# The Extreme Wind Events in the Ross Island Region of Antarctica

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Submitted to:

Weather and Forecasting

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**Abstract**

Numerous incidents of structural damage at the United States Antarctic Program (USAP) McMurdo station due to extreme wind events (EWEs) have been reported over the past decade. Utilizing nearly 20 years (~1992-2013) of University of Wisconsin Automatic Weather Station (UW-AWS) data from three different stations in the Ross Island region (Pegasus North, Pegasus South, and Willie Field), statistical analyses show no significant trends in EWE frequency, intensity, or duration. EWEs more frequently occur during the transition seasons. To assess the dynamical environments of these EWEs, Antarctic Mesoscale Prediction System (AMPS) forecast back-trajectories are computed and analyzed in conjunction with several other AMPS fields for the strongest events at McMurdo Station. The synoptic analysis reveals that McMurdo EWEs are nearly always associated with strong southerly flow due to an approaching Ross Sea cyclone and an upper level trough around Cape Adare. A Ross Ice Shelf Air Stream (RAS) environment is created with enhanced barrier winds along the Transantarctic Mountains and amplified by katabatic flow down the glaciers, downslope winds in the lee of the local topography and a tip jet effect around Ross Island. The position and intensity of these Ross Sea cyclones are most influenced by the occurrence of a Central Pacific ENSO event which causes the upper level trough to move westward. An approaching surface cyclone would then be in position to trigger an event, depending on the angle of interaction with the topography around McMurdo Station.

**1. Introduction**

There have been numerous studies on strong wind events (SWEs) throughout the Antarctic continent. SWEs in many studies have been defined by categories of the Beaufort Scale. Chenoli et al. (2012) used the Beaufort scale of 6 (11.3 m s-1) while Turner et al. (2009) used gale (17.2 m s-1) or storm (24.5 m s-1) force scales for plateau and coastal SWEs, respectively. Extreme wind events (EWEs) focus on the higher end of these categories such as the storm scale and greater to examine the events with the greatest possibility of destruction of facilities at staffed stations.

East Antarctica is especially susceptible to strong or extreme wind events due to the steeply sloping topography and the presence of intense synoptic scale cyclones. A modeling analysis of SWEs at the Australian coastal site Casey in the East Antarctic showed that synoptic winds (cyclones) and katabatic flow are equally present during the development of severe winds, even though these wind vectors are nearly perpendicular to each other in this region (Murphy and Simmonds, 1993). Further investigation into East Antarctic SWEs (utilizing models and station observations) revealed that, while downslope winds can certainly add to the severity of the wind event, extratropical cyclones are a prevalent feature of these SWEs and are the dominant forcing (Murphy, 2003). Turner et al. (2009) emphasize that the katabatic contribution to East Antarctic SWEs is crucially dependent on the specific interaction between the synoptic regime and the downslope flow, or the position of cyclones relative to valleys.

The drastically different topographical features—and the corresponding, varied responses of different flow regimes (Seefeldt et al., 2003)—in the Ross Island region warrant a separate investigation of the dynamical forcings behind McMurdo Sound severe winds. Wind events in the McMurdo and Ross Island Region in the Antarctic pose a major threat not only to structures in McMurdo Station and Scott Base, but also to flight operations and safety. Extreme winds, such as those observed in the previously studied McMurdo event on May 15-16, 2004 (Powers, 2007; Steinhoff et al., 2008), can cause significant damage to permanent structures and equipment, while winds as weak as 7 m/s can be a travel hazard due to blowing snow (Bromwich, 1988; Holmes et al., 2000; Knuth et al., 2010).

An intricate relationship exists between the wind regime and the orography in the Ross Island vicinity (Figure 1). Much of the spatial and temporal variation in the Ross Island airflow is explained by the interaction between the large-scale wind patterns with the local static stability and complex topography (Seefeldt et al., 2003). Ross Island, on the east side of McMurdo Sound, is roughly 75km long and 35km wide and encompasses both Mount Erebus and Mount Terror, two peaks that rise from sea level to over 3000m. The staffed Antarctic stations of McMurdo and Scott Base lie on the very end of Hut Point Peninsula, a 20km extension of Ross Island. On the south edge of the island, the 900km long Ross Ice Shelf begins its vast extent into the Antarctic continent. Additional orographic features in the Ross Island region include: Minna Bluff, an 800m high ridge that sits 80km to the south of Ross Island; Black Island and White Island, two features with 1000m and a 800m elevations, respectively, 30km south of Ross Island; and the Transantarctic Mountains 80km west of Ross Island, running from the Ross Sea along the western edge of the Ross Ice Shelf.

The wind in the Ross Island vicinity is highly dependent on the large-scale flow patterns over the entire Ross Ice Shelf, which can often be characterized by a semi-permanent wind regime called the Ross Ice Shelf airstream (RAS) flowing parallel to the Transantarctic Mountains from the Siple Coast up through the Ross Island region (Parish et al., 2006; Seefeldt et al., 2007; Steinhoff et al., 2009; Nigro and Cassano, 2014a; Coggins and McDonald, 2015). The RAS flow pattern is a composite of several different forcings, including katabatic winds, barrier winds, and synoptic flow (i.e. cyclones and anticyclones), all of which interact with each other (Nigro and Cassano 2014b). O’Connor et al. (1994) noted that geostrophic flow running perpendicular to the Transantarctic Mountains—such as that forced by an ice shelf cyclone—creates a dominant barrier flow that results in strong southerly flow in the Ross Island region. While attempting to characterize the dominant regimes over the Ross Ice Shelf as katabatic, barrier, or weak flow, Seefeldt et al. (2007) concluded that these wind regimes alone classify under half of the total summer hours over the shelf, implying that most of the flow in the region can be characterized by a combination of these regimes in conjunction with synoptic disturbances. Nigro and Cassano (2014b) found that the semi-permanent elevated baroclinic zone at the edge of the East Antarctic plateau provides forcing for the barrier parallel flow that characterizes the RAS. Unsurprisingly, changes in the intensity of the RAS and its contributing flow regimes have a significant impact on the severity of the wind in the Ross Ice Shelf region.

Recent research has examined McMurdo area SWEs and their associated wind regimes in the Ross Island region with a focus on in situ observations (Holmes et al., 2000), satellite observations (Bromwich, 1989), and most commonly, modeling (Seefeldt et al., 2003; Powers, 2007; Steinhoff, 2008; O’Connor et al., 1994; Monaghan et al., 2005). Due to the paucity of ground based observations, modeling studies are an important means to depict the larger scale features associated with the SWEs. The complex, small-scale topography of the area limits the models’ ability to represent the smaller scale features that are present during an SWE.

Multiple dominant dynamical features have been suspected as initiating SWEs in the Ross Island Region: katabatic winds (Bromwich, 1989; Parish and Bromwich, 1998), barrier winds along the Transantarctic Mountains (O’Connor et al., 1994), cyclonic events in the vicinity of Ross Island and McMurdo Sound (Carrasco and Bromwich, 1993; Powers, 2007; Steinhoff et al., 2008), hydraulic jumps, and potentially downslope winds accelerated by gravity waves (Steinhoff et al., 2008). The consensus is that more than one of these mechanisms occurs during a SWE. One key difference between Ross Island SWEs and the aforementioned events in the East Antarctic is the prominence of the RAS in the Ross Ice Shelf wind regime, of which barrier flow is a major component.

A recent climatology of McMurdo SWEs by Chenoli et al. (2012) revealed that, though the overall trend in the number of SWEs from 1979 to 2005 is insignificant, a bimodal distribution in the wind direction during these events exists. This bimodal distribution is consistent with Holmes et al. (2000) in that weaker SWEs tend to get blocked by terrain and flow around from the northeast, while stronger events can overcome the barriers and result in a southerly SWE (Chenoli et al., 2012). The latter of these two SWE types is consistently accompanied by deep Ross Ice Shelf depressions (Chenoli et al., 2012).

This study aims to expand upon prior research by examining both the climatology and dynamical environments of the highest-intensity extreme wind events (EWEs). Understanding EWEs is of great importance to Antarctic forecasters, as these high-profile wind events are most responsible for both structural damage at stations and perilous travel conditions for ground and aviation operations. The purpose of this study is to discover if there are any significant dynamical or climatological differences between EWEs and SWEs, and which components of the dynamical environment are most prominent in these extreme cases. Furthermore, the characteristics of top-tier wind events are of great value to the engineering community, as this knowledge can be implemented in future construction projects in the Ross Island vicinity. The above insights will be gained using in situ observations from McMurdo Station, University of Wisconsin Automatic Weather Station (AWS) data and other observational data from nearby stations, and Antarctic Mesoscale Prediction System (AMPS) forecast data. Details regarding the data and analysis methods will be discussed in Section 2. The results of the statistical analysis will be discussed in Section 3, and the dynamical study is in Section 4. Closing remarks will then be given in Section 5.

**2. Data and Methods**

For the statistical EWE analysis, quality controlled University of Wisconsin AWS data from Pegasus North, Pegasus South, and Williams (Willie) Field sites are used (Lazzara et al., 2012) (Figure 1). These stations are used because of their proximity to the staffed McMurdo Station and their long, quality-controlled records. The AWS observations are recorded every 10 minutes with the wind sensors outlined in Table 1. The threshold for EWE calculations is 24.7m/s, which is well above the 95th percentile wind speed for each station and represents the threshold for a Beaufort storm scale 10 or what is known as Category 2 (Table 2) weather event at McMurdo Station. For the AWS data, an EWE exists when over half of the 10-minute observations in a three-hour interval are over the threshold; when adjacent three-hour intervals meet this criterion, they are combined into a single event. Values recorded for these events include maximum wind speed, average resultant wind speed, resultant wind direction, starting date, ending date, and duration. EWEs are computed from 1992 to 2013, but all three stations consistently recorded data only through 2009. Pegasus North was the only operational station of the three from 2011-2013, and 2014 has been eliminated due to several months of missing data in the austral winter. McMurdo Station data is omitted from this portion of the study due to the inconsistent reporting in winter months and its lack of quality control in the earlier years.

In order to examine the synoptic conditions accompanying the occurrence of EWEs, the top twelve events between 2001 and 2013 were chosen so they can be analyzed with the AMPS model (which was developed in 2000) (Powers et al., 2012). McMurdo Station data were used to determine the events to be studied with corroboration from the three AWS listed above. Data for McMurdo Station were deliberately chosen for this analysis, since that is where significant damage has occurred during these extreme wind events. More recent McMurdo Station data does not have as many of the problems reported above and was judged acceptable for this particular analysis.

In-situ wind observations from McMurdo Station are recorded every 3 hours (with the instrumentation in Table 1) as opposed to 10 minutes at the AWS sites, necessitating a different EWE detection scheme than that used for the statistical analysis of the AWS data. An EWE is identified in the McMurdo Station data if three or more consecutive 3-hourly wind speed observations exceed the EWE threshold. If three consecutive observations exceed the threshold this results in a 6 hour long EWE, four consecutive observations result in a 9 hour EWE, etc. However, instead of the Category 2 (24.7 m/s) threshold, 15 m/s is used in order to get a larger sample size. The top wind events in McMurdo exhibit considerably weaker wind speeds than those of the EWEs from nearby AWS; this is likely due to the frictional interference of the town structures with the strong winds (Cayette, pers. comm.). From the events that meet these criteria, the top eleven events are chosen based on their maximum wind speed values. In addition to these top eleven events, the historic EWE from May 15-16, 2004 (Powers, 2007; Steinhoff et al., 2008) is also included; this event is not reported in the McMurdo data (or in the data of many of the surrounding AWS) because the winds were so strong during this event that the stations’ anemometers were destroyed or damaged. The data used to represent this event are from the Space and Naval Warfare Systems Command (SPAWAR) Arrival Heights McMurdo Area Wind Sensor network station (15-minute data), and the EWE is quantified using the same methods as used with the 10-minute AWS data in the statistical analysis. As an example of how the Arrival Heights wind data compares to the McMurdo wind data, for the event on 29 June 2005, the maximum wind speed for McMurdo was 25.2 m s-1 and at Arrival Heights the maximum was 35.4 m s-1. The resultant wind speed and direction at McMurdo was 21.6 m s-1 from 184 degrees while Arrival Heights was 21.9 m s-1 from 152 degrees. The top 12 EWE events chosen for the additional dynamical analysis are outlined in Table 3.

Forecast back-trajectories are computed for these 12 McMurdo EWE cases using the Hybrid Single Particle Lagrangian Integrated Trajectory (HySPLIT) model from the National Oceanic and Atmospheric Administration (NOAA) Air Research Laboratory forced with AMPS model data. While this is not the first time HySPLIT back-trajectories have been used in an Antarctic setting (Markle et al., 2012), most other studies have employed the NCEP-NCAR reanalysis dataset. Here, AMPS forecasts are used from 2001 to 2013 during which time the model evolved from the Fifth-Generation Penn State/NCAR Mesoscale Model(MM5) to the Weather Research and Forecasting (WRF) Model in 2006; the D2 Antarctic window used in this study started as a 30-km grid in 2000, became a 20-km grid in 2005, and finally a 15-km grid from 2008 onward (Powers et al., 2012). A forecast back trajectory for an EWE is initialized 3 days into the AMPS forecast at McMurdo Station at the time of the EWE onset and computed backwards through the zero forecast hour (some AMPS forecasts were shorter than 3 days in 2001 and 2002). These forecast back-trajectories, in conjunction with other AMPS fields, are analyzed to determine where EWE parcels come from at different levels and what kinds of synoptic scenarios are favorable for the development of extreme winds.

**3. Statistical Analysis**

Wind data from Pegasus North AWS, Pegasus South AWS, and Willie Field AWS are analyzed from 1992 to 2009 and for Pegasus North for 2010-2013 in order to determine if there is a significant trend in EWEs in the Ross Island vicinity. Throughout this time period (1992-2009), 46 EWEs were identified for Pegasus North, 26 for Pegasus South, and only 2 for Willie Field. In addition, 16 more EWEs were identified at Pegasus North during 2010-2013. The lack of EWEs at Willie Field is not unexpected, as the average monthly maximum wind speed at the station is consistently lower (by ~6 m/s) than that at Pegasus North and South; this difference appears in the average yearly maximum as well, as Willie Field’s average is just under 8 m/s lower than that of Pegasus North/South (C. Costanza, pers. comm.). The complex interaction of the winds with the topography of Black and White Islands can create localized high wind speeds at Pegasus North/South stations (Holmes et al., 2000), at which maximum wind speeds are higher than those of nearby AWS sites (Keller et al., 1996; 1997). These observations help explain why Willie Field AWS experienced a negligible number of EWEs compared to the two Pegasus AWS sites.

The monthly distribution of the EWEs (Figure 2)reveals that the most EWEs occur during the transition seasons between the austral summer and winter as the peaks in EWE count occur in May and September, with some events during June-August and no events at the AWS stations from December to February. Coggins and McDonald (2015) show that the shift of the Amundsen Sea Low (ASL) in summer moves the cyclone activity away from the Ross Sea region which decreases the likelihood of RAS events. The austral summer minimum in EWEs is consistent with the SWE distribution created by Chenoli et al. (2012), although the split peaks between spring and fall—rather than a mid-winter peak—constitute a disparity between the current results and those of Chenoli et al. (2012). The peaks in EWE frequency during the spring and fall may be a manifestation of the semiannual oscillation (SAO), or the periodic expansion/contraction of the circumpolar trough, which creates deeper and more southerly low pressure systems during the austral spring and fall (Cohen et al., 2013). The strong connection between EWEs and low pressure systems is further detailed in Section 4.

Figure 3 shows the wind roses for the EWEs at each station, indicating predominantly southerly flow during these events. This, too, is consistent with the Chenoli et al. (2012) bimodal wind direction classification of SWEs, wherein only the strongest events (EWEs) have sufficient energy to overcome topographical barriers, resulting in southerly flow at Ross Island.

Climatologically, the trends in EWE count (Figure 4) for Pegasus North for 1992-2013 and Pegasus South over 1992-2009 are slightly positive but statistically insignificant. The EWE count at Willie Field is trendless, as there are only two events. Similarly insignificant trends were found for the EWE duration and intensity at these stations. While the AWS data used for this analysis is quality-controlled, gaps in the data due to station malfunctions and instrumentation failures do exert a bias on the results, particularly during the first half of the 1992-2013 time period. Nonetheless, this analysis offers both a spatial and temporal climatological examination of EWEs in the Ross Island vicinity, revealing peaks in EWE frequency during transition seasons and insignificant trends in extreme events from 1992 to 2013.

**4. Dynamical Analysis**

The synoptic scale conditions during McMurdo EWEs are examined using AMPS data and HySPLIT forecast back-trajectories. The top 12 events (Table 2) are used as case studies for this analysis. The prevailing wind direction during these EWEs is consistent with the findings in the previous sections (and prior studies), with all of the events exhibiting predominantly southerly flow. An example of one of these events (specifically, the one that occurred on September 3, 2003) is depicted in Figure 5. The most notable features in this case, as in most EWE events, include the deep (< 960 hPa) low pressure system impinging on the Ross Ice Shelf from the north, the strong pressure gradient over the ice shelf to the south of the storm, and the ridging of the isobars to the south and southwest of Ross Island. Figure 6 shows the effect of these features at Pegasus North. The pressure, temperature, wind speed and wind direction are plotted at 10 minute intervals from 3 September 0000 UTC to 5 September 330 UTC. The pressure drops around 25 hPa (Figure 6a) while the wind speed increases to over 37 ms-1 (Figure 6b), and the wind direction is nearly constant from the south.

These synoptic scale features depicted in Figure 5 together contribute to the development of strong winds flowing parallel to the Transantarctic Mountains (the RAS). There is no apparent katabatic signal in the infrared imagery (as discussed in Bromwich, 1989), but there may still be a momentum contribution from downslope winds in the vicinity of Byrd, Mulock, and Skelton glaciers. While Figure 5only depicts this single case, this synoptic structure is fairly representative of most EWEs. Before examining the EWE cases in further detail, a composite analysis is performed in order to assess the prevailing synoptic setup for these events.

The AMPS forecasts for each EWE (around the time of onset) are averaged together to provide a visualization of the synoptic conditions that are most prominent across all events (Figure 7). The 500 hPa map (Figure 7a)reveals that a deep upper-level trough north-northwest of the Ross Ice Shelf is a defining feature of these wind events. This trough is accompanied by a ridge on either side, with the eastern ridge over West Antarctica. At the surface, the ASL has migrated to a position much further west than the mean climatological position (Fogt et al., 2012; Coggins and McDonald, 2015) and been replaced by a high pressure ridge (Figure 7b). The low pressure system is positioned so that the geostrophic winds intersect the Transantarctic Mountains orthogonally; this is a strong indicator of a barrier wind regime. The averaged surface fields for the area around McMurdo Station and the Ross Ice Shelf (Figures 7b-d) show the surface low in more detail. The barrier effect of the mountains builds high pressure along the range, as is evident in the ridging of the isohypses (O’Connor et al., 1994), which geostrophically forces a jet—or barrier wind—along the edge of the ice shelf toward Ross Island. The ground level isotachs support this idea, revealing a jet along the Transantarctic Mountains (Figure 7d) with a maximum average wind speed of roughly 20 m/s in the Ross Island vicinity. This composite analysis of the top 12 EWEs describes how the average event has a significant synoptic contribution from a Ross Sea cyclone and the barrier wind effect resulting from its orientation relative to the mountains; on average, EWEs are associated with a fairly well defined RAS event. It is, however, likely that the contribution from different forcings (i.e. katabatic flow, barrier, flow, or synoptic forcing) to the extreme winds at McMurdo varies from one case to another.

A more detailed examination of the “flavors” of EWEs represented in the top 12 McMurdo events is performed using AMPS forecast back-trajectories, which provide a Lagrangian perspective on these extreme wind regimes. The AMPS forecast back-trajectories (Figures 8a, 9a, 10a)reveal several interesting patterns in the parcel paths leading up to these top EWEs at McMurdo Station. These forecast back-trajectories have endpoints located at McMurdo Station. The endpoint heights included multiple levels at 10, 50, 100 and 500 meters above ground level. Many of the EWE trajectories exhibit a RAS-like (barrier wind) structure, with flow approaching Ross Island from the south-southeast along the Transantarctic Mountains. Figure 8a shows the trajectories for the 23 May 2003 case. Strong surface flow stretches the length of the Transantarctic Mountains due to an intense low in the Ross Sea (Figure 8 c,d,e) with a deep trough at 500 hPa (Figure 8b).

Other trajectories approach McMurdo from a more southwesterly direction at a very low elevation (Figure 9a). The 20 September 2006 case is an example of this kind of situation. The surface pressure field has more of a trough than a closed low in the western Ross Sea (Figure 9 c,d,e), while the isotachs and wind barbs point to some contribution to the flow in the vicinity of the Byrd, Mulock, and Skelton glaciers, perhaps indicating a katabatic flow. The 500 hPa height field (Figure 9b) positions the upper level trough farther away from the coast and not as intense as in Figure 8b.

A third pattern of back-trajectories reveals a cyclonic spiraling pattern in the EWE parcel paths over the Ross Ice Shelf (Figure 10a), as depicted by the 29 June 2005 case. The surface low is closer to Cape Adare and a wide band of strong winds flows the length of the Ross Ice Shelf and out into the Ross Sea (Figure 10 c,d,e). The 500 hPa heights have two large troughs on either side of the continent with the ridge over the Amundsen-Bellingshausen areas positioned farther off the coast (Figure 10b).

Every trajectory indicates southerly or near-southerly flow at the onset of the EWE at Ross Island. Thus, it is clear that the aforementioned low pressure over the Ross Ice Shelf, which generates this southerly flow, is a crucial ingredient for extreme winds at McMurdo. It is less clear how much of a contribution other forcings, such as katabatic or downslope winds, may have.

The back-trajectories reveal that, despite the near-ubiquity of the Ross Ice Shelf low investigated earlier, the EWE parcels exhibit a variety of behaviors from case to case. Looking back at the AMPS surface composite map (Figure 7b and c), it can be seen that, in addition to the barrier-like jet along the mountains, there is a split in the local wind speed maximum with one branch over the McMurdo Station/McMurdo Sound and the other over the eastern tip of Ross Island which is the outflow region for the RAS. The topography of Ross Island causes this split in the wind direction as the flow moves around both sides of the high terrain. The flow around the eastern side of Ross Island is similar to the tip jet effect described in Nigro et al., 2012 which increases the wind speed of the RAS. The flow over Hut Point Peninsula and McMurdo station is a reflection of the localized high pressure area that forms on the windward side of Ross Island (near Windless Bight) when high wind speeds impinge on the higher topography in this area (Seefeldt et al., 2003). The flow is directed around and over Hut Point with an increase in speed due to the local pressure gradient created by mass accumulation along the Transantarctic range. Looking closely at Figure 7b and c, there are also local wind speed maxima bothat the outlet of the glaciers *and* in the lee of the topography upstream of Ross Island (Steinhoff et al. (2008). indicating some contribution from katabatic flow in Byrd, Skelton, and Mulock glaciers, just upstream of McMurdo Station (relative to the RAS). This idea is supported by several of the back-trajectories discussed previously which show the air streams from the glaciers converging into a northward flow. While the synoptically-forced RAS is crucial to McMurdo Station EWEs, there may also be a contribution from the katabatic flow from nearby glaciers and/or interactions with local topography that can amplify the severity of these winds (Parish and Bromwich, 2007).

**5. Discussion**

The position of the ASL and the associated trough at 500 hPa are crucial to the setup of conditions that bring extremely high wind events into the McMurdo area. The upper level trough must be positioned farther to the west than normal so that surface cyclones are steered into the Ross Sea/Ross Ice Shelf area. Several large scale features have a strong influence on the movement of the ASL and its associated trough at 500 hPa. The work of Fogt et al. (2012) describes the position of the ASL as determined mainly by topography. The center migrates to the west and south in fall and winter and to the east in summer. In addition to the topography, the position of the ASL is also influenced by the phase of the Southern Annular Mode. A positive phase of SAM is correlated with a strong low pressure system in the ASL region. This would indicate that the possibility of a strong low pressure anomaly outside of the ASL area would be associated with a negative phase of SAM. Looking at the top 12 events discussed for the McMurdo area, 7 of the events occur with a slightly negative phase of SAM (events from 2003-2009). The first 3 events and last 2 events occur with a positive phase of SAM. The phase of SAM does not appear to have a decisive influence on the possibility of EWEs at McMurdo.

Another large scale feature which could influence the position of the cyclones is the Semiannual Oscillation (SAO) where the Antarctic circumpolar trough moves closest to the continent in March and September (van Loon, 1967; Simmonds and Jones, 1998). While this oscillation has its roots in the changing heating and cooling rates of the temperatures of the transition seasons, it may contribute to the bimodal distribution of the strong wind events studied by Chenoli et al., 2012. Since this study is looking at extreme events, there does not appear to be as great a connection, except for perhaps September.

Neither of the above possibilities seems to explain the far western position of the ASL and associated upper level trough which is necessary for the extreme wind events to occur. The ENSO Central Pacific (CP) events (Ashok et al., 2007, 2009; Kao and Yu, 2009; Capotondi et al., 2015) are another possible explanation. With a CP El Niño, the Pacific-South American stationary wave pattern is shifted to the west with a high appearing in the Amundsen Sea area. The South Pacific Convergence Zone (SPCZ) is stronger in austral winter and also shifted southwest (Wilson et al., 2014). Using the years defined by Wilson et al. (2014) as having CP events, 8 of the EWEs described here occurred during CP El Niño events and 4 occurred during CP La Niña events. As this manuscript was being prepared, another EWE occurred at McMurdo in February, 2015 during a CP El Niño event. While the CP ENSO events do not cause the EWEs to occur at McMurdo, they do appear to influence the position of the large scale circulation in such a way that favors the occurrence of such events.

**5. Conclusions**

This study provides a statistical and dynamical examination of the top-tier wind events, or EWEs, at McMurdo Station in order to assess the behavior of these storms and how they might differ from typical strong wind events (SWEs). The statistical analysis shows that EWEs tend to occur during the transitional seasons, perhaps due to the expansion and contraction of the circumpolar trough. Furthermore, there has been no statistically significant trend in the frequency, duration, or intensity of EWEs near McMurdo Station (consistent with the Chenoli et al., 2012 analysis of SWEs).

The dynamical investigation reveals a great deal about the structure and behavior of these EWEs. First, these extreme events consistently produce southerly flow at McMurdo Station due to the largeFroude number (Chenoli et al., 2012; Chenoli et al., 2015) associated with the high wind velocities that allow the air to pass over the topographical barriers. This distinguishes EWEs from SWEs, which have a bimodal wind direction distribution due to their variable interaction with the topography. Secondly, EWEs are almost always associated with a low pressure system encroaching upon the Ross Ice Shelf from the north, northeast, or even northwest. The presence of a deep trough of low pressure at 500 hPa in the vicinity or to the west of Cape Adare seems to be the key ingredient for this scenario (Coggins and McDonald, 2015). Lastly, the RAS regime created by this synoptic environment seems to be a necessary, but insufficient ingredient for producing extreme winds at McMurdo. The southerly barrier flow in the Ross Island vicinity during these EWEs is likely enhanced by the tip jet effect, local pressure gradient forces due to topography, katabatic winds from upstream glaciers, and/or downslope winds in the lee of Minna Bluff and Black and White Islands to produce a local wind speed maximum in the McMurdo region. This further differentiates EWEs from SWEs, which can be produced by any of these forcings separately.

Forecasting these events does remain a challenge. The position of the 500 hPa trough and the encroachment of a surface cyclone are determining factors for the possibility of an EWE. The incidence of a CP ENSO event appears to be a favorable influence on the upper level trough position so that an approaching surface cyclone would be more likely to trigger an event, depending on the angle of approach and interaction with the topography in the McMurdo station area. Climate studies have shown that CP El Niño events are increasing in frequency (Ashok et al. 2007) and intensity (Lee and McPhaden, 2010) which may increase the possibility of EWE events.

The insight gained about EWEs in this study has several implications for the engineering community at McMurdo Station and Scott Base. Knowing that the strongest events tend to occur in the transitional seasons can impact construction and transportation. Additionally, the knowledge that these events have southerly wind directions can aid in the design of McMurdo area structures.

**Acknowledgements**

Thanks are extended to D.J. Rasmussen for the data retrieval and analysis that formed the foundation of this study. The authors appreciate the support of the Division of Polar Programs at the National Science Foundation, NSF grant numbers ANT-0944018, ANT-1043478, ANT-1141908, ANT-1245663, and ANT-1245737 in support of the US Antarctic AWS Program and Antarctic Meteorological Research Center.

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**Figures Captions**

Figure 1. Map inset of the Ross Island region indicating staffed stations, AWSs, and important topographical features.

Figure 2. The number of EWEs at Pegasus North, Pegasus South, and Willie Field AWS (duplicates combined) during each month, summed from 1992 to 2013.

Figure 3. Normalized direction wind roses for the EWE winds at Pegasus North, Pegasus South, and Willie Field.

Figure 4. Time series of the number of extreme wind events for a) Pegasus North (1992-2013) and b) Pegasus South (1992-2009). Dotted lines indicate the least squares linear trend.

Figure 5. Infrared satellite composite over the Antarctic on 3 Sep, 2003 at 09 UTC overlaid with AMPS mean sea level pressure (yellow).

Figure 6. Times series of a) pressure and temperature and b) wind speed and wind direction for Pegasus North for 3 September 0000 UTC to 5 September 330 UTC showing the effect of the extreme wind speed event that occurred on 3 September 2003.

Figure 7. Composite fields of the twelve highest wind speed events listed in Table 3: a) 500hPa heights, b) surface wind speed (shading) and mean sea level pressure (white contours), c) surface wind speed (shading), mean sea level pressure (white contours), and vector wind barbs around McMurdo Station, and d) surface wind speed (red contours), mean sea level pressure (white contours), and terrain height (shading) around McMurdo Station.

Figure 8. a) AMPS-fed HySPLIT 3-day forecast back trajectories ending at McMurdo Station for the EWE starting at 05/23/2003. The four trajectory lines end at 10m (red), 50m (blue), 100m (green), and 500m (cyan) above ground level. b) 500hPa heights; c) surface wind speed (shading) and mean sea level pressure (white contours); d) surface wind speed (shading), mean sea level pressure (white contours) and surface wind barbs; e) surface wind speed (red contours), mean sea level pressure (white contours), and terrain height (shading) around McMurdo Station.

Figure 9. a) AMPS-fed HySPLIT 3-day forecast back trajectories ending at McMurdo Station for the EWE starting at 09/20/2006. The four trajectory lines end at 10m (red), 50m (blue), 100m (green), and 500m (cyan) above ground level. b) 500hPa heights; c) surface wind speed (shading) and mean sea level pressure (white contours); d) surface wind speed (shading), mean sea level pressure (white contours) and surface wind barbs; e) surface wind speed (red contours), mean sea level pressure (white contours), and terrain height (shading) around McMurdo Station.

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**Table Captions**

Table 1. Wind speed and direction instrumentation for McMurdo Base and Pegasus North, Pegasus South, and Willie Field AWS.

Table 2. The three weather condition levels for McMurdo Station, categorized by their wind speed, temperature, and visibility thresholds. For each condition, the station has different policies regarding travel and outdoor activity.

Table 3. The starting date, maximum speed, average speed, resultant direction (vector average), and duration of the top 12 McMurdo EWEs. \*The May 2004 EWE data was obtained from the SPAWAR Arrival Heights AWS data. The winds are considerably stronger because Arrival Heights is at a higher, more exposed location inland above McMurdo Base.

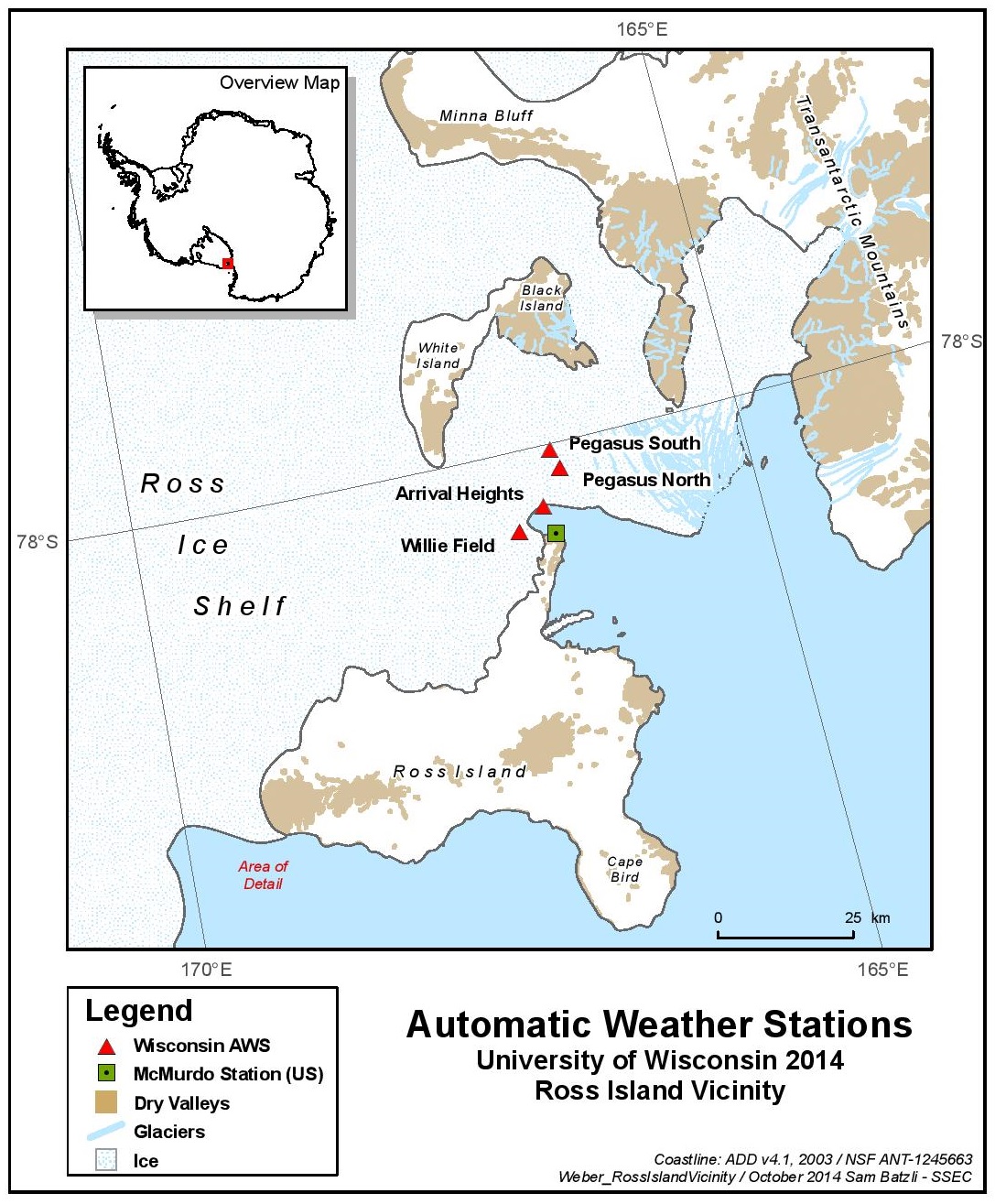


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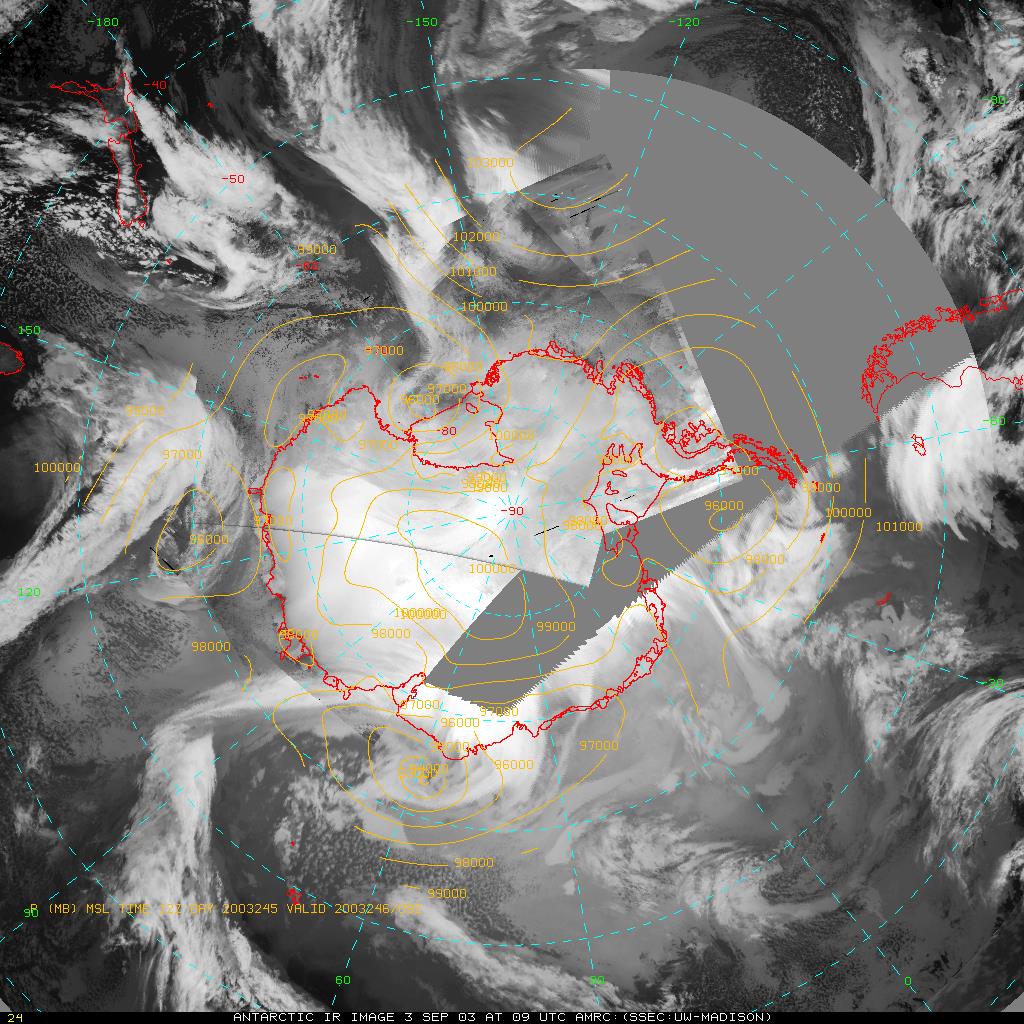


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Table 1. Wind speed and direction instrumentation for McMurdo Base and Pegasus North, Pegasus South, and Willie Field AWS.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Instrument | Sensor | Location | Resolution  (m s-1) / o | Range (m s-1) / o |
| Wind Speed | R.M. Young 01503 | Pegasus North | 0.195 | 1 to 100 |
| Pegasus South |
| Willie Field |
| Bendix/Belfort | McMurdo | 0.250 | 2 to 63 |
| Wind Direction | 10K ohm potentiometer | All | 1.5o | 0o to 355o |

Table 2. The three weather condition levels for McMurdo Station, categorized by their wind speed, temperature, and visibility thresholds. For each condition, the station has different policies regarding travel and outdoor activity.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Condition | Wind Speed | Temperature | Visibility | Travel Restrictions |
| 1 | < 48 kts | > -75 oF | > ¼ mi | None |
| 2 | 48-55 kts | -75 to -100 oF | ¼ mi to 100 ft | Only enclosed vehicles with radios can leave |
| 3 | > 55 kts | < -100 oF | < 100 ft | All personnel must stay indoors |

Table 3. The starting date, maximum speed, average speed, resultant direction (vector average), and duration of the top 12 McMurdo EWEs. \*The May 2004 EWE data was obtained from the SPAWAR Arrival Heights AWS data. The winds are considerably stronger because Arrival Heights is at a higher, more exposed location inland above McMurdo Base.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Start Date | Max Speed  (m s-1) | Ave. Speed  (ms-1) | Direction  (deg) | Duration  (h) |
| 12/12/2001 | 21.10 | 18.06 | 167.02 | 18 |
| 08/21/2002 | 21.60 | 16.68 | 183.38 | 9 |
| 05/23/2003 | 20.60 | 18.87 | 174.03 | 6 |
| 09/03/2003 | 27.20 | 19.35 | 154.79 | 15 |
| 12/01/2003 | 22.10 | 18.50 | 173.29 | 9 |
| 05/15/2004\* | 48.30 | 29.10 | 160.60 | 9 |
| 06/29/2005 | 25.20 | 21.58 | 183.77 | 9 |
| 09/20/2006 | 20.60 | 18.87 | 170.00 | 6 |
| 04/12/2009 | 26.20 | 21.38 | 196.59 | 12 |
| 04/19/2009 | 25.20 | 20.80 | 183.89 | 9 |
| 05/08/2012 | 26.60 | 22.90 | 188.40 | 6 |
| 05/21/2012 | 22.60 | 18.88 | 181.00 | 12 |