1-14-2004

Climatology of Katabatic Winds in the McMurdo Dry Valleys, Southern Victoria Land, Antarctica

Thomas H. Nylen

Andrew G. Fountain
Portland State University

Peter T. Doran

Citation Details

Nylen, T. H., A. G. Fountain, and P. T. Doran (2004), Climatology of katabatic winds in the McMurdo dry valleys, southern Victoria Land, Antarctica, J. Geophys. Res., 109, D03114, doi:10.1029/2003JD003937.

Climatology of katabatic winds in the McMurdo dry valleys, southern Victoria Land, Antarctica

Thomas H. Nylen and Andrew G. Fountain
Department of Geology and Department of Geography, Portland State University, Portland, Oregon, USA

Peter T. Doran
Department of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, Illinois, USA

Received 1 July 2003; revised 16 October 2003; accepted 3 December 2003; published 14 February 2004.

[1] Katabatic winds dramatically affect the climate of the McMurdo dry valleys, Antarctica. Winter wind events can increase local air temperatures by 30°C. The frequency of katabatic winds largely controls winter (June to August) temperatures, increasing 1°C per 1% increase in katabatic frequency, and it overwhelms the effect of topographic elevation (lapse rate). Summer katabatic winds are important, but their influence on summer temperature is less. The spatial distribution of katabatic winds varies significantly. Winter events increase by 14% for every 10 km up valley toward the ice sheet, and summer events increase by 3%. The spatial distribution of katabatic frequency seems to be partly controlled by inversions. The relatively slow propagation speed of a katabatic front compared to its wind speed suggests a highly turbulent flow. The apparent wind skip (down-valley stations can be affected before up-valley ones) may be caused by flow deflection in the complex topography and by flow over inversions, which eventually break down. A strong return flow occurs at down-valley stations prior to onset of the katabatic winds and after they dissipate. Although the onset and termination of the katabatic winds are typically abrupt, elevated air temperatures remain for days afterward. We estimate that current frequencies of katabatic winds increase annual average temperatures by 0.7° to 2.2°C, depending on location. Seasonally, they increase (decrease) winter average temperatures (relative humidity) by 0.8° to 4.2° (−1.8 to −8.5%) and summer temperatures by 0.1° to 0.4°C (−0.9% to −4.1%). Long-term changes of dry valley air temperatures cannot be understood without knowledge of changes in katabatic winds. *INDEX TERMS:* 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; 1620 Global Change: Climate dynamics (3309); 1610 Global Change: Atmosphere (0315, 0325); 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; *KEYWORDS:* Antarctica, dry valleys, katabatic winds

Citation: Nylen, T. H., A. G. Fountain, and P. T. Doran (2004), Climatology of katabatic winds in the McMurdo dry valleys, southern Victoria Land, Antarctica, *J. Geophys. Res.*, *109*, D03114, doi:10.1029/2003JD003937.

1. Introduction

[2] Katabatic winds were first documented during the early expeditions to Antarctica. At Cape Denison, Adélie Land, wind speeds were recorded in excess of 66 m s^{-1} [*Mawson*, 1915], an unlikely speed according to the scientific community at the time. Now it is recognized that these strong winds are a significant climatic feature of Antarctica, especially along the continental margin [*Streten*, 1968]. The winds evolve high on the Antarctic Plateau where net long-wave radiation losses cool the near-surface air. The air density increases and flows downslope, replacing the less dense air at lower elevations [*Hoinkes*, 1961; *Ishikawa et al.*, 1982]. Consequently, katabatic winds display strong directional consistencies [*King and Turner*, 1997]. In the continental interior, katabatic wind speeds are low because of the small topographic slopes, but near the steep-sloped coast, wind speeds increase. Also, coastal topography can channel airflow, causing it to reach great speeds [*Parish and Bromwich*, 1987].

[3] Surface airflow in the continental interior of Antarctica is dominated by the drainage of cold, dense air (katabatic winds) and is the primary influence on the surface wind patterns [*Allison*, 1985; *Parish and Bromwich*, 1987; *Streten*, 1968]. Aloft, warm air is advected poleward to replace the drainage of surface air and reduces the equator-pole temperature gradient [*King and Turner*, 1997]. The frequency of katabatic winds in the coastal regions depends on a pool of cold, dense air on the continental plateau and synoptic scale forcing [*King*, 1989; *Kottmeier*, 1986;

0148-0227/04/2003JD003937

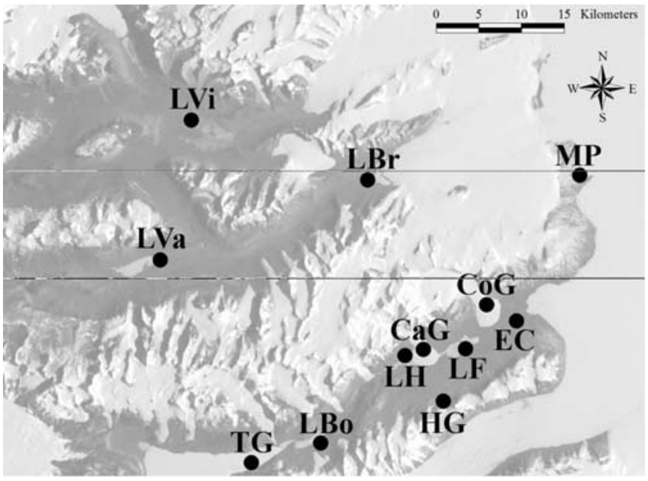

Figure 1. Location of meteorological stations and other major features in the McMurdo dry valleys, Antarctica. Abbreviations are CaG, Canada glacier; CoG, Commonwealth glacier; EC, Explorers Cove; HG, Howard glacier; LBo, Lake Bonney; LBr, Lake Brownworth; LF, Lake Fryxell; LH, Lake Hoare; LVa, Lake Vanda; Lvi, Lake Vida; MP, Marble Point; TG, Taylor glacier. The Landsat image was modified from *Malin Space Science Systems* [2001].

Murphy and Simmonds, 1993; *Parish*, 1982]. The interplay between katabatic winds, synoptic depressions generated in the southern oceans, and local topography defines meteorological conditions along the coast.

2. Background

[4] The McMurdo dry valleys (MCM) are located along the continental margin of Antarctica in southern Victoria Land at 77°30′S and 162°00′E (Figure 1). Our site is part of the Long-Term Ecological Research (LTER) Network, which has one other site in Antarctica and 22 in the United States. The MCM 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. Valley bottom elevations vary from 0 to 400 m above sea level, and the intervening mountains rise to 2500 m. The MCM generally trend E-W, with the exception of Victoria Valley, which trends NW-SE (Figure 1). The Wilson Piedmont Glacier blocks all but Taylor Valley from McMurdo Sound. The dry valley landscape is characterized by cold desert soils with alpine glaciers descending from the surrounding mountains, outlet glaciers penetrating the valleys from the ice sheet, and numerous perennial ice-covered lakes.

[5] The MCM are a polar desert. Air temperatures hover near freezing during the summer months of December and January and drop as low as −65°C in winter. Average annual air temperatures vary between −15° and −30°C [*Doran et al.*, 2002]. Because of the high latitude, the MCM receive solar radiation only between the months of August and April. Average wind speeds range from 2.5 to 5.3 m s^{-1}. Wind direction is typically controlled by valley orientation. During calm periods, gentle drainage winds flow down the valley sides and alpine glaciers to the valley bottom [*Clow et al.*, 1988]. Annual precipitation in the valley bottoms is <10 cm water equivalent [*Keys*, 1980].

3. Data Collection

[6] Twelve year-round meteorological stations have been deployed in the valleys (Figure 1 and Table 1) [*Doran et al.*, 1995]. Each station monitors wind direction and speed, air temperature, and humidity at ∼3 m above the ground surface. The sensors collect data every 30 s (4 s for wind speed). At 15-min intervals the data are averaged and recorded by a Campbell Scientific solid-state data logger. A more extensive description of the sensors, accuracies, and data corrections of the meteorological stations on the valley bottom is provided by *Doran et al.* [2002]. The glacier stations listed in Table 1 use the same sensors as the valley bottom stations described by *Doran et al.* [2002]. The Marble Point station is part of the Antarctica automatic weather station (AWS) network [*Stearns et al.*, 1993].

[7] For our purposes, we define summer as December to February, autumn as March to May, winter as June to August, and spring as September to November. In our investigation we use only the 1999 data for comparison purposes because all the stations were working properly over the entire year. The relationships found between stations are similar in other years. For the temporal

Table 1. List of Meteorological Stations in the McMurdo Dry Valleys[a]

Location	Valley	Latitude, °S	Longitude, °E	Elevation, m	Surface	Season Station Installed	Years of Record
Lake Bonney	Taylor	−77.714	162.464	60	soil	1993/1994	8
Lake Brownsworth	Wright	−77.434	162.704	280	soil	1994/1995	7
Canada Glacier	Taylor	−77.613	162.963	264	ice	1994/1995	7
Commonwealth Glacier	Taylor	−77.564	163.280	290	ice	1993/1994	8
Explorers Cove	Taylor	−77.589	163.418	26	soil	1997/1998	4
Lake Fryxell	Taylor	−77.611	163.170	20	soil	1987/1988	14
Lake Hoare	Taylor	−77.625	162.900	72	soil	1985/1986	16
Howard Glacier	Taylor	−77.671	163.079	472	ice	1993/1994	8
Taylor Glacier	Taylor	−77.740	162.128	334	ice	1994/1995	7
Lake Vanda	Wright	−77.517	161.011	125	soil	1987/1988	14
Lake Vida	Victoria	−77.378	161.801	390	soil	1995/1996	6
Non-LTER station Marble		−77.44	163.75	120	soil	1979/1980	1

[a]The first set of stations are run and maintained by the LTER project and the non-LTER station is part of the Antarctica AWS network. The surface column refers to the typical condition of the ground surface.

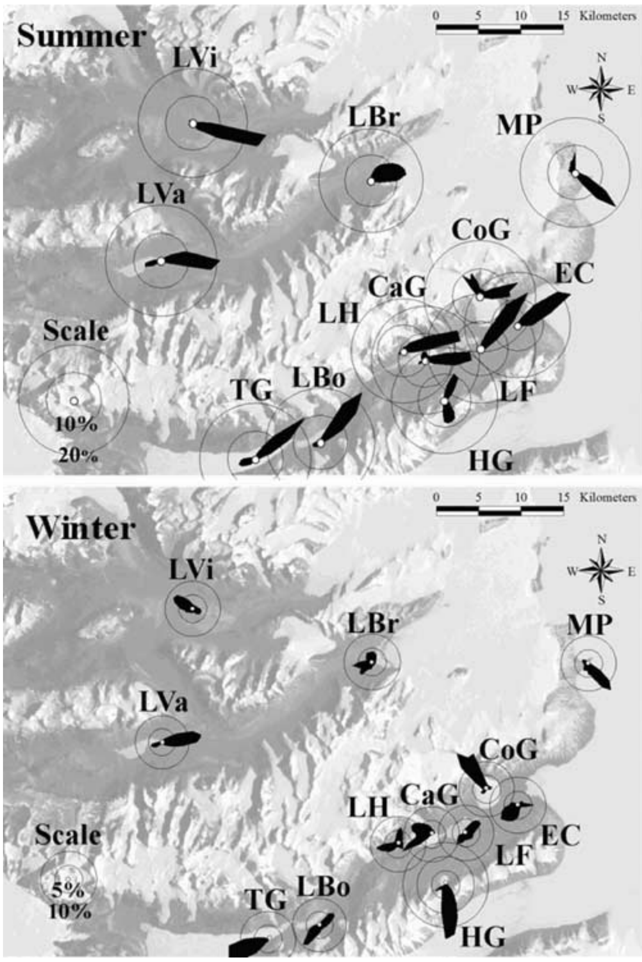

Figure 2. (top) Summer and (bottom) winter wind direction frequency (percent of total) for the meteorological stations in the McMurdo dry valleys during the same period. The directional plots are divided into 36 intervals. The magnitude of each interval is given as the percent of the overall record. The Landsat image was modified from *Malin Space Science Systems* [2001].

analysis we use data from Lake Hoare, collected between 1989 and 2001.

4. Results and Analysis

4.1. General Wind Flow Patterns

[8] Principal wind directions for the valley bottom stations are parallel to valley orientation, either up valley from the ocean or down valley from the plateau (Figure 2). For Marble Point, located along McMurdo Sound, the winds are from the southeast, consistent with observations on the Ross Ice Shelf. For the stations on the alpine glaciers a third principal wind direction exists down glacier. In summer, the most frequent direction (~66%) in the valley bottom is up-valley winds (sea breezes). For the glacier stations Howard and Commonwealth the summer wind pattern is bimodal. Down-glacier winds occur when the Sun is low along the southern horizon, and heating of valley soils is minimal. The spatial influence of the down-glacier winds is limited on the basis of results from Canada Glacier station, which is closer to the valley bottom than other glacier stations. It exhibits characteristics more similar to the valley stations. For both the valley and glacier stations, westerly winds occur infrequently, but they exhibit the greatest wind speeds (up to 37 m s^{-1}).

[9] During winter the valley stations have a bimodal wind direction. The down-valley (katabatic) winds are not only more frequent than in summer but also stronger. Lake Hoare is greatly influenced by flow down the adjacent valley walls. The glacier stations develop a trimodal wind pattern dominated by down-glacier winds that flow at similar speeds as in summer. We distinguish between katabatic and down-glacier winds, which are both drainage winds [*Obleitner*, 1994] because of the magnitude and scale differences. Down-glacier winds drain a much smaller area and have much lower wind speeds and temperature increases associated with them.

4.2. Seasonal and Spatial Distribution of Katabatic Winds

[10] Seasonal and spatial variations of katabatic winds are significant and persistent features of the MCM climate [*Bromley*, 1985; *Clow et al.*, 1988], as well as most of the Antarctic continent. The effects of katabatic winds on wind speeds, air temperatures, and relative humidity have long been recognized [*Murphy and Simmonds*, 1993; *Streten*, 1963]. To automatically identify katabatic winds in the LTER meteorological records, we used wind direction and speed. Figure 3 shows the distribution of winter wind direction versus wind speed measured at Lake Hoare. The katabatic winds do not consistently come from the same westerly direction but vary according to wind speed. Strong katabatic winds overwhelm topographic controls (E-W), and the wind flow is from the south-southwest. Because of this variability we selected a range of 180°–315° for our search criteria. For Lake Vida a broader range was used (180°–360°) to account for the orientation of Victoria Valley. To differentiate between katabatic winds from the plateau and local drainage winds, we selected a minimum wind speed of 5 m s^{-1}. The search criteria did not include the rise (or drop) in temperature or humidity because no

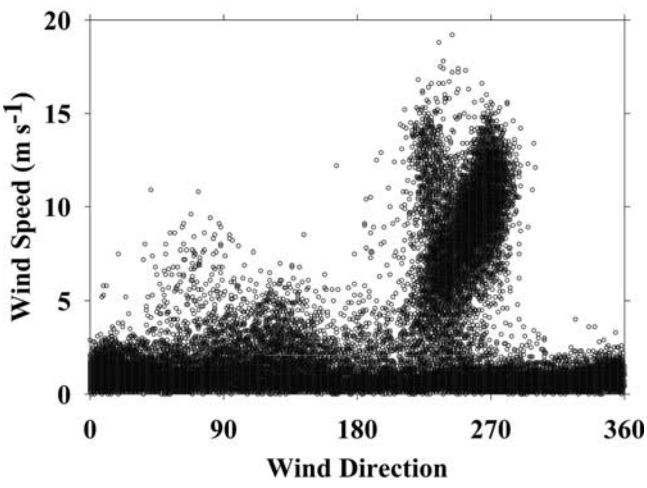

Figure 3. Winter wind direction versus wind speed measured at Lake Hoare meteorological station between 1997 and 2002.

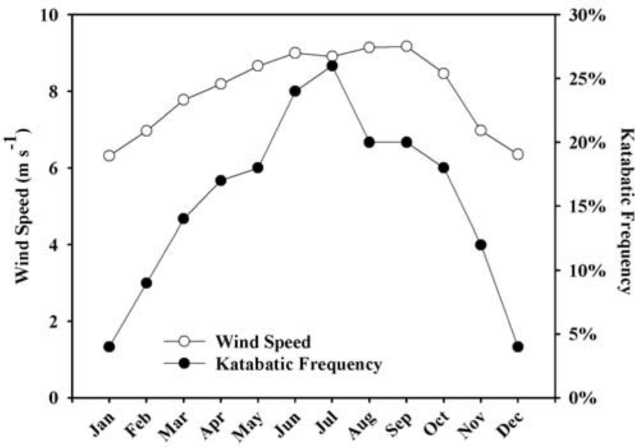

Figure 4. Monthly average katabatic frequency and katabatic wind speeds at Lake Hoare between 1989 and 2001.

distinct threshold existed. We spot-checked the meteorological records to confirm the accuracy of the classification parameters. However, identifying events at Taylor Glacier, an outlet glacier of the East Antarctic Ice Sheet, is a problem because there is overlap between strong local down-glacier winds and weak katabatic winds.

[11] Considerable differences exist in the monthly average frequency of katabatic winds. The frequency of katabatic winds over the 13-year record at Lake Hoare is greatest during winter (26% in July) and least during summer (4% in December; Figure 4). Wind speeds for winter katabatics average 9.0 m s^{-1}, compared to 6.5 m s^{-1} for summer events. Greater katabatic frequencies (and higher wind speeds) in winter are also reflected in the other stations (Figure 5). The highest frequency is on Taylor Glacier in May (68%). In December and January, katabatic frequencies are low and vary from 1% at Explorers Cove to 16% at Taylor Glacier. The western part of Taylor Valley, closer to the ice sheet, experiences more katabatic winds than the eastern part (Figure 6). In winter the gradient in katabatic frequency is 14% per 10 km inland (r^2 = 0.90, $P <$ 0.001), while in summer it is only 3% per 10 km (r^2 = 0.96, $P < 0.001$). Gradients during the autumn and spring are 12% per 10 km (r^2 = 0.78, P = 0.003) and 9% per 10 km (r^2 = 0.97, $P < 0.001$), respectively. The increasing frequency inland probably results from being closer to the katabatic source. Comparison of katabatic winds in Taylor Valley with those in the Wright and Victoria Valleys presents a confusing picture (Figures 5 and 6), especially in terms of Lakes Vanda and Vida. We believe that differences between the valleys are due to differences in inversion strengths, discussed in section 4.

4.3. Inversions and the Effect of Katabatic Winds on Meteorological Conditions

[12] Katabatic conditions are warmer than nonkatabatic conditions, but the temperature difference changes with the seasons (Figure 7). In the valley bottoms, for average monthly values (average temperatures during katabatic winds minus temperatures during nonkatabatic conditions), the smallest difference occurs in summer (~4°C), and the largest occurs in winter (~17°C). On the glaciers, winter temperature differences are smaller than in the valley bottom (~6°C). As expected from the temperature differences, the relative humidities (RH) in the valley bottom are much lower during katabatic winds (~35%) compared to nonkatabatic conditions (~60%). The absolute humidity, however, increases 1.0 g m^{-3} during winter katabatic winds, suggesting that the ice surfaces are rapidly sublimating.

[13] The larger temperature differences at the valley stations compared to the glacier stations are probably due to differences in inversion strength. Winter temperatures of the glacier stations are ~10°C warmer than the valley stations. Katabatic winds disrupt the inversions and mix the colder surface air with warmer air aloft and with adiabatically warmed air of the katabatic itself. *Doran et al.* [2002] suggested that Lake Vanda and particularly Lake Vida experience stronger and more persistent inversions, which explains their larger temperature differences between katabatic and nonkatabatic conditions as compared to Taylor Valley. Figure 8 shows an advanced very high resolution radiometer (AVHRR) satellite images using channel 4 (10.3–11.3 μm). We infer that the light areas (cold) in Victoria valley and in lower Taylor Valley are indicative of inversions. This temperature contrast in the AVHRR images during the nonsummer months is persistent, especially in Victoria Valley. During katabatic winds, the light areas in the valleys turn dark in the AVHRR images, which indicates the disruption of surface inversions [*Bromwich*, 1989].

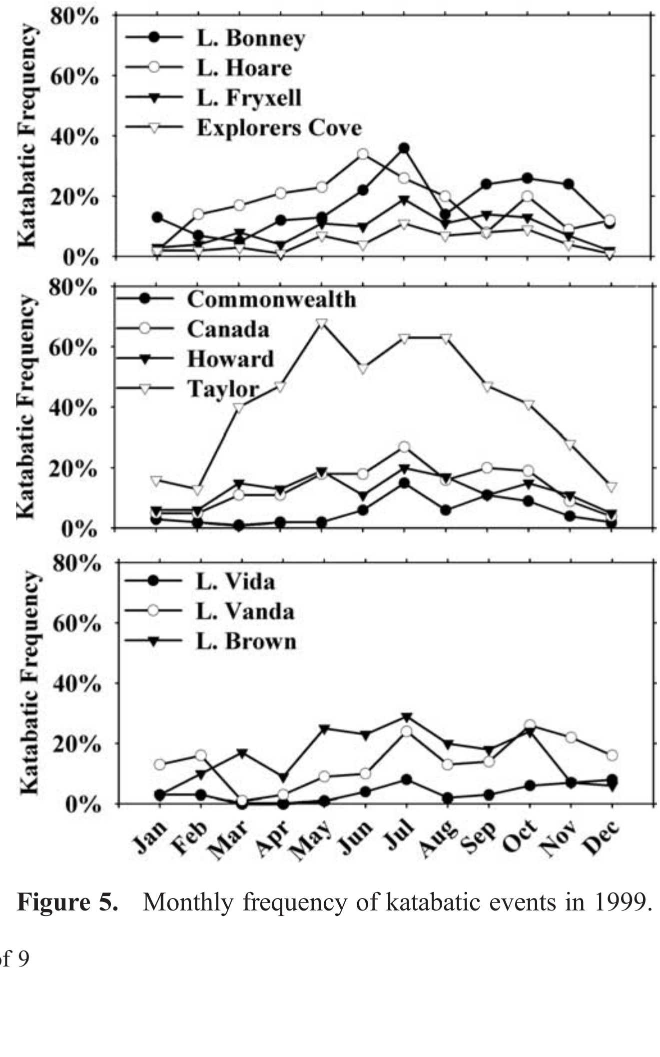

Figure 5. Monthly frequency of katabatic events in 1999.

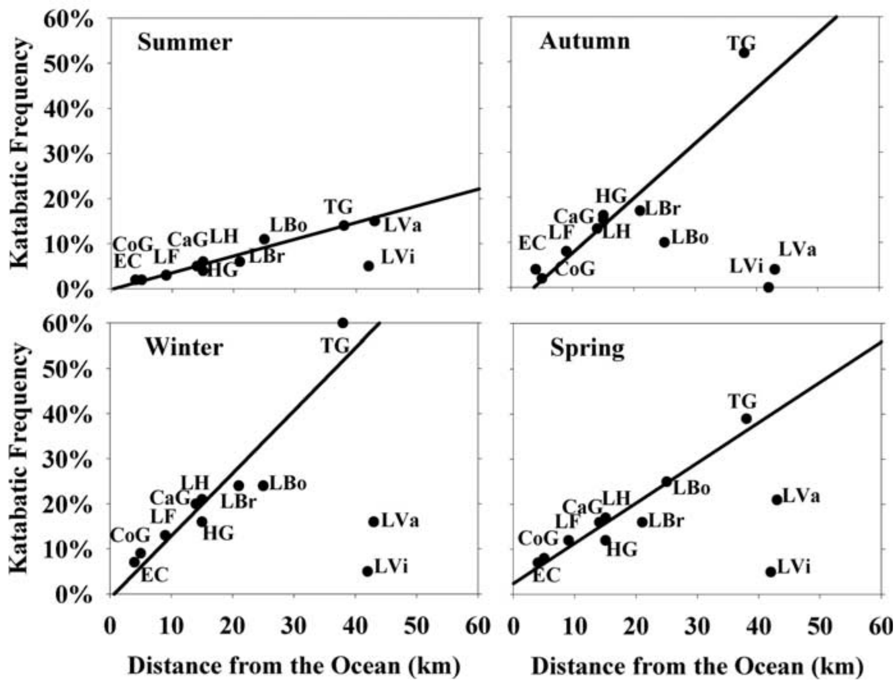

Figure 6. The 1999 Katabatic seasonal frequencies versus distances from the ocean. The regression line is fitted to all stations except Lakes Vanda and Vida. Abbreviations are CaG, Canada glacier; CoG, Commonwealth glacier; EC, Explorers Cove; HG, Howard glacier; LBo, Lake Bonney; LBr, Lake Brownworth; LF, Lake Fryxell; LH, Lake Hoare; TG, Taylor glacier; LVa, Lake Vanda; LVi, Lake Vida.

[14] Thus winter temperatures in the valley bottoms are controlled by several competing processes. First, radiation cools the surface and stabilizes the air column through density stratification. Second, katabatic winds bring warmer, drier air than normally found in a local air column. Finally, large-scale advection of warm and cold air affects regional temperatures. The relative strength of each process influences the surface temperature. For example, if the katabatic winds are relatively weak and inversions are comparatively strong, the winds may not significantly disrupt the inversions. This may explain why the Vanda and Vida stations do not follow the trend of increasing katabatic frequency with distance from the ocean because of strong and persistent inversions (Figure 6). The glacier stations, which are generally warmer on average than the valley floor, are apparently less affected by inversions.

[15] *Doran et al.* [2002] show that the spatial distribution of mean annual air temperatures for the valley stations cannot be explained by elevation differences (adiabatic lapse rate) because of the influence of katabatic winds. To examine the influence of katabatic winds without the elevation effect, we compare the average potential temperature to katabatic frequency (Figure 9). The near-constant summer potential temperature ($r^2 = 0.56$, $P = 0.05$) suggests that katabatic winds play a small role in determining summer temperature relative to station elevation. For the other seasons, katabatic frequency affects the potential temperatures in the valley bottoms but not on the glaciers. This suggests that the lapse rate becomes more important away from the valley bottoms and the inversions. Explorers Cove (EC) has warmer temperatures than predicted by the frequency of katabatic winds. Why this station deviates from the frequency/temperature relation is unclear. Perhaps the inversions are disrupted near the mouth of Taylor Valley by conditions in the McMurdo Sound.

[16] On the basis of the frequency of katabatic winds and their temperature and humidity differences we estimate that without katabatic winds the summer average air temperature in the valley bottoms would be 0.1°–0.3°C colder and winter temperatures would be 1.4° to 4.3°C colder, depending on the location (Table 2). Overall, the annual average temperatures would be 0.7°–2.3°C colder (not shown in Table 2). The relative humidity would be 1.3–3.2% (1.6–7.2%) higher in summer (winter) and wind speed would be 0.2–0.8 (0.6–2.3) m s^{-1} slower. The alpine glaciers are less affected, as expected from Figure 9. Commonwealth and Howard glaciers would be less affected by the absence of katabatic winds (average difference of −0.8°C). Taylor Glacier, on the other hand, would be significantly affected (average difference of −3.5°C) because of the high frequency of katabatic winds (∼60%) during the winter.

4.4. Characteristics of Individual Katabatic Winds

[17] To illustrate the character of katabatic winds propagating down valley, a "typical" katabatic wind is examined. Data from two valley stations are shown in Figure 10, and other stations are included in the discussion. The katabatic winds began on 28 May 1998 and lasted for 3 days, affecting all the stations. Prior to the event, temperatures were cold (<−35°C), wind speeds were light (<3 m s^{-1}), and wind directions were variable. Several days prior to the event, air temperatures were slowly increasing at all stations, and relative humidity remained nearly constant. The westernmost station, Taylor Glacier, was the first to detect

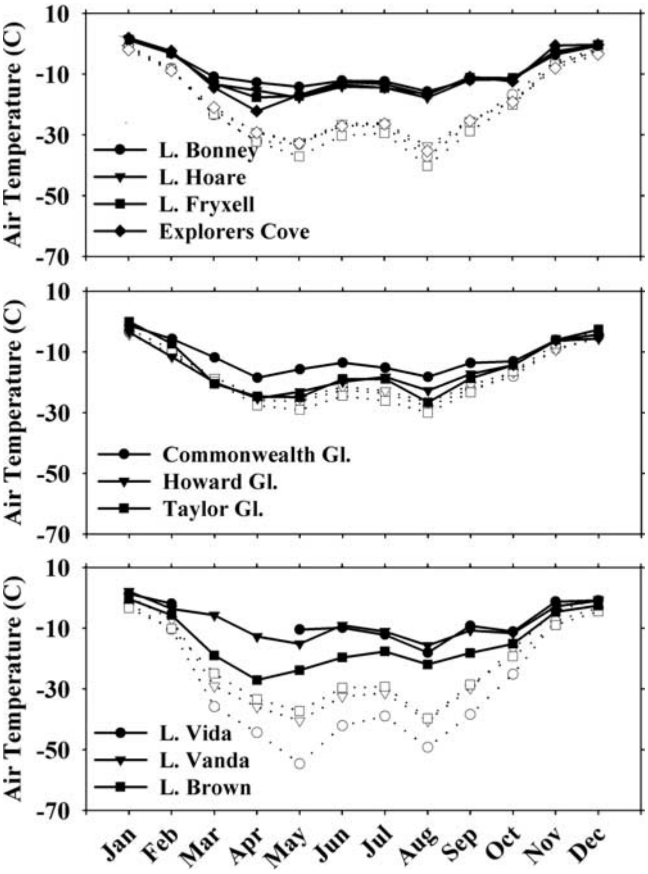

Figure 7. The 1999 monthly average air temperatures for stations in Victoria, Wright, and Taylor Valleys during katabatic and nonkatabatic conditions. The katabatic conditions are noted by solid symbols and lines, and nonkatabatic conditions are noted by open symbols and dashed lines.

the katabatic wind, followed 5.5 hours later by Lake Bonney. Both stations exhibited similar responses. Wind direction changed to a persistent westerly flow, and speeds increased beyond 10 m s^{-1}. At the same time, air temperature warmed and humidity dropped. The winds reached Lake Fryxell 17 hours after arriving at Lake Bonney, yielding a propagation rate of 0.41 m s^{-1}. The rate between each station was 0.46 m s^{-1} (Lake Bonney and Lake Hoare), 0.23 m s^{-1} (Lake Hoare to Lake Fryxell), and 0.35 m s^{-1} (Lake Fryxell to Explorers Cove). The katabatic winds started to decrease first, down valley at Lake Fryxell and 5.5 hours later at Lake Bonney. As the speeds dropped, the wind directions reversed to the east, starting with the stations closest to the ocean. The air became calm for all stations at about the same time.

[18] Although the sequence of events was broadly similar between stations, intriguing differences exist. When the high winds arrived at Lake Fryxell, they came from the east and swung to the west 8 hours later. The wind speed increased less quickly than at Lake Bonney but reached faster speeds. Near the middle of the event the wind direction shifted at Lake Fryxell by 30° (230°–200°) and was followed 5 hours later by a shift at Lake Bonney (240°–280°). The glacier stations responded somewhat differently. Katabatic winds reached several glacier stations before the valley stations; Canada Glacier responded about 3.5 hours before adjacent Lake Hoare, located 2 km up valley.

[19] Our concept of a katabatic wind is that of a highly turbulent air mass flowing off the East Antarctic Ice Sheet. The turbulent nature is suggested by the propagation rates of the event, which are 1–2 orders of magnitude smaller than the wind speed itself. The difference in propagation rates, faster on the glaciers at an altitude of several hundred meters and slower on the valley bottoms, may be due in part to the difference in wall drag as the core of the katabatic moves faster than the margins. In Taylor Valley, the 700 m tall hill in the middle of the valley deflects the katabatic winds aloft because the down-valley stations experience an easterly up-valley flow prior to being engulfed by the westerly flowing katabatic. If an inversion is present, katabatic winds probably flow over the inversion and erode its upper layers, reaching the higher glacier stations before the lower valley stations. As the event weakens, the flow no longer reaches the valley floor near the ocean, and an easterly return flow may dominate for a short period before returning to prekatabatic wind conditions. One of the lasting effects is the elevated air temperature, which slowly cools over several days.

5. Discussion

[20] The frequency and magnitude of katabatic winds are an important feature of the MCM climate. Observed wind speeds typically reach 20 m s^{-1} with gusts exceeding

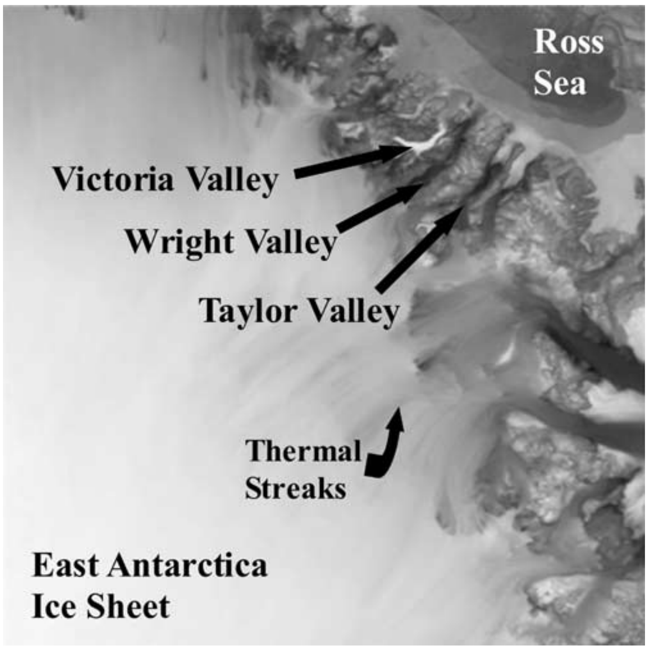

Figure 8. AVHRR image (band 4) of McMurdo dry valleys and surrounding region. Warm areas are dark, and cold areas are light. The wind direction can be seen in the dark streaks over the white snow. Note the streaks of warm air in the lee of rock outcrops in the ice. The image was taken on 31 August 1999 at 1837 UT.

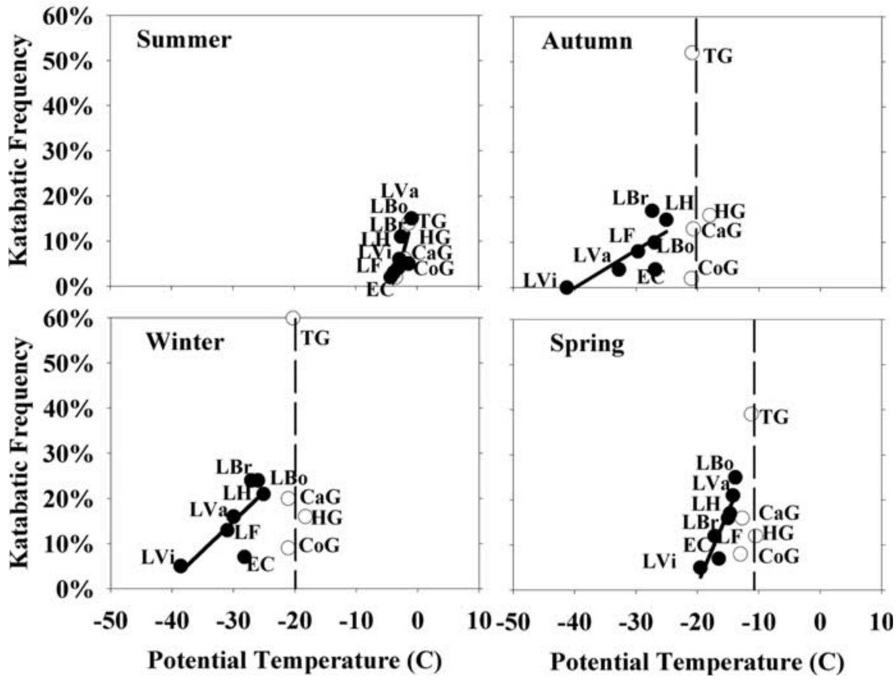

Figure 9. The 1999 average seasonal katabatic frequencies versus average potential temperatures (corrected for elevation) for stations in the MCM. The solid circles are the stations in the valley bottoms, and the open circles are glacier stations. The solid lines indicate a fit with the valley stations with a linear regression, and the dashed lines indicate an approximate fit with the glacier stations.

37 m s^{-1}. These winds are not as strong or frequent as those found in other sites around Antarctica [*King and Turner*, 1997], but they are similar to those found in other dry valleys [*Solopov*, 1967]. Katabatic winds increase air temperatures and decrease humidity because of the compressional warming air as it descends from the polar plateau. In winter, local air temperatures can increase by 30°C in a few hours. Such large temperature changes are also a feature of Chinook or foehn winds in the western United States [*Whiteman*, 2000]. The occurrence of more katabatic winds in winter than summer is consistent with results elsewhere in Antarctica [*Pettré et al.*, 1993]. This seasonal pattern results from the variation in radiative heat loss in the source region on the ice sheet and from the strength and location of synoptic depressions [*Kodama et al.*, 1988]. Summer katabatic winds are not as strong as those in winter, in part because of differences in how much heat can be lost from the source region and to local sea breezes that buffer the weaker katabatic winds. Sea breezes dominate the summer wind regime because of the heating of the soil-covered valley floors compared to the cooler ice-covered ocean. Spatial patterns in katabatic frequency show a decrease away from the East Antarctic Ice Sheet toward the ocean. Deviations from this pattern, particularly in the nonsummer months, are probably due to the development of local inversions, which depend on favorable topography such as closed basins.

[21] In winter, constant twilight eliminates solar heating of the valley floor, and shore breezes do not occur. Instead, strong inversions develop in the valley bottoms because of the radiative heat loss, similar to other ice-free areas in Antarctica [*Solopov*, 1967]. Although inversions form any time of year, they are most frequent and intense during winter. During August, for example, the average temperature difference between the valley bottom and 300 m elevation on an adjacent glacier is 9°C, or +3°C per 100 m. We presume that the inversions can be intensified by descending air during well-developed anticyclonic circulation [*Solopov*, 1967]. Inversions occur everywhere in the valley bottoms, but they are more persistent in the closed basins and in the smaller closed-off valleys. Particularly intense inversions develop in Victoria Valley, resulting in the coldest temperatures in the MCM [*Doran et al.*, 2002]. The inversions seem to be less important or weaker on the glaciers. This may be due to the elevation of the glaciers, which are several hundred meters off the valley floor and therefore closer to the top of the inversion; it may also be

Table 2. Average Air Temperature, RH, and Wind Speed Differences When the Effects of Katabatic Winds are Removed

	Air Temperature Differences, °C		RH Differences		Wind Speed Differences, m s^{-1}	
	Summer	Winter	Summer	Winter	Summer	Winter
Lake Bonney	−0.3	−4.3	2.8%	7.2%	−0.4	−2.3
Lake Vanda	−0.3	−3.4	2.0%	5.0%	−0.8	−1.7
Lake Hoare	−0.2	−3.2	2.2%	6.5%	−0.3	−1.9
Lake Brownsworth	−0.3	−3.2	3.2%	5.4%	−0.4	−1.8
Lake Fryxell	−0.2	−2.5	1.5%	3.0%	−0.3	−1.5
Explorers Cove	−0.2	−1.4	1.3%	2.4%	−0.2	−0.7
Lake Vida	−0.4	−2.2	2.1%	1.6%	−0.3	−0.6
Taylor Glacier	−0.2	−3.5	4.1%	8.5%	−0.8	−3.2
Howard Glacier	−0.1	−0.8	1.5%	1.7%	−0.3	−0.8
Commonwealth Gl.	−0.1	−0.8	0.9%	1.3%	−0.1	−0.5

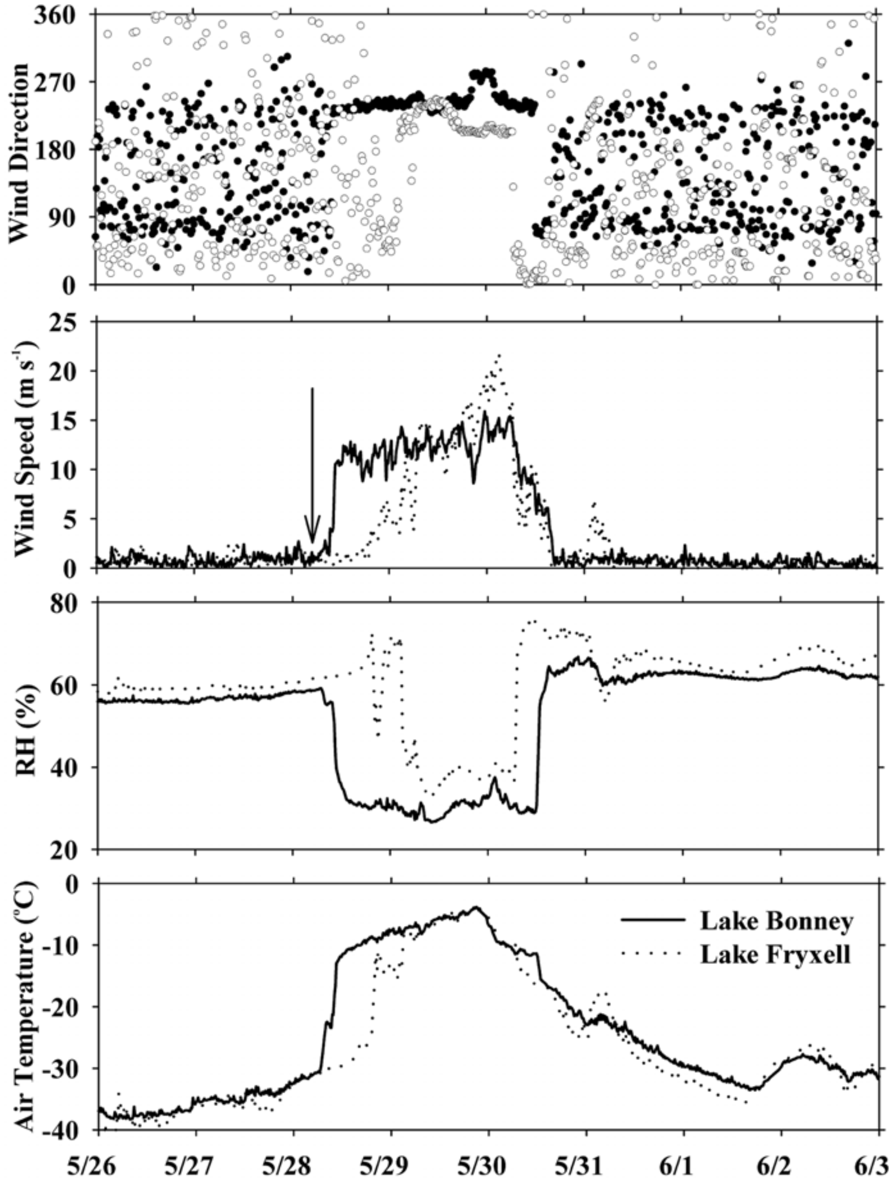

Figure 10. Meteorological conditions at stations in Taylor Valley during a winter katabatic event from late May to early June 1998. The arrow points to the start of the katabatic event at the Taylor Glacier meteorological station.

due to the glacier winds, which can reach 4 m s^{-1} and locally disrupt the inversion.

[22] Although each katabatic wind has its own unique features, we review the general characteristics. The onset of the event is signaled by a sharp rise in wind speed, and the wind direction shifts to a persistent westerly direction. Some down-valley stations experience an easterly wind for several hours before abruptly shifting to the west. This may reflect return flow up valley prior to being engulfed in the katabatic winds. Winter events exhibit a more abrupt onset than summer ones, probably because of preexisting inversions that resist the weaker leading winds. The air temperature rises (and humidity drops) with the onset of the winds, despite wind direction. Event decay is signaled by a decrease in wind speed at the down-valley stations and a shift in direction back to an easterly flow. The up-valley stations soon follow, and the valley returns to prekatabatic conditions. After the wind event, however, air temperature remains elevated over a period of days. *Bromley* [1985] described similar conditions during winter katabatic winds in Wright Valley.

[23] The propagation of katabatic winds through the valleys is complex. The propagation rate of the katabatic "front" is 0.5 m s^{-1}, slower than the wind speed itself, which reaches 30 m s^{-1}. The winds reach some stations down valley before reaching some up-valley ones, and they can affect the higher elevation glacier stations hours before reaching adjacent stations in the valley bottom. Our conceptual model is that of strong winds that flow fastest over the mountain peaks. Surface pressures drop because of katabatic winds aloft, and surface temperatures warm as heat disperses from the warmer katabatic layer. As the event

builds, it slowly overcomes the local meteorological regime of onshore winds in summer and inversions in winter, and the katabatic winds descend into the valleys in a down-valley direction. This explains why glacier stations at higher elevations tend to detect the katabatic wind before the adjacent stations on the valley bottom. The initial easterly flow observed at the stations down valley is probably return flow prior to the katabatic reaching the valley floor. Because of the complex terrain, the wind may skip and affect stations located in the broad, open area down valley before affecting up-valley stations located along the valleys walls or in topographic pockets. We infer that the katabatic core away from the valley walls moves faster than along the valley walls and bottom because of wall drag and form drag. As the event weakens, the down-valley stations again experience a return flow for a period of time, and the event dissipates up valley.

6. Conclusions

[24] Katabatic winds play an important role in shaping the climate of the MCM and other regions of Antarctica. Katabatic winds are more frequent in winter (5–55% per month) than summer (1–11%). Spatial variations in katabatic frequency are dependent on location relative to the source (East Antarctic Ice Sheet) and strength and persistence of inversions during the nonsummer months. Monthly average temperatures and relative humidity differences resulting from katabatic versus nonkatabatic conditions are +10° to +30°C and −20% to −30%, respectively. Katabatic winds increase (decrease) average winter temperatures (relative humidity) by 1.4°–4.3°C (1.6–7.2%) and summer by 0.2°–0.4°C (1.3–2.8%). For every 1% increase in katabatic frequency average, summer air temperatures increase by 0.4°C, and average winter temperatures increase by 1°C.

[25] These results underscore the point that to understand the temperature, humidity, and wind speed variations of the McMurdo dry valleys, one also has to understand the frequency of katabatic winds. A measured warming or cooling in the MCM may result from a change in the wind regime.

[26] **Acknowledgments.** This work was funded by the National Science Foundation, Office of Polar Programs, grant OPP-0086645, and by the NASA Exobiology Program. We thank Gary Glow and Chris McKay for contributions of pre-LTER data. We want to acknowledge the helpful discussions with our colleagues in the McMurdo dry valley LTER project.

References

Allison, I. (1985), Diurnal variability of surface wind and air temperature at an inland Antarctic site: 2 years of AWS data, in *Australian Glaciological Research, 1982–1983*, *ANARE Res. Notes*, vol. 28, edited by T. H. Jacka, pp. 81–92, Aust. Natl. Antarct. Res. Exped., Melbourne, Victoria, Aust.
Bromley, A. M. (1985), Weather observations, Wright valley, Antarctica, N. Z. Meteorol. Serv., Wellington.
Bromwich, D. H. (1989), Satellite analyses of Antarctic katabatic wind behavior, *Bull. Am. Meteorol. Soc.*, *70*(7), 738–749.
Clow, G. D., C. P. McKay, G. M. J. Simmons, and R. A. Wharton (1988), Climatological observations and predicted sublimation rates at Lake Hoare, Antarctica, *J. Clim.*, *1*(7), 715–727.
Doran, P. T., G. L. Dana, J. T. Hastings, and R. A. J. Wharton (1995), McMurdo dry valleys Long-Term Ecological Research (LTER): LTER automatic weather network (LAWN), *Antarct. J. U. S.*, *30*(5), 276–280.
Doran, P. T., C. P. McKay, G. D. Clow, G. L. Dana, A. G. Fountain, T. H. Nylen, and W. B. Lyons (2002), Valley floor climate observations from the McMurdo dry valleys, Antarctica, 1986–2000, *J. Geophys. Res.*, *107*(D24), 4772, doi:10.1029/2001JD002045.
Hoinkes, H. (1961), Studies of solar radiation and net radiation in the Antarctic, *Arch. Meteorol. Geophys. Bioklimatol., Ser. B*, *10*, 175–181.
Ishikawa, N., S. Kobayashi, T. Ohtake, and S. Kawaguchi (1982), Some radiation properties at Mizuho Station, East Antarctica in 1980, *Mem. Natl. Inst. Polar Res. Spec. Issue*, *24*, 19–31.
Keys, J. R. (1980), Air temperature, wind, precipitation and atmospheric humidity in the McMurdo region, *Publ. 17*, 52 pp., Dep. of Geol. Victoria Univ. of Wellington, Wellington.
King, J. C. (1989), Low-level wind profiles at an Antarctic coastal station, *Antarct. Sci.*, *1*, 169–178.
King, J. C., and J. Turner (1997), *Antarctic Meteorology and Climatology*, 409 pp., Cambridge Univ. Press, New York.
Kodama, Y., G. Wendler, and N. Ishikawa (1988), The diurnal variation of the boundary layer in summer in Adélie Land, eastern Antarctica, *J. Appl. Meteorol.*, *28*, 16–24.
Kottmeier, C. (1986), The influence of baroclinicity and stability on the wind and temperature conditions at the Geor von Neumayer Antarctic station, *Tellus*, *38*, 263–276.
Malin Space Science Systems (2001), Landsat image of ice-free valleys, San Diego, Calif.
Mawson, D. (1915), *The Home of the Blizzard, Being the Story of the Australasian Antarctic Expedition, 1911–1914*, 2 vols., W. Heinemann, London.
Murphy, B. F., and I. Simmonds (1993), An analysis of strong wind events simulated in a GCM near Casey in the Antarctic, *Mon. Weather Rev.*, *121*, 522–534.
Obleitner, F. (1994), Climatological features of glacier and valley winds at the Hintereisferner (Ötztal Alps Austria), *Theor. Appl. Climatol.*, *49*, 225–239.
Parish, T. R. (1982), Surface airflow over East Antarctica, *Mon. Weather Rev.*, *110*, 84–90.
Parish, T. R., and D. H. Bromwich (1987), The surface wind field over the Antarctic ice sheets, *Nature*, *328*, 51–54.
Pettré, P., C. Payan, and T. R. Parish (1993), Interaction of katabatic flow with local thermal effects in a coastal region of Adelie Land, East Antarctica, *J. Geophys. Res.*, *98*(D6), 10,429–10,440.
Solopov, A. V. (1967), Oases in Antarctica, translated from Russian by Isr. Program for Sci., 46 pp., Natl. Sci. Found., Arlington, Va.
Stearns, C. R., L. M. Keller, G. A. Weidner, and M. Sievers (1993), Monthly mean climatic data for Antarctic automatic weather stations, in *Antarctica Meteorology and Climatology: Studies Based on Automatic Weather Stations*, *Antarct. Res. Ser.*, vol. 61, edited by D. H. Bromwich and C. R. Stearns, pp. 1–21, AGU, Washington, D.C.
Streten, N. A. (1963), Some observations of Antarctica katabatic winds, *Aust. Meteorol. Mag.*, *24*, 1–23.
Streten, N. A. (1968), Some characteristics of strong wind periods in coastal East Antarctica, *J. Appl. Meteorol.*, *7*, 46–52.
Whiteman, C. D. (2000), *Mountain Meteorology: Fundamentals and Applications*, 355 pp., Oxford Univ. Press, New York.

P. T. Doran, Department of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, IL, USA. (pdoran@uic.edu)
A. G. Fountain and T. H. Nylen, Department of Geology, Portland State University, P.O. Box 751, Portland, OR 97207-0751, USA. (andrew@pdx.edu; nylent@pdx.edu)