8.3 FOEHN WINDS IN THE MCMURDO DRY VALLEYS OF ANTARCTICA

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1. INTRODUCTION

A foehn wind is a warm, dry, downslope wind resulting from synoptic-scale, cross-barrier flow over a mountain range. Foehn winds are a climatological feature common to many of the world's mid-latitude mountainous regions, where they can be responsible for wind gusts exceeding 50 m s^{-1} and adiabatic warming at foehn onset of +28°C. Intensive monitoring experiments in mid-latitude regions such as the Alpine Experiment (ALPEX) in the eastern Alps (Seibert 1990) and the Mesoscale Alpine Programme (MAP) in the Rhine Valley (Bougeault et al. 2001) have detailed the complex atmospheric processes that occur during foehn by use of high density observational networks, aircraft, satellite imagery and mesoscale numerical modelling. However, foehn winds in high latitudes and polar regions have not been studied extensively. Analysis of meteorological records from the McMurdo Dry Valleys (MDVs), a unique ice-free area of the Antarctic, has identified that foehn winds (termed *polar foehn*) are responsible for unprecedented temperature changes of >40°C. The resulting warm, dry and gusty winds are suspected to have significant effects on landscape forming processes in the MDVs including glacial melt (Doran et al. 2008), rock weathering (Selby et al. 1973), niveo-aeolian processes (Ayling and McGowan 2006; Speirs et al. 2008) and biological productivity (Fountain et al. 1999; Foreman et al. 2004). It is also interesting to speculate the role that warm foehn winds in the MDVs have regarding the lack of extensive ice-cover in this region.

Despite the significance of the polar foehn, no detailed scientific investigation of foehn has been conducted in the MDVs. Periods of strong dry westerly winds that cause large increases in air temperature in the MDVs have generally been attributed to adiabatic compression causing warming of the air mass, but there is disagreement regarding the exact mechanism for their origin with some studies referring to them as katabatic while others have invoked a foehn mechanism (Thompson et al. 1971; Thompson 1972; Keys 1980; Clow et al. 1988; McKendry and Lewthwaite 1990; 1992; Doran et al. 2002; Nylen et al. 2004). Katabatic winds are believed responsible for the strong winds at confluence zones in the large glacier valleys south and north of the MDVs, but the valleys themselves do not lie in a confluence zone of katabatic winds (Parish and Bromwich 1987; Clow et al. 1988; Parish and Bromwich 2007). Various studies including that by McKendry and Lewthwaite (1990; 1992), Doran et al. (2002) and Nylen et al. (2004) have identified a poor understanding, need for detailed measurement, and the considerable scope for research on the local wind regime in the MDVs. McKendry and Lewthwaite (1992, p596) concluded that "further work is required to clarify the interactions between synoptic-scale flow and the rather unusual topographic setting, and to explain the exact mechanism by which upper level flow is deflected into the [Wright] valley". Since this statement 15 years ago, these knowledge gaps and research requirements remain. A more complete understanding of synoptic scale circulation, local meteorological conditions and environmental interactions in the MDVs could potentially benefit the independent and cooperative research projects undertaken in the region which, since discovery by Robert Falcon Scott's expedition in 1903, has become the most intensely studied region in the Antarctic. Understanding of turbulent lower and upper atmospheric airflow is also crucial for the safe operation of helicopter and light aircraft regularly traversing this region. Furthermore, investigation into synoptic scale processes and resulting meteorological influences has significance in terms of understanding regional and local effects of global climate variability and change.

This paper presents initial findings resulting from the ongoing collaborative research between The University of Queensland and The Ohio State University combining observational and model data to broaden the

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understanding of the complex meteorology in the MDVs. This paper presents output from the Antarctic Mesoscale Prediction System (AMPS) applied to a strong winter foehn wind event in 2007. Onset of foehn winds occurred on 21 May 2007 and lasted 5 days with wind gusts to 38.9 m s^{-1} and induced warming at the valley floor by +48.5°C. This paper presents the meteorological conditions and synoptic forcing mechanisms associated with this event followed by a synoptic climatology of the polar foehn through 2006 and 2007.

2. PHYSICAL SETTING

The MDVs are situated in the Transantarctic Mountains, bounded by the McMurdo Sound/Ross Sea to the east and the East Antarctic Ice Sheet to the west (Figure 1). The MDVs consist of three large northeast-southwest trending ice-free valleys (the Victoria, Wright and Taylor Valleys), which collectively cover an area of approximately 4800 km^2, the largest ice-free area in Antarctica. Large mountain ranges rising over 2000 m ASL separate the valleys, which have a polar desert climate due to their location in a precipitation shadow of the Transantarctic Mountains (Monaghan et al. 2005). Annual precipitation is < 50 mm water equivalent with precipitation decreasing away from the coast (Fountain et al. *in press*). Mean annual air temperature from seven valley floor automatic weather stations (AWS) range between -14.8°C to -30°C depending on site location and period of measurement (Doran et al. 2002). The wind regime of the MDVs is strongly dominated by either up- or down-valley topographically channelled airflow. During summer, thermally generated easterly valley winds dominate. This circulation develops due to differential surface heating between the low-albedo, valley floors and the high-albedo glacier surfaces to the east, analogous to sea/lake breeze circulations elsewhere (McKendry and Lewthwaite 1990). In winter, wind direction is typically more variable. Topographically modified southwesterly wind events, believed to be foehn are frequently experienced throughout the year in the MDVs (Thompson 1972; Keys 1980; Clow et al. 1988; McKendry and Lewthwaite 1990; 1992; Ayling and McGowan 2006). Doran et al. (2002) notes the highest frequency of these strong westerly winds in the MDVs occur in the winter months.

3. METHODS

Meteorological data presented in this paper were obtained from automatic weather stations (AWS) operated by the McMurdo Dry Valleys Long Term Ecological Research (LTER) program (Doran et al. 1995). Table 1 outlines the location and station ID for the AWS used here. The configuration of these stations is detailed at http://www.mcmlter.org/queries/met/met_home.jsp and in Doran et al. (2002). Measurements were collected at 3 m above the surface except for Canada Glacier (TCa), where air temperature and relative humidity measurements are from 2 m above the surface. No data was available from Lake Brownworth during the foehn event presented here. A selection criterion was developed to identify foehn wind events in the MDVs AWS records. Foehn onset was detected by an increase of wind speed above 5 m s^{-1} from a southwesterly direction, a warming of at least +1°C per hour and a decrease of relative humidity by at least 5 % per hour. Due to the transient nature of some foehn events, an additional criterion of a 'foehn day' was developed to identify strong events. A foehn day at an AWS station is defined as a day that has detected foehn onset and experiences 6 or more continuous hours of foehn conditions with wind speed >5 m s^{-1} from a consistent southwesterly direction. Preliminary validation suggests that the criterion is able to successfully identify foehn events with at least 95 % accuracy.

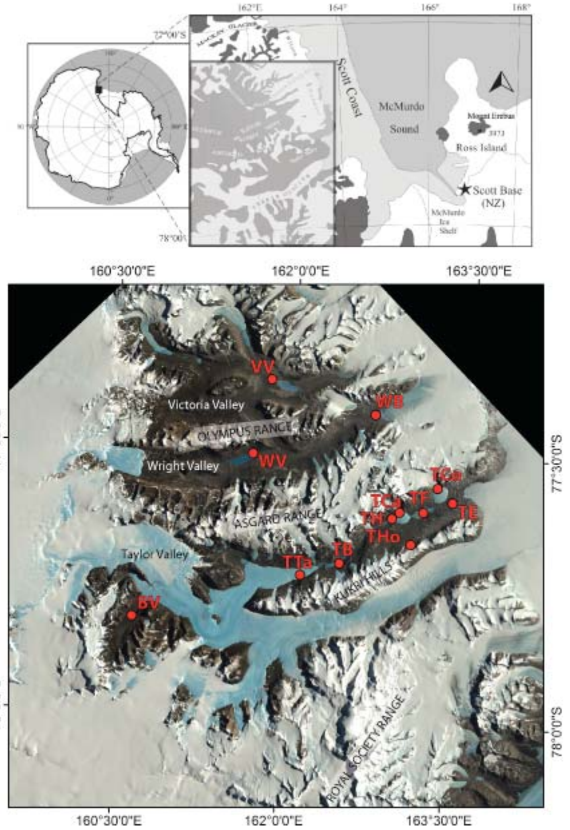

Figure 1. McMurdo Dry Valleys AWS network. Landsat ETM+ image captured 21 Nov 2001.

Numerical model products presented here are obtained from the Antarctic Mesoscale Prediction System (AMPS), a high-resolution numerical forecasting model operated by the Polar Meteorology Group, Byrd Polar Research Center and the National Center for Atmospheric Research (NCAR). AMPS employs a polar modified version of the fifth generation Pennsylvania

Table 1: MDV AWS information

ID	Location	Station	Latitude, longitude	Elevation (m asl)
VV	Victoria Valley	Lake Vida	-77.3778, 161.8006	351
WV	Wright Valley	Lake Vanda	-77.5168, 161.6678	296
WB		Lake Brownworth	-77.4335, 162.7036	279
TE	Taylor Valley	Explorers Cove	-77.5887, 163.4175	26
TF		Lake Fryxell	-77.6109, 163.1696	19
TH		Lake Hoare	-77.6254, 162.9004	78
TB		Lake Bonney	-77.7144, 162.4641	64
TTa		Taylor Glacier	-77.7402, 162.1284	334
THo		Howard Glacier	-77.6715, 163.0791	472
TCa		Canada Glacier	-77.6127, 162.9634	264
TCo		Commonwealth Glacier	-77.5637, 163.2801	290
BV	Beacon Valley	Beacon Valley	-77.8280, 160.6568	1176

State University/NCAR Mesoscale Model (Polar MM5; Bromwich et al. 2001; Cassano et al. 2001). A review of AMPS model components is provided by Powers et al. (2003) and evaluations of the model system are given by Guo et al. (2003) and Bromwich et al. (2005). Monaghan et al. (2005) reviewed the climate of the McMurdo region (including the MDVs) in the 3.3 km grid domain and shows AMPS successfully captured important temporal and spatial aspects of the region's climate. Additionally, Steinhoff et al. (2008) demonstrated that the 3.3 km domain is valuable on an event basis in the analysis of a downslope windstorm near McMurdo.

Comparisons of AMPS time series and AWS data in this project shows that the newly implemented 2.2 km domain performs reasonably well in the MDVs, effectively able to identify the onset and cessation of strong foehn wind events. At present, the model is unable to capture dynamic temperature and humidity changes on the valley floors, however, on the valley side walls away from cold air pooling on the valley floor, model performance is markedly improved. This issue is believed to be related to the smoothed model topography and the planetary boundary layer scheme used by the model. In this paper, AMPS products for the 2.2 km domain are used to determine the regional flow characteristics in which the influence of these effects is markedly reduced. Subsets of the 20 km domain are also utilized to examine synoptic circulation characteristics during foehn events.

4. RESULTS AND DISCUSSION

4.1 Foehn characteristics

Using the foehn identification criteria we identified a strong foehn event in the MDVs AWS records with onset on 21 May 2007, lasting 5 days. Prior to foehn onset, weak pressure gradients were evident over the western Ross Sea region (Figure 2) associated with a large anticyclone centred over Victoria Land. Surface air flow over the study region at this time was dominated by katabatic winds draining from the Antarctic interior. These diverge behind the MDVs with winds draining out of the large glacial valleys south (Byrd, Mulock and Skelton Glaciers) and north (David and Reeves Glaciers) of the MDVs. Meteorological conditions on the floors of the MDVs were cold and calm while at the higher elevation glacier stations, cold and moist downslope flow approached 8 m s^{-1}. These winds are localized cold air drainage winds from the surrounding mountain ranges and glaciers with flow at TTa, TCa, TCo and Tho directed towards the valley center. Cold air draining to the valley floor accumulates at the topographic low points (lakes) resulting in stable cold air pools with near-surface (3 m) air temperatures below -40 °C and relatively humidity > 80 %. Coldest air temperatures were recorded at VV (-53.5 °C), which reflects the relative strength of cold pool formation in the Victoria Valley compared to the Wright and Taylor Valleys. Doran et al. (2002) suggested that the greater cold pool strength near Lake Vida is related to the valley's bowl-shaped topography. The exposed yet closed topography would result in more intense radiative cooling and formation of a stronger temperature inversion (e.g. Clements et al. 2003).The stably stratified inversion in the valley floors may decouple from winds above and explain why drainage winds recorded at the glacial stations are not observed at the valley floor stations in the days leading to foehn onset. AMPS cross-sections during this time (not shown) suggest stable stratification of the atmosphere above the MDVs to at least 8 km ASL.

Between 19 May 2007 and 22 May 2007, a cyclonic depression off the coast of Adelie Land (Fig. 2) tracked eastward and strengthened with a minimum central pressure of 950 hPa. The cyclonic system slowed and remained relatively stationary off the coast of Marie Byrd Land between the Ross and Amundsen Seas (Fig. 3). This synoptic setting produced a strong zonally-oriented pressure gradient across the western Ross Sea and Transantarctic Mountains region. Between 09:30 and 10:00 UTC on 20 May 2007, a gradual warming commenced at all MDV AWSs. This warming characterizes the 'pre-foehn conditions' of foehn events in the MDVs as noted in other case studies by McGowan and Speirs (2008) and is believed to be associated with the gradual erosion of the stably stratified cold air pool in the valley floors from above by the foehn. Warming of approximately 10°C was observed over the 24 hours prior to onset of strong foehn winds (Fig. 4).

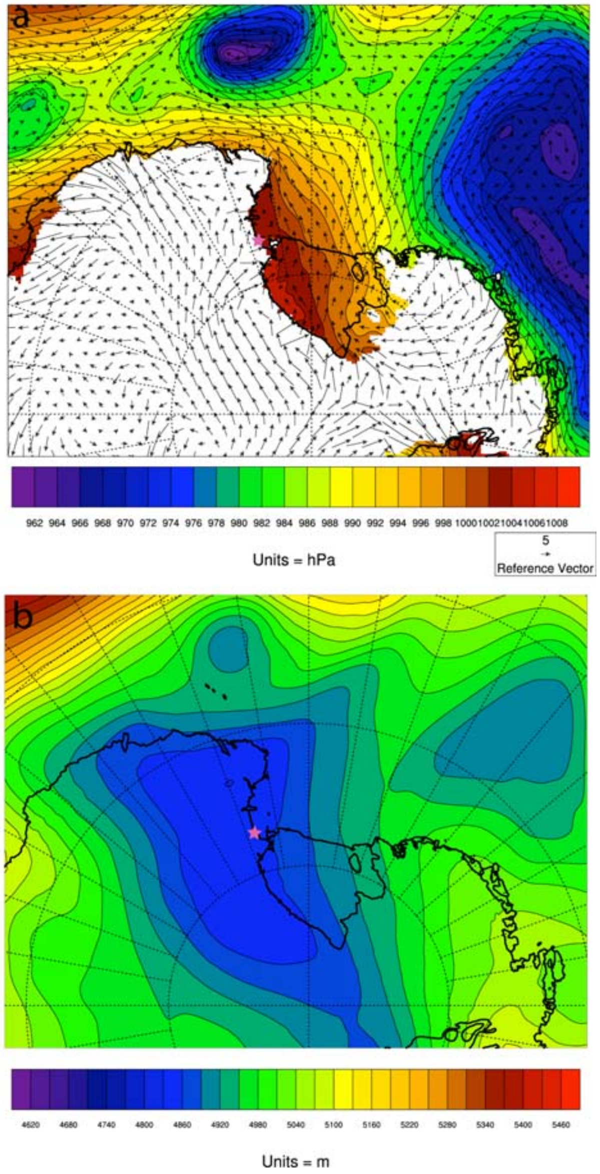

Figure 2. AMPS a) MSLP and wind vectors from σ=0.9983 and b) 500 hPa geopotential height analyses prior to foehn event (19 May 2007 00:00 UTC). Note MSLP data above 500 m is masked due to inaccuracies in calculating MSLP over the cold and high elevation Antarctic continent. Magenta star represents MDV location.

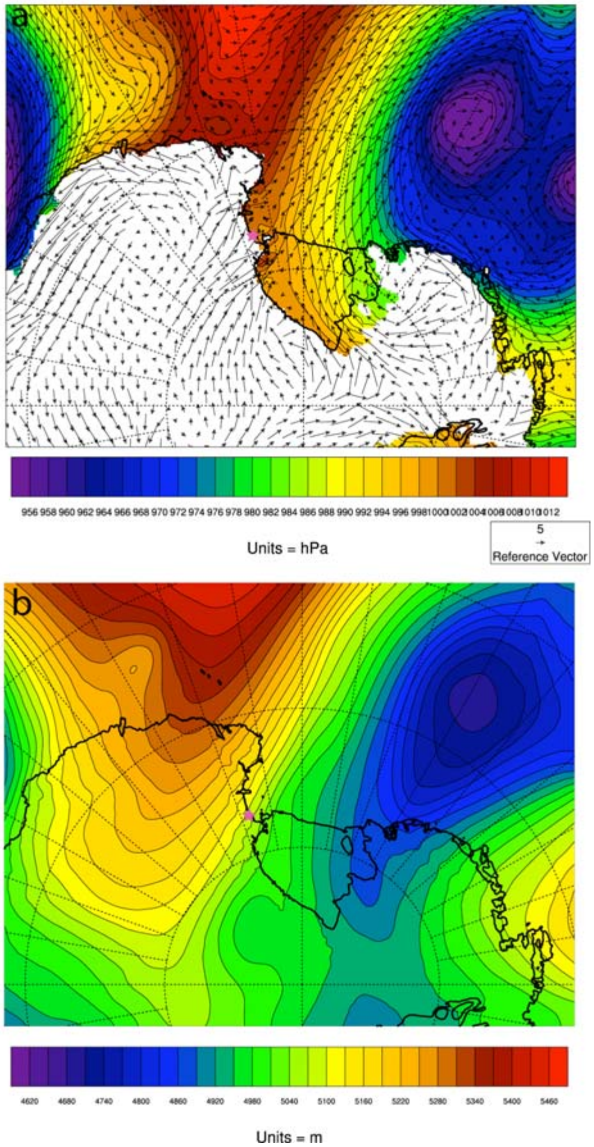

Figure 3. Same as Fig. 2 except for at (23 May 2007 12:00 UTC).

Grounding of the foehn winds shows significant spatial complexity through the Victoria, Wright and Taylor Valleys (Table 2). Foehn conditions were initially observed in the western Taylor Valley, a characteristic also noted by Nylen et al. (2004). Onset of strong foehn winds first occurred at TTa (21 May 2007 03:15 UTC) and TB (09:45 UTC) followed by WV in the adjacent Wright Valley. It was characterized by an immediate increase in wind speed >10 m s^{-1} from a consistent southwest direction, increase in temperature and decrease in relative humidity. It was almost 24 hours after initial foehn onset in the western Taylor Valley when strong winds were recorded at the eastern stations (TH, TF, TE, TCa, TCo, THo). Lake Vida was the last station to identify foehn onset later on 22 May 2007 at 17:00 UTC (Table 2). During this event strong southerly foehn winds are observed in the Beacon Valley in the southwest MDV region (see Fig. 1). The Beacon Valley is sheltered by mountain ranges in all directions except to the northeast where it opens to the upper Taylor Glacier. Given these topographic constraints it is unlikely katabatic drainage from the East Antarctic Ice Sheet could enter the Beacon Valley.

Cross sections and trajectory analyses from the AMPS 2.2 km grid domain (Figs. 5 and 6) confirm that

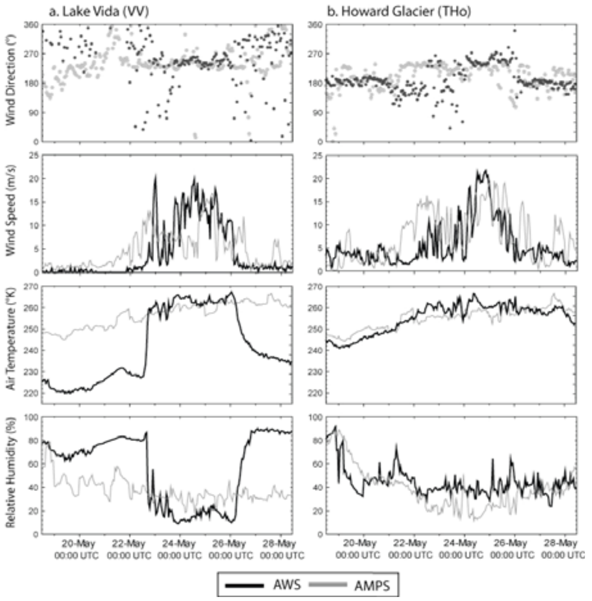

Figure 4. Foehn meteorological observations (AWS and AMPS) at Lake Vida (VV, Victoria Valley) and Howard Glacier (THo, Taylor Valley).

southerly flow is deflected from higher atmospheric levels to the surface as initially proposed by McKendry and Lewthwaite (1990). Backward trajectories presented in Fig. 5 illustrate that flow is south-westerly (parallel to the 500 hPa height contours) before arrival to the valley surface. Upstream flow over the ice sheet shows relatively stable vertical stratification (Fig. 6).

Flow appears to diverge to either side of Taylor Dome (peak elevation of 2450 m) and is forced to cross the mountain ranges separating the valleys. A prominent large-amplitude mountain wave pattern develops with vertical propagation to levels at least 8 km above sea level. Mountain wave activity is commonly associated with foehn winds in mid-latitude regions (e.g. Beer 1976; Durran 1990; Seibert 1990; Zängl 2003) but have not been linked to foehn winds in the MDVs until now. Dramatic temperature changes on the valley floor at foehn onset can be explained by the displacement of cold stable air by potentially warmer air from upper levels, in addition to adiabatic warming as air is brought to the surface from above ridge level. Regions of lower wind speeds appear above the valley centers associated with the mountain wave crests while wind speed maximums occur at the wave trough near the north-facing valley walls. Figure 5 also shows deflection of flow along the valley axis, particularly in the Wright Valley. This is a combination of forced channelling owing to the westerly component of the upstream flow but also pressure-driven channelling (see Whiteman and Doran 1993) associated with the strong horizontal pressure gradient across the MDVs. During the strongest winds later on 24 May 2007, wind direction at TTa turned almost southerly demonstrating air flow overcame topographic controls as it descended the slopes of the Kukri Hills (See Fig. 1).

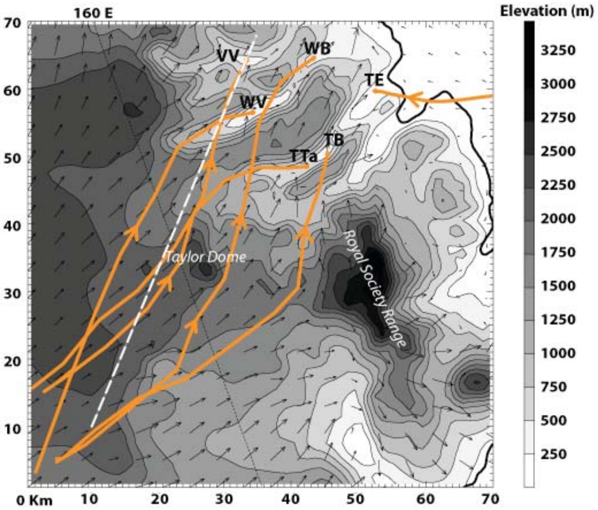

Figure 5. AMPS backward trajectories for air parcels arriving at MDV AWS station sites (~12.9 m above the modelled surface) for 24 May 2007 12:00 UTC. Dashed line shows the location of the cross-section in Figure 6. Wind vectors are for the lowest model level (~12.9 m above the surface).

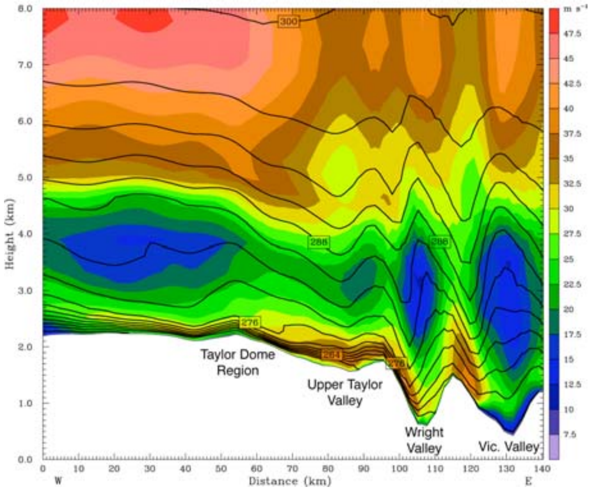

Figure 6. AMPS cross-section of wind speed and potential temperature (solid lines) for 24 May 2007 12:00 UTC. Location of cross-section shown in Figure 5.

Foehn cessation was first observed in the eastern Taylor Valley on 24 May 21:30 UTC with strengthening of cool and moist easterly winds with initial gusts up to 26.2 m s^{-1}. Wind speed later decreased to below 10 m s^{-1} on 25 May 09:00 UTC. Onset of strong easterlies caused foehn cessation at TE, TF, TH, TCa and TCo in the Taylor Valley, however, at THo on the southern valley wall (Kukri Hills) foehn conditions prevailed until 26 May 02:00 UTC when it was replaced by the onset of light southerly drainage winds. Foehn conditions ceased at all remaining western stations (TB, TTa, WV, VV, BV) by 26 May 07:45 UTC with return to pre-foehn conditions dominated by light cold drainage winds.

Table 2: Foehn characteristics at MDVs AWS

AWS	Onset (UTC)	Succession (UTC)	Min. Pre-foehn air temp (°C)	Max. foehn air temp (°C)	Min. foehn relative humidity (%)	Mean foehn wind direction	Max. foehn gust speed (m s^{-1})
TTa	05/21/2007 03:15	05/26/2007 13:45	-34.2	-5.1	10.1	224.8	33.3
TB	05/21/2007 09:45	05/26/2007 06:30	-41.4	-3.5	6,9	247.9	31.9
TH	05/22/2007 03:00	05/25/2007 23:15*	-36.1	-3.9	12.8	237.5	29.6
TF	05/22/2007 05:00	05/25/2007 02:45*	-44.1	-7.3	13.8	234.3	34.5
TE	05/22/2007 07:00	05/24/2007 21:30*	-40.8	-8.1	17.0	238.2	29.9
TCa	05/22/2007 03:00	05/25/2007 08:00*	-31.6	-5.4	12.5	234.8	35.7
TCo	05/22/2007 04:45	05/24/2007 23:00*	-32.0	-7.5	13.2	245.8	38.9
THo	05/22/2007 05:00	05/26/2007 02:00	-30.9	-6.1	10.9	215.6	34.8
WV	05/21/2007 23:15	05/26/2007 07:45	-46.5	-4.6	12.1	251.6	32.3
VV	05/22/2007 17:00	05/26/2007 07:15	-53.5	-5.0	7.9	232.8	27.9
BV	05/22/2007 16:15	05/26/2007 03:45	-36.2	-10.0	7.0	195.2	32.7

* Non-continuous foehn conditions between onset and cessation.

Foehn cessation at these stations was marked by an immediate drop in wind speed, a gradual decrease in air temperature and increase in relative humidity. The wave pattern evident in Fig. 6 significantly dampened with a return to near stable stratification due to weakening of the synoptic cyclone off Marie Byrd Land and associated pressure gradients. Post-foehn air temperatures remained elevated (compared to pre-foehn) for several days following the event, a feature also noted by Nylen et al. (2004).

4.2 Synoptic climatology

Foehn events such as the 21-26 May 2007 are a common occurrence in the MDVs. In the two calendar years of 2006 and 2007, foehn days occurred 28% of all days at THo, 27% at WV and 10% of days at VV. Data suggests higher frequency occurs at TB in the western Taylor Valley region, however incomplete AWS data prevents analysis. Highest frequency of events occurred in winter (MJJ, 41%) followed by spring (ASO, 33%), summer (NDJ, 13%) and autumn (FMA, 13%). Composite MSLP and wind vectors for 2006 and 2007 were constructed based on 172 foehn days recorded at 3 or more stations compared to 172 non-foehn days when no stations recorded foehn conditions. There were 398 total non-foehn days through 2006 and 2007, 172 selected to match the sample number of foehn days. Non-foehn days were purposely excluded if they occurred on either side of a foehn event to reduce the chance of pre-foehn and post-foehn conditions being included in the non-foehn analyses. Annual, summer (NDJ), and winter (MJJ) mean MSLP and surface wind vectors presented in Figs. 7-9, respectively, clearly identify the presence of a strong cyclonic system off the coast of Marie Byrd Land during foehn days in contrast to weak pressure gradients during non-foehn days. Interestingly, the cyclonic system is stronger in summer (Fig. 8a) than in winter (Fig. 9a). This could be related to the strong easterly ‘sea breeze’ circulation that develops in the MDVs during summer. The easterly circulation is extremely well-developed in terms of its strength, depth and persistence compared to thermal winds of lower latitudes (McKendry and Lewthwaite 1990) and may prevent grounding of foehn winds for extended periods (> 6 hours) to the valley floors unless overcome by particularly strong synoptic forcing.

The cyclonic system and associated pressure gradients present on MDV foehn days have widespread effects across East Antarctica. Composites of winter mean wind speed (Fig. 10) highlight stronger airflow across the Ross Ice Shelf and Ross Sea Coast during foehn days. Seefeldt et al. (2007) noted that strong katabatic winds across the Ross Ice Shelf occur when pressure gradients are perpendicular to the Transantarctic Mountains similar to those shown in Fig. 7a. A tongue of stronger airflow can also be seen east of Ross Island which is related to the climatological ‘‘Ross Ice Shelf air stream’’ or “RAS” (Parish and Bromwich 1998; Parish et al. 2006). Additionally, these composites indicate this synoptic situation is responsible for stronger airflow across north Victoria Land and Adelie Land.

This investigation demonstrates how cyclonic systems near the coast of Marie Byrd Land (between the Ross and Amundsen Seas) result in winds over the MDVs that lead to foehn. The Ross and Amundsen Seas are climatologically-favored regions for the persistence of cyclonic systems (Voskresenskii and Chukanin 1987; Simmonds and Keay 2000) and account for the high frequency of foehn events in the MDVs. The position and intensity of low pressure systems in this region displays one of the most prominent ENSO signals in the Antarctic (Carrasco and Bromwich 1993; Cullather et al. 1996; Gallée 1996; Kwok and Comiso 2002). During neutral and La Niña phases of ENSO, a region of low pressure occupies a position near the eastern Ross Ice Shelf. Conversely, during El Niño the low occupies a location further east towards the Antarctic Peninsula (Bromwich et al. 1993; Cullather et al. 1996; Carleton 2003; Bromwich et al. 2004).

Accordingly, we suggest that the significant interannual climate variability and ENSO signal that exists in the MDVs (Welch et al. 2003; Bertler et al. 2006; Doran et al. 2008) may be caused by the regions foehn wind regime (and warming) during La Niña phases and a less prominent foehn regime (cooling)

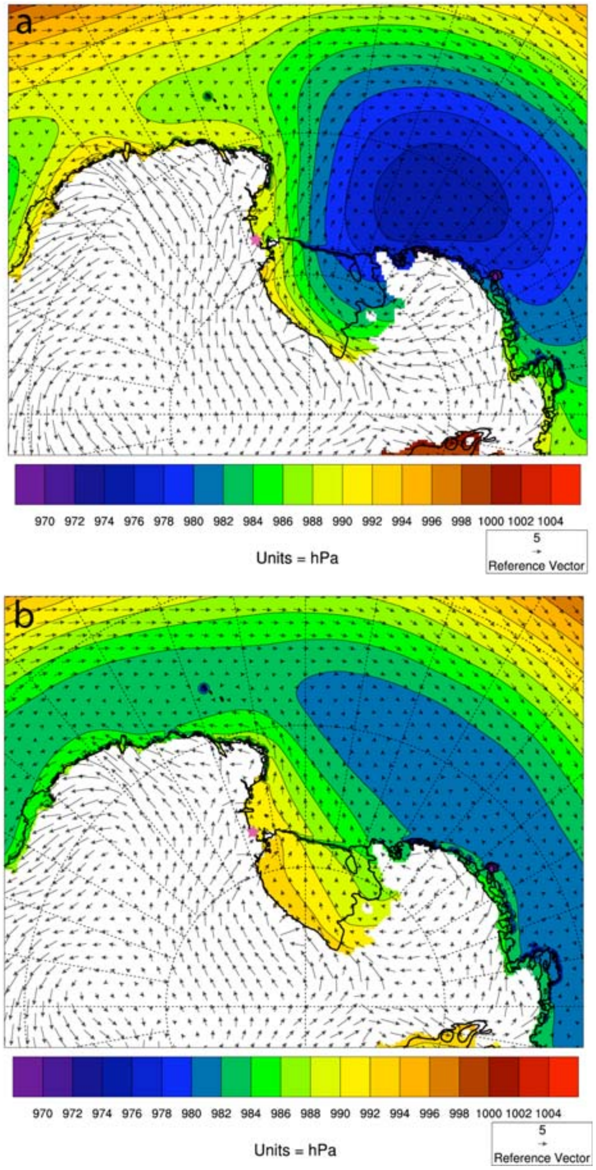

Figure 7: Subset of the AMPS 20 km grid MSLP and surface wind vector composites for 2006 and 2007 a) foehn days and b) non-foehn days.

during El Niño phases. It is postulated that the frequency and intensity of foehn events in the MDVs may provide an indicator for assessing changes in large-scale circulation patterns such as those associated with ENSO in this part of the Antarctic.

5. CONCLUSION

The MDVs frequently experience episodes of warm, dry and gusty foehn winds which are a dramatic climatological feature of this snow and ice free environment. This paper presents initial findings resulting from the ongoing collaborative work combining observational and model data to further the understanding of complex atmospheric and climate dynamics in the MDVs, particularly during foehn events. A winter foehn event examined here presents the spatial and temporal complexity associated with foehn onset and cessation in the MDVs. Model products from the AMPS 2.2 km domain indicate topographic interaction of synoptically forced airflow with the Transantarctic Mountains causes mountain wave activity which may contribute to foehn wind genesis in the MDVs. Importantly, this paper clarifies that a foehn mechanism is responsible for such strong wind events in the MDVs and the influence of katabatic surges from the polar plateau triggering events is minimal. A climatological analysis of all 2006 and 2007 foehn events was performed and illustrates a strong cyclonic low pressure system off the coast of Marie Byrd Land and resulting strong pressure-gradients over the

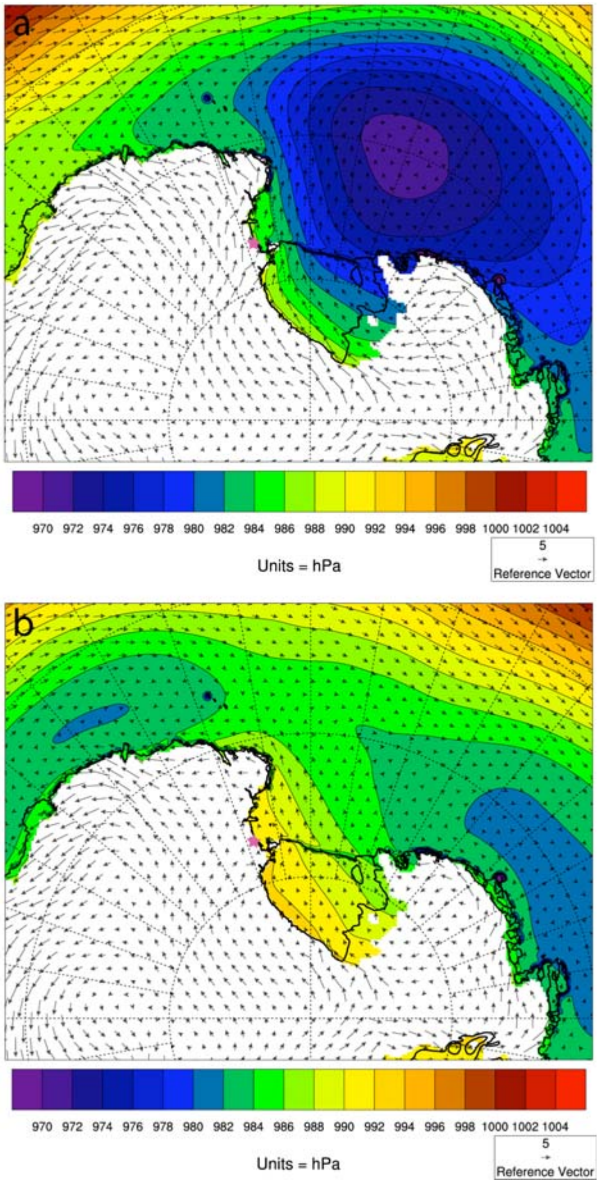

Figure 8. Same as Figure 7 but for summer (NDJ).

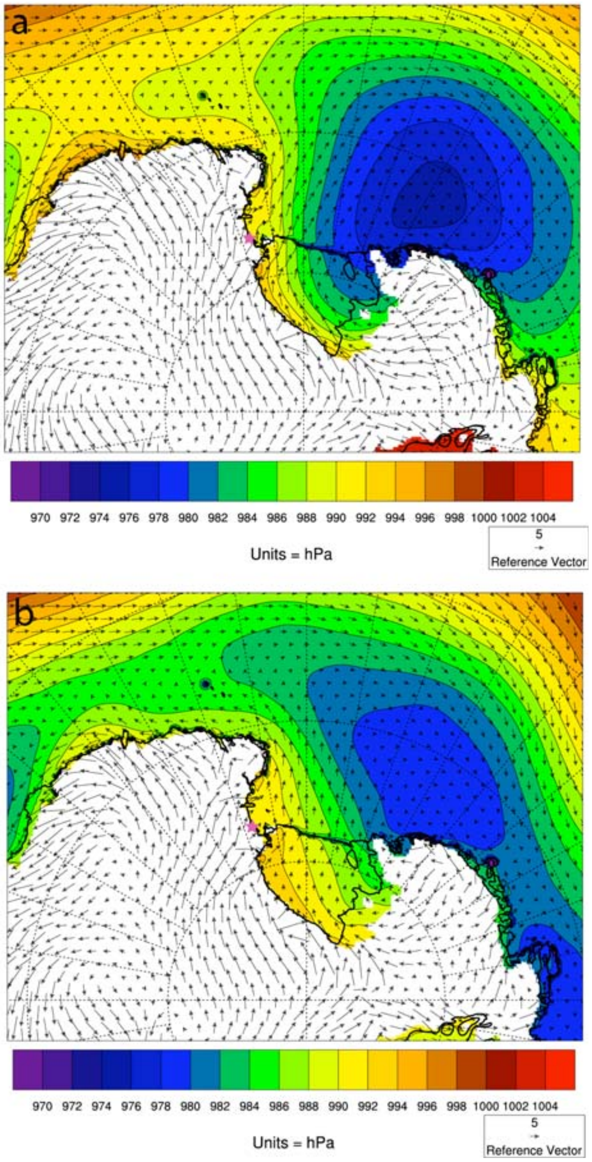

Figure 9. Same as Figure 7 but for winter (MJJ).

mountain ranges of the MDVs are responsible for foehn in the MDVs during all seasons. Accordingly, it is postulated that the frequency and intensity of foehn events may vary with ENSO and other linked teleconnections such as the Southern Annular Mode (Fogt and Bromwich 2006), which influence the position and frequency of these cyclonic systems in the Ross Sea region.

Further research is in progress detailing the synoptic climatology during foehn events and modelling of the complex atmospheric structure during the foehn event presented here. Future 1.1 km domain model runs with AMPS moving from MM5 to the Weather Research and Forecasting model (WRF; Skamarock et al. 2005) should improve model representations due to the higher order numerics in WRF. Important model validation by field research is planned in 2009 and 2011.

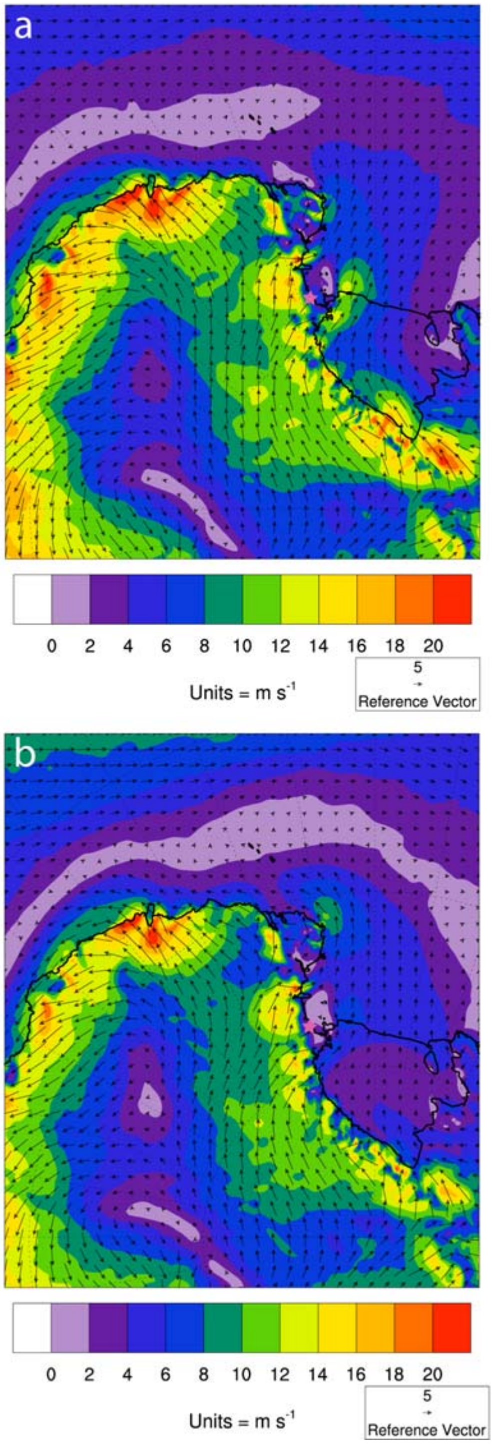

Figure 10. Subset of the AMPS 30km grid showing average winter (MJJ) wind speed for 2006 and 2007 a) foehn days and b) non-foehn days.

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