

FOEHN MECHANISM IN THE McMURDO DRY VALLEYS FROM POLAR WRF

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1. INTRODUCTION

The McMurdo Dry Valleys (hereafter “MDVs”) are the largest ice-free region in Antarctica, featuring perennially ice-covered lakes that are fed by ephemeral melt streams in the summer. The MDVs have been an NSF-funded Long-Term Ecological Research (LTER) site since 1993, and LTER research has shown that the hydrology and biology of the MDVs are extremely sensitive to small climatic fluctuations, especially during summer when temperatures episodically rise above freezing. However, the atmospheric processes that control MDVs summer climate are not well understood. Speirs et al. (2010) resolved a long-standing dispute that the forcing for the strong, warm westerly wind events is a foehn mechanism associated with large-amplitude mountain waves, rather than katabatic surges as some researchers had thought. Here we use Polar WRF simulations, tailored for the MDVs environment, from a case study in December 2006 / January 2007 to show that a series of mesoscale processes leads to warm, westerly winds in the MDVs that ultimately drive summer temperature anomalies and glacial melt.

2. DATA AND METHODS

Polar WRF Version 3.2.1 is used for all simulations (Skamarock et al. 2008; Hines and Bromwich 2008; Bromwich et al. 2009; Hines et al. 2011). Outer nested domains of 32, 8, and 2 km are run, with a separate 500 m domain nested inside the 2 km domain with WRF’s “ndown” function. A portion of the 500 m domain is shown in Fig. 1. There are 56 vertical levels, with the lowest level about 25 m AGL, and model top at 50 hPa. Physics options include WSM6 microphysics, Dudhia shortwave radiation (with terrain shading effects), RRTM longwave radiation, MYNN Level 2.5 PBL and surface layer, and NOAH LSM. For the 500 m domain, horizontal diffusion is calculated truly horizontally, rather than on model vertical levels as is normally done. Truly horizontal diffusion improves simulation of temperature and humidity along valley slopes (Zängl 2002).

Besides the modifications inherent to Polar WRF, several additional changes are made for the MDVs environment. Input snow cover is removed over the MDVs, and is prevented from returning, as snow cover in the MDVs rarely lasts longer than a few days. A bare ground land use category is used for the MDVs, based on maps provided by Kevin Manning. Soil is specified as “loamy sand”, which better fits MDVs soil properties than the WRF default “silty clay loam” category. A one-year spinup simulation for the soil state was performed with the outer domains, initialized with climatological soil temperature and moisture values from past field studies.

ERA-Interim is used as initial and boundary conditions for the outermost domain. The outermost 32 km domain is nudged to ERA-Interim in all model levels above 1.5 km AGL, as without it model drift is problematic after a few days. All simulations feature lower boundary condition updates for SST using NOAA OI Daily 0.25° analyses (Reynolds et al. 2007) and for sea ice using 6-km resolution charts based on AMSR-E data from the University of Bremen (Spreen et al. 2008). Climatological values of sea ice thickness and snow thickness on sea ice are used, and taken from annual averages from the ASPeCT project (Worby et al. 2008). Terrain height is defined from the 200 m RAMP dataset (Liu et al. 2001).

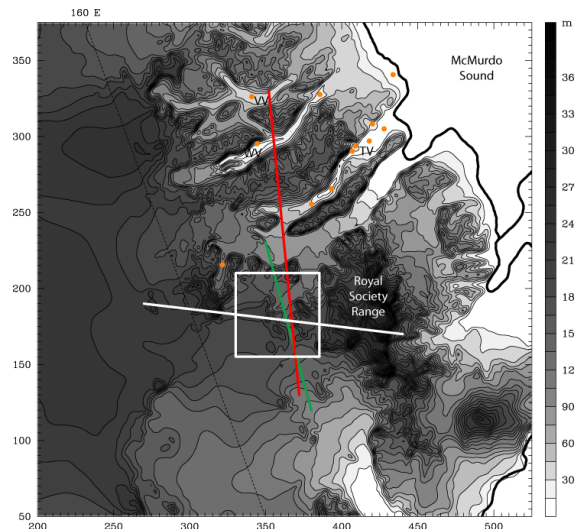


Figure 1. A portion of the 500 m domain over the MDVs, with terrain height shaded. White transect used in Fig. 2, green transect and white averaging box used in Fig. 3, and red transect used in Fig. 4. Orange dots represent LTER AWS station locations.

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3. FOEHN MECHANISM

a. Gap Flow

Figure 2 shows a cross section of terrain height south of the MDVs. A gap of varying depth and about 40 km width is located between the Royal Society Range to the east and the expansive East Antarctic Ice Sheet to the west. As cyclonic flow over the Ross Ice Shelf approaches the Royal Society Range from either the south or east, it is blocked and surface pressure increases upstream associated with the accumulation of mass. The pressure difference between the regions upstream and downstream of the gap drives *gap flow*, bringing strong southerly flow into the western MDVs. Figure 3 shows time series of the reduced pressure difference across the gap (pressure reduced upwards to the highest point along a transect, using the model virtual temperature profile) and the near-surface gap wind speed. The gap wind speed largely tracks with the gap pressure difference, although there are times when deviations occur. These deviations occur when the ambient flow has an off-continent component, and the importance of blocking and gap flow effects lessens. Still, gap flow is the primary forcing mechanism for southerly flow into the western MDVs.

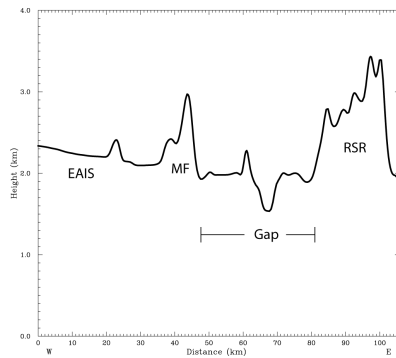


Figure 2. Profile of terrain height along the white transect in Fig. 1. “EAIS” is East Antarctic Ice Sheet, “MF” is Mount Feather, and “RSR” is the Royal Society Range.

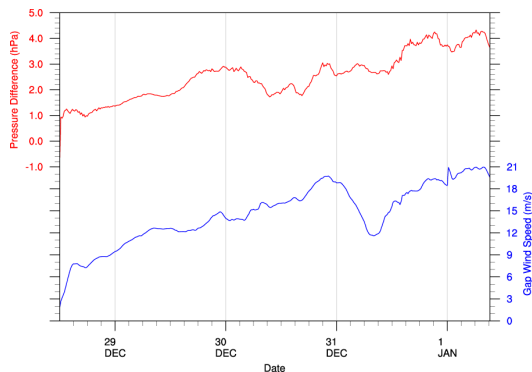


Figure 3. Time series of reduced pressure difference across the gap (green transect in Fig. 1, red line) and near-surface gap wind speed averaged over the white box in Fig. 1 (blue).

b. Mountain Waves

The gap upstream of the MDVs is elevated and features complex terrain, and mountain wave effects can be the dominant forcing mechanism for strong gap winds (Pan and Smith 1999; Gaberšek and Durran 2004). Figure 4 shows an example of mountain waves over the gap and western MDVs at 1800 UTC 30 December 2006. Shooting flow develops in the lee of the gap terrain, and large-amplitude waves are present all along the transect. The wave response and locations of hydraulic jumps are strongly tied to the upstream wind speed and wind direction. When upstream winds are weaker (as often occurs with a southerly wind component, due to upstream blocking along the Transantarctic Mountains), wave breaking occurs at lower levels of the troposphere, preventing extensive vertical propagation of waves, and limiting the downstream extent of the shooting flow. Wave response is also affected by critical layers, resulting in wave reflection and amplification when cross-ridge ambient wind component goes to zero at some height aloft. Such critical layers have been found when the ambient flow is easterly. The forced descent in the lee of the gap is responsible for the foehn effect, and this warm air is advected into the western MDVs by the shooting flow. This southerly flow into the western MDVs results in mass accumulation from blocking against the Asgard Range or hydraulic jumps.

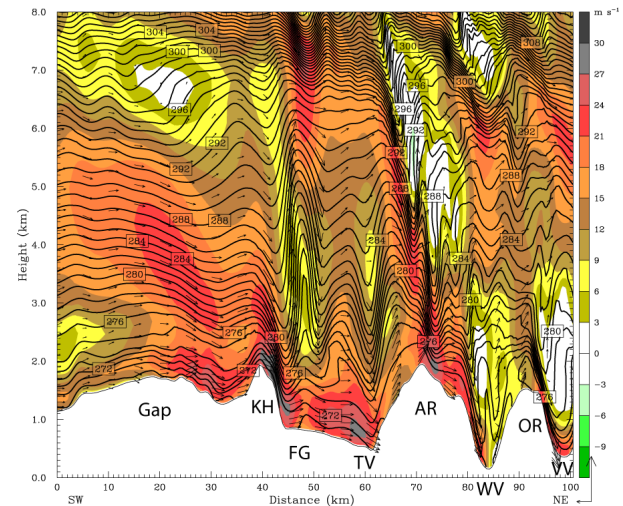


Figure 4. Vertical cross section of potential temperature (K, contours), wind speed along the red transect in Fig. 1 and circulation vectors at 1800 UTC 30 December 2006. “Gap” is the elevated gap, “KH” is Knobhead, “FG” is Ferrar Glacier, “TV” is Taylor Valley, “AR” is Asgard Range, “WV” is Wright Valley, “OR” is Olympus Range, and “VV” is Victoria Valley.

c. Pressure-driven Channelling and Easterly Intrusions

The imposing Royal Society Range prevents flow from directly reaching the eastern MDVs, so another process must be responsible for directing warm foehn air down-valley. Figure 5 shows the sea-level pressure distribution in the MDVs at 0900 UTC 30 December 2006. A localized high-pressure region is found in western Taylor and Wright Valleys, due to mass accumulation associated with the upstream gap flow. A down-valley directed pressure gradient force is responsible for the strong westerly flow observed in the MDVs during foehn events. Flow is constrained by the valley walls and flows down the pressure gradient, known as *pressure-driven channelling* (Whiteman and Doran 1993).

This westerly flow can be interrupted at times by cool, moist easterly flow from McMurdo Sound. While these easterly intrusions have been attributed to sea-breeze effects, such a thermally-forced circulation is not feasible during the winter when such easterly intrusions have also been observed to occur. An alternative explanation is that the mesoscale high-pressure region south of Ross Island in Windless Bight directs ambient southerly flow around Ross Island, and this flow is then blocked by the Antarctic continent, setting up a localized high-pressure region that provides an opposing forcing to the down-valley PGF. The near-surface streamlines and wind speed at 0900 UTC 30 December 2006 are shown in Fig. 6. Southerly flow is deflected westward around Ross Island, and a convergence zone forms offshore of the MDVs. When flow deflection around Ross Island is weak, dynamical forcing is weaker over McMurdo Sound, and any easterly intrusions are instead forced by thermal (sea-breeze) effects.

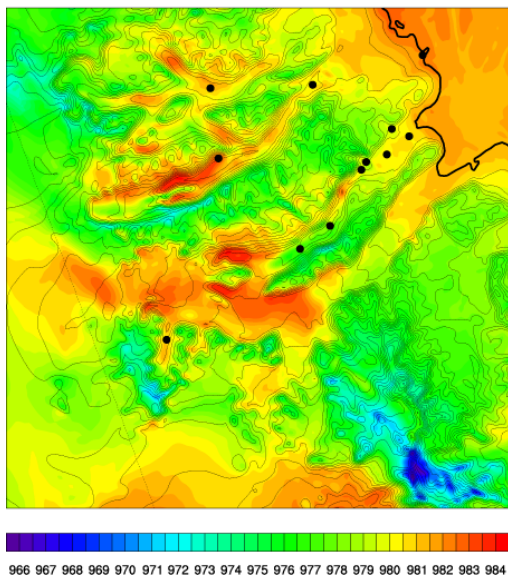


Figure 5. Polar WRF sea-level pressure at 0900 UTC 30 December 2006.

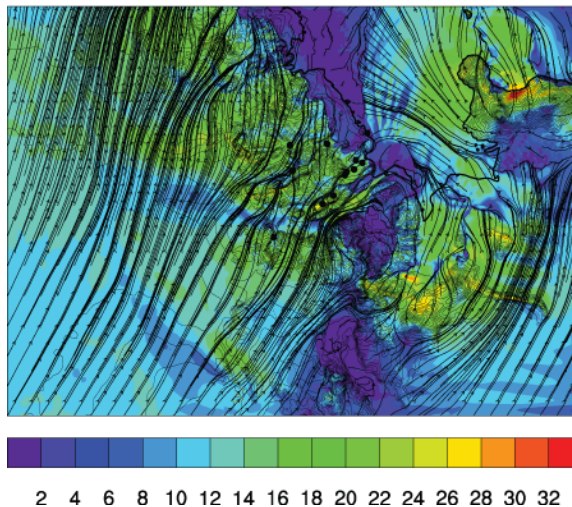


Figure 6. Polar WRF near-surface wind speed and streamlines at 0900 UTC 30 December 2006.

4. CONCLUSIONS

For the first time, the physical mechanisms responsible for foehn events in the MDVs have been explored. A series of mesoscale processes are involved in the foehn mechanism, including gap flow, mountain wave effects, pressure-driven channelling, and opposing up-valley forcing from flow deflection around Ross Island. Polar WRF simulations for 15 summers at 2-km grid spacing show that the gap flow and mountain wave response dependence on upstream wind direction are both robust across many foehn events.

Strong ambient winds aloft (at least 6 m s^{-1}) are required to activate the foehn mechanism, meaning that an amplified circulation pattern is generally required for foehn events in the MDVs.

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