INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2012)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3481

Regional climate variability driven by foehn winds in the McMurdo Dry Valleys, Antarctica

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ABSTRACT: Warm, dry and gusty foehn winds are frequently experienced in the McMurdo Dry Valleys (MDVs), Antarctica; however, their significance in the region's climate is unknown. Foehn events in the MDVs are caused by topographic modification of southwesterly airflow which is related to the occurrence of synoptic-scale cyclones in the Amundsen/Ross Sea region. The intra- and interannual frequency and intensity of foehn events therefore varies in response to the position and frequency of cyclones in this region that are believed to be strongly influenced by the El Niño Southern Oscillation (ENSO) and the Southern Annular Mode (SAM). Here, we present a 20-year climatology of foehn winds from observational records in the MDVs. The SAM is found to significantly influence foehn wind frequency during the Antarctic summer and autumn months, whereas ENSO only holds significant correlations with winter air temperatures in the MDVs. The positive relationship between the SAM and the foehn wind regime in summer is particularly significant as foehn winds frequently cause summer temperatures to rise above 0 °C leading to extensive melt and thaw in MDVs. Foehn winds are a major climatological feature of the MDVs with their frequency and duration affecting the region's temperature records and their trends. Accordingly, analysis of the region's weather and climate records and predictions of future impacts of climate change on the MDVs is incomplete without consideration of foehn winds and their influence. Copyright © 2012 Royal Meteorological Society

KEY WORDS foehn; Föhn; katabatic; climate variability; dry valleys; Antarctica

Received 13 April 2011; Revised 3 November 2011; Accepted 11 March 2012

1. Introduction

Foehn winds are warm, dry and gusty downslope winds that occur in the lee of mountain barriers. While several thermodynamic mechanisms can result in foehn winds (Seibert, 1990; Zängl, 2003) they are commonly caused by topographic modification of strong airflow. Foehn winds are frequently experienced in the McMurdo Dry Valleys (MDVs) of Antarctica where they cause dramatic warming at onset and are suspected to have significant effects on landscape forming processes including glacial melt, streamflow (Welch *et al.*, 2003; Doran *et al.*, 2008), rock weathering (Selby *et al.*, 1973), aeolian processes (Ayling and McGowan, 2006; Speirs *et al.*, 2008) and biological productivity (Fountain *et al.*, 1999; Foreman *et al.*, 2004). Despite the significance of foehn winds to the landscape, little research has been conducted on the forcing mechanisms and variability. As a response, warm wind events in the MDVs have been historically misinterpreted as adiabatically warmed katabatic winds draining from the polar plateau. Recently, Speirs *et al.* (2010) clarified that a foehn mechanism is responsible for these events as originally proposed by Thompson *et al.* (1971) and McKendry and Lewthwaite (1990). Through analysis of automatic weather station (AWS) records and modelling using the Antarctic Mesoscale Prediction System (AMPS), Speirs *et al.* (2010) show that foehn winds in the MDVs are caused by topographic modification of south-southwesterly airflow which is channelled down into the valleys from above ridge-top. Modelling of a winter foehn event identified mountain wave activity similar to that observed during mid-latitude foehn winds (Beer, 1976; Durran, 1990; Seibert, 1990; Zängl, 2003). Foehn events were found to be associated with strong pressure gradients over the mountain ranges of the MDVs commonly caused by synoptic-scale cyclones positioned in the Ross Sea region.

The MDVs are known to exhibit significant interannual climate variability (Welch *et al.*, 2003), although the role of foehn frequency on this variability is unknown. The El Niño Southern Oscillation (ENSO) displays a prominent signal in the Antarctic on interannual and interdecadal time scales (see Yuan, 2004; and review by Turner, 2004). It is believed that the ENSO signal reaches the high southern latitudes via a Rossby wave train termed the Pacific South American (PSA) pattern triggered by changes in tropical convection (Karoly, 1989; Revell

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et al., 2001). The most pronounced ENSO signal found in the Antarctic is related to the mean position and intensity of depressions and anticyclonic blocking (Chen *et al.*, 1996; Renwick, 1998; Bromwich *et al.*, 2004) and in particular, the position of a climatologically favoured region of cyclonic circulation known as the Amundsen Sea Low (Cullather *et al.*, 1996; Kwok and Comiso, 2002a). During neutral and La Niña phases of ENSO, this 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, 2004; Cullather *et al.*, 1996; Carleton, 2003;). ENSO-related variability has been found in precipitation (Cullather *et al.*, 1996; Bromwich *et al.*, 2000), sea ice extent (Yuan, 2004; Pezza *et al.*, 2008), sea surface temperature (Ledley and Huang, 1997), surface temperature (Kwok and Comiso, 2002b) and air temperature (Smith *et al.*, 1996). Several studies have noted, however, that despite correlations to ENSO signals, there are inconsistent responses between events and climate variability over the Antarctic continent (Smith and Stearns, 1993; Lachlan-Cope and Connolley, 2006; Gregory and Noone, 2008). ENSO coupling with the Southern Annular Mode (SAM) is believed to account for some of this variability (Fogt and Bromwich, 2006; L'Heureux and Thompson, 2006; Fogt *et al.*, 2011).

The SAM, also known as the high-latitude mode (HLM) or the Antarctic oscillation (AAO), is seen as the leading empirical orthogonal function (EOF) in Southern Hemisphere zonal pressure anomalies (Thompson and Wallace, 2000; Gong and Wang, 1999; Kidson, 1999), and is increasingly recognized as the most dominant source of climate variability in the southern high latitudes (Marshall, 2003). The SAM is also described by a meridional index of the zonally averaged pressure difference between middle and high latitudes, which is a measure of the strength of the polar vortex (Gong and Wang, 1999; Thompson and Wallace, 2000; Marshall, 2003). During the positive phase of the SAM, lower pressures are observed around Antarctica and higher pressures in the mid-latitudes and vice versa during the negative phase. An increase in cyclone depth and density around Antarctica is also associated with the positive phase of the SAM (Kidson and Sinclair, 1995; Sinclair *et al.*, 1997; Pezza *et al.*, 2008). A positive trend in the SAM over the past ~50 years (Marshall, 2003), has been linked to warming in the Antarctica Peninsula region (Marshall *et al.*, 2006) and cooling across continental Antarctica (van den Broeke and van Lipzig, 2004; Kwok and Comiso, 2002b). The recent trend in the SAM has been linked to ozone depletion, greenhouse gases (and other anthropogenic forcings) but also natural forcings such as ENSO (Marshall *et al.*, 2004; Arblaster and Meehl, 2006; Fogt and Bromwich, 2006). Modulation of the SAM and ENSO by other teleconnections such as the semi-annual oscillation (SAO; van den Broeke, 2004), Antarctic circumpolar wave (ACW; White and Peterson, 1996), in addition to feedbacks from sea ice and ocean circulation increases the complexity in understanding variability in the Antarctic climate system.

Climate variability in the MDVs has previously been linked to ENSO (Welch *et al.*, 2003; Bertler *et al.*, 2004; Patterson *et al.*, 2005), and the SAM (Bertler *et al.*, 2006); however, it is unclear how these signals are transmitted to the region. Welch *et al.* (2003) noted a negative relationship between the Southern Oscillation Index (SOI) and stream discharge and found that summers of highest stream flows (and warming) generally occur when SOI is negative (El Niño) or near neutral, while lowest stream flows (and cooling) coincide with neutral to positive SOI (La Niña). This relationship, however, was not statistically significant and several summers showed a positive relationship (Welch *et al.*, 2003). Bertler *et al.* (2004) analysed snow pits on the Victoria Lower Glacier and re-analysis data (ERA-40) from the European Centre for Medium-Range Weather Forecasts. They found a positive relationship between the SOI and summer temperature and noted that the MDVs frequently experience warmer temperatures during La Niña and cooler temperatures during El Niño. Similar results were presented by Patterson *et al.* (2005) who analysed a 50 year ice core record also from the Victoria Lower Glacier. Patterson *et al.* (2005) and Bertler *et al.* (2006) postulate that such signals may manifest themselves in the MDVs via the advection of warmer marine air into the MDVs during La Niña and colder katabatic surges from West Antarctica during El Niño. Bertler *et al.* (2006) present a lead/lag relationship in the SOI, SAM and Scott Base temperature records and suggest that the influence of SAM can explain the variability in ENSO forcing on temperature. In terms of temperature trends, Doran *et al.* (2002b) showed that surface air temperature measurements from automatic weather stations in the MDVs displayed a cooling of 0.7 °C per decade between 1986 and 2000. The cooling trend was significantly correlated with decreased winds and increased clear-sky conditions (Doran *et al.*, 2002b). They suggested the MDVs cooling was part of a larger scale and longer term net cooling, while Bertler *et al.* (2004) invoke an ENSO mechanism to explain the cooling. Despite the apparent cooling of air temperatures, little change in glacier mass balance has occurred and the MDV's glaciers are therefore believed to be in equilibrium with the current climate (Fountain *et al.*, 2006).

This article investigates the influence of foehn winds on the MDVs climate system, including its temperature regime. A 20 year (1987 to 2008) observational record is used to examine connections between synoptic circulation, foehn wind frequency and climate variability. Doran *et al.* (2002b, p. 518) stated that 'estimating long-term temperature change in coastal Antarctica requires an understanding of the synoptic controls on surface wind variability, which at present are incompletely understood'. Understanding the role of foehn winds in the climate of the MDVs is therefore essential to understanding this unique region's climate, its trends and possible impacts of future climate change.

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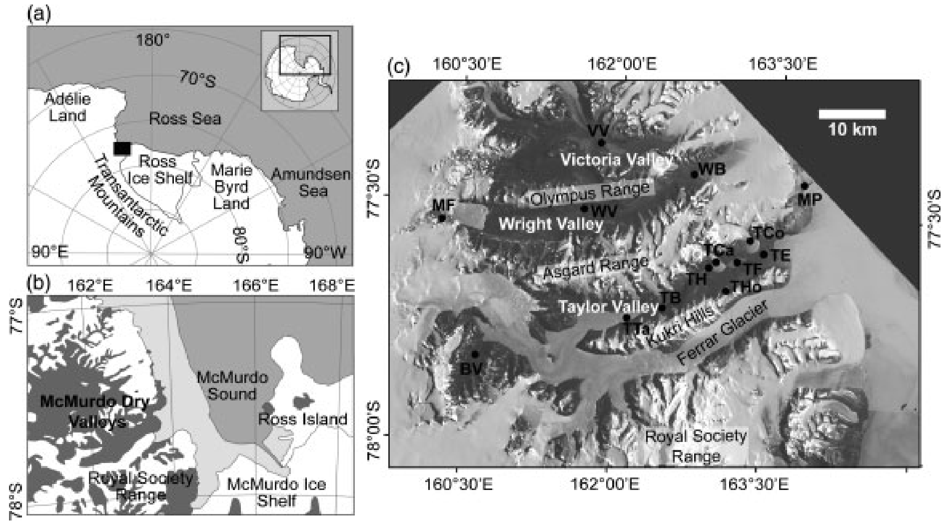

Figure 1. (a) Map of the Ross Sea region of Antarctica. (b) Inset of black box in (a) showing McMurdo Dry Valleys region. (c) The McMurdo Dry Valleys AWS network used in this study. See Table 1 for AWS information. Landsat ETM+ image captured 21 November 2001.

2. 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 above sea level separate the valleys, which have a polar desert climate due to their location in a precipitation shadow (Monaghan *et al.*, 2005). Annual precipitation is <50 mm water equivalent with precipitation decreasing away from the coast (Fountain *et al.*, 2010). Mean annual air temperature from seven valley floor AWS range between $-14.8\,°\mathrm{C}$ and $-30\,°\mathrm{C}$ (Doran *et al.*, 2002a). The wind regime of the MDVs is characterized by up- or down-valley topographically channelled airflow. During summer, thermally generated easterly winds dominate (McKendry and Lewthwaite, 1990). This circulation develops due to differential surface heating between the low-albedo valley floors and the high-albedo ice and water surfaces to the east, analogous to sea/lake breeze circulations elsewhere. The difference in heat capacity between the bare-ground surfaces in the MDVs and the open water of McMurdo Sound/Ross Sea to the east during summer may also help facilitate the thermally generated easterly circulation. In winter, wind direction is typically more variable with cold air pools forming in topographic low points of the valleys with light winds and minimum temperatures $< -50\,°\mathrm{C}$ (Doran *et al.*, 2002a). Topographically channelled southwesterly foehn winds, are frequently recorded throughout the year (Speirs *et al.*, 2010).

3. Methods

Meteorological data were obtained from AWS operated by the McMurdo Dry Valleys Long-Term Ecological Research (LTER) program (Doran *et al.*, 1995). Data from the Mount Fleming site was provided by the United States Department of Agriculture Natural Resources Conservation Service (USDA/NRCS) and the Marble Point site operated by the University of Wisconsin Antarctic Automatic Weather Station (UW AWS) Program (Stearns *et al.*, 1993). Table I lists the location and station ID for the AWSs used in this study. The configuration of these MDVs LTER program stations is detailed at http://www.mcmlter.org/queries/met/met_home.jsp and in Doran *et al.* (2002a). Meteorological measurements by the AWS are made at 3 m above the surface.

A selection criterion to identify foehn wind events in the MDVs AWS records was applied to data from Lake Hoare (TH), Lake Bonney (TB), Lake Vanda (WV) and Lake Vida (VV) AWS. These valley floor stations have the longest and near continuous meteorological records which are detailed in Figure 2. They are also centrally located in the valleys and are less influenced by easterly or glacial winds. Periods of missing data were excluded from analyses. Foehn onset was identified by an increase of wind gust speed above 5 m s^{-1} from a westerly direction, a warming of at least $+1\,°\mathrm{C}$ per hour and a decrease of relative humidity of at least 5% per hour. The wind directions used in the criteria are 180° to 315° at TH, TB, WV and 180° to 360° at VV to account for the more open nature of the valley at this site. The introduction of temperature and humidity criteria compared to earlier work by, for example, Nylen *et al.* (2004) reduces the misclassification of westerly glacial winds as foehn winds as these winds can, at times, exceed 5 m s^{-1} (Speirs *et al.*, 2010). Owing to 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 or more hours of foehn conditions with wind gust speed >5 m s^{-1} from the southwesterly directions previously mentioned. The foehn day criteria works on a moving

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Table I. MDVs AWS information.

ID	Location	Station	Latitude, longitude	Elevation (m asl)
VV	Victoria Valley	Lake Vida	77.38 S, 161.80 E	351
WV	Wright Valley	Lake Vanda	77.52 S, 161.67 E	296
WB		Lake Brownworth	77.43 S, 162.70 E	279
TE	Taylor Valley	Explorers Cove	77.59 S, 163.42 E	26
TH		Lake Hoare	77.63 S, 162.90 E	78
TB		Lake Bonney	77.71 S, 162.46 E	64
TTa		Taylor Glacier	77.74 S, 162.13 E	334
THo		Howard Glacier	77.67 S, 163.08 E	472
TCo		Commonwealth Glacier	77.56 S, 163.28 E	290
BV	Beacon Valley	Beacon Valley	77.83 S, 160.66 E	1176
MF	Mount Fleming	Mount Fleming	77.55 S, 160.29 E	1697
MP	Marble Point	Marble Point	77.44 S, 163.75 E	108

window and is not constrained to a calendar day. If 6 or more hours of foehn conditions are observed, then a foehn day is recorded on the day of foehn wind cessation. When sampling intervals were > 1 h (e.g., pre-1995 at Lake Hoare), the criteria was altered accordingly and foehn days were identified manually. A manual check of the foehn day criteria against 2 years of data at Lake Hoare found that the automated approach was 93 % accurate in identifying foehn periods > 6 h. Foehn days were missed 3% of the sample period and 4% were overestimated. These misclassifications primarily occurred during pre-foehn or post-foehn conditions due to sensitivities in the criteria during the transitional periods. 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, a criterion such as the foehn day is necessary.

Numerical forecast model products presented here were obtained from the Antarctic Mesoscale Prediction System (AMPS, Powers *et al.*, 2003). AMPS is an experimental forecasting system developed jointly by the Polar Meteorology Group of the Byrd Polar Research Center, The Ohio State University, and the Mesoscale and Microscale Meteorology division of the National Center for Atmospheric Research (NCAR) in support of United States Antarctic Program (USAP) operations. AMPS Polar MM5 output is used in this study with 20 km grid spacing, on a grid domain covering Antarctica and much of the surrounding Southern Ocean. There are 31 vertical half-sigma levels, with 11 levels in the lowest 1000 m to capture the complex processes in the planetary boundary layer. The lowest half-sigma level is about 13 m above the surface. AMPS Polar MM5 is initialized twice daily at 0000 and 1200 UTC. Guo *et al.* (2003) evaluated Polar MM5 performance over Antarctica for a 1 year period (1993) on a 60 km resolution domain and showed that the intra- and interseasonal variability in pressure, temperature, wind and moisture are well resolved. Bromwich *et al.* (2005) evaluate d2 years of AMPS Polar MM5 forecasts on the 30 km domain and showed that the same variables are well resolved at synoptic time scales.

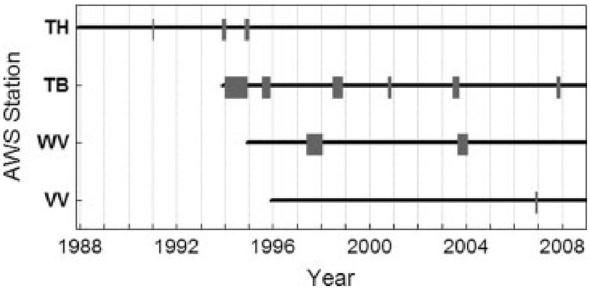


Figure 2. AWS record length (black line) and missing data (grey bands) relevant to foehn identification.

The Japanese Reanalysis Project (JRA-25, Onogi *et al.*, 2005., 2007) data is used here to study longer term variability in synoptic circulation that affect the MDVs. The JRA-25 has 6 hourly data assimilation cycles, model resolution of T106 (1.125°, ~125 km), with 40 vertical levels. Bromwich *et al.* (2007) evaluated the performance of the JRA-25 reanalyses against the European Centre for Medium-Range Weather Forecasts (ECMWF) 40 year reanalysis (ERA-40) and the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) global reanalysis in the Antarctic. They found that while some large differences between the reanalyses products existed, particularly over the Antarctic interior, all three reanalyses are fairly consistent and capture interannual variability in 500 hPa geopotential height well (Bromwich *et al.*, 2007). In this study, sea level pressure composites of the JRA-25 6-hourly datasets are used over the 1980–2008 period.

4. Results and analysis

4.1. Significance of foehn winds in the MDVs climate

Examples of summer and winter foehn events in the MDVs are shown in Figure 3. These two events were associated with the movement of large cyclones into the Ross Sea which resulted in strong synoptic pressure gradients and strong winds in the Transantarctic Mountains

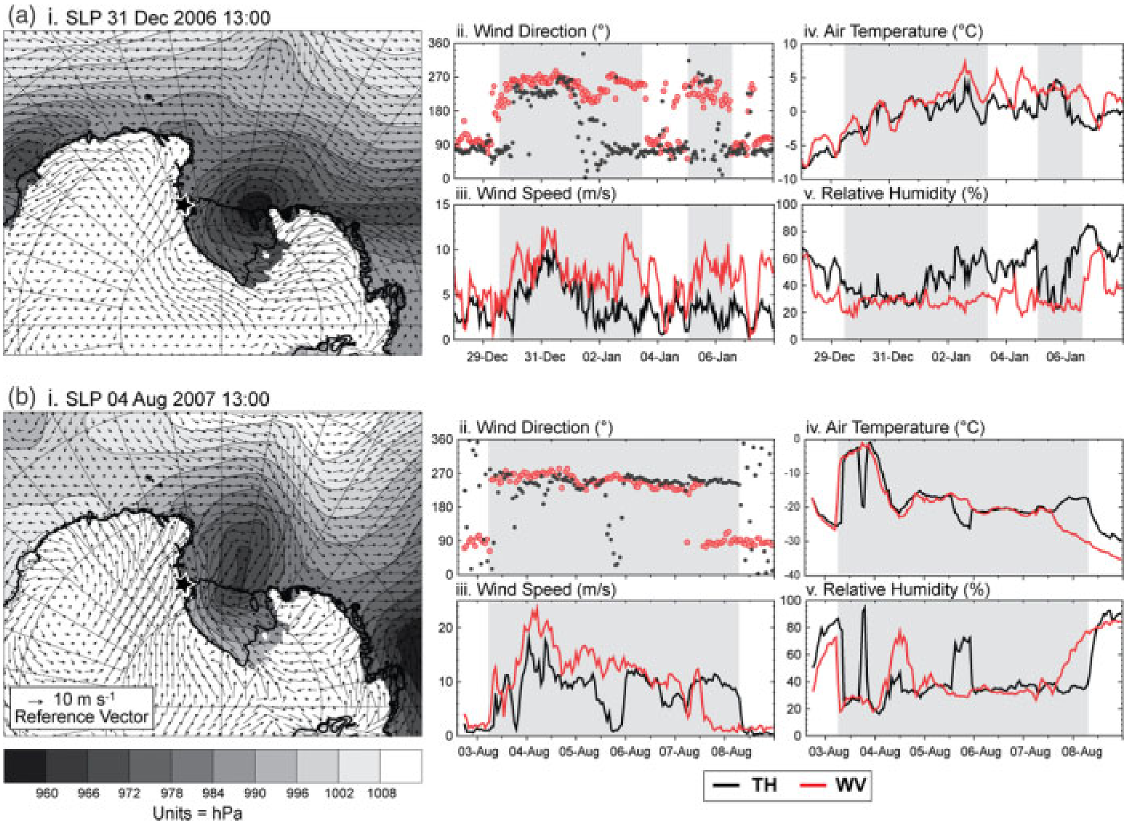


Figure 3. Meteorological conditions during (a) summer and (b) winter foehn wind events in the MDVs: i. AMPS SLP and near-surface wind vectors, ii–v. hourly averaged automatic weather station data for TH (Lake Hoare, Taylor Valley) and WV (Lake Vanda, Wright Valley). Shading in ii–v. highlights foehn conditions. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

and MDVs region. Onset of foehn winds in the MDVs is characterized by a sudden shift to southwesterly wind direction, increases in wind speed and air temperature and a corresponding decrease in relative humidity. During the summer event (29 December 2006 to 6 January 2007; Figure 3(a)) maximum wind gusts of 22.7 m s^{-1} at Lake Vanda and 18.0 m s^{-1} at Lake Hoare were recorded. Air temperatures reached a remarkable +7.8 °C and +6.5 °C at these stations, respectively. The foehn event lasted longer at Lake Vanda than Lake Hoare where it decoupled earlier from the surface due to the penetration of the easterly 'sea-breeze' from McMurdo Sound. Air temperatures remained elevated in the MDVs for several days after foehn cessation which we believe is the result of warming from surface sensible heat fluxes as a result of the foehn.

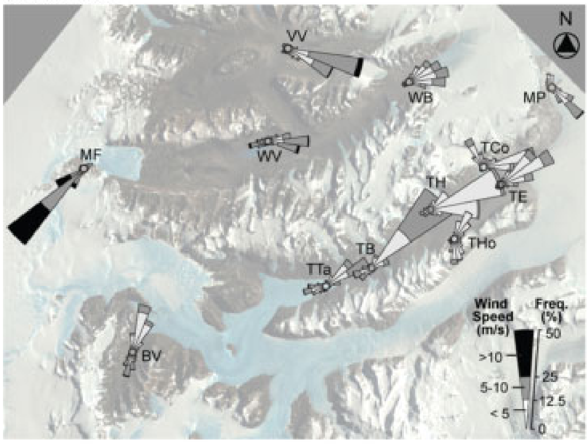
Figure 3(b) presents a winter foehn event (3 August 2007 to 8 August 2007) which developed in response to southwesterly airflow over the MDVs caused by cyclogenesis in the Ross Sea (Figure 3(b)). In this case, air temperatures in the MDVs were already slightly elevated due to a previous foehn event and reached maximum temperatures of +0.3 °C at Lake Vanda and −0.3 °C at Lake Hoare. Such high temperatures are believed to be unprecedented at similar latitudes during the Antarctic winter. Maximum wind gusts reached 34.4 m s^{-1} at Lake Vanda and 28.3 m s^{-1} at Lake Hoare. Similar to the case study shown in Speirs *et al*. (2010) a break in foehn conditions at Lake Hoare occurred during this event as synoptically forced easterlies entered the Taylor Valley. Foehn conditions were re-established at Lake Hoare and persisted for almost 30 h after cessation at Lake Vanda before a return to cool and calm conditions dominated by local cold air drainage winds and cold pool formation.

Foehn wind events such as those presented in Figure 3 play a significant role in the overall wind regime of the MDVs. Figure 4 displays summer and winter wind roses for the region and extend the results of Nylen *et al*. (2004) with longer sampling periods and introducing wind speed classes to identify strong winds. These highlight the strong topographic controls of the region's wind regime with wind directions at the valley floor sites controlled by valley orientation. During summer (Figure 4(a)) thermally generated easterly winds dominate all sites on the valley floors. The easterly wind regime is extremely well developed in terms of its strength and depth (McKendry and Lewthwaite, 1992) and is also observed on the valley sidewalls at the Commonwealth (TCo, 290 m asl) and Howard Glaciers (THo, 472 m asl). Light downslope glacier winds also prevail at these sites, predominantly during the summer 'night' hours when solar radiation is reduced and shading of these sites occurs. In the westernmost regions of the valleys (e.g., Taylor Glacier site, TTa), light summer winds can have a westerly direction which may be due to a combination of downslope and thermally generated flow developing between the dry valley floors and the western ice and glacial surfaces. During winter (Figure 4(b)) calmer conditions are more prevalent and a wider range of wind directions are observed due to the cold air drainage off glaciers which pond at topographical low points in the valleys. Foehn winds can be seen in Figure 4 as the strong south-southwesterly component of the wind regime. Foehn winds are the predominant source of strong winds in the MDVs. They comprise an annual average of 65 % of days with mean wind speed >5 m s^{-1} and 91% of days with mean wind speed >10 m s^{-1}.

Out of the valleys, for example, at Mt. Fleming (1697 m asl, MF) the dominant wind direction is from the southwest and shows little seasonal variation. The Mt. Fleming station is on an exposed site and the southwesterly wind direction observed here is believed to be primarily gradient airflow. The Marble Point station (MP) borders McMurdo Sound and the southeasterly dominated wind direction at this site is attributed to the channelling of southerly flow between Ross Island and the mainland (O'Connor and Bromwich, 1988). Southwesterly foehn winds are, on occasion, experienced at Marble Point upon exiting the Taylor Valley. The Beacon Valley station (BV) also experiences thermally generated winds during summer and foehn winds throughout the year. At this location, winds are topographically channelled by the north-south valley orientation (i.e., southerly foehn, northerly thermally generated flow).

The annual distribution of foehn days for the selected stations (Lake Hoare, Lake Bonney, Lake Vanda and Lake Vida) as defined by the foehn criteria is shown in Figure 5. The winter maximum in foehn events, as noted by Speirs *et al.* (2010), corresponds to the winter maximum in cyclonic activity in the Ross Sea (Simmonds *et al.*, 2003). The two stations in the Taylor Valley (Figure 5(a)) show a similar annual foehn distribution pattern although Lake Hoare has slightly fewer foehn events owing to the station's more easterly location being more susceptible to easterly winds, either thermally-generated in summer or strong synoptically forced easterlies which may occur year round. Foehn frequency is greater in summer at Lake Vanda compared to Lake Bonney and Lake Hoare, possibly due to greater effect of easterlies in the Taylor Valley. The annual distribution pattern of foehn winds in Lake Vanda and Lake Vida (Figure 5(b)) are similar, despite being located in different valleys, with lowest foehn frequency in the months February–April. During winter, Lake Vida records the lowest foehn frequency due to intense cold pooling that

(a) Summer



(b) Winter

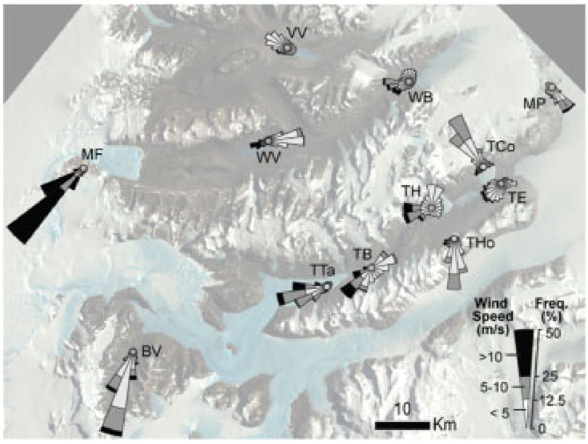


Figure 4. Wind roses displaying wind speed frequency and distributions for sites within the MDVs during (a) summer (DJF) and (b) winter (JJA). Data are from the 10 year period 1999–2008 except for Mount Fleming which are for the 2002–2008 period. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

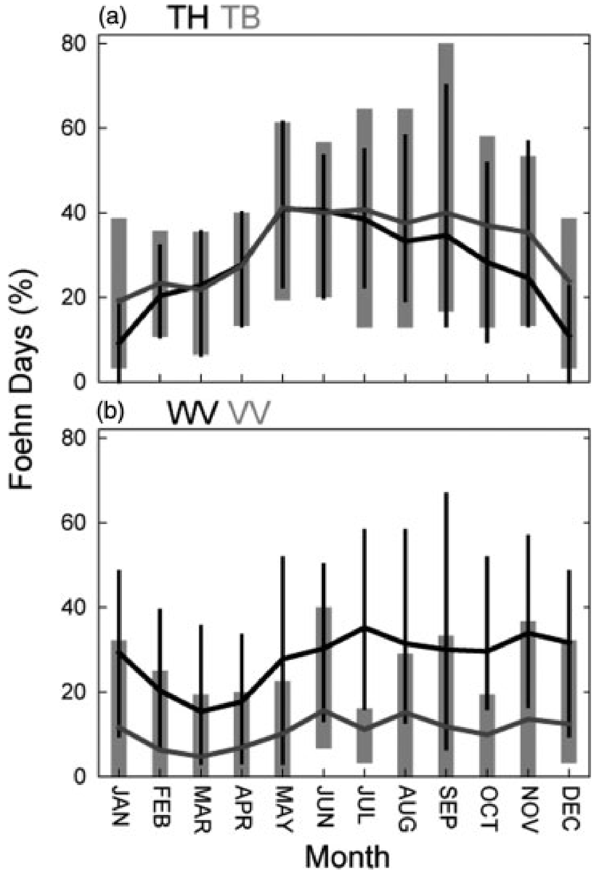


Figure 5. Monthly mean (solid line), minimum and maximum (bars) foehn days for (a) Lake Hoare (TH) and Lake Bonney (TB) and (b) Lake Vanda (WV) and Lake Vida (VV) between 1996 and 2008.

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is thought to inhibit the grounding of foehn to the surface (Doran *et al*., 2002a, 2002b). Foehn forcing mechanisms may also become dampened in the northernmost valley (contributing to the year-round low foehn frequency at Lake Vida), although such complexities within the atmosphere are yet to be confirmed by high-resolution modelling in the MDVs. Figure 5 also highlights the significant interannual variability in the occurrence of foehn winds in the MDVs, as seen in the minimum and maximum range bars.

Warmer air brought to the surface from upper levels and from adiabatic warming during foehn significantly influences the temperature regime of the MDVs. The relationship between seasonal mean air temperature and foehn frequency is shown in Figure 6. The strongest foehn effect on mean temperature is seen during the austral autumn where every 1% increase in seasonal foehn day frequency is equivalent to a +0.57 °C temperature increase. Frequent foehn events during these months can prevent cooling of the landscape as solar insolation decreases leading into winter. During spring, high foehn frequency can flush cold air from the valleys and facilitate snow and ice ablation thereby allowing greater solar insolation into the low albedo ice-free sand and rock surfaces. The averaging of large swings in temperature during winter events can explain the more variable nature of the relationship during this season. The influence of foehn on mean seasonal temperatures is weakest in summer when foehn is less frequent, events are shorter due to increased dominance of easterly winds, and temperature changes during this season are less dramatic as a result of higher ambient air temperatures. Despite this, foehn during summer is still very influential on the temperature regime. Foehn events comprise 38% of days with a mean daily air temperature >0 °C. When a 48 h temperature lag is taken into account as is often observed during summer foehn events (Nylen *et al*., 2004; Speirs *et al*., 2008), then foehn comprise 58 % of days with a mean daily air temperature >0 °C.

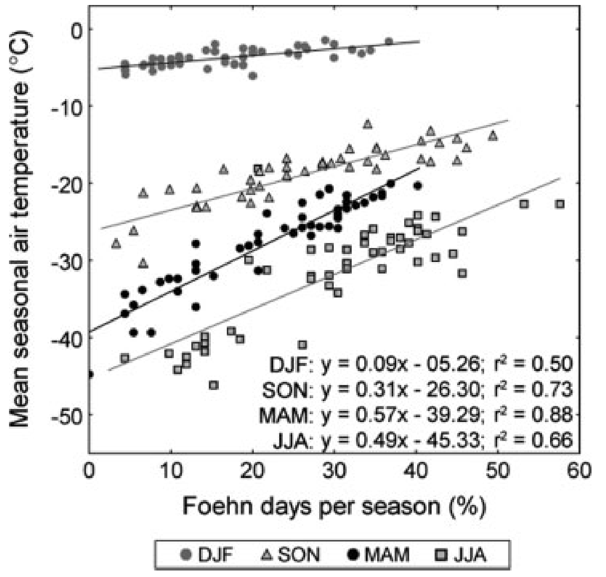

Figure 6. Relationship between seasonal mean air temperature and foehn day frequency. Data is combined for TH, TB, WV and VV for the 1996–2008 period. Note: the visual appearance of summer would suggest a higher r^2 than stated; however, this is a result of a similar variation of foehn days but a much lower temperature range compared to other seasons.

4.2. Foehn wind variability 1987–2008

Figure 7 presents the standardized monthly foehn anomaly against air temperature anomalies for Lake Hoare. Monthly data is standardized by subtracting the 1987–2008 mean and dividing by the standard deviation. This relationship is statistically significant ($r^2 = 0.34$, $p < 0.05$), which is not surprising given the strong influence of foehn on mean air temperatures (Figure 6). Figure 8 displays the seasonal frequency of foehn days in the MDVs over the length of the station records. All four stations show a similar pattern in variability which can be expected given the regional scale of foehn events in the MDVs. Interannual variability is largest in spring (standard deviation (σ) = 7.83), followed by winter ($\sigma = 6.81$) and summer ($\sigma = 6.57$). Autumn shows the least interannual variability compared to the other seasons ($\sigma = 4.75$). Lake Hoare and Lake Bonney show similar seasonal characteristics and similarly, patterns at Lake Vanda and Lake Vida show a resemblance. In the foehn record for summer, the seasons of 1999/2000 and 2001/2002 stand out with particularly high frequency of foehn days.

Both Figures 7 and 8 show evidence of significant variability in the foehn and temperature records. Considering that SAM and ENSO are known to affect synoptic circulation in the Ross/Amundsen Seas, we investigate the relationship between these teleconnections on foehn frequency and temperature in the MDVs. The correlation statistics for seasonally averaged foehn days and air temperature against the SOI and the SAM index are shown in Table II. The SOI used in these analyses is obtained from the NOAA Climate Prediction Center (http://www.cpc.noaa.gov/data/indices/) while the SAM index used is the observationally based Marshall (2003) index http://www.antarctica.ac.uk/met/gjma/sam.html).

In the time periods examined here (1995–2008 and 1987–2008 for Lake Hoare), no statistically significant linear relationships are evident between the SOI and foehn days. A positive correlation with winter air temperature and the SOI is however evident ($r = 0.68$, $p < 0.05$), suggesting warmer winter conditions occur during the La Niña phase of ENSO compared to El Niño. Interestingly, if the time period of these analyses is isolated to the most recent decade (1999–2008, not shown), a strong positive correlation with foehn days appears in spring ($r = 0.79$, $p < 0.05$) suggesting a nonlinear SOI–foehn relationship may exist during this season. Despite no statistically significant correlation between the SOI and foehn days in winter, the relationship between the SOI and air temperature is still at least partly caused by the foehn wind regime considering the significant relationship between air temperature and foehn days during

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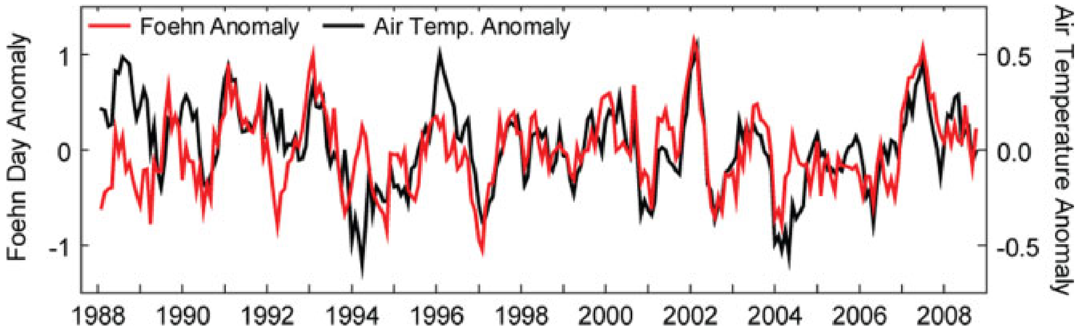

Figure 7. Monthly standardized foehn anomaly compared with the standardized air temperature anomaly for Lake Hoare. Data are smoothed with a 5 month moving average. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

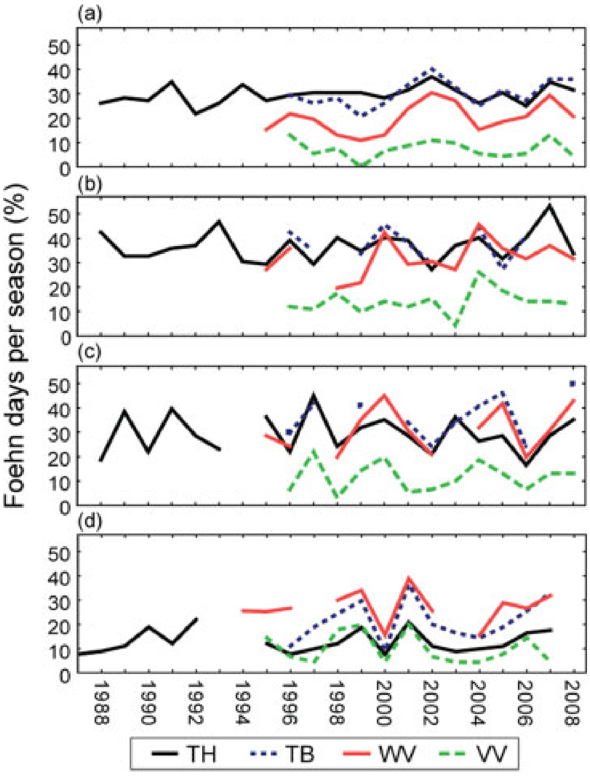

Figure 8. Foehn days per season for selected sites in the MDVs. (a) Autumn (MAM), (b) Winter (JJA), (c) Spring (SON), (d) Summer (DJF). For summer, the year denotes December. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Table II. Correlation statistics for average seasonal foehn days (FD) and air temperatures against ENSO and SAM. All data is averaged between stations (TH, TB, WV, VV) for the 1995–2008 period while Lake Hoare (TH) data is for the 1987–2008 period. Statistical significance at the 95% level is highlighted in bold.

	Trend FD/10 year^{-1}; °C/10 yr−$^{-1}$	SOI r	SAM index r
DJF FD	+1.58	+0.37	**+0.75**
(TH)	+0.70	+0.62	+0.40
MAM FD	+2.71	−0.30	**−0.77**
(TH)	+1.70	−0.19	−0.15
JJA FD	+4.66	+0.01	−0.36
(TH)	+1.48	+0.19	+0.05
SON FD	+1.54	+0.09	+0.08
(TH)	−0.43	−0.16	+0.04
DJF Air Temp.	−0.004	−0.09	+0.01
(TH)	−0.14	−0.17	+0.04
MAM Air Temp.	+0.08	−0.07	−0.50
(TH)	−0.06	+0.17	−0.37
JJA Air Temp.	+0.11	**+0.68**	−0.10
(TH)	−0.06	**+0.50**	−0.31
SON Air Temp.	−0.08	+0.23	+0.29
(TH)	−0.06	+0.12	−0.27

winter ($r^2 = 0.66$, $p < 0.05$; Figures 6 and 7). Warmer conditions in the MDVs are associated with more frequent foehn wind events, reduced cool easterlies from the coast and less frequent calm conditions which promote local cold air drainage wind and stagnation.

The synoptic circulation over the region during ENSO phases has been well documented (Karoly, 1989; Kwok and Comiso, 2002a; Bromwich *et al.* 2004; Turner, 2004). During neutral and La Niña phases of ENSO the Amundsen Sea Low occupies a position near the eastern Ross Sea resulting in increased southerly geostrophic winds in the Ross Ice Shelf/Sea region (Kwok and Comiso, 2002a). This is likely a result of enhanced cyclone activity or intensity which could cause an increase in foehn winds and warming in the MDVs through topographic modification of the southerly airflow. During the El Niño phase of ENSO when the Amundsen Sea low shifts further towards the Antarctic Peninsula, cyclone activity in the Ross Sea and foehn winds in the MDVs decrease, causing a cooling. The relationship in winter coincides with the strongest correlation between the SOI and cyclone anomalies found by Sinclair *et al.* (1997). It should be noted that SOI connections are limited over this relatively short dataset given the long periodicity of ENSO. Another constraint on the SOI–foehn relationship is related to Antarctic variability in the ENSO signal across the time period being examined here. Bromwich *et al.* (2000) found that a close relationship between West Antarctic net precipitation and the SOI switched signs between the 1980s and 1990s. Fogt and Bromwich (2006) relate these changes in ENSO to interaction between the PSA pattern and the SAM. The late 1990s show a much stronger ENSO

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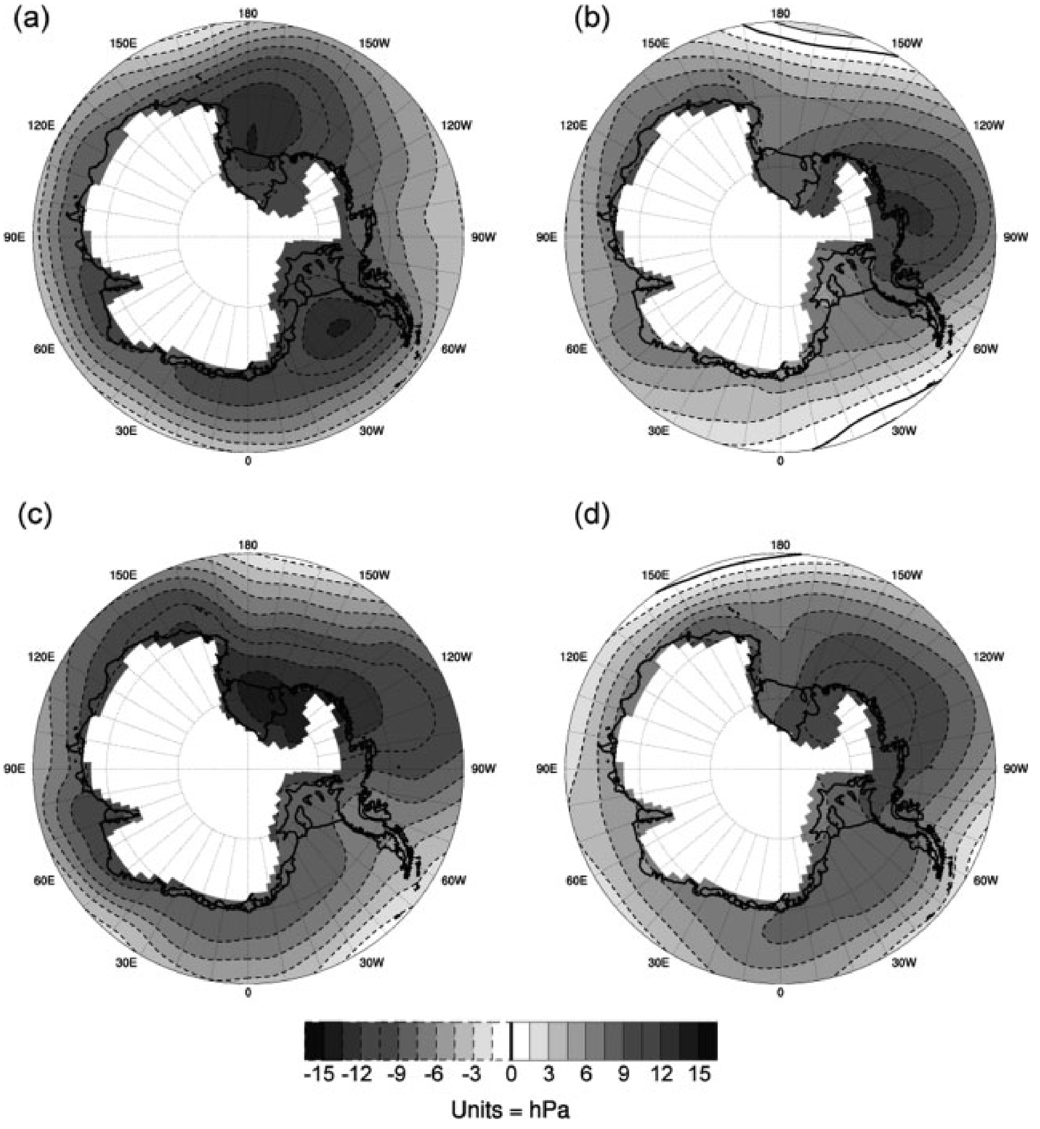

Figure 9. JRA-25 MSLP differences for positive SAM seasons minus negative SAM season over the 1980–2008 period: (a) DJF, (b) MAM, (c) JJA, (d) SON. The zero line is marked in bold and positive MSLP is shown by solid lines (only evident for MAM, plots are mainly negative). Note: SLP is masked above 500 m terrain due to uncertainties calculating SLP over the cold and high-elevation Antarctic continent.

teleconnection in a large area of the South Pacific and Amundsen-Bellingshausen Seas particularly during the spring months (Fogt and Bromwich, 2006). This variability in ENSO is perhaps why more significant linear correlations between the SOI and foehn frequency are not seen in this analysis.

The SAM shows linear correlations with foehn wind frequency in the MDVs with a positive relationship between average summer foehn and the SAM index evident for the 1995–2008 period (Table II). A positive relationship with SAM can be expected as high SAM indices are associated with decreased MSLP and greater cyclonic density around the Antarctic (Sinclair *et al.*, 1997; Pezza *et al.*, 2008). Interestingly, a negative correlation is evident for autumn in the 14 year averaged foehn record, but not in the longer record at Lake Hoare. A negative SAM–air temperature relationship is also evident, although this is only significant at the 90% confidence level. This relationship could be considered of less importance than during summer considering that the variability of foehn in autumn is lower.

To further examine differences in atmospheric circulation during contrasting phases of SAM and the relation to foehn in the MDVs, seasonal SLP differences for positive and negative phases of SAM are presented in Figure 9. The purpose of this figure is to better understand the processes relating to foehn wind variability rather than analyse the robustness and statistical significance of the SAM on Antarctic circulation (this can be found elsewhere, e.g., Kidson, 1999; Jones *et al.*, 2009). Positive SAM seasons were defined as those that exceed +2 of the SAM index and negative SAM seasons as those with a SAM index less than −2, similar to Marshall *et al.* (2006). This analysis was extended to examine the 'contemporary era' from 1980 to 2008. The seasons used in this analysis are shown in Table III. Several of the strongly positive or negative SAM years are also El Niño/La Niña years (highlighted in Table III) hence an ENSO signal could

Table III. Negative and positive SAM seasons used in the composite analysis for Figure 9. Years in bold denote El Niño years while those in bold-italics denote La Niña years (based on NOAA Climate Prediction Center classification: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

Season	Phase	Composite analysis years					
MAM	−SAM	1980	1981	1986	1990	2002	
	+SAM	1982	***1989***	1993	***1999***	***2000***	
JJA	−SAM	**1992**	1995	2007			
	+SAM	1993	***1998***	**2004**			
SON	−SAM	1980	***1988***	**1994**	1996	***2000***	**2002**
	+SAM	1983	1985	1993	***1999***	2001	
DJF	−SAM	**1982**	***1984***	2005			
	+SAM	**1994**	***1998***	***1999***	2001	***2007***	

be mixed here. The effect of combinations of SAM and ENSO phases on circulation anomalies in the Antarctic can be found in Fogt *et al.* (2011).

Negative pressure differences dominate all seasons in Figure 9 which can be expected given the zonally symmetric, pressure-based definition of the SAM. Several asymmetrical features do, however, appear in the difference plots in Figure 9. A difference in MSLP of 12−15 hPa exists between positive and negative SAM summers in a large area of the Ross Sea (Figure 9(a)). A region of lower MSLP in this region during positive SAM summers is likely associated with greater cyclonic activity (Sinclair *et al.*, 1997), increased southerly winds in the Ross Sea region (Lefebvre *et al.*, 2004), and greater frequency of foehn days in the MDVs. In the Lake Hoare foehn record, 58% more foehn days occur in positive SAM summers compared to negative SAM summers. During winter, a smaller region of lower MSLP is evident in the eastern Ross Ice Shelf/Marie Byrd Land area (Figure 9(c)), yet no apparent correlation of the SAM to foehn days is evident in the MDVs (Table II). This may be a factor of lower MSLP during positive SAM winters but not necessarily increased cyclone activity that affects foehn in the MDVs. During autumn and spring most of the larger pressure differences between the two phases of SAM are located in the Peninsula region of West Antarctica. Pressure fields in Figure 9 are comparable to those presented in van den Broeke and van Lipzig (2004). They find significant cooling over East Antarctica associated with the positive phase of SAM, particularly in the autumn months. The cause of the cooling is likely associated with intensification of the surface temperature inversion associated with suppressed meridional air exchange and weakening of near-surface winds (van den Broeke and van Lipzig 2004). The negative relationship between the SAM and foehn frequency during autumn presented here indicates that the MDVs may follow this larger-scale relationship with decreased foehn frequency (from suppressed synoptic forcing) during autumn causing a cooling.

A relationship between foehn days and the SAM in summer holds important repercussions for landscape processes in the MDVs. The conditions observed during the 2001/2002 summer are a good example of the effect of strongly positive SAM in the MDVs landscape. During the 2001/2002 summer a strong blocking pattern in the Weddell Sea lead to low pressure anomalies in the Bellingshausen, Amundsen and Ross Seas and the development of an amplified wave-number 3 pattern in the Southern Ocean (Turner *et al.*, 2002; Massom *et al.*, 2006). This pattern resembles the SAM which persisted in the positive phase during 2001 with an annual 2002 DJF SAM index of +2.56. An average of 26.3 foehn days were observed during this summer compared to the 1995−2008 average of 15.4 foehn days. Many aspects of the MDVs environmental system were affected by the increase in foehn frequency as a result of the anomalous atmospheric conditions. Mean air temperature during the 2001/2002 summer were −2.0 °C at the four stations we focus on here, +1.6 °C above average. Maximum temperatures during this season exceeded +10 °C during foehn events (e.g. Lake Vanda, +10.7 °C on 12 January 2002 and Lake Bonney, +10.6 °C on 30 December 2001). These conditions resulted in major glacial melt and streamflow and significant loss of glacial mass (Doran *et al.*, 2008). Fresh water contributions increased lake levels and thinned permanent lake ice covers which, together with increased turbidity and increased nutrient loadings, affected lake biota by reducing primary productivity (Foreman *et al.*, 2004).

5. Discussion and conclusions

Previous studies of temperature trends and climate variability in the MDVs have not considered the fundamental meteorological and synoptic processes which drive the climate of this unique region. Foehn winds are frequently experienced in the MDVs and this research has shown that these wind events are a major part of the MDVs climate system. Katabatic drainage winds in this region of the Antarctic appear to diverge and flow out of the larger basins of the Byrd Glacier to the south and Terra Nova Bay in the north (Parish and Bromwich, 1987, 2007). While synoptically driven winds in this region may have a small katabatic component, katabatic winds do not instigate foehn wind events. Strong synoptic forcing in the region is frequently associated with cyclones positioned in the Ross Sea such as those in the summer and winter SLP analyses presented here. This situation causes strong pressure gradients and synoptically forced south-southwesterly winds along the Transantarctic Mountains which are deflected by the northeast-southwest orientated valleys of the MDVs causing mountain wave activity and foehn winds (Speirs *et al.*, 2010). Foehn winds are frequently experienced in the MDVs due to the Ross Sea being a climatologically favoured region for cyclonic activity with consistently high frequencies of both cyclogenesis and cyclosis (Simmonds *et al.*, 2003).

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Owing to the lack of consideration of the local and regional meteorology in previous studies, it has been unclear how known drivers of variability could transmit a signal to the MDVs region. Given the strong influence of foehn winds on the MDVs climate, it is logical that variability in the track and intensity of cyclonic systems in the Ross and Amundsen Seas is a major contributor to MDVs climate variability. The relationships between foehn frequency, temperature, the SAM and ENSO examined here show statistically significant correlations between summer and autumn foehn days and the SAM, as well as the SOI and winter temperatures. Over the shorter period of 10 years (1999–2008) the SOI also correlates with foehn days in spring.

The positive relationship between foehn and the SAM during summer holds important landscape implications considering the influence of foehn on increasing temperatures above 0 °C and triggering melt. This effect was observed during the 2001/2002 summer. The SAM has shown significant positive trends in recent decades (Marshall, 2003) which is most significant during summer (Marshall *et al*., 2006). This trend implies a strengthening of the circumpolar vortex, intensification of the circumpolar westerlies, reduced pressures and greater cyclone density in the southern high latitudes (Marshall *et al*., 2006; Pezza *et al*., 2008). Recent studies have linked changes in ENSO to SAM variability (Fogt and Bromwich, 2006; L'Heureux and Thompson, 2006), while several modelling studies have suggested that a combination of greenhouse gas increases and ozone depletion is primarily responsible for this positive trend (Kushner *et al*., 2001; Shindell and Schmidt, 2004). Intensification of the westerlies associated with the summer trend in SAM has been linked to significant warming in the Antarctic Peninsula associated with a foehn effect as air is forced over the peninsula barrier (Marshall *et al*., 2006; Orr *et al*., 2008), but also regional cooling across continental Antarctica (Kwok and Comiso, 2002b; van den Broeke and van Lipzig, 2004). While the length of the AWS records in the MDVs is too short to examine significant trends, the weak positive trend in summer foehn days (Table II) is possibly a response of the positive trend in the SAM.

Anthropogenic greenhouse gases and ozone depletion both force the positive phase of the SAM and recent modelling suggests that ozone recovery during the 21st century will cause the recent effects of SAM to subside or possibly reverse the potential atmospheric effects caused by greenhouse gases (Perlwitz *et al*., 2008; Polvani *et al*., 2011). If a positive SAM trend continues into the future, the MDVs could experience increased summer foehn frequency and increased frequency of air temperatures >0 °C and in turn, a range of environmental processes could be affected. Our results suggest that similar to the Antarctic Peninsula, the MDVs may warm during summer under a positive SAM scenario. Conversely, if the trend in SAM reverses, the MDVs could observe a cooling during summer. It needs to be stressed, however, that given the foehn wind regime, the MDVs cannot be presumed to follow the same temperature trends as other continental areas of the Antarctic or even other areas in the Ross Sea region.

Our research has shown that an ENSO signal exists in winter air temperatures in the MDVs observational records in addition to a possible nonlinear relationship with foehn days during spring. Foehn wind frequency largely controls winter temperatures, and we believe that, similarly to the SAM, ENSO may affect the MDVs via synoptic cyclone and foehn wind variability. The SOI–foehn relationship during the time period of this study is limited by the relatively long periodicity of ENSO and its decadal variability (Fogt and Bromwich, 2006). Fogt *et al*. (2011) show that interaction between the SAM and ENSO has the potential to enhance or inhibit circulation anomalies. They find that significant teleconnections of ENSO to the South Pacific are only found when they occur in phase with SAM (i.e., positive SAM/La Niña or negative SAM/El Niño). During in-phase events, transient eddy momentum flux and associated wave propagation interact to amplify the circulation anomalies (Fogt *et al*., 2011). A more detailed analysis of the effect of these combined signals on the MDVs foehn wind regime is warranted as the length of meteorological records grow, and a greater number of strong SAM and ENSO phases are observed.

Results presented here are generally in agreement with Bertler *et al*. (2004) who found a similar cooling in the western Ross Sea and MDVs during El Niño and that the SAM-ENSO are likely to have a combined influence in the MDVs (Bertler *et al*., 2006). However, their mechanism of cooling/warming associated with these teleconnections does not consider the foehn wind regime. Bertler *et al*. (2004) suggest that the El Niño position of cyclonic activity enhances katabatic surges from the East Antarctic Ice Sheet (EAIS) to the western Ross Sea area, importing cooler air to the region. Conversely during La Niña, when the Amundsen Sea low is stronger and typically located north of the Ross Sea, they suggest this may transport warmer and moist maritime air into the western Ross Sea and MDVs area. This may be true for other locations on the Ross Ice Shelf, however, since the katabatic influence in the MDVs is considered minimal, it is more likely that change in foehn frequency from variability in the track and intensity of cyclonic systems in the Ross and Amundsen Seas drive MDVs climate variability. A decrease (increase) in cyclonic activity and foehn frequency would cause a regional cooling (warming) in the MDVs. A warming elsewhere in the western Ross Ice Shelf during times of increased cyclonic activity can be attributed to intensification of katabatic winds along the Ross Ice Shelf by synoptically forced southerly winds (Bromwich *et al*., 1993; Seefeldt *et al*., 2007). Near-surface warm signatures associated with turbulent katabatic surges flowing northward from the glaciers along the Ross Ice Shelf are enhanced during cyclonic activity in the Ross Sea (Bromwich *et al*., 1993). The warming (relative to the surroundings) of katabatic winds only exists in a shallow layer on the surface but as a whole the katabatic jet is cooler and negatively

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buoyant (Bromwich *et al.*, 1993), unlike foehn winds. This intensification of wind speed on the Ross Ice Shelf was shown to occur synchronously with foehn wind events in the MDVs (Speirs *et al.*, 2010) and is also responsible for the expansion of the polynya north of the Ross Ice Shelf (Bromwich *et al.*, 1993). Evidently, the effects of cyclone activity in the Ross Sea are synchronous and widespread across this region of the Antarctic.

Besides the SAM and ENSO, other factors influencing synoptic activity in the Ross Sea region such as the ACW and sea ice concentrations may contribute to foehn variability. The influence of mesocyclones on triggering foehn events in the MDVs is expected to be minimal. Carrasco *et al.* (2003) note that the majority of mesoscale cyclone features in the Ross Sea/Ross Ice Shelf region are shallow features <700 mb depth. Winds at this height would be unable to produce significant cross-barrier flow and initiate mountain wave activity into upper atmospheric levels and are therefore unlikely to influence foehn frequency. Foehn frequency will naturally be highly variable as the Ross Sea is a climatologically favoured region for cyclonic activity and individual cyclones will enter this region and affect foehn frequency regardless of teleconnections. While most foehn events are related to cyclonic activity, exceptions do occur when other synoptic situations cause strong flow aloft that can generate foehn winds in the MDVs. These exceptions contribute to nonlinear relationships in foehn variability.

Future observational and modelling studies combined with longer meteorological records will provide more detail on the dynamics of foehn winds. Westerly-located valley floor sites (e.g., Lake Bonney and Lake Vanda) are preferable for the study of foehn frequency, as foehn winds at more easterly-located sites (e.g., Lake Hoare) are often masked by the intrusion of both synoptically- and thermally-generated easterly winds. Forthcoming field and high-resolution modelling work will shed new light on little known aspects of foehn winds such as the complex interactions of foehn with the easterly valley wind circulation and cold-air pool formation and flushing.

Acknowledgements

The authors would like to acknowledge the McMurdo LTER Program for use of observational data. This work is supported by the Australian Antarctic Division project (Project 3119) and the School of Geography, Planning and Environmental Management at the University of Queensland. DFS and DHB are supported by the National Science Foundation via NSF Grant ANT-0636523. Thanks also go to Andy Monaghan for his advice and earlier work on the McMurdo Dry Valleys project. Byrd Polar Research Center contribution number 1415.

References

Arblaster JM, Meehl GA. 2006. Contributions of external forcings to Southern Annular Mode trends. *Journal of Climate* **19**: 2896–2905.

Ayling BF, McGowan HA. 2006. Niveo-aeolian sediment deposits in coastal south Victoria Land, Antarctica: Indicators of regional variability in weather and climate. *Arctic, Antarctic and Alpine Research* **38**: 313–324.

Beer T. 1976. Mountain waves. *Science Progress* **63**: 1–25.

Bertler NAN, Barrett PJ, Mayewski PA, Fogt RL, Kreutz KJ, Shulmeister J. 2004. El Nino suppresses Antarctic warming. *Geophysical Research Letters* **31**: L15207, DOI: 10.1029/2004GL020748.

Bertler NAN, Naish TR, Oerter H, Kipfstuhl S, Barrett PJ, Mayewski PA, Kreutz K. 2006. The effects of joint ENSO-Antarctic Oscillation forcing on the McMurdo Dry Valleys, Antarctica. *Antarctic Science* **18**: 507–514.

Bromwich DH, Carrasco JF, Liu Z, Tzeng RY. 1993. Hemispheric atmospheric variations and oceanographic impacts associated with katabatic surges across the Ross Ice Shelf, Antarctica. *Journal of Geophysical Research-Atmospheres* **98**: 13045–13062.

Bromwich D, Rogers A, Kållberg P, Cullather R, White J, Kreutz K. 2000. ECMWF analyses and reanalyses depiction of ENSO signal in Antarctic precipitation. *Journal of Climate* **13**: 1406–1420.

Bromwich DH, Monaghan AJ, Guo Z. 2004. Modeling the ENSO Modulation of Antarctic Climate in the Late 1990s with the Polar MM5. *Journal of Climate* **17**: 109–132.

Bromwich DH, Monaghan AJ, Manning KW, Powers JG. 2005. Real-time forecasting for the Antarctic: An evaluation of the Antarctic Mesoscale Prediction System (AMPS). *Monthly Weather Review* **133**: 579–603.

Bromwich D, Fogt R, Hodges K, Walsh J. 2007. A tropospheric assessment of the ERA-40, NCEP, and JRA-25 global reanalyses in the polar regions. *Journal of Geophysical Research* **112**: 10111.

Carleton AM. 2003. Atmospheric teleconnections involving the Southern Ocean. *Journal of Geophysical Research-Oceans* **108**: 8080, DOI: 10.1029/2000JC000379.

Carrasco JF, Bromwich DH, Monaghan AJ. 2003. Distribution and characteristics of mesoscale cyclones in the Antarctic: Ross Sea eastward to the Weddell Sea. *Monthly Weather Review* **131**: 289–301.

Chen B, Smith SR. Bromwich DH. 1996. Evolution of the tropospheric split jet over the South Pacific ocean during the 1986-89 ENSO cycle. *Monthly Weather Review* **124**: 1711–1731.

Cullather R, Bromwich D, Van Woert M. 1996. Interannual variations in Antarctic precipitation related to El Nino-southern oscillation. *Journal of Geophysical Research* **101**: 19109.

Doran PT, Dana GL, Hastings JT, Wharton RA, Jr. 1995. McMurdo Dry Valleys Long-Term Ecological Research (LTER): LTER automatic weather network (LAWN). *Antarctic Journal of the United States* **30**: 276–280.

Doran PT, McKay CP, Clow GD, Dana GL, Fountain AG, Nylen T, Lyons WB. 2002a. Valley floor climate observations from the McMurdo Dry Valleys, Antarctica, 1986–2000. *Journal of Geophysical Research* **107**: 4772, DOI: 10.1029/2001JD002045.

Doran PT, Priscu JC, Lyons WB, Walsh JE, Fountain AG, McNight DM, Moorhead DL, Virginia RA, Wall DH, Clow GD, Fritsen CH, McKay CP, Parsons AN. 2002b. Antarctic climate cooling and terrestrial ecosystem response. *Nature* **415**: 517–520.

Doran PT, McKay CP, Fountain AG, Nylen T, McKnight DM, Jaros C, Barrett JE. 2008. Hydrologic response to extreme warm and cold summers in the McMurdo Dry Valleys, East Antarctica. *Antarctic Science* **20**: 499–509.

Durran DR. 1990. Mountain waves and downslope winds. In *Atmospheric Processes Over Complex Terrain*, Vol. 23 Blumen, W. (ed)/American Meteorological Society: Boston, MA, 59–81.

Fogt RL, Bromwich DH. 2006. Decadal variability of the ENSO teleconnection to the high-latitude South Pacific governed by coupling with the southern annular mode. *Journal of Climate* **19**: 979–997.

Fogt RL, Bromwich DH, Hines KM. 2011. Understanding the SAM influence on the South Pacific ENSO teleconnection. *Climate Dynamics* **36**: 1555–1576, DOI: 10.1007/s00382-010-0905-0.

Foreman CM, Wolf CF, Priscu JC. 2004. Impact of episodic warming events on the physical, chemical and biological relationships of lakes in the McMurdo Dry Valleys, Antarctica. *Aquatic Geochemistry* **10**: 239–268.

Fountain AG, Lyons WB, Burkins MB, Dana GL, Doran PT, Lewis KJ, McKnight DM, Moorhead DL, Parsons AN, Priscu JC, Wall DH, Wharton RA, Virginia RA. 1999. Physical controls on the Taylor Valley ecosystem. *Bioscience* **49**: 961–971.

Fountain AG, Nylen TH, MacClune KL, Dana GL. 2006. Glacier mass balances (1993–2001), Taylor Valley, McMurdo Dry Valleys, Antarctica. *Journal of Glaciology* **52**: 451–462.

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Fountain A, Nylen T, Monaghan A, Basagic H, Bromwich D. 2010. Snow in the McMurdo Dry Valleys, Antarctica. *International Journal of Climatology* **30**: 633–642.

Gong DY, Wang SW. 1999. Definition of Antarctic Oscillation Index. *Geophysical Research Letters* **26**: 459–462.

Guo Z, Bromwich D, Cassano J. 2003. Evaluation of Polar MM5 simulations of Antarctic atmospheric circulation. *Monthly Weather Review* **131**: 384–411.

Gregory S, Noone D. 2008. Variability in the teleconnection between the El Niño-Southern Oscillation and West Antarctic climate deduced from West Antarctic ice core isotopic records. *Journal of Geophysical Research* **113**: D17110, DOI: 10.1029/2007JD009107.

Jones J, Fogt R, Widmann M, Marshall G, Jones P, Visbeck M. 2009. Historical SAM variability. Part I. Century-length seasonal reconstructions. *Journal of Climate* **22**: 5319–5345.

Karoly DJ. 1989. Southern Hemisphere circulation features associated with El Niño-Southern Oscillation events. *Journal of Climate* **2**: 1239–1252.

Kidson J. 1999. Principal modes of Southern Hemisphere low-frequency variability obtained from NCEP–NCAR reanalyses. *Journal of Climate* **12**: 2808–2830.

Kidson J, Sinclair M. 1995. The influence of persistent anomalies on Southern Hemisphere storm tracks. *Journal of Climate* **8**: 1938–1950.

Kushner P, Held I, Delworth T. 2001. Southern Hemisphere atmospheric circulation response to global warming. *Journal of Climate* **14**: 2238–2249.

Kwok R, Comiso JC. 2002a. Southern Ocean climate and sea ice anomalies associated with the Southern Oscillation. *Journal of Climate* **15**: 487–501.

Kwok R, Comiso JC. 2002b. Spatial patterns of variability in Antarctic surface temperature – connections to the Southern Hemisphere Annular Mode and the Southern Oscillation. *Geophysical Research Letters* **29**: 50–51.

L'Heureux ML, Thompson DWJ. 2006. Observed relationships between the El Niño–Southern Oscillation and the Extratropical Zonal-Mean Circulation. *Journal of Climate* **19**: 276–287.

Lachlan-Cope T, Connolley W. 2006. Teleconnections between the tropical Pacific and the Amundsen-Bellinghausens Sea: role of the El Niño/Southern Oscillation. *Journal of Geophysical Research* **111**: D23101, DOI: 10.1029/2005JD006386.

Ledley T, Huang Z. 1997. A possible ENSO signal in the Ross Sea. *Geophysical Research Letters* **24**: 3253–3256.

Lefebvre W, Goosse H, Timmermann R, Fichefet T. 2004. Influence of the Southern Annular Mode on the sea ice–ocean system. *Journal of Geophysical Research* **109**: C09005.

Marshall G. 2003. Trends in the Southern Annular Mode from observations and reanalyses. *Journal of Climate* **16**: 24.

Marshall G, Stott P, Turner J, Connolley W, King J, Lachlan-Cope T. 2004. Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. *Geophysical Research Letters* **31**: L14205.

Marshall G, Orr A, van Lipzig N, King J. 2006. The impact of a changing Southern Hemisphere Annular Mode on Antarctic Peninsula summer temperatures. *Journal of Climate* **19**: 5388–5404.

Massom R, Stammerjohn S, Iannuzzi R, Martinson D, Smith R, Pook M, Adams N, Vernet M, Fraser W, Quetin L. 2006. Extreme anomalous atmospheric circulation in the West Antarctic Peninsula region in austral spring and summer 2001/2002, and its profound impact on sea ice and biota. *Journal of Climate* **19**: 3544–3571.

McKendry IG, Lewthwaite EWD. 1990. The vertical structure of summertime local winds in the Wright Valley, Antarctica. *Boundary-Layer Meteorology* **51**: 321–342.

McKendry IG, Lewthwaite EWD. 1992. Summertime along-valley wind variations in the Wright Valley Antarctica. *International Journal of Climatology* **12**: 587–596.

Monaghan AJ, Bromwich DH, Powers JG, Manning KW. 2005. The climate of the McMurdo, Antarctica, region as represented by one year of forecasts from the Antarctic Mesoscale Prediction System. *Journal of Climate* **18**: 1174–1189.

Nylen TH, Fountain AG, Doran PT. 2004. Climatology of katabatic winds in the McMurdo Dry Valleys, Southern Victoria Land, Antarctica. *Journal of Geophysical Research* **109**: D03114, DOI: 10.1029/2003JD002927.

O'Connor WP, Bromwich DH. 1988. Surface air-flow around windless bight, Ross Island Antarctica. *Quarterly Journal of the Royal Meteorological Society* **114**: 917–938.

Onogi K, Koide H, Sakamoto M, Kobayashi S, Tsutsui J, Hatsushika H, Matsumoto T, Yamazaki N, Kamahori H, Takahashi K. 2005. JRA 25: Japanese 25 year re analysis project – progress and status. *Quarterly Journal of the Royal Meteorological Society* **131**: 3259–3268.

Onogi K, Tsutsui J, Koide H, Sakamoto M, Kobayashi S, Hatsushika H, Matsumoto T, Yamazaki N, Kamahori H, Takahashi K. 2007. The JRA-25 reanalysis. *Journal of the Meteorological Society of Japan* **85**: 369–432.

Orr A, Marshall GJ, Hunt JCR, Sommeria J, Wang CG, van Lipzig NPM, Cresswell D, King JC. 2008. Characteristics of summer airflow over the Antarctic Peninsula in response to recent strengthening of westerly circumpolar winds. *Journal of the Atmospheric Sciences* **65**: 1396–1413.

Parish TR, Bromwich DH. 1987. The surface windfield over the Antarctic ice sheets. *Nature* **328**: 51–54.

Parish TR, Bromwich DH. 2007. Reexamination of the near-surface airflow over the Antarctic continent and implications on atmospheric circulations at high southern latitudes. *Monthly Weather Review* **135**: 1961–1973.

Patterson NG, Bertler NAN, Naish TR, Morgenstern U. 2005. ENSO variability in the deuterium-excess record of a coastal Antarctic ice core from the McMurdo Dry Valleys, Victoria Land. *Annals of Glaciology* **41**: 140–146.

Perlwitz J, Pawson S, Fogt RL, Nielsen JE, Neff WD. 2008. Impact of stratospheric ozone hole recovery on Antarctic climate. *Geophysical Research Letters* **35**: L08714.

Pezza A, Durrant T, Simmonds I, Smith I. 2008. Southern Hemisphere synoptic behavior in extreme phases of SAM, ENSO, sea ice extent, and Southern Australia rainfall. *Journal of Climate* **21**: 5566–5584.

Polvani LM, Previdi M, Deser C. 2011. Large cancellation, due to ozone recovery, of future Southern Hemisphere atmospheric circulation trends. *Geophysical Research Letters* **38**: L04707.

Powers JG, Monaghan AJ, Cayette AM, Bromwich DH, Kuo YH, Manning KW. 2003. Real-time mesoscale modeling over Antarctica: the Antarctic mesoscale prediction system. *Bulletin of the American Meteorological Society* **84**: 1533–1545.

Renwick JA. 1998. ENSO-related variability in the frequency of South Pacific blocking. *Monthly Weather Review* **126**: 3117–3123.

Revell MJ, Kidson JW, Kiladis GN. 2001. Interpreting low-frequency modes of Southern Hemisphere atmospheric variability as the rotational response to divergent forcing. *Monthly Weather Review* **129**: 2416–2425.

Seefeldt MW, Cassano JJ, Parish TR. 2007. Dominant regimes of the Ross Ice Shelf surface wind field during austral autumn 2005. *Journal of Applied Meteorology and Climatology* **46**: 1933–1955.

Seibert P. 1990. South foehn studies since the ALPEX experiment. *Meteorology and Atmospheric Physics* **43**: 91–103.

Selby MJ, Palmer RWP, Smith CJR, Rains RB. 1973. Ventifact distribution and wind directions in the Victoria Valley, Antarctica. *New Zealand Journal of Geology and Geophysics* **16**: 303–306.

Shindell D, Schmidt G. 2004. Southern Hemisphere climate response to ozone changes and greenhouse gas increases. *Geophysical Research Letters* **31**: L18209.

Simmonds I, Keay K, Lim EP. 2003. Synoptic activity in the seas around Antarctica. *Monthly Weather Review* **131**: 272–288.

Sinclair MR, Renwick JA, Kidson JW. 1997. Low-frequency variability of southern hemisphere sea level pressure and weather system activity. *Monthly Weather Review* **125**: 2531–2543.

Smith R, Stammerjohn S, Baker K. 1996. Surface air temperature variations in the western Antarctic Peninsula region. *Antarctic Research Series* **70**: 105–121.

Smith SR, Stearns, CR 1993. Antarctic pressure and temperature anomalies surrounding the minimum of the Southern Oscillation Index. *Journal of Geophysical Research* **98**: 13071–13083.

Speirs JC, McGowan H, Neil DT. 2008. Meteorological controls on sand transport and dune morphology in a polar-desert: Victoria Valley, Antarctica. *Earth Surface Processes and Landforms* **33**: 1875–1891.

Speirs J, McGowan H, Steinhoff D, Bromwich D, Monaghan A. 2010. Foehn winds in the McMurdo Dry Valleys, Antarctica: the origin of extreme warming events. *Journal of Climate* **23**: 3577–3598.

Stearns CR, Keller LM, Weidner GA, Sievers M. 1993. Monthly mean climatic data for Antarctic automatic weather stations. In

Antarctic Meteorology and Climatology: Studies Based on Automatic Weather Stations. Antarctic Research Series, Vol. 61. Bromwich DH, Stearns C R (eds). American Geophysical Union: Washington, DC, 1.

Thompson DC, Craig RMF, Bromley AM. 1971. Climate and surface heat balance in an Antarctic Dry Valley. *New Zealand Journal of Science* **14**: 245–251.

Thompson DWJ, Wallace JM. 2000. Annular modes in the extratropical circulation. Part I. Month-to-month variability. *Journal of Climate* **13**: 1000–1016.

Turner J. 2004. The El Nino-Southern Oscillation and Antarctica. *International Journal of Climatology* **24**: 1–31.

Turner J, Harangozo S, Marshall G, King J, Colwell S. 2002. Anomalous atmospheric circulation over the Weddell Sea, Antarctica during the Austral summer of 2001/02 resulting in extreme sea ice conditions. *Geophysical Research Letters* **29**: 2160.

van den Broeke MR. 2004. The semi-annual oscillation and Antarctic climate. Part 1. Influence on near surface temperatures (1957–79). *Antarctic Science* **10**: 175–183.

van den Broeke M, van Lipzig N. 2004. Changes in Antarctic temperature, wind and precipitation in response to the Antarctic Oscillation. *Annals of Glaciology* **39**: 119–126.

Welch KA, Lyons WB, McKnight DM, Doran PT, Fountain AG, Wall D, Jaros C, Nylen T, Howard-Williams C. 2003. Climate and hydrological variations and implications for lake and stream ecological response in the McMurdo Dry Valleys, Antarctica. In *Climate Variability and Ecosystem Response at Long-Term Ecological Research Sites*. Greenland D, Goodin DG, Smith RC (eds). Oxford University: New York, 174–195.

White WB, Peterson RG. 1996. An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent. *Nature* **380**: 699–702.

Yuan X. 2004. ENSO-related impacts on Antarctic sea ice: a synthesis of phenomenon and mechanisms. *Antarctic Science* **16**: 415–425.

Zängl G. 2003. Deep and shallow south foehn in the region of Innsbruck: typical features and semi-idealized numerical simulations. *Meteorology and Atmospheric Physics* **83**: 237–261.

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