the individual AMPS 3-hourly forecasts (not shown) indicates that the southeast winds are often associated with the passage of mesocyclones moving across the Ross Ice Shelf. Elaine AWS, located near Beardmore Glacier, experiences primarily southerly and southwesterly winds that are representative of both the katabatic flow down Beardmore Glacier (Carrasco and Bromwich

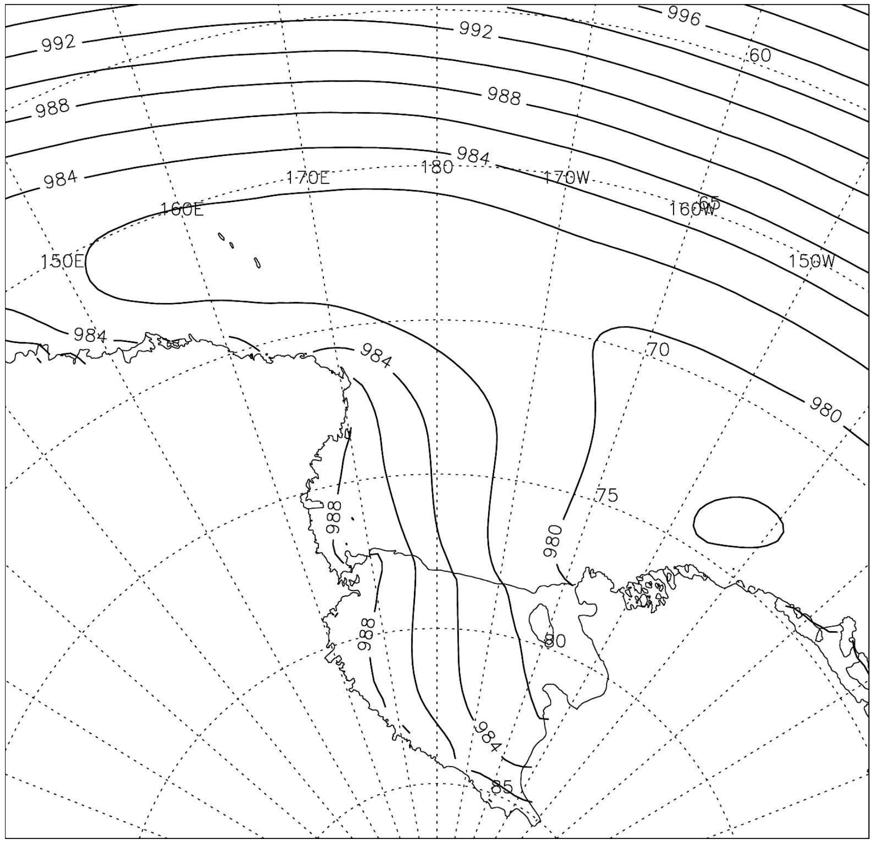

FIG. 3. Average sea level pressure analysis for the greater Ross Ice Shelf region. The analysis is based on averaging AMPS forecasts at 3-h intervals for austral autumn 2005. Contour interval (CI) for isobars is 2 hPa.

1993) and barrier winds along the Transantarctic Mountains (O'Connor et al. 1994).

The average sea level pressure for autumn 2005 (Fig. 3) shows a mean seasonal pressure gradient across the Ross Ice Shelf, with pressure decreasing from west to east. The average sea level pressure was calculated by averaging all of the 3-hourly AMPS 12–21-h forecasts for the 2005 austral autumn season (1 February through 30 April). Locations with elevations above 250 m are not included in the sea level pressure analysis because of the difficulties involved with making sea level pressure adjustments in the Antarctic environment where sharp and shallow temperature inversions are common near the surface. A seasonal low pressure is located near Cape Colbeck, off the coast of Antarctica. An extended low pressure band extends from Cape Colbeck toward the west, across the northern Ross Sea. This seasonal low pressure trough indicates the path traveled most frequently by cyclones moving from west to east across the northern Ross Sea (King and Turner 1997).

4. Dominant wind regimes

a. Barrier wind

1) SELECTION CRITERIA FOR THE BARRIER WIND REGIME

When a stably stratified airflow is directed toward a large barrier, such as the Transantarctic Mountains, the flow will often be unable to pass over the barrier resulting in the accumulation of air against the barrier. The accumulation of air results in an increase in pressure at the base of the barrier producing a pressure gradient directed perpendicular to the barrier. In response to this pressure gradient a geostrophic flow oriented parallel to the barrier develops. Friction near the surface will cause the surface wind to turn slightly to the right of the geostrophic wind direction. Along the Transantarctic Mountains the airflow is primarily strong and southerly at all locations on the western Ross Ice Shelf (Schwerdtfeger 1984). Based on the conceptual model of barrier winds and previous research on barrier winds, the barrier wind regime is identified when six of

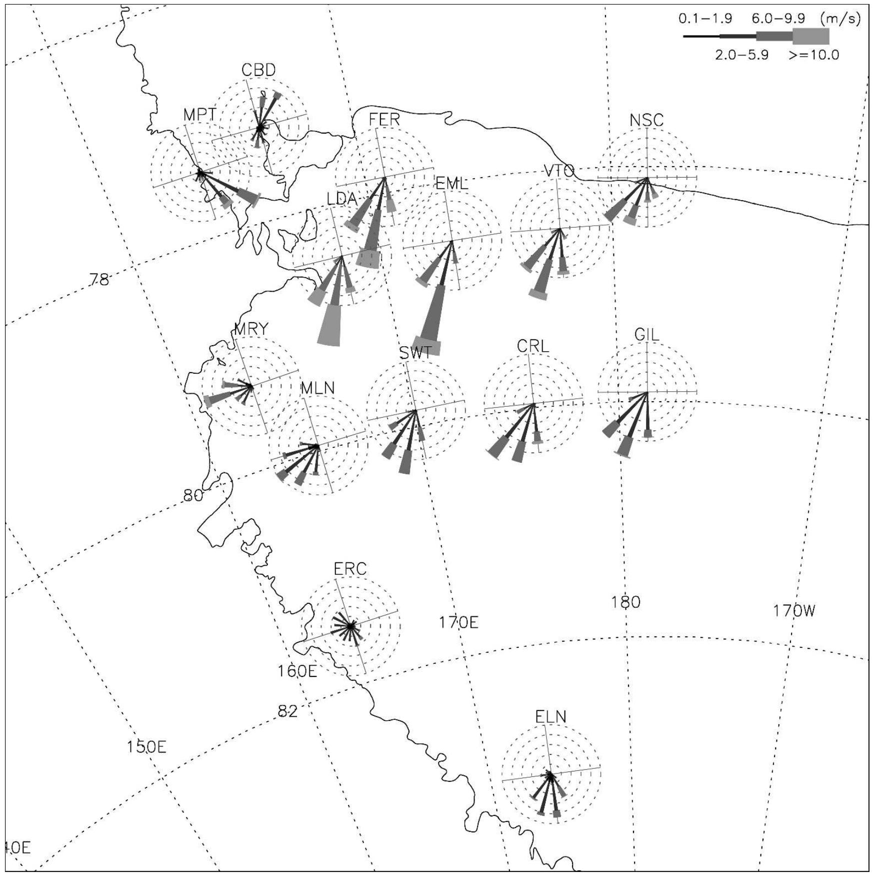

FIG. 4. As in Fig. 2, but for the barrier wind regime.

the following seven criteria occur: a wind direction between 168.8° and 236.7° at Gill, Linda, Emilia, Vito, and Ferrell; a wind direction at Elaine between 168.8° and 213.2°; and a wind speed greater than 5 m s^{-1} at Linda (Table 2). A total of 350 h during 21 events, or 16.4% of the possible observations for autumn 2005, meet these criteria.

2) Characterization of the barrier wind regime

Figure 4 is a wind rose analysis of the wind speed and wind direction observations for the barrier wind regime for austral autumn 2005. The prevalence of the barrier wind is observed in the AWS sites along 80°S. At Schwerdtfeger, Carolyn, and Gill AWS, the wind direction is almost exclusively from 169° to 236°. Marilyn AWS indicates some westerly flow, which is most likely related to katabatic drainage during some of the events. The frequency of westerly winds decreases from west to east across 80°S as the influence of the katabatic drainage down Byrd Glacier decreases with increasing distance from Byrd Glacier. The wind is channeled into an even narrower sector along the AWS extending east from Minna Bluff. The winds at Linda, Emilia, and Vito AWS are nearly all from 169° to 213°. Linda has the strongest winds with over 20% of the observations greater than 10 m s^{-1}. The AWS observations indicate an airflow that is slightly to the right of parallel to the barrier and not the expected barrier parallel flow. One reason for this difference is the slowing and turning of the wind by surface friction. The influence of the inertial propagation of katabatic winds flowing down the glaciers in the Transantarctic Mountains and across the Ross Ice Shelf is a possible additional reason.

Eric AWS exhibits minimal barrier wind effects. This site is likely too close to the barrier to experience the barrier wind. Seefeldt et al. (2003) shows the doming of air in front of Ross Island in a region called Windless Bight. The airflow incident to the barrier piles up at the base and a dome of lower potential temperature air accumulates. The doming of the cooler air results in a weak pressure gradient and varying winds immediately adjacent to the barrier. A similar situation is anticipated to be occurring at the base of the Transantarctic Mountains near Eric AWS. Snow observations during the installation of Eric AWS also confirm the presence

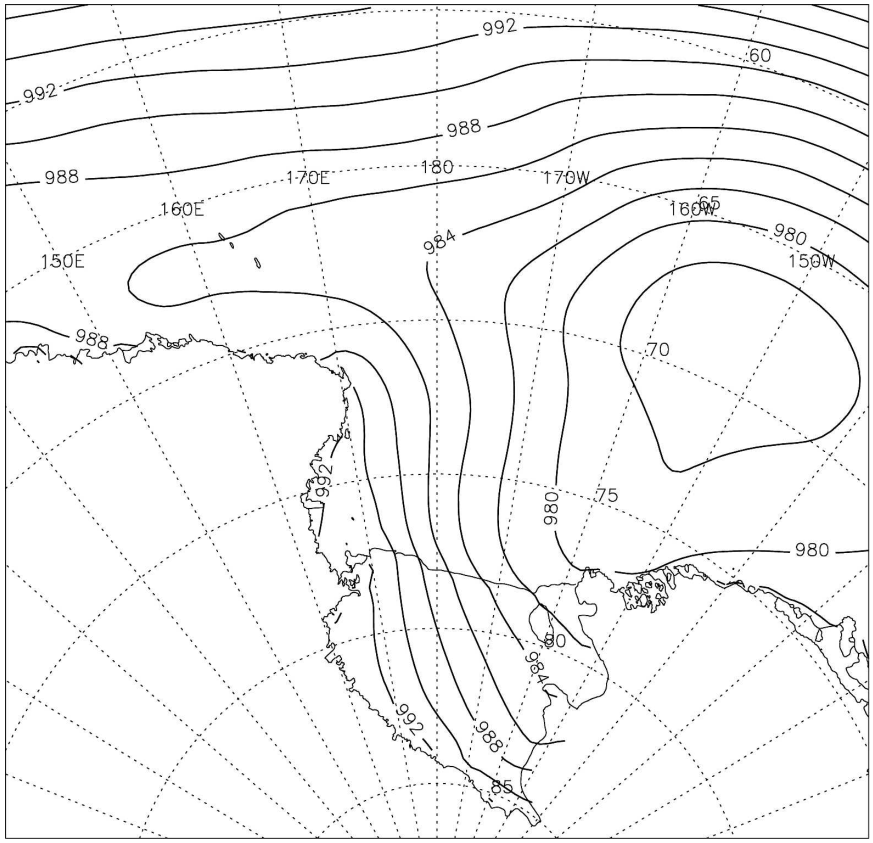

FIG. 5. As in Fig. 3 except that the analysis is based on averaging AMPS 3-hourly forecasts, which are within 1 h of a barrier wind event as determined by the selection criteria.

of light and varying winds with a light, powdery, and deep snow base.

Figure 5 is a plot of average sea level pressure for the barrier wind regime. All representative 3-hourly AMPS forecasts that are within 1 h of a barrier wind event are included in the averaging. For example, for the barrier event from 1000 to 1900 UTC 26 March the valid forecasts for 0900, 1200, 1500, and 1800 UTC 26 March are included in the averaged analysis. The AMPS sea level pressure gradient for the barrier wind regime is oriented perpendicular to the Transantarctic Mountains with the higher pressure at the base of the mountains and decreasing pressure extending to the east. This pressure gradient results in a geostrophic wind that is parallel to the barrier as should be expected for a barrier wind. The average sea level pressure plot indicates that the barrier wind events often occur with a cyclone located in the eastern Ross Sea near Cape Colbeck.

3) CASE STUDY REPRESENTING THE BARRIER WIND REGIME

A case study of a barrier wind event from 0700 to 2300 UTC 11 March 2005 is used to provide an in-depth analysis of the formation and forcing of a barrier wind event. The selected event has a well-defined barrier pattern and it has one of the largest pressure gradients across the Ross Ice Shelf of all the barrier wind events. The duration of this event is 17 h, of which 2 h did not match the barrier wind criteria.

The sea level pressure analyses (Fig. 6) show the passage of a large synoptic-scale cyclone from west to east across the northern Ross Sea, which results in the development of the barrier wind event. Prior to the event, the cyclone is located off of the Antarctic continent north of Cape Adare (72°S, 170°E), the pressure gradient is weak across the Ross Ice Shelf, and the AWS observations indicate light winds with varying wind directions. At 0000 UTC 11 March (Fig. 6a) the initial signs of the development of a barrier wind event are apparent. The air is channeled into the Ross Sea/Ross Ice Shelf basin with the clockwise cyclonic airflow around the low pressure center. The air accumulates on the Ross Ice Shelf and the surface pressure increases at the base of the Transantarctic Mountains in comparison with 6 h earlier (not shown). At 0600 UTC the cyclone continues to move toward the east (Fig. 6b), the pres-

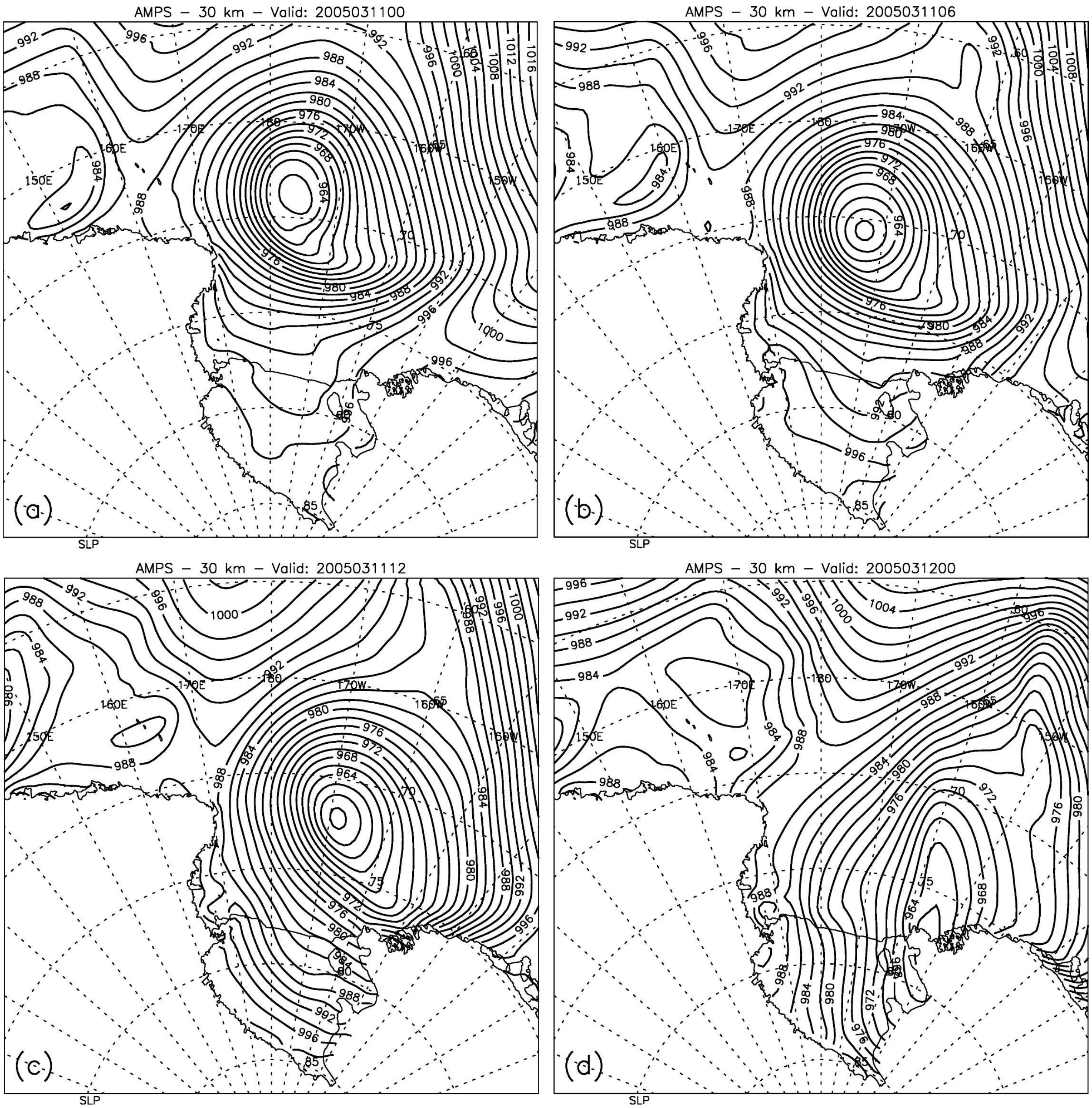

FIG. 6. AMPS sea level pressure analysis (CI = 2 hPa) for the greater Ross Ice Shelf region for an example of a barrier wind event.

sure at the base of the barrier increases slightly, and wind observations (Fig. 7b) are from the south to southwest with moderate wind speeds. A well-developed barrier wind event is in place at 1200 UTC. The cyclone is near the eastern Ross Sea with a 958-hPa central pressure (Fig. 6c). The isobars are nearly parallel to the barrier with a 20-hPa pressure difference from southwest to northeast across the Ross Ice Shelf, a distance of approximately 400 km. Wind observations are southerly to southwesterly, with speeds greater than 10 m s^{-1} at all AWS sites across the Ross Ice Shelf (Fig. 7c). The cyclone is in the process of filling and stalls near the edge of West Antarctica by 0000 UTC 12 March (Fig. 6d). The strong pressure gradient is still present across the Ross Ice Shelf but it is no longer perpendicular to the Transantarctic Mountains. The orientation of the pressure gradient and wind observations at Marilyn and Mary AWS (Fig. 7d) are similar to what is observed with the onset of a strong katabatic event.

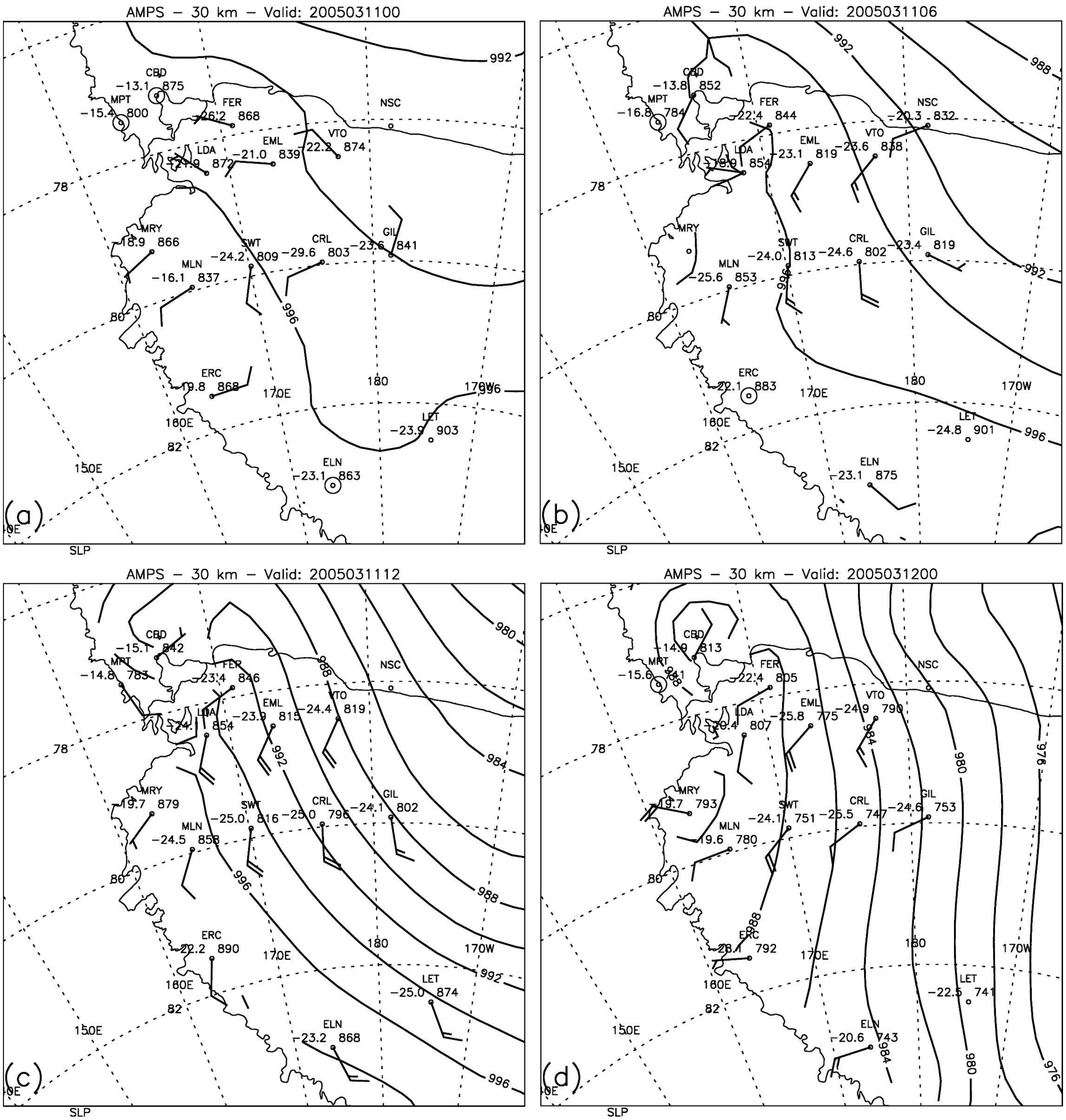

FIG. 7. Ross Ice Shelf region AMPS sea level pressure analysis (CI=2 hPa) with overlying AWS station plots for an example of a barrier wind event. The AWS station plots (half barb = 2.5 m s^{-1}; full barb = 5.0 m s^{-1}) have temperature (°C) and station pressure (tenths of hPa) plotted in the upper-left and upper-right positions.

b. *Strong katabatic*

1) SELECTION CRITERIA FOR THE STRONG KATABATIC WIND REGIME

Strong winds flowing from the direction of Byrd Glacier are used to define a strong katabatic event. The definition for a katabatic event is based on the high likelihood that wind from this direction originated over Byrd Glacier as katabatic winds that then continue to propagate across the Ross Ice Shelf as shown in King and Turner (1997, their Fig. 6.6). The criteria for a strong katabatic wind event are based on Marilyn and Schwerdtfeger AWS. The observation at Marilyn AWS must have a wind speed greater than 5 m s^{-1} and a wind

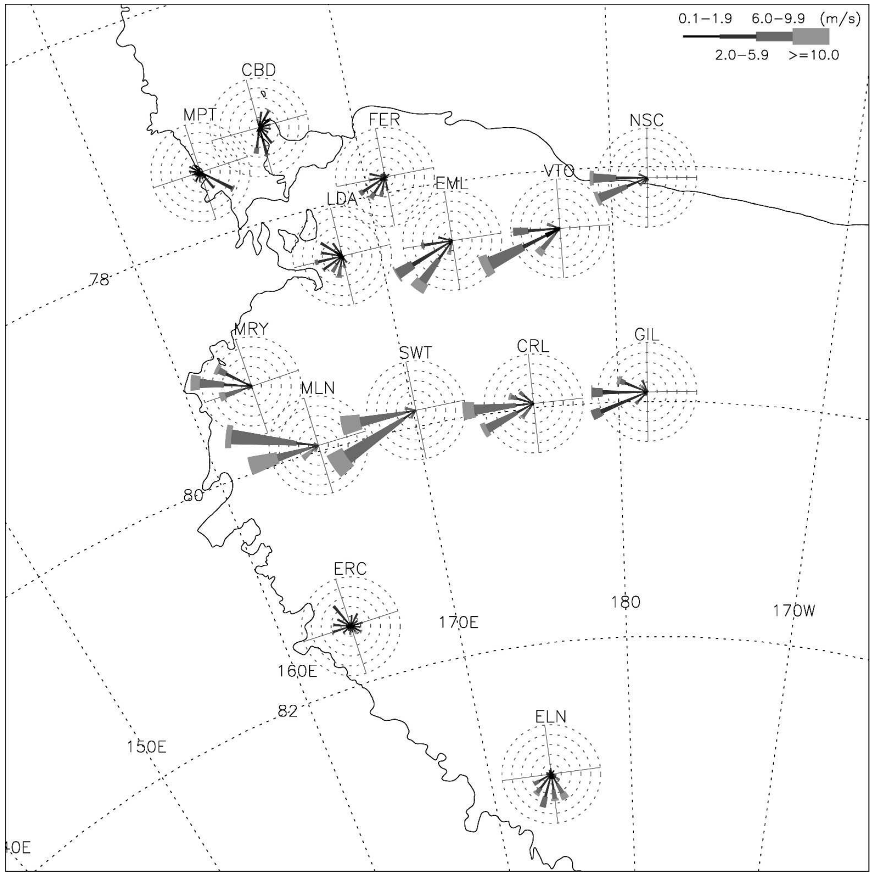

FIG. 8. As in Fig. 2, but for the strong katabatic regime.

direction from 236° to 304°, and Schwerdtfeger AWS must have a wind direction from 214° to 304° (Table 2). Thirteen events were identified covering 278 h or 13.0% of the autumn observations.

2) Characterization of the strong katabatic wind regime

West winds are apparent at all AWS sites along the transect of 80°S for the strong katabatic events (Fig. 8). Wind speeds decrease from the west (Marilyn AWS) to the east (Gill AWS) as friction is likely slowing the katabatic wind as it propagates away from its source region. A large percentage of the observations, approximately 20%, have speeds greater than 10 m s^{-1} at Marilyn AWS. The directional constancy decreases from west to east. This is expected to be due to a decrease in the inertial strength of the katabatic flow. The westerly winds are also observed at the northern AWS sites. West to southwesterly winds are observed at Emilia and Vito and extending as far east as Nascent AWS. The strong katabatic events represent a rare occurrence where the wind at Linda is not from the south to southwest. AWS sites in the Ross Island region, Ferrell, Cape Bird, and Marble Point indicate light and varying winds at all locations. Such observations indicate that strong synoptic forcing is unlikely to be solely responsible for the strong westerly winds at the other AWS sites.

The average sea level pressure, from the AMPS archive for the strong katabatic events (Fig. 9), indicates isobars that are aligned at an angle to the Transantarctic Mountains. A mean cyclone is located at the edge of the continent, near Cape Colbeck. This is located father south than indicated for the barrier wind regime and approximately the same as the location of the cyclone at the end of the barrier wind case study. The orientation of the isobars indicates that the geostrophic flow is now partially directed down the glacial valleys of the Transantarctic Mountains. Yet even with this favorable orientation of the isobars, a strong katabatic wind event requires a pool of cold air on the East Antarctic ice sheet to provide the negatively buoyant air to descend through the glacier valleys. Breckenridge et al. (1993) found that strong katabatic winds were associated with large differences in the near-surface AWS temperature observations between the Ross Ice Shelf and the polar

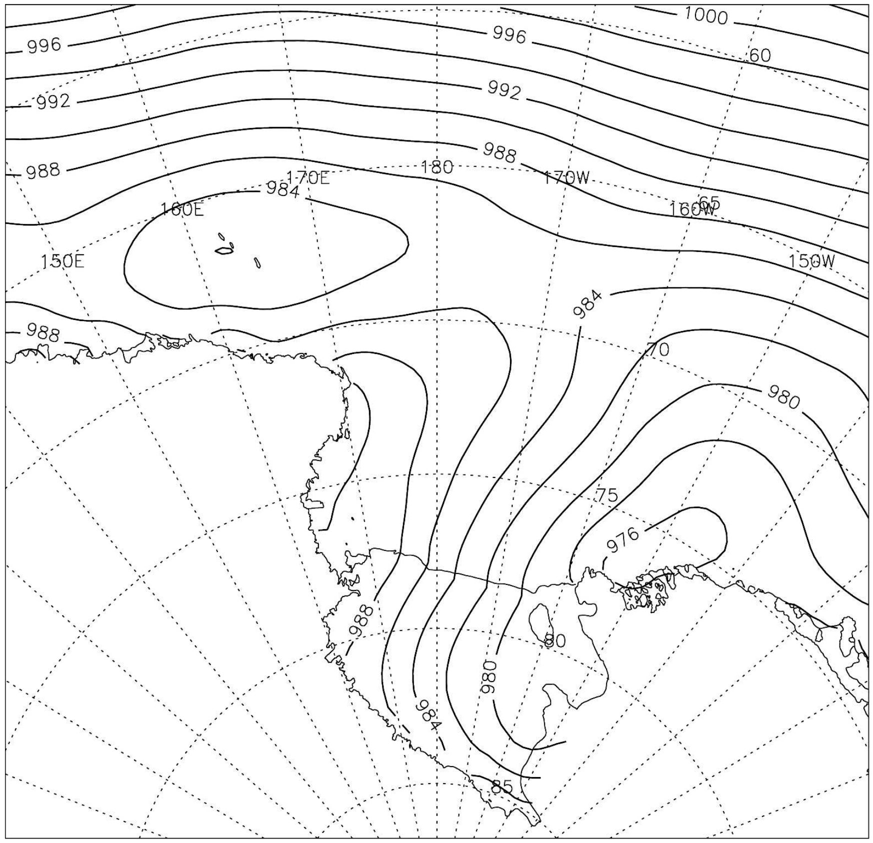

FIG. 9. As in Fig. 3 except that the analysis is based on averaging AMPS 3-hourly forecasts, which are within 1 h of a strong katabatic event as determined by the selection criteria.

plateau. It can also be hypothesized that the strong katabatic events are not a purely katabatic event. Instead the strong katabatic events are possibly the combination of the inertial katabatic flow with additional forcing from the ambient pressure gradient. When this ambient pressure gradient is in a preferred direction it allows for propagation of the katabatic flow across the flat ice shelf for large distances with large wind speeds. The result of this hypothesis is that referencing this dominant regime as a strong katabatic may not be entirely accurate. Parish and Cassano (2003) present a study of the forcing mechanisms for the strong wind field at Cape Denison (67°S, 143°E). They concluded that the forcing mechanisms for flows appearing to be katabatic (i.e., downslope) are not always of a katabatic origin (i.e., negatively buoyant air over sloped terrain) but are also due to the adjustment process between the ice surface and the ambient pressure field.

3) CASE STUDY REPRESENTING THE STRONG KATABATIC WIND REGIME

The selected case study for the strong katabatic event is from 1600 UTC 8 April to 1500 UTC 9 April 2005. The case lasts for 24 h with observations for two hours not matching the criteria. The selected event has a similar sea level pressure pattern as all of the other strong katabatic events but it has a slightly stronger airflow than most of the events. The case study starts with conditions similar to what is seen at the end of a typical barrier wind event (Fig. 6d). A cyclone is located off the coast of Antarctica near Cape Colbeck with a central pressure of 944 hPa and the pressure gradient is oriented so that the geostrophic wind is directed from south to north across the Ross Ice Shelf. At 1200 UTC 8 April (Fig. 10a) the cyclone moves over the continent and maintains a 944-hPa central pressure. The isobars are intersecting the Transantarctic Mountains over the southern Ross Ice Shelf but remain parallel to the barrier farther to the north near Byrd Glacier. The AWS observations (Fig. 11a) along 80°S are indicating flow that is nearly perpendicular to the isobars. This is a good indication that there is relatively strong katabatic drainage occurring at this time, since near-surface flow influenced solely by the synoptic pressure gradient and friction would be from a southwest direction. At 1800 UTC (Fig. 10b) the center of the cyclone has become

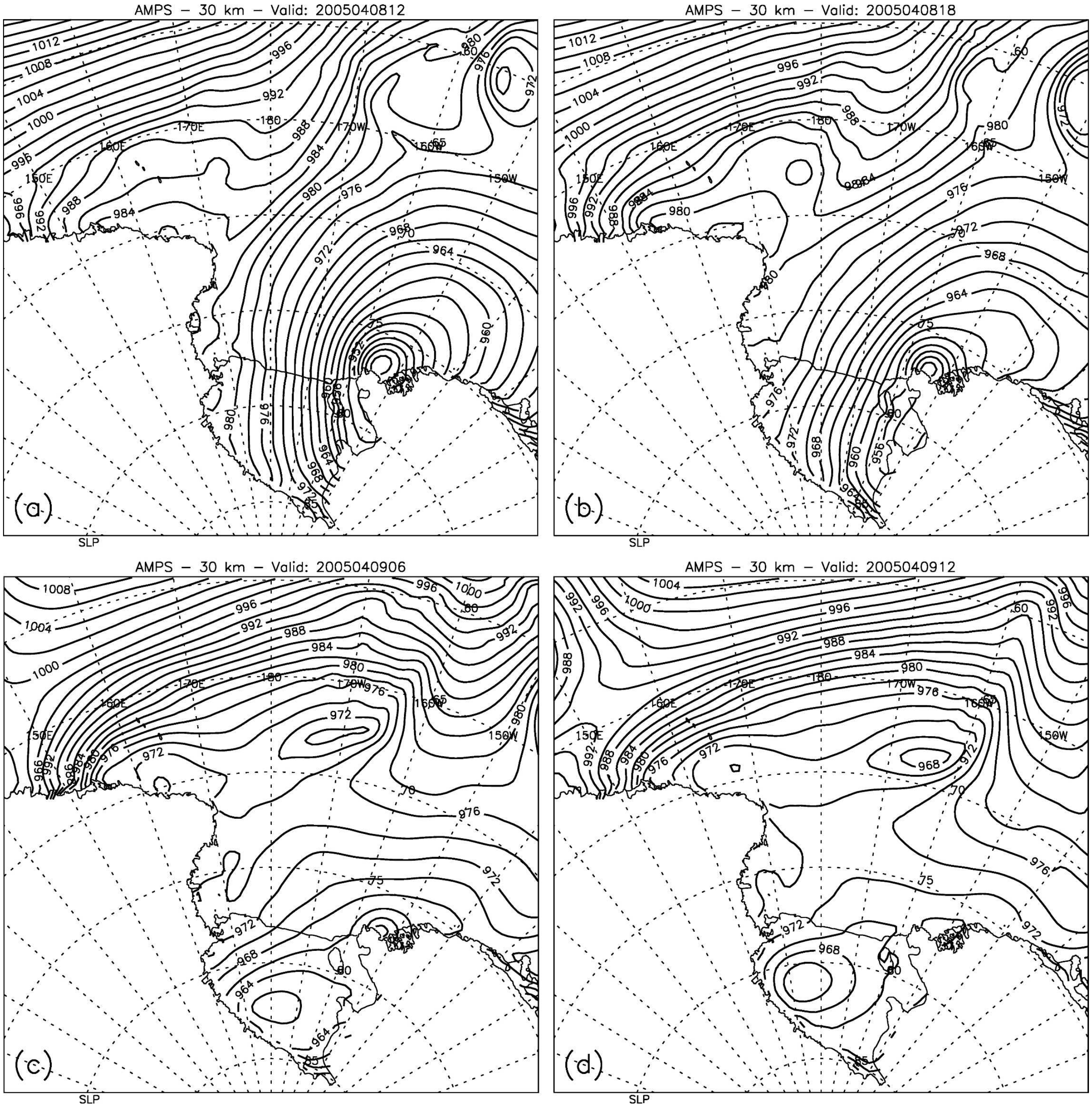

FIG. 10. As in Fig. 6, except as an example of a strong katabatic event.

stationary near Cape Colbeck and it has started to decrease in intensity. The larger cyclone has rotated so that the isobars are now at an angle to the Transantarctic Mountains at all locations on the Ross Ice Shelf. Geostrophic flow now has a component oriented away from the Transantarctic Mountains providing additional forcing for the westerly flow across the ice shelf. The AWS observations (Fig. 11b) indicate that westerly flow is seen at all locations across the western Ross Ice Shelf. At 0000 UTC a new low pressure center forms on the Ross Ice Shelf near the Siple Coast and by 0600 UTC (Fig. 10c) this cyclone starts to move across the western Ross Ice Shelf. Wind observations remain from the west with wind speeds above 10 m s^{-1} at AWS locations (Fig. 11c) along 80°S and extending from Minna Bluff. The cyclone near Cape Colbeck is nearly no longer recognizable by 1200 UTC (Fig. 10d). The cyclone on the Ross Ice Shelf continues to move toward the north and remains in a favorable position for westerly flow at the AWS sites (Fig. 11d) along 80°S.

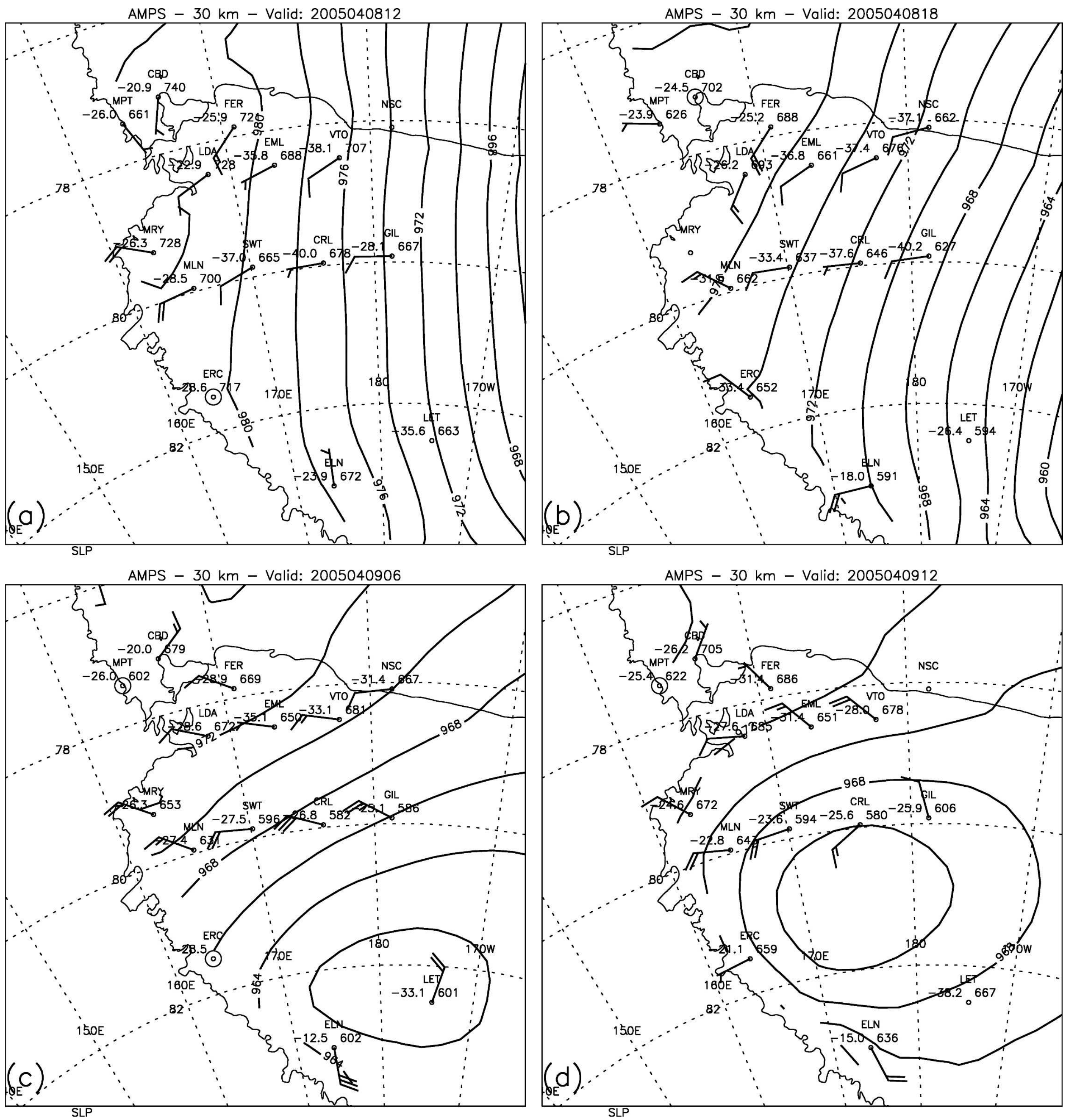

FIG. 11. As in Fig. 7, except as an example of a strong katabatic event.

c. *Weak katabatic*

1) SELECTION CRITERIA FOR THE WEAK KATABATIC WIND REGIME

The weak katabatic wind regime is defined by weak winds blown from the direction of Byrd Glacier. As with the strong katabatic regime, this wind direction is assumed to represent katabatic flow originating over Byrd Glacier and propagating across the Ross Ice Shelf. The selection criterion for the weak katabatic wind regime includes a wind speed between 1.0 and 4.9 m s^{-1} at Marilyn and Schwerdtfeger AWS and 2 of the 3 wind direction observations from Marilyn, Schwerdtfeger, and Mary AWS must occur within the designated favorable katabatic wind direction sector (Table 2). This wind speed criterion is weaker than the strong katabatic regime while maintaining the westerly winds generally associated with down-glacier flow. A total of 12 events

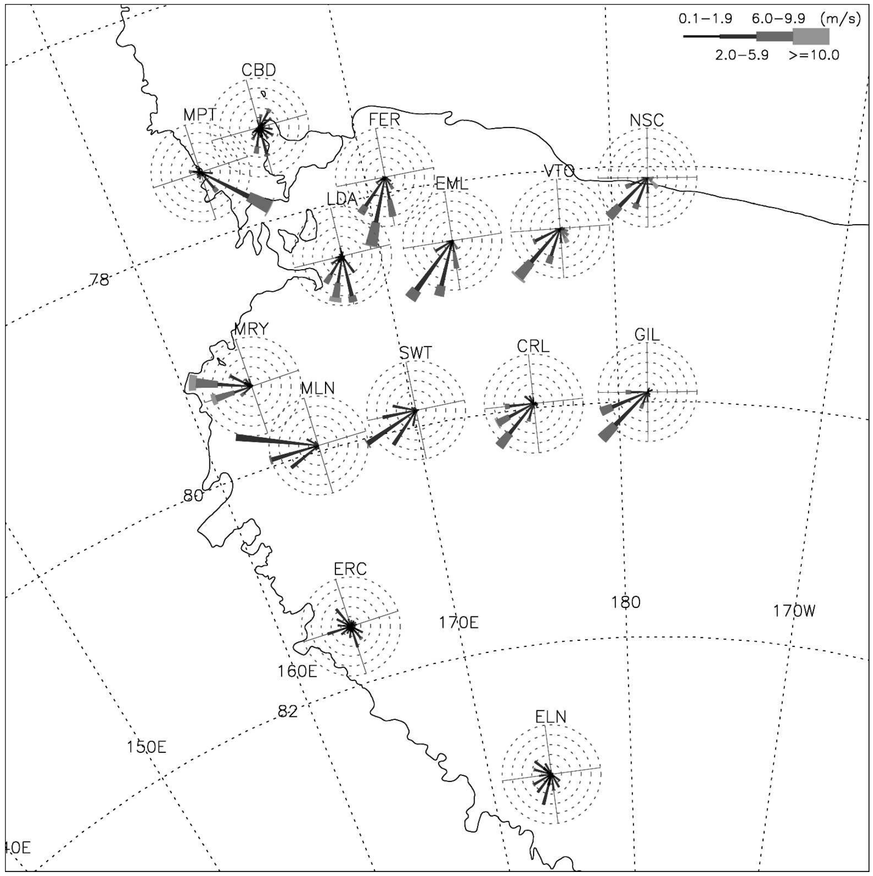

FIG. 12. As in Fig. 2, but for the weak katabatic regime.

were selected, which cover 227 h or 10.6% of the autumn observations.

2) Characterization of the weak katabatic wind regime

Figure 12 indicates the presence of a weak katabatic flow extending eastward along 80°S. The winds at Mary AWS indicate likely katabatic flow down Mulock Glacier. Eric and Elaine AWS indicate some down-glacier flow through the Transantarctic Mountains. There is little indication of katabatic winds at the northern Ross Ice Shelf AWS sites: Emilia, Vito, and Nascent. This is in contrast to the strong katabatic wind regime that indicated strong west-southwest flow at these sites. Nineteen percent of the weak katabatic observations are also classified with the barrier wind regime. The overlapping of observations between two wind regimes reveals a limitation in using criteria-based wind regime classifications. In certain conditions the observations may match a specified regime criteria yet the actual atmospheric forcing is inconsistent with what is typical for that regime.

The weak katabatic wind regime is often associated with a weak pressure gradient across the Ross Ice Shelf and the lack of a significant cyclone in the Ross Sea (Fig. 13). A 6-hPa pressure difference across the Ross Ice Shelf is present in comparison with the average value of 10 hPa for the austral autumn season and 12 hPa for the barrier and strong katabatic wind regimes. An analysis of the sea level pressure maps for the individual events (not shown) shows that the weak katabatic wind is often associated with a weak pressure gradient directed from the southwest to the northeast across the Ross Ice Shelf. The greater Ross Sea and Ross Ice Shelf region is generally absent of any major synoptic-scale features.

3) Case study representing the weak katabatic wind regime

An event from 1500 UTC 7 February to 0100 UTC 9 February 2005 will be used as the case study for the weak katabatic regime. The selected event is typical of all the events for the weak katabatic regime. The case study indicates a weak to moderate pressure gradient

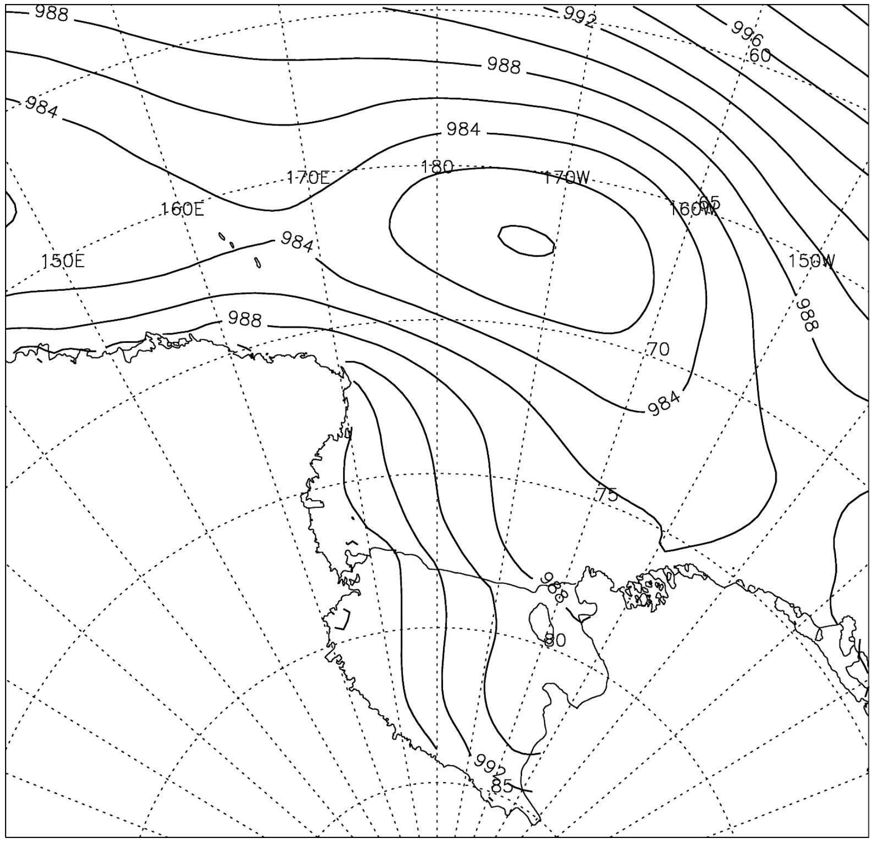

FIG. 13. As in Fig. 3, but for the weak katabatic regime.

across the Ross Ice Shelf at 1500 UTC 7 February 2005 (Fig. 14a). The only synoptic-scale activity in the greater Ross Ice Shelf region is a weak cyclone off of Cape Adare. During the course of this case study the cyclone moves slowly to the northeast while maintaining its intensity. The pressure gradient is oriented from northeast to southwest across the Ross Ice Shelf. The pressure difference across the Ross Ice Shelf is approximately 8 hPa and remains relatively constant throughout the case study. Down-glacier flow is indicated along the Transantarctic Mountains at Elaine, Eric, Marilyn, and Mary AWS (Fig. 15a). The down-glacier flow remains present at all of these AWS sites throughout the case study. The AWS sites extending from Minna Bluff, and in the northwest Ross Ice Shelf region, show flows similar to the seasonal averaged conditions with primarily southwest to southerly winds.

d. Light wind

1) SELECTION CRITERIA FOR THE LIGHT WIND REGIME

Light wind conditions at AWS sites across the Ross Ice Shelf, at locations away from the influence of the Transantarctic Mountains and the complex topography of the Ross Island region, will be used to define the light wind regime. Observations with a wind speed less than 4 m s^{-1} at four of the following five AWS sites—Emila, Vito, Schwerdtfeger, Carolyn, and Gill—satisfy the light wind regime criteria (Table 2). The five AWS sites were chosen because they are located away from the influence of the Transantarctic Mountains. A total of 10 events with durations greater than 10 h, with a total of 172 h or 8.1% of the autumn observations, make up the light wind regime.

2) CHARACTERIZATION OF THE LIGHT WIND REGIME

For the light wind regime the wind rose plot (Fig. 16) indicates light wind speeds with varying wind direction, primarily from the southern sector, across the center of the Ross Ice Shelf. Light to moderate katabatic flow is likely based on the observed down-glacier winds along the Transantarctic Mountains at Elaine, Marilyn, and Mary AWS. The AWS sites in the Ross Island region indicate a terrain following pattern as expected with light winds and stable conditions (Seefeldt et al. 2003).

The averaged AMPS sea level pressure (Fig. 17)

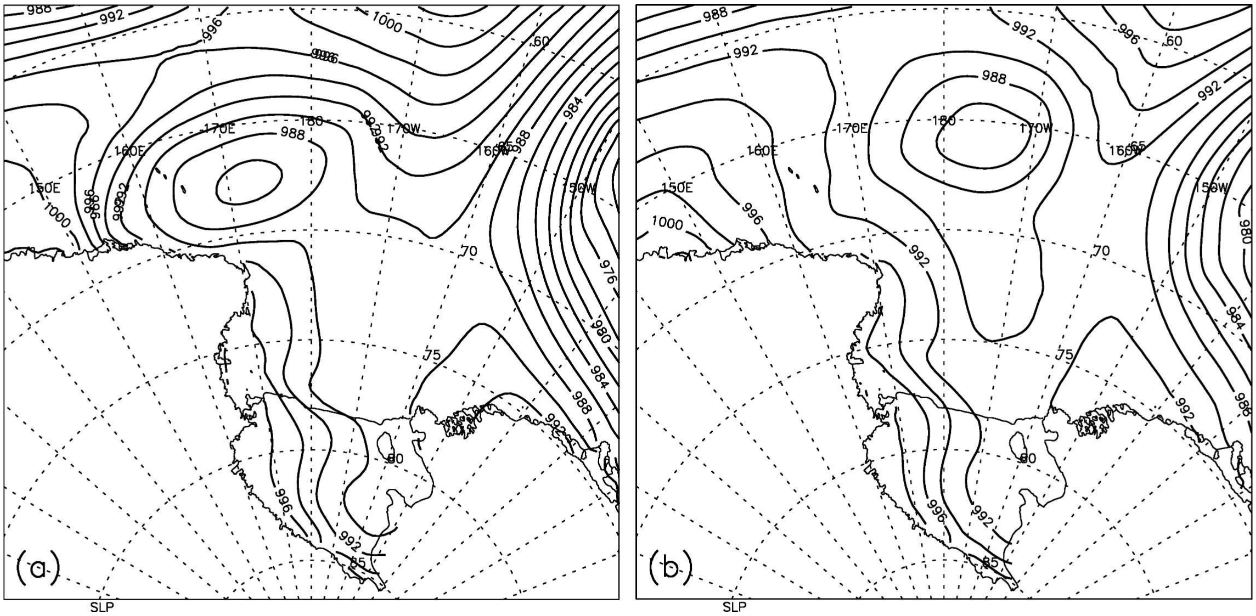

FIG. 14. As in Fig. 6, except as an example of a weak katabatic event.

shows a weak pressure gradient with less than a 6-hPa difference across the Ross Ice Shelf, similar to the weak katabatic regime. The pressure gradient is oriented from the northeast to the southwest. Analysis of individual sea level pressure plots (not shown) for times that satisfy the weak wind criteria indicate that weak cyclones are often present and moving from west to east across the northern Ross Sea. The typical track of these cyclones is indicated by the trough in the sea level pressure in the northern Ross Sea. These weak cyclones are likely to have a minimal influence on the surface wind field of the Ross Ice Shelf region. This is in contrast to the stronger cyclones present during the barrier wind and the strong katabatic wind regimes.

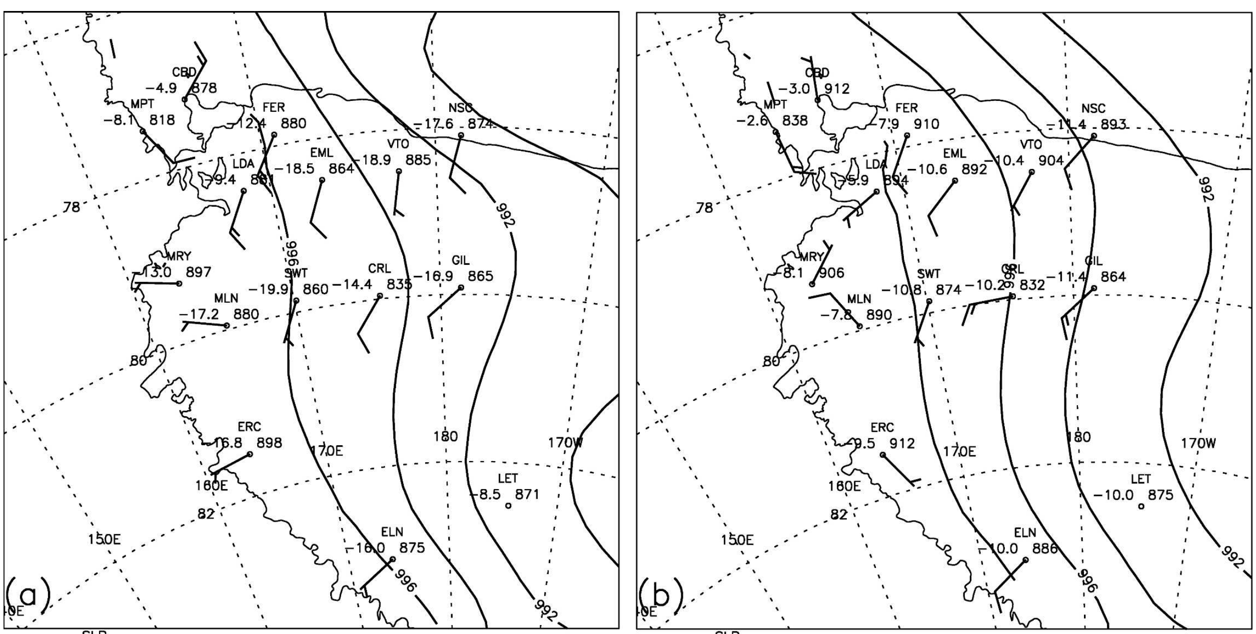

FIG. 15. As in Fig. 7, except as an example of a weak katabatic event.

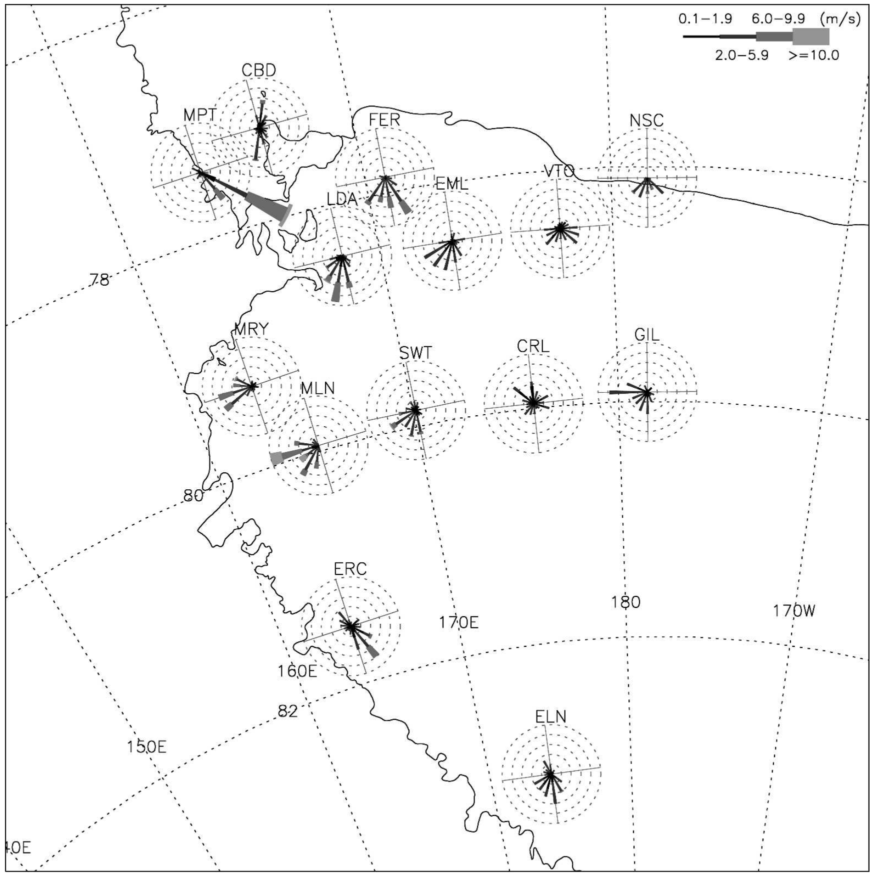

FIG. 16. As in Fig. 2, but for the light wind regime.

3) CASE STUDY REPRESENTING THE LIGHT WIND REGIME

The selected case study for the light wind regime is from 0700 UTC 18 February to 0700 UTC 19 February 2005. The event lasted for 25 h with observations for 5 h not matching the criteria. The selected event is typical of all light wind events in that it has a weak pressure gradient across the Ross Ice Shelf. The surface high pressure system located over the northwestern Ross Ice Shelf is atypical of what is commonly observed in the region. Considering the lack of major changes in the dynamical forcing over the course of the event, the event will be studied only from 1200 UTC 18 February to 0600 UTC 19 February 2005. There is a minimal pressure gradient across the Ross Ice Shelf with a 6-hPa difference from west to east. A weak cyclone is traveling from west to east across the northern Ross Sea (Figs. 18a,b). There are no indications of any influence of this cyclone on the AWS observations on the Ross Ice Shelf. The pressure gradient remains weak across the Ross Ice Shelf during the entire case study. Winds (Figs. 19a,b) remain weak with varying directions at all sites on the Ross Ice Shelf that are away from the Transantarctic Mountains. On occasion, the observations at Elaine, Eric, and Marilyn AWS indicate weak winds from the down-glacier direction.

5. Conclusions

A description of the surface wind field for the Ross Ice Shelf in austral autumn 2005 has been presented in this study. AWS observations were used to define dominant wind regimes as well as in the creation of wind rose plots for the characterization of the surface wind field. Sea level pressure analyses from the AMPS 30-km archive were used to provide an understanding of the forcing for the surface wind field. This methodology was chosen as it allows for the identification of specific patterns in a complex flow. By isolating all of the cases of a given wind pattern it is then possible to study the forcing mechanisms for that pattern. The analysis of the forcing for the wind regimes identified in this paper is the goal of on-going research efforts with a focus on the RAS.

Previous Antarctic research has focused on indi-

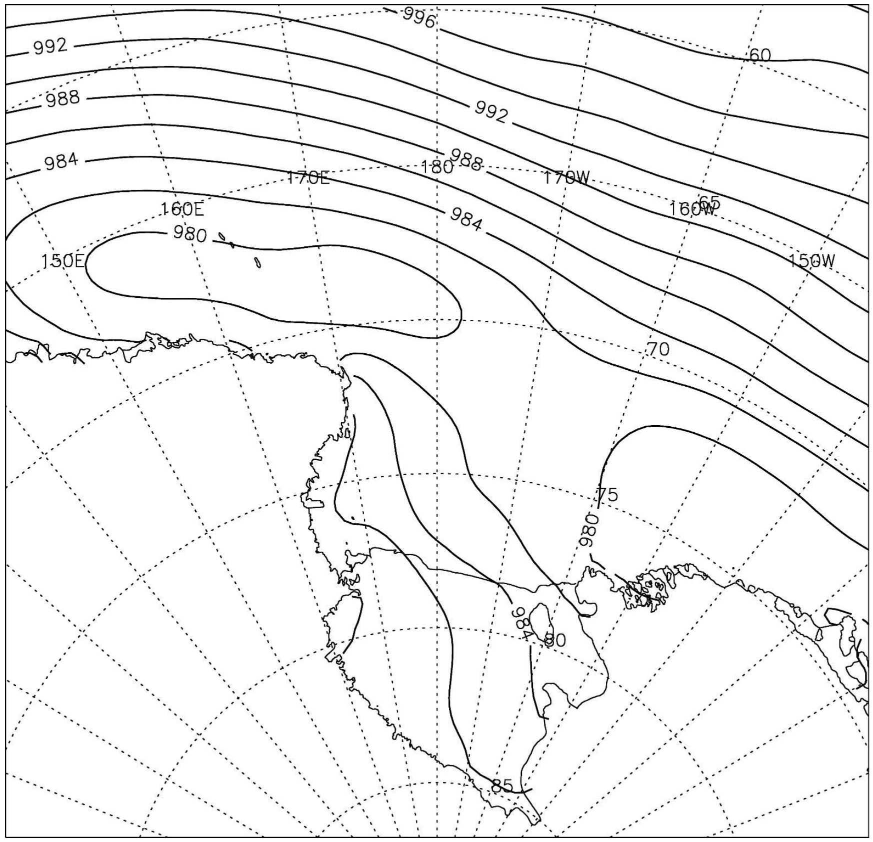

FIG. 17. As in Fig. 3, but for the light wind regime.

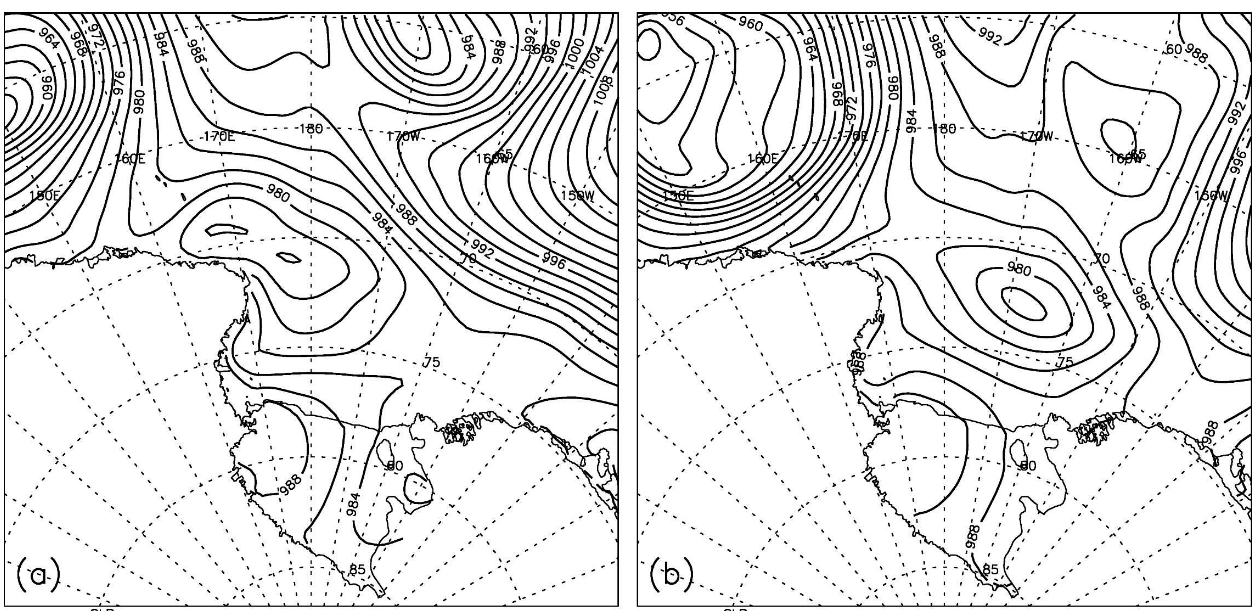

FIG. 18. As in Fig. 6, except as an example of a light wind event.

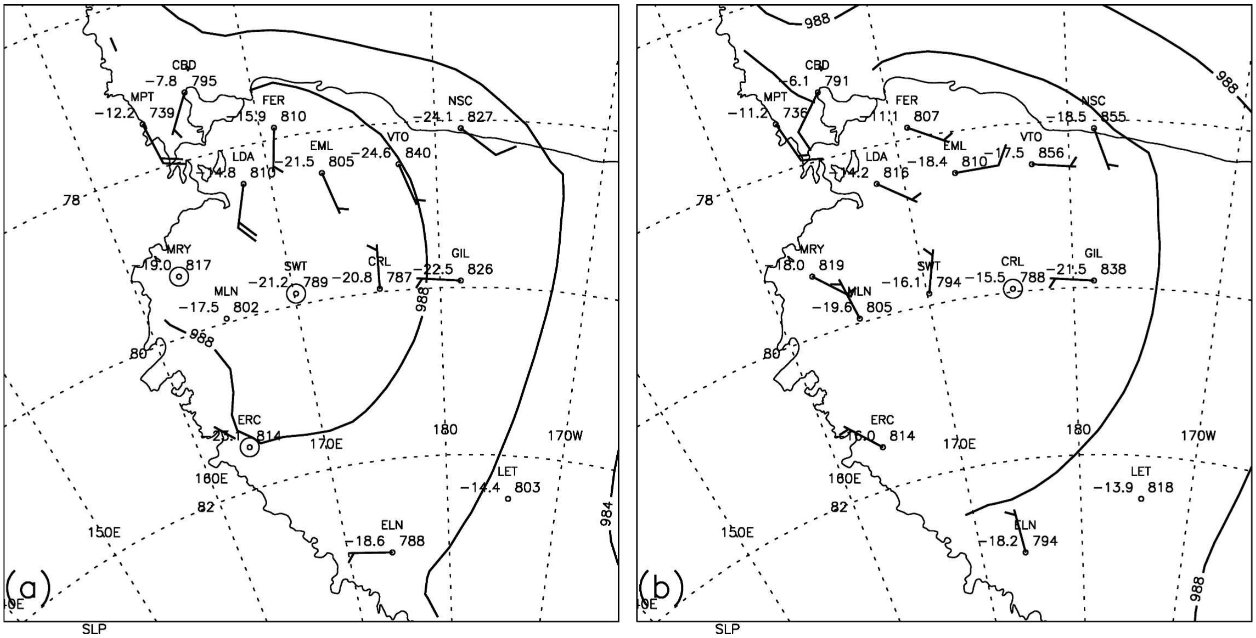

FIG. 19. As in Fig. 7, except as an example of a light wind event.

vidual patterns composing the surface wind field, such as katabatic winds, barrier winds, and the winds associated with the passage of cyclones and mesocyclones. Based on this previous research, four dominant wind regimes were defined in this study. The dominant wind regimes required matching wind speed and wind direction observations at several AWS sites and for durations of greater than 10 h. The barrier wind regime is classified as the occurrence of south to southwesterly winds at several AWS sites along 80°S and extending to the east from Minna Bluff. The strong katabatic wind regime is defined as strong down-glacier-directed winds at Marilyn and Schwerdtfeger AWS near the base of the Byrd Glacier. The weak katabatic wind regime is defined as weak winds from the down-glacier direction at Marilyn, Schwerdtfeger, and Mary AWS. The light wind regime is defined by light wind speed values at several AWS sites on the Ross Ice Shelf located away from the Transantarctic Mountains. The four dominant wind regimes make up a total of 44.1% of the autumn 2005 observations. The remaining 55.9% of the observations are likely either a mixture of several forcing conditions (events with durations less than 10 h) or associated with the passage of cyclones and mesocyclones. A study on the passage of cyclones and mesocyclones was difficult to conduct using this regime matching methodology because of the expected spatial and temporal variability of the winds with this type of forcing. The results indicate that the previous understanding of the Ross Ice Shelf surface wind field, focusing primarily on katabatic and barrier winds, is a simplified perspective that accounts for less than half of the overall conditions in austral autumn 2005.

A wind rose analysis and average sea level pressure analysis were used to characterize near-surface conditions in the Ross Sea region for each dominant wind regime. The barrier wind regime has a strong south-southwesterly flow at all AWS locations along 80°S and east of Minna Bluff. The observations at Eric and Elaine AWS appear to be removed from the dominant barrier flow. A strong pressure gradient across the Ross Ice Shelf is generally present during a barrier wind event. The strong katabatic wind regime has strong westerly flow at all of the AWS sites along 80°S and east of Minna Bluff, except for Linda AWS. This wind regime is thought to be driven by katabatic drainage through the glacial valleys of the Transantarctic Mountains with likely additional forcing by an ambient pressure gradient force directed nearly parallel to the Transantarctic Mountains near Byrd Glacier. The weak katabatic wind regime has westerly winds at AWS sites near Byrd, Skelton, and Mulock glacier valleys and less-defined patterns at AWS sites away from the Transantarctic Mountains. The light wind regime has light and varying winds at most of the Ross Ice Shelf AWS sites and typical terrain following observations for the AWS sites near Ross Island. A case study has been presented for each dominant wind regime highlighting some of the factors that play a role in the formation and evolution of each regime.

The following is a summary of the results regarding the Ross Ice Shelf surface wind field:

- The typical signature of the barrier and katabatic wind regimes are most noticeable at AWS sites closer to the Transantarctic Mountains. Eric AWS, located near the base of the Transantarctic Mountains, is the exception as it experiences minimal influence.
- The barrier wind regime is indicated by a strong airflow from the south to the southwest at nearly all AWS sites on the Ross Ice Shelf. The barrier wind regime is associated with a strong pressure gradient oriented perpendicular to the Transantarctic Mountains, with high pressure at the base of the Transantarctic Mountains and decreasing pressure to the east.
- A difference between the strong katabatic regime and the weak katabatic regime is the orientation of the pressure gradient on the Ross Ice Shelf. A pressure gradient perpendicular to the Transantarctic Mountains is often associated with the weak katabatic regime, and a pressure gradient that is nearly parallel to the barrier is typical of the strong katabatic regime. This indicates that the ambient pressure gradient and resultant geostrophic wind on the Ross Ice Shelf is often a contributing factor with strong katabatic winds.

Other applications with limited observations in a region with consistent and frequent wind patterns may benefit from using a similar wind regime matching classification. The following is a summary of the results regarding the use of dominant wind regimes:

- Filtering the observations into dominant wind regimes provides a greater understanding of the typical patterns and forcing mechanisms that are consistent for a specified regime.
- The use of dominant wind regimes is dependent on a complete set of observations, which limits the application of the methodology over long periods of time. For example, the barrier wind regime was no longer able to be identified in 2005 after Linda AWS stopped transmitting in June 2005.
- Sometimes the necessary criteria to define a dominant wind regime to capture all of the expected events also includes events that are not the result of similar forcing mechanisms. For example, 12.3% of the barrier wind regime observations overlapped with the weak katabatic wind regime. An analysis of the evolution of these events indicates that they do not agree with the conceptual model of barrier wind events.

The results of this study provide a better understanding of the surface wind field across the Ross Ice Shelf and highlight the fact that previous studies of the airflow over the Ross Ice Shelf, focusing on barrier and katabatic winds, account for less than half of the observed winds. This study leads to a better understanding of the RAS as it starts to incorporate many of the previously understood surface wind patterns into a larger and more systematic framework. The RAS now appears to be a combination of these different wind regimes that are frequently observed in a sequential pattern. This sequential pattern appears to involve the passage of a cyclone in the northern Ross Sea leading to the development of a barrier wind. As the cyclone moves near Cape Colbeck, the winds modify to a strong katabatic pattern that is followed by a weak katabatic pattern. Further study of the forcing for the Ross Ice Shelf surface wind field can provide additional insight into the characteristics of the RAS. If possible, applying similar techniques to an entire year of AWS data to characterize the wind field over the course of the year would be beneficial. Unfortunately, such a study is contingent on continued successful year-round operation of the AWS sites, which has been difficult. Classifications of wind fields using a more objective clustering method should be performed. Cluster analysis schemes by Darby (2005), Weber and Kaufmann (1995), and Kaufmann and Weber (1996) provide some examples that could be applied to this problem. High-resolution simulations can be conducted in the future to gain a more complete understanding of the three-dimensional airflow across the Ross Ice Shelf, the forcing mechanisms for this flow, and the role of the different surface wind fields present in this region. Future measurements using an airborne platform to collect above-surface in situ observations will likely provide new insight into the understanding of the Ross Ice Shelf surface wind field. In particular, detailed three-dimensional measurements can better describe the depth and geometry of cold air pooling adjacent to the barrier winds.

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