FOEHN WINDS IN THE MCMURDO DRY VALLEYS:
IMPLICATIONS FOR CLIMATE VARIABILITY AND LANDSCAPE EVOLUTION

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1. INTRODUCTION

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 (Speirs *et al*. 2010). 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 record of foehn winds from automatic weather station observations 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.

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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.

2. DATA

Observations:
Meteorological data were obtained from automatic weather stations (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).

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.

Modelling:
Numerical forecast model products presented here were obtained from the

Antarctic Mesoscale Prediction System (AMPS, Powers *et al.*, 2003). 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. The Japanese Reanalysis Project (JRA-25, Onogi *et al.*, 2005; Onogi *et al.*, 2007) data is used here to study longer term variability in synoptic circulation that affect the MDVs.

3. RESULTS AND ANALYSIS

Characteristics of foehn wind events

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. An example of local meteorological conditions during a foehn event in May 2007 is shown in Figure 1. The Lake Vida AWS is located on the valley floor of the Victoria Valley while the Howard Glacier AWS is located on the valley wall of the Taylor Valley, approximately 400m above the valley floor.

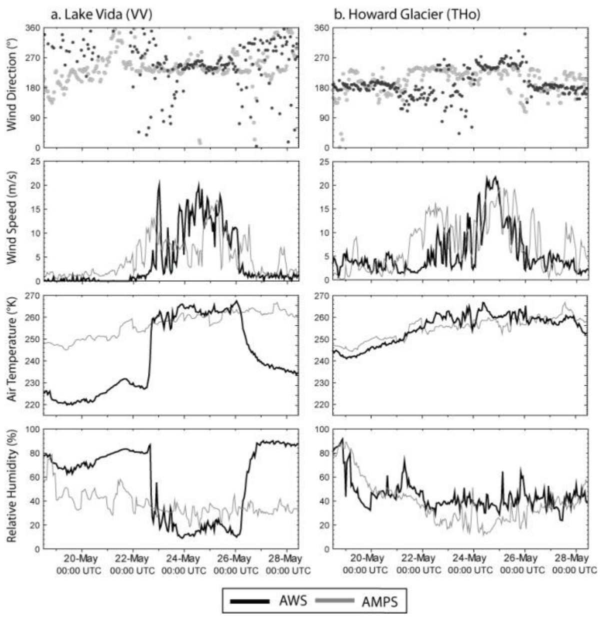

FIGURE 1. Foehn meteorological observations (AWS and AMPS) at Lake Vida (VV, Victoria Valley) and Howard Glacier (THo, Taylor Valley).

A selection criterion for identifying foehn wind events in the meteorological records was developed. Foehn onset was identified by an increase of wind gust speed above 5 ms^{-1} from a westerly direction, a warming of at least +1°C per hour and a decrease of relative humidity of at least 5% per hour. An additional criterion of a 'foehn day' was developed that defines a day that experiences 6 or more hours of continuous foehn conditions with wind gust speed >5 ms^{-1} from a southwesterly direction. Figure 2 shows composites of sea level pressure and wind vectors for 2006 and 2007 (a) 172 non-foehn days and (b) 172 foehn days. Figure 2b clearly identifies the presence of a strong cyclonic system in the Ross/Amundsen Seas, (off the coast of Marie Byrd Land) during foehn days in contrast to weak pressure gradients during non-foehn days. This cyclone position has been shown to produce strong southerly winds in the Transantarctic Mountains region which trigger mountain wave development and foehn winds in the MDVs (Speirs *et al*., 2010)

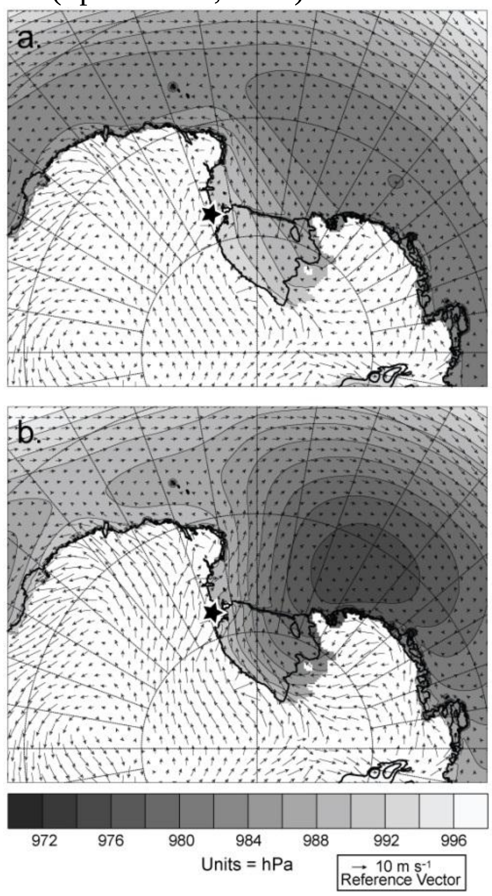

FIGURE 2. Mean meteorological conditions during non foehn (a) and foehn days (b): AMPS sea level pressure and near-surface wind vectors (after Speirs et al. 2010)

Implications for climate variability

Warmer air brought to the surface from upper levels and from adiabatic warming during foehn significantly influences the temperature regime of the MDVs. Figure 3 presents the standardized monthly foehn anomaly against air temperature anomalies for Lake Hoare for the 1987-2008 period. This relationship is statistically significant ($r^2 = 0.34$, $p < 0.05$).

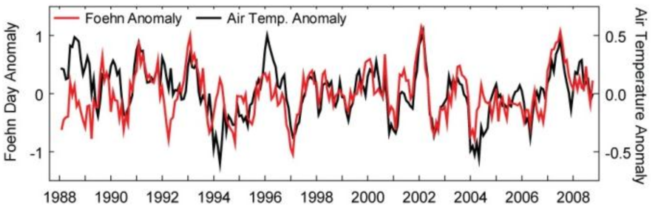

FIGURE 3. Monthly standardised foehn anomaly compared with the standardised air temperature anomaly for Lake Hoare. Data are smoothed with a 5 month moving average.

Considering that SAM and ENSO are known to affect synoptic circulation in the Ross/Amundsen Seas (e.g., Bromwich and Wang, 2008; Fogt *et al.*, 2011), 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 1. The SOI used in these analyses is sourced 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, 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 winter ($r^2 = 0.66$, $p < 0.05$). 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 winds and stagnation.

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 1). A positive relationship with SAM can be expected as high SAM indices are associated with decreased MSLP and greater cyclonic density around the Antarctic (Pezza *et al.*, 2008; Sinclair *et al.*, 1997).

TABLE 1. Correlation statistics for average seasonal foehn days (FD) and air temperatures against ENSO and SAM. Statistical significance at the 95% level is highlighted in red.

	SOI *r*	SAM *r*
DJF FD	+0.37	**+0.75**
MAM FD	-0.30	**-0.77**
JJA FD	+0.01	-0.36
SON FD	+0.09	+0.08
DJF Air Temp.	-0.09	+0.01
MAM Air Temp.	-0.07	-0.50
JJA Air Temp.	**+0.68**	-0.10
SON Air Temp.	+0.23	+0.29

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 4. 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 1980-2008.

Positive pressure differences dominate all seasons in Figure 4 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 4. A difference in MSLP of 12-15 hPa exists between positive and negative SAM summers. MSLP is 12-15 hPa lower (higher) during positive (negative) SAM summers in a large area of the Ross Sea (Figure 4a). 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.

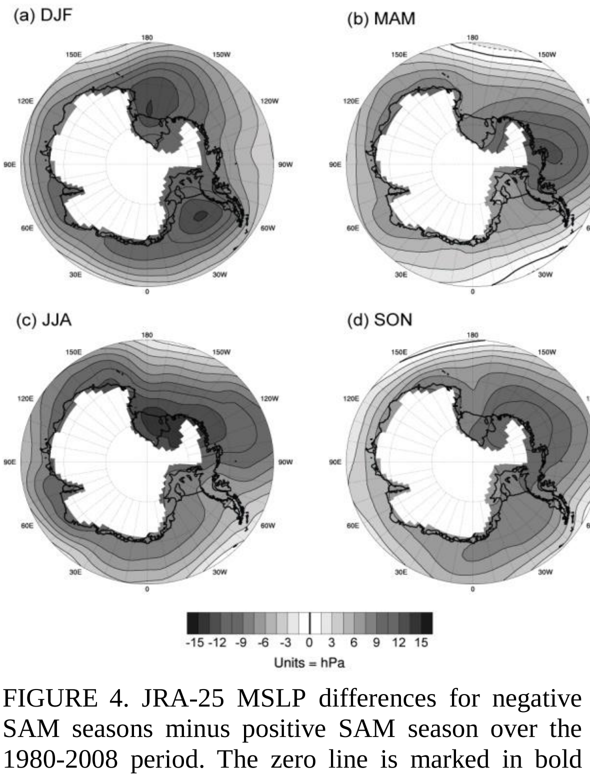

FIGURE 4. JRA-25 MSLP differences for negative SAM seasons minus positive SAM season over the 1980-2008 period. The zero line is marked in bold and negative MSLP is shown by a dashed line (only evident for MAM, plots are mainly positive).

Implications for landscape evolution

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. The influence of foehn in the landscape also outlives the duration of the event. Figure 5 shows the mean lag effect in soil temperature, melt water discharge and potential evaporation/sublimation following foehn days. Warm air brought to the surface by foehn winds play a large role in heating the ice-free valley floors and triggering large volumes of melt water. The effect of foehn on temperature, humidity and wind speed variables also is favourable for conditions of increased evaporation of surface moisture and sublimation of snow and ice deposits.

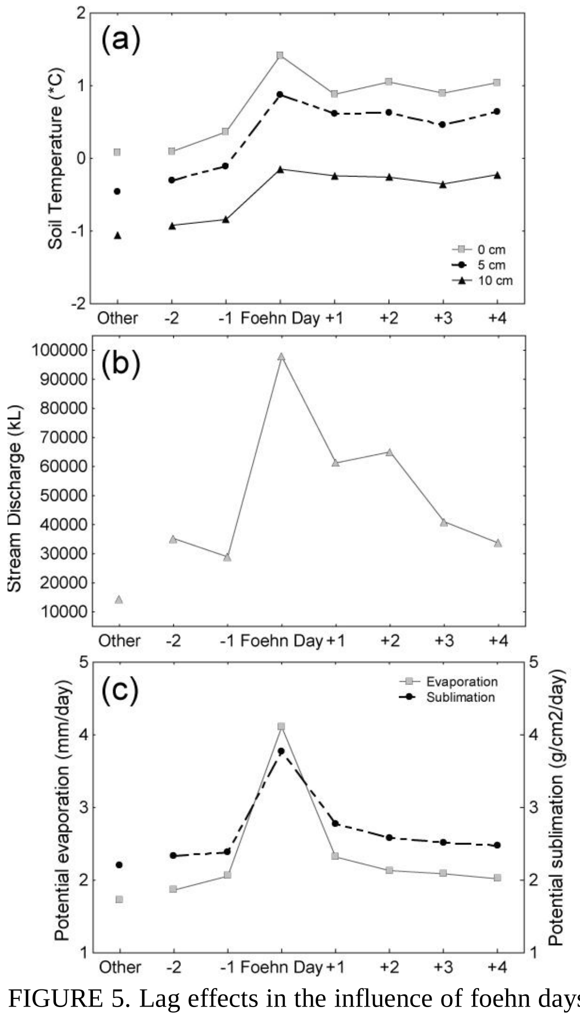

FIGURE 5. Lag effects in the influence of foehn days on summer average (a) soil temperature, (b) daily discharge in the Onyx River and (c) potential evaporation and sublimation. Data are averaged over the 1999-2008 decade. Negative (-1,-2) variables

denote the number of days prior to a foehn day while positive (+1,+2,+3,+4) variables denote the number of days after a foehn event. 'Other' refers to other days not occurring in the vicinity of a foehn day.

4. DISCUSSION AND CONCLUSIONS

Due 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 which is influenced by ENSO and SAM 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.

The SAM has shown significant positive trends in recent decades (Marshall, 2003) which is most significant during summer (Marshall *et al.*, 2006). If this relationship and 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. 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.

Foehn winds play a large role in keeping the valleys snow and ice free. Any precipitation that does fall is quickly evaporated/sublimated by foehn winds. Foehn wind events may also have played a pivotal role in the creation of large liquid lakes that were believed to have occupied the valley floors during the LGM and early Holocene (e.g. Lyons *et al*., 1998; Hall *et al*., 2001), and the subsequent removal of these water bodies.

Future observational and modelling studies combined with longer meteorological records will provide more detail on the dynamics of foehn 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.

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