Foehn Winds in the McMurdo Dry Valleys, Antarctica: The Origin of Extreme Warming Events*

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ABSTRACT

Foehn winds resulting from topographic modification of airflow in the lee of mountain barriers are frequently experienced in the McMurdo Dry Valleys (MDVs) of Antarctica. Strong foehn winds in the MDVs cause dramatic warming at onset and have significant effects on landscape forming processes; however, no detailed scientific investigation of foehn in the MDVs has been conducted. As a result, they are often misinterpreted as adiabatically warmed katabatic winds draining from the polar plateau. Herein observations from surface weather stations and numerical model output from the Antarctic Mesoscale Prediction System (AMPS) during foehn events in the MDVs are presented. Results show that foehn winds in the MDVs are caused by topographic modification of south-southwesterly airflow, which is channeled into the valleys from higher levels. Modeling of a winter foehn event identifies mountain wave activity similar to that associated with midlatitude foehn winds. These events are found to be caused by strong pressure gradients over the mountain ranges of the MDVs related to synoptic-scale cyclones positioned off the coast of Marie Byrd Land. Analysis of meteorological records for 2006 and 2007 finds an increase of 10% in the frequency of foehn events in 2007 compared to 2006, which corresponds to stronger pressure gradients in the Ross Sea region. It is postulated that the intra- and interannual frequency and intensity of foehn events in the MDVs may therefore vary in response to the position and frequency of cyclones in the Ross Sea region.

1. Introduction

Foehn winds result from topographic modification of flow in the lee of mountain barriers. They are a climatological feature common to many of the world’s midlatitude mountainous regions, where they can be responsible for wind gusts exceeding 50 m s⁻¹ (Brinkmann 1971;
McGowan and Sturman 1996a) and warming at foehn onset of $+28^\circ$C (Math 1934). Intensive monitoring experiments in midlatitude regions such as the Alpine Experiment (ALPEX) (Kuettner 1986; Seibert 1990) and the Mesoscale Alpine Programme (MAP; Bougeault et al. 2001) in the Alps have detailed the complex atmospheric processes that occur during foehn by use of high-density observational networks, aircraft, satellite imagery, and mesoscale numerical modeling. The classic mechanism used to describe foehn from midlatitude studies involves forced orographic lifting of moist air over a mountain barrier. As the air rises it cools at the dry-adiabatic lapse rate (DALR) of 9.8°C km$^{-1}$. If saturation occurs, then further lifting will result in the air cooling at the slower saturated adiabatic lapse rate of 4°–6°C km$^{-1}$. Descending air on the lee side of the barrier compresses and warms at the DALR, also reducing the relative and absolute humidity of the air (Barry and Chorley 2003). However, as discussed by Seibert (1990), the classic foehn mechanism does not always fit with observations because moisture removal and cloud formation over mountains is not necessary for foehn development. Foehn winds can develop as air is forced to descend over lee slopes, resulting from large-amplitude mountain waves (e.g., Klemp and Lilly 1975; Flamant et al. 2002; Jiang et al. 2005), and by the blocking of low-level winds upwind of mountain barriers, causing subsequent descent of air over lee slopes from near the ridge top (e.g., Parish 1983; Doyle and Shapiro 2000; Gohm et al. 2004; Jiang et al. 2005). Generally, for the development of foehn, the flow needs to be directed within 30° of perpendicular to the ridgeline with a steep pressure gradient across the mountain (Durran 1990). The strongest foehn winds are associated with flow nearly normal to the ridgeline (Zangl 2003).

Studies of foehn in high latitudes and polar regions, however, are rare. Analysis of meteorological records from the McMurdo Dry Valleys (MDVs), a unique ice-free area of the Antarctic, has identified that foehn winds are responsible for unprecedented temperature changes of $>+40^\circ$C. The resulting warm, dry, and gusty winds are suspected to have significant effects on landscape forming processes in the MDVs, including glacial melt (Welch et al. 2003; Doran et al. 2008), rock weathering (Selby et al. 2003; Doran et al. 2008), and biological productivity (Fountain et al. 1999; Foreman et al. 2004).

Despite the significance of foehn in this region, no detailed scientific investigation of foehn has been conducted in the MDVs. As a result, the cause of these warm winds remains equivocal, with some studies invoking adiabatic warming of katabatic winds descending from the polar plateau to explain their occurrence (Bull 1966; Doran et al. 2002; Nylen et al. 2004), while others have suggested that the winds are foehn and result from the topographic modification of southwesterly airflow (Thompson et al. 1971; Thompson 1972; Riordan 1975; Keys 1980; Bromley 1985; Clow et al. 1988; McKendry and Lewthwaite 1990, 1992).

Episodes of strong and warm westerly airflow in the MDVs have generally been attributed to adiabatic warming of descending air, however, the disagreement lies with the exact forcing mechanisms. Katabatic terminology was initially used by Bull (1966) to explain the westerly winds in surface-based meteorological observations in the MDVs. Based on the thermal characteristics of the westerly flow, Thompson et al. (1971) and Thompson (1972) reject a katabatic origin of these winds and suggest they are foehn resulting from the aerodynamic deflection of strong southerly-to-westerly midtropospheric flow to the valley floor. Similarly, Riordan (1975), Keys (1980), and Bromley (1985) all note that the westerlies are more likely of foehn origin rather than katabatic. Clow et al. (1988) also identified strong westerly winds as foehn and noted that the MDVs do not lie in a katabatic convergence zone; however, they consider the foehn winds to be instigated by katabatic surges draining from the continental interior. The only research on the atmospheric structure during westerly airflow was by McKendry and Lewthwaite (1990, 1992) in the Wright Valley during summer using observations from pilot balloons, airsondes, an acoustic sounder, and a network of surface-based weather stations. These authors concluded that the westerly winds are foehn, caused by strong upper-level flow deflected down into the valley and related to a synoptic situation characterized by low surface pressure in the Ross Sea. They note an atmospheric structure similar to foehn winds elsewhere with a stagnant layer and a midtropospheric capping inversion above the strong near-surface winds. Despite these observations, McKendry and Lewthwaite (1990) did not dismiss the alternate explanation that westerlies are associated with katabatic surges from the polar plateau. In more recent studies, Doran et al. (2002) and Nylen et al. (2004) classified all strong down-valley, westerly winds in the MDVs as katabatic winds draining from the polar plateau, although no investigations into the forcing mechanisms were undertaken. They did, however, document important spatial and annual statistics of these “warm” winds, such as the increase in frequency in the western sections of the valleys with the highest frequency of events occurring in winter. Two coauthors (J. C. Speirs and H. A. McGowan) have personally observed lenticular clouds in the MDVs during the warm westerly wind events in summer, which are indicative of mountain wave activity and deep transbarrier flow rather than shallow katabatic drainage from the polar plateau.
McKendry and Lewthwaite (1992, p. 596) 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 McKendry and Lewthwaite’s statement almost two decades ago, no comprehensive study into the meteorology of foehn wind events of the MDVs has been undertaken and the cause of these winds remains a subject of considerable debate. This study presents 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 understanding of the complex terrain mountain meteorology in the MDVs. Model output from the Antarctic Mesoscale Prediction System (AMPS) project is combined with data from a network of automatic weather stations (AWSs) to 1) detail the typical meteorological conditions and synoptic forcing mechanisms associated with a foehn wind event, and 2) provide a 2-yr synoptic climatology of foehn wind events during the calendar years of 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 (Fig. 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 km², the largest ice-free area in Antarctica. Large mountain ranges rising over 2000 m above sea level separate the valleys, which have a polar desert climate because of 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. 2009). Mean annual air temperature from seven valley floor AWSs range between −2.14.8°C and −2.30°C, depending on site location and the period of measurement (Doran et al. 2002). The wind regime of the MDVs is strongly dominated by either up- or down-valley topographically channeled 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. Cold air pools associated with light winds and minimum temperatures <−50°C often occupy topographic low points of the valleys during winter (Doran et al. 2002). Topographically channeled southwesterly wind events that we report here as foehn winds are frequently recorded throughout the year in the MDVs (Thompson 1972; Keys 1980; Clow et al. 1988; McKendry and Lewthwaite 1990; 1992; Ayling and McGowan 2006; Speirs et al. 2008).

3. Methods

Meteorological data presented here were obtained from AWSs operated by the McMurdo Dry Valleys Long-Term
Ecological Research (LTER) program (Doran et al. 1995). Table 1 lists the location and station identification for the AWSs used here. The configuration of these stations is detailed online (see http://www.mcmter.org/queries/met/met_home.jsp; see also Doran et al. 2002). Measurements are collected at 3 m above the surface except for the Canada Glacier (TCa), where air temperature and relative humidity measurements are made 2 m above the surface.

A selection criterion was developed to identify foehn wind events in the MDVs AWS records similar to studies of Northern Hemisphere foehn, such as Richner et al. (2006) and Gaffin (2007). Foehn onset in the MDVs was identified by an increase of wind speed above 5 m s\(^{-1}\) from a southwesterly direction, a warming of at least 1°C h\(^{-1}\), and a decrease of relative humidity of at least 5% h\(^{-1}\). Glacier AWSs were excluded from the foehn identification criteria because topographically controlled glacier winds experienced at these stations have a westerly component and, in addition to weak warming associated with mixing, glacier winds can obscure onset and cessation of foehn winds. Because of the transient nature of some foehn events, an additional criterion of a “foehn day” was developed. A foehn day at an AWS station is defined as a day that experiences 6 h or more of continuous foehn conditions with wind speed >5 m s\(^{-1}\) from a consistent southwesterly direction. We accept that the classification of a foehn day excludes weak and brief periods (<6 h) of foehn winds, which are more difficult to distinguish from, for example, local glacier winds. To quantify temporal and spatial trends of foehn events in the AWS observations and link to model circulation data, a criterion such as the foehn day is necessary.

Numerical forecast model products presented here were obtained from AMPS (Powers et al. 2003). AMPS is a collaboration between the Mesoscale and Microscale Meteorology (MMM) division of the National Center for Atmospheric Research (NCAR) and the Polar Meteorology Group at the Byrd Polar Research Center, The Ohio State University (OSU) in support of U.S. Antarctic Program (USAP) operations. AMPS employs a version of the fifth-generation Pennsylvania State University (PSU)–NCAR Mesoscale Model (MM5; Grell et al. 1994), Polar MM5, which is optimized for use in polar regions by OSU (Bromwich et al. 2001; Cassano et al. 2001). Polar MM5 includes a modified parameterization for the prediction of ice cloud fraction, improved cloud–radiation interactions, an optimal stable boundary layer treatment, improved calculation of heat transfer through snow and ice surfaces, and the addition of a fractional sea ice surface type.

AMPS output used in this case study is at 20-km resolution, on a grid domain covering Antarctica and much of the surrounding Southern Ocean, and at 2.2-km resolution on a grid encompassing the Ross Island area, extending into the MDVs. There are 31 vertical half-sigma levels, with 11 levels in the lowest 1000 m to capture the complex interactions in the planetary boundary layer. The lowest half-sigma level is about 13 m above the surface. For comparisons with AWS observations at 3 m above the surface, AMPS winds were interpolated logarithmically from the lowest model level. Air temperature was interpolated linearly between the surface and the lowest model level, while relative humidity was estimated with the interpolated temperatures, mixing ratios, and calculated pressure.

AMPS Polar MM5 is initialized twice daily at 0000 and 1200 UTC. The initial and boundary conditions are derived from the National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) model. AMPS uses three-dimensional variational data assimilation (3DVAR; Barker et al. 2004). The observations available for assimilation into AMPS include reports from radiosondes, surface synoptic (SYNOP) reports, AWS observations, ship and buoy reports, atmospheric motion vector winds from satellites, and GPS radio
occultation soundings. AMPS ingests sea ice data daily from the National Snow and Ice Data Center for its fractional sea ice depiction.

Guo et al. (2003) evaluate Polar MM5 performance over Antarctica for a 1-yr period (1993) on a 60-km-resolution domain and show that the intra- and interseasonal variability in pressure, temperature, wind, and moisture are well resolved. Bromwich et al. (2005) evaluate 2 yr of AMPS Polar MM5 forecasts on the 30-km domain and show that the same variables are well resolved at synoptic time scales. Monaghan et al. (2005) reviewed the climate of the McMurdo region (including the MDVs) in the 3.3-km-grid domain and show that AMPS captured important temporal and spatial aspects of the region’s climate with skill. 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 at Ross Island. In terms of numerical modeling of foehn events elsewhere, MM5 has been successfully used to model foehn dynamics in the European Alps as part of MAP (Gohm et al. 2004; Zängl 2003).

Comparisons of AMPS time series and AWS data by this study shows that the 2.2-km domain performs well in the MDVs. The model points chosen for this comparison were those closest to the AWS location and elevation. In this paper, AMPS products for the 2.2-km domain are utilized to examine synoptic-scale circulation characteristics during foehn events.


a. Synoptic environment

The synoptic-scale meteorological situation associated with a winter foehn event is presented here. This event is representative of other events in the MDVs, including those in summer [synoptic composites presented in the following section; see also McEndry and Lewthwaite (1990) and Speirs et al. (2008) for field observations of summer foehn events]. Using the foehn identification criteria we isolated a strong foehn event in the MDVs AWS records with onset on 21 May 2007. This event lasted 5 days with wind gusts up to 38.9 m s\(^{-1}\) and induced warming of up to +48.5°C at the valley floor. Figure 2 shows the synoptic scale meteorology at 0000 UTC 19 May 2007 (prior to foehn onset). The sea level pressure (SLP) charts at this time (Fig. 2a) show a cyclonic depression north of the Adélie Land coast with a minimum central pressure of 962 hPa, a broad area of low pressure over the western Ross Sea region. Surface airflow over the study area in the days...
prior to foehn onset was dominated by katabatic winds draining from the east Antarctic ice sheet and localized cold air drainage winds in the MDVs. Surface wind vectors at the lowest model sigma level (approximately 13 m above surface; Fig. 2a) show katabatic divergence west of the MDVs with winds draining out the large glacial valleys south (Byrd, Mulock, and Skelton Glaciers) and north (David and Reeves Glaciers) of the MDVs. Higher-resolution streamlines (not shown) also display this katabatic divergence west of the MDVs.

By 0000 UTC 23 May 2007, the cyclone evident in Fig. 2a had tracked eastward and strengthened with a minimum central pressure of 950 hPa (Fig. 3a). During this time, a large ridge developed over east Antarctica as seen in the 500-hPa chart in Fig. 3b. The cyclonic system then slowed and remained relatively stationary in a position north of the coast of Marie Byrd Land between the Ross and Amundsen Seas (Fig. 3) until 26 May 2007. This synoptic setting produced a baroclinic zone (not shown) with a strong southeast–northwest pressure gradient and strong southwesterly airflow across the western Ross Sea and Transantarctic Mountains region for several days (Fig. 3b). The cyclonic system then began to weaken on 26 May 2007 and the region of low pressure propagated eastward around the West Antarctic coast.

b. Local meteorological observations

AWS observations and AMPS model forecasts (for grid points nearest and most representative of the AWS locations) during the foehn event are shown in Fig. 4 for the western MDVs region and Fig. 5 for the eastern Taylor Valley region. Model performance is described further in the following section. Prior to foehn onset, meteorological conditions on the floors of the MDVs were cold and calm, while at the higher-elevation glacier stations, cold and moist downslope winds approached \(8 \text{ m s}^{-1}\) [e.g., Howard Glacier (THo); see Fig. 5c]. These winds are localized glacier or slope winds from the surrounding mountain ranges with flow at Taylor Glacier (TTa), TCa, Commonwealth Glacier (TCo), and THo (Fig. 1c) directed toward the valley floor. Cold air draining to the valley floor accumulates at the topographic low points resulting in stable cold air pools with near-surface (3 m) air temperatures below \(-40^\circ\mathrm{C}\) and relative humidity >80%. Coldest air temperatures are recorded at Lake Vida (VV; \(-53.5^\circ\mathrm{C}\)), which reflects the relative strength of cold pool formation in the Victoria Valley compared to the Wright and Taylor Valleys (Doran et al. 2002). It is difficult to accurately estimate the inversion strength and depth of the near-surface cold pools in the MDVs because vertical profile observations during winter are unavailable. Whiteman et al. (2004) demonstrate that valley sidewall temperatures can be used in place of free-air vertical profile measurements under clear and stable conditions. Accordingly, comparisons of temperatures on the valley sidewalls in the MDVs to those on the valley floor would suggest that cold pooling may be in the order of \(10^\circ\mathrm{C}\) in the Taylor Valley [Lake Fryxell (TF); Lake Bonney (TB)], \(15^\circ\mathrm{C}\) in the Wright Valley [Lake Vanda (WV)], and \(20^\circ\mathrm{C}\) in the Victoria Valley (VV). Doran et al. (2002) suggest 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.

Between 0930 and 1000 UTC 20 May 2007, a gradual warming commenced at all MDV valley floor AWSs (Figs. 4 and 5). This warming characterizes the “prefoehn 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 h prior to onset of strong foehn winds. Coupling of foehn winds to the surface shows significant spatial complexity through the Victoria, Wright, and Taylor Valleys (Table 2). Foehn conditions were initially monitored in the western Taylor Valley, a characteristic also noted by Nylen et al. (2004), although they referred to the winds as katabatic. Onset of strong foehn winds first occurs on 21 May 2007 at TTa (0315 UTC) and TB (0945 UTC), followed by WV (2315 UTC) in the adjacent Wright Valley (Table 2). Onset is characterized by an immediate increase in wind speed >10 m s\(^{-1}\) from a consistent southwest direction, an increase in air temperature, and a decrease in relative humidity. It is almost 24 h after initial foehn onset in the western Taylor Valley when strong winds are recorded at the eastern stations (TE, TF, TH, TCa, TCo, and THo). Lake Vida was the last station to identify foehn onset at 1700 UTC 22 May 2007. This station is often the last to record foehn winds, possibly because of the longer time required to erode the cold air pool that forms over the Lake Vida depression and the more open nature of the valley topography. As the cold air pool was eroded by foehn winds, a warming of +29.7°C in 3 h was recorded at foehn onset and +48.5°C over the course of the event. While the most dramatic warming occurred on the valley
floors, valley sidewall stations still exhibited significant warming with temperature changes of $+24.8^\circ$, $+24.5^\circ$, and $+26.2^\circ$C observed at THo, TCo, and TCa respectively during the foehn event.

A break in westerly foehn winds was monitored in the eastern Taylor Valley (TE, TF, TH, TCa, and TCo) on 23 May 2007 and continued until early 24 May 2007. During this time, easterly winds intruded from McMurdo Sound with speeds $<10$ m s$^{-1}$ and relative humidity $>90\%$ and caused air temperatures to fall below $-25^\circ$C (Figs. 5a,b). The influence of these easterlies decreased at sites further west in the MDVs, with Lake Hoare (TH) only briefly experiencing a break in foehn. Foehn conditions then became reestablished at all stations following the break when maximum wind gusts were recorded (Table 2).

Foehn cessation was first observed in the eastern Taylor Valley on 2130 UTC 24 May with a 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 0900 UTC 25 May. 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 0200 UTC 26 May when it was replaced by the onset of light southerly drainage winds. Foehn conditions ceased at all remaining western valley floor stations [TB, WV, VV, and Beacon Valley (BV)] by 0745 UTC 26 May with the return to pre-foehn conditions dominated by light cold drainage winds. Foehn cessation at these stations was marked by an immediate drop in wind speed, a gradual decrease in air temperature, and an increase in relative humidity. Postfoehn air temperatures remained elevated (compared to prefoehn) for several days following the event, a feature also noted by Nylen et al. (2004). Foehn cessation at Taylor glacier (TTa) was not clearly identifiable because of the strong westerly glacier winds experienced at this station; however, temperature began to decrease and relative humidity increased at 1000 UTC 26 May, which may signify cessation of foehn winds.
During this event strong southerly foehn winds were monitored 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 negatively buoyant katabatic drainage from the east Antarctic ice sheet could enter the Beacon Valley.

c. Model performance in the MDVs

Prior to foehn onset, AMPS has difficulty representing the near-surface inversion associated with local cold air pooling observed at the valley floor AWSs. At individual grid points, AMPS shows light winds and a warm/dry bias while near calm conditions are observed at the valley floor AWSs (Figs. 4 and 5). The errors appear to increase with strength of cold air pooling with prefoehn temperature bias (model-observed) of +12.7°C on the valley floor in the Taylor Valley (TE, TF, TH, and TB), +22.8°C in the Wright Valley (WV) and +26.4°C in the Victoria Valley (VV). These issues could be due to the smooth modeled topography which may not accurately detail the topographic low points in the valleys and also due to the PBL physics in AMPS. Monaghan et al. (2003) and Steinhoff et al. (2009) both note similar problems with AMPS temperature and humidity during stable conditions and attributed these issues to the PBL scheme. Temperature and humidity model errors in the MDVs are only substantial during weak mixing conditions on the valley floor. At glacier stations away from the influence of localized cold air pooling, the temperature bias (+4.6°C at THo, TCa, and TCo) is markedly reduced and AMPS closely follows AWS observations (e.g., THo in Fig. 5c).

AMPS performance is greatly improved during foehn conditions where stronger forcings are present. Onset and cessation of strong westerly winds are identified well in AMPS with strengthening (weakening) of wind speed at foehn onset (cessation) within 12 h of the observed increase (decrease) in the AWS records from all stations. Mean wind speeds during foehn were overestimated in the eastern Taylor Valley (+2.9 m s\(^{-1}\)) at TE, TF, and TH) while they were underestimated at the western surface stations (−2.5 m s\(^{-1}\)) at TB, WV, and VV). Temperature errors were markedly reduced during foehn with mean bias of −4.0°C at valley floor stations. On the valley sidewalls (THo, TCa, and TCo) mean temperature errors were reduced to −1.8°C during foehn conditions. The break in foehn conditions and intrusion of easterly winds in the eastern Taylor Valley is also represented in the AMPS model at Explorer’s Cove (TE) and TF. AMPS output suggests that these easterlies are caused by forced deflection of southerly winds by Ross Island (not shown).

Evidently, even with a relatively finescale spatial resolution (2.2 km), AMPS has difficulties reproducing point observations of the near-surface conditions. This emphasizes the complexity of the local-scale mixing processes in the MDVs environment, particularly during weak-mixing conditions. However, the AMPS-AWS comparisons presented here do demonstrate that AMPS resolves the onset and cessation of foehn winds on the valley floors and reasonably replicates meteorological parameters on the valley sidewalls, away from the influence of localized effects. It is especially encouraging that AMPS recognizes the onset and cessation of strong wind events in the MDVs considering the variation of timing of foehn onset between stations. The ability of AMPS to approximate the observed foehn events at fine scales suggests that the regional and large-scale forcing in the outer AMPS domains is accurate. Therefore, we conclude that AMPS is suitable for analyzing the regional airflow and synoptic conditions during foehn in the MDVs, the primary focus of this study.

### Table 2. Foehn characteristics at MDV AWSs.

<table>
<thead>
<tr>
<th>AWS</th>
<th>Onset (UTC)</th>
<th>Cessation (UTC)</th>
<th>Min prefoehn air temperature (°C)</th>
<th>Max foehn air temperature (°C)</th>
<th>Min foehn RH (%)</th>
<th>Mean foehn wind direction (°)</th>
<th>Max foehn gust speed (m s(^{-1}))</th>
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<tbody>
<tr>
<td>TTa</td>
<td>0315 UTC 21 May 2007</td>
<td>1000 UTC 26 May 2007</td>
<td>−34.2</td>
<td>−5.1</td>
<td>10.1</td>
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<td>0630 UTC 26 May 2007</td>
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<td>−3.5</td>
<td>6.9</td>
<td>247.9</td>
<td>31.9</td>
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<tr>
<td>TH</td>
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<td>−36.1</td>
<td>−3.9</td>
<td>12.8</td>
<td>237.5</td>
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<tr>
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<td>0245 UTC 25 May 2007</td>
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<td>−8.1</td>
<td>17.0</td>
<td>238.2</td>
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<tr>
<td>TCa</td>
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<td>0800 UTC 25 May 2007</td>
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<td>−5.4</td>
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* Noncontinuous foehn conditions between onset and cessation.
d. Modeled foehn dynamics

Backward air parcel trajectories from 0600 UTC 25 May 2007 are presented in Fig. 6 in order to help identify the origin of air arriving at model points (lowest vertical level) best representing the AWSs in the MDVs during the foehn event. The trajectories are three-dimensional with both vertical and horizontal motions considered and were run backward for 6 h prior to 0600 UTC 25 May. Figure 7 shows cross sections of wind speed and potential temperature (at 0000 UTC 20 May and 0600 UTC 25 May) for the dashed line evident in Fig. 6 and highlight the marked difference in atmospheric structure associated with foehn onset in the MDVs.

Prior to foehn onset, light winds and stable stratification of the lower troposphere are evident (Fig. 7a). During the foehn event, near-surface wind vectors (Fig. 6) show evidence of flow divergence on either side of the Royal Society Range (peak elevation > 4000 m) and, to a lesser extent, Taylor Dome (peak elevation of 2450 m). A layer <700 m above the Taylor Dome region is characterized by wind speeds >30 m s\(^{-1}\), a shallow near-neutral layer adjacent to the surface capped by an inversion layer of ~23 K (Fig. 7b). Upstream winds are forced by the strong synoptic pressure gradient; however, given that an inversion is present, a small component of this flow may also be buoyancy-related flow. As these strong winds arrive to the MDVs, they interact with topography and are forced to cross the mountain ranges rather than simply draining into the upper reaches of the valleys from the west. In response, a prominent large-amplitude mountain wave pattern develops with vertical propagation to levels at least 8 km above sea level (Fig. 7b). The downward displacement of the isentropes in the valleys implies a foehn mechanism. Similar mountain wave activity is commonly associated with foehn winds in mountainous midlatitude regions (e.g., Beer 1976; Durran 1990; Seibert 1990; Zängl 2003). Wave development appears to commence at the Taylor Dome region with flow relatively laminar over the ice sheet west of the MDVs before reaching this rise in topography. Wave amplitude increases above the MDVs as strong flow crosses the chain of mountain ridges. Large regions of lower wind speeds appear above the valley centers associated with ascending air to the mountain wave crests, while wind speed maxima occur at the wave troughs near the north-facing valley.
walls. To examine the potential for downslope flow acceleration associated with mountain wave activity, the Froude number (Fr) was calculated, which can be represented as

$$Fr = \frac{u}{\left(\frac{\theta}{\Delta \theta} gh\right)^{1/2}},$$

where $u$ is the wind speed, $h$ is the height of the inversion layer, $\theta$ is the average potential temperature of the layer, $\Delta \theta$ is the potential temperature deficit (inversion strength), and $g$ is gravity. This definition of Fr is often used to examine katabatic jump behavior (e.g., Yu et al. 2005), but it can be applied here to demonstrate the potential for downslope flow acceleration associated with mountain waves when flow is supercritical ($Fr > 1$). Clearly, Fr values are $>1$ for most the MDVs region during foehn with peaks in the calculations on the lee slopes in the Wright Valley and the upper reaches of the Taylor Valley demonstrating significant flow acceleration (Fig. 7).

Deflection of airflow is evident along the valley axis, particularly in the Wright Valley (Fig. 6). This is a combination of forced channeling owing to the westerly component of the upstream flow but also pressure-driven channeling (see Whiteman and Doran 1993) associated with the strong horizontal pressure gradient across the MDVs from west to east. During the strongest winds late on 24 May 2007, wind direction at TTa turned almost southerly, demonstrating that airflow overcame topographic controls as it descended the slopes of the Kukri Hills (See Fig. 1). The trajectory analysis was performed when foehn winds ceased in the eastern Taylor Valley stations (TF and TE) and moist easterlies intruded from McMurdo Sound.

The wave pattern evident in Fig. 7b remains relatively stationary through the course of the foehn event. Weakening of the synoptic cyclone off Marie Byrd Land and associated pressure gradients later on 26 May 2007 dampened the wave pattern with a return to near-stable stratification by 27 May 2007.

5. Foehn climatology 2006/07

a. Temporal and spatial variability

Foehn events such as the 20–27 May 2007 event are a common occurrence in the MDVs. Figure 8 shows the frequency of foehn days for 2006 and 2007 at MDV valley floor AWSs. Most foehn events last less than 5 days, although occasional events exceed a week in length. In the two calendar years of 2006 and 2007, foehn days occurred on 28% of all days at TH, 27% at WV, and 10% of days at VV. Data suggest that a slightly higher frequency occurs at TB in the western Taylor Valley region, although incomplete AWS data prevent a complete analysis. The highest frequency of foehn days occurred in winter (JJA, 33% of winter days) followed by autumn (MAM, 21%), spring (SON, 18%), and summer (DJF, 16%). Because of the high frequency of winter foehn events, nonfoehn conditions may only prevail for 1–2 days before onset of another foehn event. Winter events frequently see temperature changes $>40^\circ$C, and on occasions cause temperatures to rise above 0$^\circ$C as occurred on 3 August 2007 during a 5-day foehn event (+0.3$^\circ$C at WV). Summer foehn events also regularly cause temperatures to rise above freezing and, in combination with intense
solar radiation, temperatures can exceed +10°C. The highest temperatures during 2006 and 2007 were achieved during a 3-day event in January 2007, which resulted in a maximum temperature of +8.6°C (WV).

Figure 8 highlights significant spatial variability and complexity in the onset and duration of foehn events through the MDVs. Sites within the Taylor Valley (TB, TH, TF, and TE) generally monitor foehn conditions concurrently; however, on occasion, foehn winds can be experienced at either the eastern or western end of the valley only. All events at Lake Vida in the Victoria Valley occur simultaneously with events in the Taylor and Wright Valleys.

Foehn wind frequency on the valley floors increases substantially from an average of 16% foehn days in 2006 to 26% in 2007. This increase in foehn days is observed at all stations and during all seasons and represents an increase in foehn event frequency in addition to an increase in the duration of events. As a result of increased foehn (and warming) in 2007, annual average air temperatures at valley floor stations in the MDVs were 2.3°C–3.3°C warmer than 2006. This increase is in accordance with Nylen et al. (2004), who suggest that an increase of katabatic [foehn] wind frequency in the MDVs would increase mean annual temperatures.

b. Synoptic climatology

Annual mean sea level pressure and near-surface wind vector composites presented in Figs. 9a,b demonstrate a slight tightening of isobars in the western Ross Sea region in 2007 compared to 2006. The area of low pressure is also more confined and centered closer to the Ross Sea in 2007. Figure 9c shows the sea level pressure differences between 2007 and 2006 and statistical significance (using a two-tailed Student’s t test) while Fig. 9d demonstrates the pressure gradient differences using a first-order centered finite difference of the averaged pressure gradient of 2006 and 2007. The direction of the pressure gradient (from low to high pressure) is shown by an arrow at a sample location on the Ross Ice Shelf. Positive statistically significant differences in synoptic pressure gradients are evident across the Ross Ice Shelf and near the MDVs between 2006 and 2007 and is likely associated with the increase of foehn winds in 2007.

To isolate the synoptic configuration associated with foehn in the MDVs, composites of SLP field and wind vectors for 2006 and 2007 were constructed based on 172 foehn days recorded at three or more valley surface stations, compared to the 172 nonfoehn days. There were 398 total nonfoehn days through 2006 and 2007, 172 were selected to match the sample number of foehn days. Nonfoehn days were purposely excluded if they occurred on either side of a foehn event to reduce the chance of prefoehn and postfoehn conditions being included in the nonfoehn analyses. AMPS backward trajectories were produced for these 172 foehn days (Fig. 10) and display south-southwesterly, cross-barrier flow similar to the case study of 20–27 May 2007. The trajectories of VV are more consistent near the AWS site than TB, with air being channeled to VV along the Balham and McKelvey Valleys in the upper reaches of Victoria Valley. At TB, the air parcels either cross the
Kukri Hills at a location near TB (similarly to Fig. 6) or enter the Taylor Valley farther west and are deflected by the Asgard Range and channeled down valley along the valley axis.

Mean conditions presented in Figs. 11–13 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 nonfoehn days. Sea level pressure differences and pressure gradient differences were calculated in Figs. 11–13, similar to Fig. 9 except subtracting nonfoehn days from foehn days. Statistically significant differences in sea level pressure and pressure gradients can be seen in the Ross Sea region for the annual (Fig. 11c) and summer (Fig. 12c) foehn composites. Differences in sea level pressure between foehn and nonfoehn days are not statistically significant in winter (Fig. 13c) because of the quasi-stationary nature of cyclones in the Ross Sea during these months (Simmonds et al. 2003). However, the mean cyclone on winter foehn days has a more closed pressure pattern with tightened isobars in the Ross Sea area, which would generate the statistically significant stronger pressure gradients (Fig. 13d) and stronger winds (Fig. 14c) along the Transantarctic Mountains.

**FIG. 9.** AMPS SLP and near-surface wind vector annual composites for (a) 2006 and (b) 2007, (c) SLP difference (2007 − 2006), and (d) pressure gradient difference (2007 − 2006). In (c) and (d) stippling is for positive differences, hatching is for negative differences. Light stippling/hatching refers to 90% confidence level, heavy stippling/hatching refers to 95% confidence level. Star denotes location of MDVs and arrow in (d) shows the direction of the pressure gradient.
FIG. 10. AMPS backward trajectories for all 172 foehn days at (a) VV and (b) TB. The trajectories represent air parcels arriving to the surface at 1800 UTC on the foehn day.
The cyclonic system and associated pressure gradients present on MDV foehn days have widespread effects across East Antarctica. Composites of the winter mean wind speed (Fig. 14) highlight stronger airflow across the Ross Ice Shelf and Ross Sea coast during foehn days. Bromwich et al. (1993) and Seefeldt et al. (2007) both note that strong katabatic winds across the Ross Ice Shelf occur when pressure gradients are perpendicular to the Transantarctic Mountains similar to those shown in Figs. 11d–13d. A tongue of stronger airflow can also be seen east of Ross Island, which is related to the climatological Ross Ice Shelf airstream (RAS; see Parish and Bromwich 1998; Parish et al. 2006; Seefeldt and Cassano 2008; Steinhoff et al. 2009).

6. Discussion

The MDVs frequently experience episodes of warm, dry, and gusty winds, which are a dramatic climatological feature of this snow- and ice-free environment. AWS observations of foehn events in the MDVs are not consistent with observations of katabatic winds elsewhere in Antarctica (e.g., Wendler et al. 1997; Davolio and Buzzi 2002; Renfrew and Anderson 2006). Cross sections and trajectory analyses from the AMPS 2.2-km-grid domain...
confirm that south-southwesterly cross-barrier airflow is deflected from higher atmospheric levels to the surface as initially proposed by Thompson et al. (1971) and McKendry and Lewthwaite (1990). This suggests that a foehn mechanism is responsible for such strong wind events in the MDVs and that the influence of katabatic surges from the polar plateau triggering events is minimal. A near-surface inversion layer is present on the polar plateau upstream of the valleys and a small component of this upstream flow may be buoyancy driven, however, the dominant driving mechanism for foehn wind occurrence in the MDVs is the strong synoptic pressure gradients (and strong winds) in the Transantarctic Mountain region caused by cyclonic activity in the Ross Sea.

Foehn-induced warming frequently exceeds $40^\circ C$ within several hours at valley surfaces in the MDVs during winter. 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. South-southwesterly upper-level airflow is deflected by the valley walls, observed as a southwesterly wind at the valley floor. In addition to forced deflection, a component of the flow may be driven down valley from high to low pressure with the strong along-valley pressure gradient.

Although foehn in the MDVs does not follow the idealized foehn formation mechanism with moisture removal on the windward side during upslope flow, the cross sections of potential temperature illustrate significant mountain wave activity similar to those commonly associated with foehn winds in midlatitude regions (e.g., Durran 1990;
It is difficult to draw detailed comparisons between mountain wave patterns in the MDVs to those of midlatitude regions given the markedly different environments and topographic setup. However, some similarities can be seen between the “deep foehn” in the Innsbruck region of the Alps, which displays comparable depth of wave disturbances in the atmosphere (>8 km; see Zängl 2003; Gohm et al. 2004). Deep foehn in the Alps occurs when the large-scale wind direction is approximately perpendicular to the ridge line resulting in wind speeds >30 m s⁻¹ and warming up to 15°C at the surface (Zängl 2003; Gohm et al. 2004). A critical layer in the upper troposphere is likely to play a role in trapping and amplification of the wave pattern in the MDVs similar to cases modeled by Zängl et al. (2004) and Zängl and Hornsteiner (2007) in the Alps, although this requires further examination beyond the scope of this paper.

The lower frequency of foehn events during summer compared to winter, also noted by Nylen et al. (2004), may be accounted for by reduced synoptic activity in the Ross Sea in summer (Simmonds et al. 2003). Although mean synoptic activity is reduced, synoptic composites indicate that the “mean” cyclonic system that develops in this region during summer events is comparable in size and strength to winter. A well-defined synoptic-scale cyclone may be necessary for the formation of foehn winds in summer due to interactions with the thermally driven easterly circulation. This circulation is extremely well developed in terms of its strength, depth, and persistence (McKendry and Lewthwaite 1990), and may
decouple from airflow aloft, preventing the grounding of foehn winds to the valley floors for extended periods (>6 h) unless overcome by particularly strong synoptic forcing. Vertical wind profiles by McKendry and Lewthwaite (1990) during a foehn event in the Wright Valley show evidence of foehn overriding cooler easterly winds. Decoupling of foehn winds from local thermal winds (lake breeze) at the surface was also found by McGowan and Sturman (1996b) in the southern Alps, New Zealand. When southerly gradient winds are strong enough or the easterly circulation weakens (e.g., at night when solar radiation is low) in the MDVs, foehn winds are able to descend to the surface.

Results presented here extend observations of the temporal and spatial characteristics of foehn in the MDVs, while our modeling study clarifies several aspects of foehn behavior in this unique environment. 1) Down-valley stations are sometimes affected before up-valley stations. Foehn onset in the MDVs may occur at down-valley locations before sites in the upper valleys because of the topographically modified foehn south-southwesterly entering the valleys from an acute angle to the valley axis such as through mountain passes (shown in Fig. 6). Turbulent motion associated with mountain waves may also cause foehn onset at different times and locations along the valley axis, while the warm and dry down-valley foehn may decouple from the surface on encountering local cold air drainage or cold air pools. The foehn may then ground farther down valley, possibly in response to local convective turbulence and associated mixing over the warm snow-free dry valley floors. 2) Down-valley stations experience strong easterlies during foehn events. As occurred in
the foehn case study presented here, cool easterly winds can penetrate into the eastern section of the Taylor Valley from McMurdo Sound undercutting the foehn and causing it to decouple from the surface. These easterlies are associated with cyclonic low pressure systems and southerly flow parallel to the Transantarctic Mountains. Strong southerly near-surface flow along the Ross Ice Shelf is deflected by Ross Island and forced to flow in a northwesterly direction toward the MDVs (O’Connor and Bromwich 1988; Seefeldt et al. 2003). When foehn winds are weak in the eastern sections of the MDVs, easterlies are able to penetrate into the valleys and are often observed immediately prior to foehn onset and/or cessation. The concept of an easterly “return flow” suggested by Nylen et al. (2004) is not plausible with a foehn mechanism. Foehn winds are synoptically driven unlike circulations such as valleys winds where conservation of mass infers the existence of an antwind or return flow. 3) Increasing foehn frequency with distance from the coast. Our analysis does indicate that a higher frequency of foehn events occurs in the western sections of the MDVs. This appears to be related to the intrusion of strong synoptically deflected easterly flow (all seasons) or thermally generated easterly winds (in summer) into the eastern sections of MDVs, thereby reducing the frequency of foehn at the surface in these areas. Lower topography at the eastern end of the Kukri Hills may also contribute to reduced frequency of foehn in the eastern Taylor Valley region.

This research demonstrates how cyclonic systems near the coast of Marie Byrd Land (between the Ross and Amundsen Seas) result in strong gradient winds over the MDVs that lead to foehn formation. The Ross Sea is a climatologically favored region for a high density of cyclonic systems (Simmonds et al. 2003; Uotila et al. 2009), which are crucial in the development of southerly winds over the MDVs and the associated development of foehn winds. Accordingly, variability in cyclone activity and the development of strong southerly pressure gradients in this region will directly influence foehn frequency in the MDVs as shown in this study with 10% more foehn events in 2006 than 2007. The MDVs are known to exhibit significant interannual climate variability (Welch et al. 2003; Bertler et al. 2006; Doran et al. 2008), yet the causal mechanisms have not been explored. Given the strong influence foehn winds have on the MDVs climate, it is highly likely that variability in the track and intensity of cyclonic systems in the Ross and Amundsen Sea is a major contributor to MDV climate variability. Furthermore, 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; Kwok and Comiso 2002; Bromwich et al. 2004). 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 (e.g., Fogt and Bromwich 2006), which influence the position and frequency of these cyclonic systems in the Ross Sea region. An analysis of foehn events in the MDVs AWS records over a longer time period is underway and will further the understanding of how ENSO and other known drivers of climate variability such as the southern annular mode are translated into interannual climate variability in the MDVs.

Additionally, variability seen in environmental processes in the MDVs may be linked to variability in the foehn wind regime. For instance, Doran et al. (2008) suggests that an increase in “down-valley winds” (foehn) in the summer of 2001/02 compared to 2000/01 was related to significant glacier mass loss and an increase in streamflow. The warmer foehn temperatures and increased glacial melt during the 2001/02 summer also led to an increase in lake levels, the thinning of the permanent ice covers, and other environmental effects (e.g., Foreman et al. 2004; Barrett et al. 2008). Although foehn warming in summer is not as dramatic as in winter, foehn frequently induces temperatures to rise above 0°C, an important environmental threshold.

7. Conclusions

This paper presents initial findings from the analysis of observational records and modeling to further understand the complex meteorology of the unique 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. AMPS output from the AMPS 2.2-km domain indicates that topographical interaction of synoptically forced airflow with the Transantarctic Mountains causes mountain wave activity that contributes to foehn wind genesis in the MDVs. 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 mountain ranges of the MDVs are responsible for foehn in the MDVs during all seasons. Importantly, this paper clarifies that a foehn mechanism is responsible for such strong warm wind events in the MDVs and the influence of katabatic surges from the polar plateau as an origin or triggering mechanism of events is minimal. Accordingly, we suggest the “katabatic” terminology adapted by researchers in the MDVs when referring to these wind events be replaced by “foehn” to reflect their correct origin.

This study has demonstrated that AMPS products are an effective tool to assist understanding large-scale circulations, regional airflow and local-scale atmospheric
dynamics in this region of the Antarctic where few observations exist. Further research is in progress detailing the complex atmospheric structure in the MDVs. Model simulations with high horizontal and vertical resolution using a polar-modified version of the Weather Research and Forecasting model (WRF; Skamarock et al. 2005), tailored for use in the MDVs, will be run to explore meteorological features in greater detail. Important model validation by field research is planned in 2011 and 2012.

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