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Valley Floor Climate Observations from the McMurdo Dry Valleys, Antarctica, 1986-2000

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[1] Climate observations from the McMurdo dry valleys, East Antarctica are presented from a network of seven valley floor automatic meteorological stations during the period 1986 to 2000. Mean annual temperatures ranged from −14.8°C to −30.0°C, depending on the site and period of measurement. Mean annual relative humidity is generally highest near the coast. Mean annual wind speed increases with proximity to the polar plateau. Site-to-site variation in mean annual solar flux and PAR is due to exposure of each station and changes over time are likely related to changes in cloudiness. During the nonsummer months, strong katabatic winds are frequent at some sites and infrequent at others, creating large variation in mean annual temperature owing to the warming effect of the winds. Katabatic wind exposure appears to be controlled to a large degree by the presence of colder air in the region that collects at low points and keeps the warm less dense katabatic flow from the ground. The strong influence of katabatic winds makes prediction of relative mean annual temperature based on geographical position (elevation and distance from the coast) alone, not possible. During the summer months, onshore winds dominate and warm as they progress through the valleys creating a strong linear relationship (r^2 = 0.992) of increasing potential temperature with distance from the coast (0.09°C km^{-1}). In contrast to mean annual temperature, summer temperature lends itself quite well to model predictions, and is used to construct a statistical model for predicting summer dry valley temperatures at unmonitored sites. *INDEX TERMS:* 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; 1610 Global Change: Atmosphere (0315, 0325); 1650 Global Change: Solar variability; *KEYWORDS:* Antarctica, dry valleys, climate, katabatic wind

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1. Introduction

[2] The McMurdo dry valleys, with a combined area of approximately 4800 km^2, is the largest ice-free area in Antarctica. This region was discovered by members of Robert Falcon Scott's party during their 1903 expedition to reach the South Pole [*Scott*, 1905]. The dry valleys became one of the most intensely studied areas of Antarctica starting in the IGY, owing to the interest in the conundrum of this large ice-free area in a region dominated by thick ice. Much of the focus of study in the region has turned to the local climatic, glacial, and geologic history, and the nature of an extreme ecosystem that is driven by melt of glacier ice and snow during the summer months [*Priscu*, 1998; *Green and Friedmann*, 1993]. The quick response of the dry valley ecosystem to even relatively short-term changes in climate has been recently highlighted by *Doran et al.* [2002].

[3] Historical weather observations in the dry valleys have provided a first indication of the climate at selected sites. The New Zealand Antarctic Program carried out manual weather observations at Lake Vanda Station during periods of station operation since 1958. Observations were mostly in summer but did include 3 years of year-round observations [*Riordan*, 1975; *Bromley*, 1985]. Published weather data from automatic weather stations include 1 year of data from the shore of Lake Hoare in Taylor Valley [*Clow et al.*, 1988] and several years of data from high elevation sites on Linneus Terrace in Wright Valley [*Friedmann et al.*, 1987; *Stearns et al.*, 1993; *McKay et al.*, 1993]. Combined, these studies have pointed to the importance of

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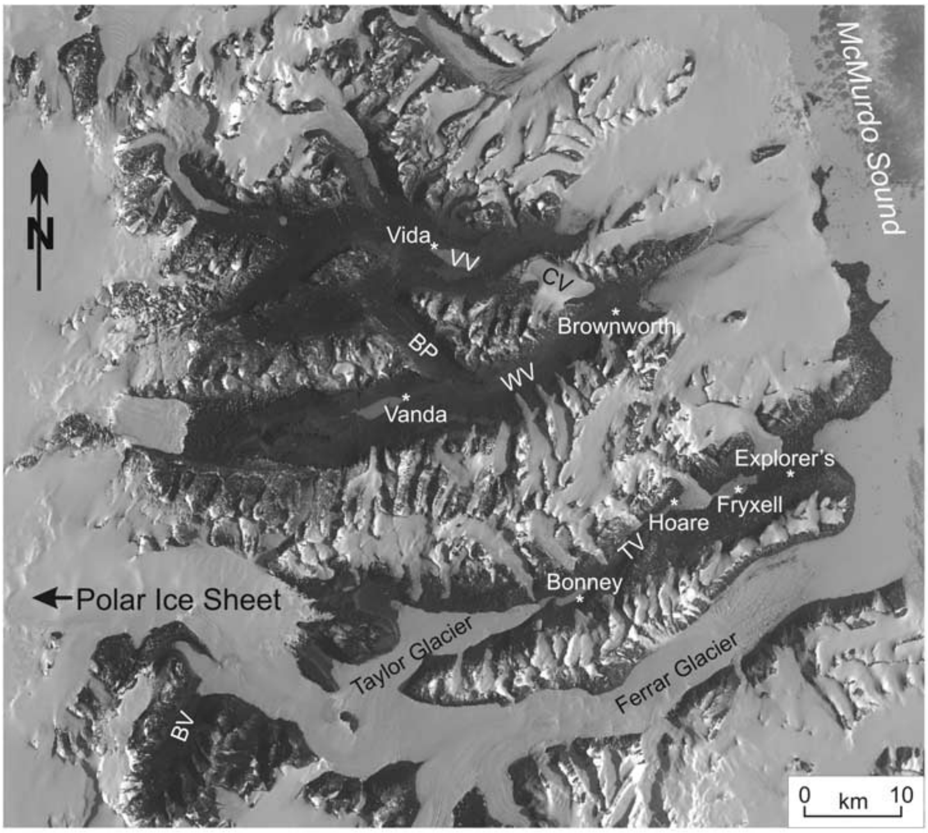

Figure 1. Landsat image of the dry valleys region showing the location of the meteorological stations (labeled asterisks). Different valleys and passes discussed in the text are marked as Taylor Valley (TV), Wright Valley (WV), Victoria Valley (VV), Clark Valley (CV), Beacon Valley (BV), and Bull Pass (BP). Elevations of individual meteorological stations are listed in Table 1.

katabatic wind in dictating local climate, particularly winter climate, but the measurement coverage has been sparse, and a more complete picture of dry valley climate is warranted. In this paper, we report on and discuss a summary of micrometeorological data from automatic weather stations at seven sites spread throughout the three main McMurdo dry valleys (Taylor, Wright and Victoria) between 1986 and 2000. All sites are valley floor land-based stations (as apposed to glacier stations), and the parameters chosen for comparison (temperature, humidity, wind speed and direction, solar flux, and photosynthetically active radiation) are measured at all sites.

2. Site Description

[4] Relief in the dry valleys ranges from sea level to more than 2000 m, and the landscape is a mosaic of ice-covered lakes, ephemeral streams, arid rocky soils, ice-cemented soils, and surrounding glaciers (Figure 1). Since the dry valleys receive very little precipitation, melt from the surrounding glaciers supplies the majority of water that feeds the lakes that form on the valley bottoms [*Fountain et al.*, 1999]. Water flows primarily from glaciers to streams to lakes, while wind disperses particulate matter throughout the valleys.

[5] McMurdo Station, 100 km to the southeast of the dry valleys, has maintained year-round weather observations since 1956, which provide a nearby long-term climate record. During calm conditions, the region is dominated by a strong boundary layer temperature inversion. Strong katabatic winds draining the polar plateau frequently disrupt this inversion. At McMurdo, winter temperatures are relatively high for the Antarctic coastal region. *Keys* [1980] suggests the warmer winters are due to the heat flux from the soil and McMurdo Sound, but more recent studies [e.g., *Bromwich et al.*, 1992] have suggested that the blocking of wind from the Ross Ice Shelf by the island itself is more important.

[6] The dry valleys generally experience warmer summers (DJF) and colder winters (JJA) than McMurdo [*Keys*, 1980]. The wind regime is markedly different because the long-axis of the valleys runs transverse to the major katabatic flow from the Ross Ice Shelf [*Parish and Bromwich*, 1987]. Similarly, the valleys can experience strong local glacier drainage winds, which do not occur in McMurdo. Although, the steep-sided valleys can also reduce solar incidence, McMurdo receives less sunshine in the summer due to the frequent occurrence of fog as the sea ice edge approaches the station.

[7] Previous studies have reported a range of mean annual temperatures in the dry valleys between -17 to $-20°C$ [*Thompson et al.*, 1971; *Riordan*, 1975; *Keys*, 1980; *Hervey*, 1984; *Bromley*, 1985; *Friedmann et al.*, 1987; *Clow*

et al., 1988], implying a thickness of permafrost in the region of 240 to 970 m [*Decker and Bucher*, 1980]. Limited precipitation data suggest that the mean annual precipitation is received only as snow and is <100 mm, water equivalent, with as little as 7 mm recorded by direct observations [*Bromley*, 1985]. This value is well below measured ablation rates which have ranged from 150 to >1000 mm a^{-1} [*Hendersen et al.*, 1965; *Clow et al.*, 1988; P. T. Doran, unpublished data, 2002]. The low precipitation relative to potential evaporation, low surface albedo, and dry katabatic winds descending from the Polar Plateau result in extremely arid conditions [*Clow et al.*, 1988].

3. Methods

[8] Data presented in this paper were collected by Campbell Scientific data logger (CR10 and 21X) based weather stations. All stations measure at least wind speed and direction, incoming solar flux, relative humidity, and air temperature. Additional parameters are measured at the various sites [*Doran et al.*, 1996], but not reported here as we chose to compare common parameters at all stations. Programmed sampling intervals over the period of record ranged from 30 s to 60 s, while averaging varied between 10 min and 6 hours. All meteorological sensors used to produce data in this paper were mounted on either a metal tripod or guyed metal mast. Further details about the network and data are given by *Doran et al.* [1996] and/or http://huey.colorado.edu.

[9] The air and soil thermistors were Fenwal Electronics type UUT51J1. The accuracy of these thermistors is a combination of Fenwal's interchangeability specification, the precision of the bridge resistors, and the polynomial error, which becomes significant below −35°C. To correct for the polynomial error we converted the fitting equation from the polynomial supplied by Campbell Scientific, to the Steinhart-Hart equation [*Steinhart and Hart*, 1968]. Applied to the Fenwal thermistors, the Steinhart-Hart equation results in a fit that is ±0.02°C over −40 to +60°C (G.D. Clow, unpublished data, 1991). Below −40°C, error due to extremely low voltage output versus precision of the voltage measurement (±1 μV) becomes significant and increases with decreasing temperature. This error is ±0.03 at −40°C and doubles for every 10°C temperature drop below (e.g., it is ±0.12 at −60°C).

[10] Humidity was measured with a model 207 Phys-Chem relative humidity sensor contained in a non-aspirated radiation shield (combined sensor with the air temperature thermistor). Water layers adsorb on the surface of the sensor in an amount that is dependent on the ambient relative humidity with respect to liquid water. The resistance of the sensor decreases with increasing humidity with a separate temperature dependence. Relative humidity accuracy is a combination of the accuracy of the humidity sensor and the thermistor (since temperature is used to remove the slight temperature dependence of the reading). Relative humidity output from the sensor was corrected to use the Steinhart-Hart temperature. Combined, these errors provide for a relative humidity accuracy of about 5% (at 25°C) over the humidity range 12% to 100%. Due to high resistance values, the RH sensor does not accurately record humidity less than 12%. The sensor operates equally well over the entire temperature range and shows no systematic errors at low temperatures. However, when air temperatures were below freezing, humidity data were corrected to correspond to the relative humidity with respect to ice. This was achieved by multiplying RH output when below freezing by the ratio (determined from tables and fit to a polynomial over the range 0° to −60°C) of the vapour pressure over ice and the vapour pressure over super-cooled water. Humidity transducer chips were replaced every 2 years after 1993, and infrequently prior to that.

[11] Prior to 1993, wind was measured with Met One wind sets (three-cup anemometers and vanes for wind speed and direction). These instruments are rated for winds of 0–45 m/s, with a starting threshold of 0.45 m/s. Wind speed accuracy is 1.5% and direction accuracy is ±4E. More recent wind measurements have been made by Model 05013 RM Young propeller type monitors with a stated wind speed accuracy of 2% up to 60 m s^{-1}. The lowest speed which will start the propeller is stated as 0.9 m s^{-1}, yet speeds lower than this have been noted turning the propeller in the field. The uncertainty in the wind direction is less than 5°. All RM Young wind monitors were cleaned and recalibrated at least once since their deployment in 1993.

[12] Solar flux was measured using Licor LI200SZ pyranometers which are cosine-corrected silicon photodiodes with a spectral response that is proportional to the solar energy received by a horizontal surface. A typical response curve is very low at 400 nm, increases nearly linearly to a peak at ~950 nm, and decreases nearly linearly to a cutoff near to 1200 nm. The Licor measurement has an absolute error of ±5% maximum, typically ±3% for angles less than 80°. Drift of the sensor is <2% yr^{-1}. Each Licor pyranometer was calibrated against Eppley pyranometers at the factory. We maintained a 2-year factory recalibration schedule for these sensors since 1993. Prior to 1993, sensors were recalibrated irregularly.

[13] Photosynthetically active radiation (PAR) was measured using Licor LI190SB Quantum sensors. This sensor accurately measures photon flux density between 400 and 700 nm wavelength. All quantum sensors were swapped with factory calibrated sensors every 2 years. Factory calibration is performed against a National Bureau of Standards lamp (G.E. 1000 watt type DXW quartz halogen) supplied with a spectral irradiance table. The uncertainty of the calibration is ±5%. Drift of the sensor is <2% yr^{-1}.

4. Dry Valley Temperature, Wind, and Radiation Regime

4.1. General

[14] The range of mean annual air temperatures on the floor of the dry valleys is −14.8°C at Lake Hoare to −30.0°C at Lake Vida (Table 1). The mean annual temperature relationship in the dry valleys is Taylor Valley > Wright Valley > Victoria Valley (Figure 2a). The historical trends from our longest data set (Lake Hoare) have been discussed previously by *Doran et al.* [2002]. The summer melting potential is represented by degree-days above freezing, which is also a function of summer temperature. Lake Vanda is consistently the warmest site during the summer, on average having twice the degree days of the

Table 1. Summary Climate Statistics for the McMurdo Dry Valleys

			Taylor Valley			Wright Valley		Victoria Valley
		Explorer's Cove	Lake Fryxell	Lake Hoare	Lake Bonney	Lake Brownworth	Lake Vanda	Lake Vida
Period of station record	start	21 Nov 1997	28 Oct 1987	12 Dec 1985	24 Nov 1993	31 Dec 1994	08 Nov 1987	24 Nov 1995
	end	25 Jan 2000	25 Jan 2000	24 Jan 2000	25 Jan 2000	26 Jan 2000	26 Jan 2000	26 Jan 2000
Station elevation, m asl		26	20	72	60	280	125	390
Distance from coast, km		4	9	15	25	21	43	42
Air Temperature, °C	avg mean annual	−19.6	−20.2	−17.7	−17.9	−20.9	−19.3	−27.4
	max mean annual	−19.2	−16.7	−14.8	−16.2	−19.8	−17.2	−25.4
	min mean annual	−20.2	−23.1	−19.8	−19.1	−22.0	−22.3	−30.0
	absolute maximum	7.3	9.2	10.0	9.0	8.2	10.0	8.1
	absolute minimum	−49.0	−60.2	−45.4	−47.9	−51.9	−53.7	−65.7
Degree days above freezing	mean annual	16.9	25.5	24.6	34.3	6.2	74.7	22.2
Soil temperature at 0 cm, °C	avg mean annual	−19.2	−18.4	−19.6	−17.1	−20.2	−20.1	−26.1
	absolute max	17.2	22.7	25.7	22.6	18.0	21.6	20.8
	absolute min	−44.6	−52.0	−46.7	−49.4	−52.2	−54.5	−59.2
Soil temperature at 5 cm, °C	avg mean annual	NA	−16.7	NA	−16.7	−20.1	NA	−25.7
	absolute max	NA	10.2	NA	15.3	9.7	NA	7.9
	absolute min	NA	−47.5	NA	−46.4	−49.4	NA	−55.2
Soil temperature at 10 cm, °C	avg mean annual	NA	−17.5	−18.8	−16.6	−20.0	−19.6	−25.4
	absolute max	NA	7.0	4.2	16.7	8.2	7.8	5.2
	absolute min	NA	−45.0	−37.8	−46.0	−45.2	−48.5	−53.5
RH, %	avg mean annual	74	69	66	62	66	55	66
	absolute max	100	100	100	100	100	100	100
	absolute min	<12.4	<15.5	<19.2	<12	<18.3	<17.7	<19
Wind speed, m/s	avg mean annual	2.5	3.1	2.8	3.9	3.1	4.1	2.5
	absolute max	32.2	37.8	36.3	35.6	32.0	35.3	32.3
solar flux, W/m^2	avg mean annual	106.7	100.1	83.6	94.1	108.7	86.4	101.8
	max mean annual	108.9	113.7	93.2	102.9	116.9	95.3	107.9
	min mean annual	97.1	83.0	71.4	76.1	101.0	78.7	93.3
	average summer solar noon	504.6	514.8	471.2	497.0	555.8	413.8	476.6
PAR, $\mu einsteins/m^2/s$	avg mean annual	231.6	222.9	182.2	206.1	215.9	195.0	208.3
	max mean annual	234.6	238.3	195.2	215.7	228.6	205.3	216.6
	min mean annual	223.6	205.5	169.4	200.3	203.1	180.2	194.4

next warmest site, Lake Bonney (Figure 2b). Eastern Wright Valley (Lake Brownworth) has the coldest summer temperatures. Summers in Victoria Valley are similar to those in Taylor Valley.

[15] Typical mean annual relative humidity ranges from 55% at Lake Vanda to 74% at Explorer's Cove (Table 1). Relative humidity decreases with distance from the coast at a rate of 0.3% per km ($r^2 = 0.71$, $P = 0.018$). All sites reach saturation, and all sites have periods of humidity close to the low end of the sensors measurement capability.

[16] Lake Vanda on average is the windiest site in the network annually, while Explorer's Cove and Lake Vida are least windy. Mean annual wind speed increases with proximity to the polar plateau. The highest maximum wind speed (37.8 m/s) was recorded at Lake Fryxell during a katabatic event in mid-October.

[17] Mean annual solar flux in the dry valleys ranges from 73 to 117 W m^{-2} (Figure 3a). Lake Hoare consistently has the lowest mean annual solar flux in the dry valleys while Lake Fryxell, only 6 km to the east, consistently receives about 20% more solar flux. Similar differences are seen in photosynthetically active radiation, with an observed range of 170 to 238 μmoles sec^{-1} m^{-2} (Figure 3b). Exposure explains the comparative radiation flux between sites. Site-to-site variations in radiation flux due to topographic effects require a topographic analysis. Using a topographic solar

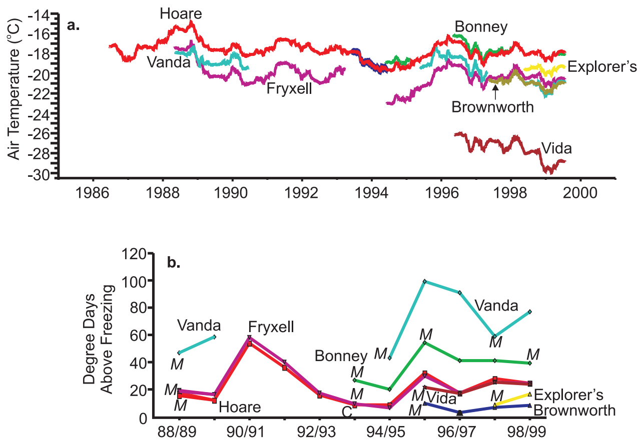

Figure 2. (a) Running mean annual temperatures in the dry valleys. For the Lake Hoare record, 17 missing days were filled with the mean temperature value for each day from all other years. A range is shown for the affected period using the maximum and minimum values from all other years for each of the 17 days. (b) Degree-days above freezing for all stations. Points marked "M" are missing data during potential above freezing periods so represent minimum values. The point marked "C" is potentially missing above freezing values but likely very few, so the values are considered minimums, but close to the actual value.

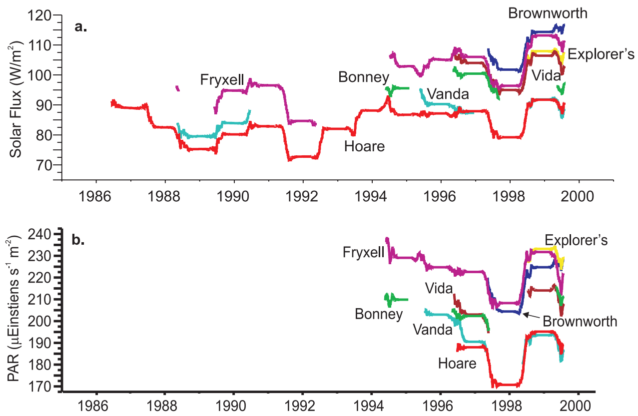

Figure 3. (a) Running mean annual solar flux (fill period for Lake Hoare is the same as in (Figure 2) and (b) photosynthetically active radiation at all sites.

radiation model, *Dana et al.* [1998] showed that considerable spatial variation in solar radiation occurs in the dry valleys due to mountainous topography and low solar elevation. For example, in December, the Lake Hoare station receives a significant amount of shading each day because it is positioned immediately adjacent to the Asgard Range, which rises steeply to the north. It also receives shading late in the day from Andrew's Ridge to the south. In contrast, Lake Fryxell's higher solar flux values can be explained in part, by the station's well-exposed position on the south side of the lake, which is not shaded at all during December. Lake Fryxell is in a broader valley with less shadowing compared to Lake Hoare. Differential cloudiness was also proposed by *Dana et al.* [1998] as a mechanism for causing site-to-site differences in solar flux in the dry valleys, but they did not evaluate a long enough period for the model to capture longer-trends in cloudiness. While the temporal trends shown in Figures 3a and 3b are for the most part similar among stations, there are instances of divergence and convergence of mean annual radiation between stations (e.g., Vanda solar flux converges with Lake Hoare in 1996), which are likely due to differences in cloudiness. Cloudiness can readily be inferred as an explanation for the overall temporal variation in radiation seen at all dry valleys stations. As pointed out by *Doran et al.* [2002] the long-term trend is an increasing solar radiation over the last 1.5 decades due to cooler less cloudy conditions (inferred from a decreased solar flux over time at the Lake Hoare station).

4.2. Taylor Valley

[18] Taylor Valley is at the lowest elevation of all the valleys. *Clow et al.* [1988] pointed out the importance of katabatic winds to the Lake Hoare region of Taylor Valley. Katabatics descending from the polar plateau generally have the character of high wind speeds, increased temperature and decreased humidity. For the single year of Lake Hoare record they analyzed, Clow et al. showed the strong influence of westerly katabatic drainage during the non-summer months, and easterly winds from the McMurdo Sound region during the summer. Our longer-term analysis of the Lake Hoare data supports this, as does similar analysis for Lake Bonney compared to Lake Fryxell (Figure 4). Although our analysis shows that wind speeds are consistently higher from the west than from the east regardless of season, winds from both directions are almost equally frequent in the winter, but winds are dominantly from the east in the summer.

[19] It has been proposed that physical obstacles in Taylor Valley such as Nuessbalm Reigal tend to create isolated weather systems [*Fountain et al.*, 1999]. This hypothesis was formed to help explain field observations of extreme katabatic winds at Lake Bonney during calm conditions at Lake Hoare and Lake Fryxell, and to explain inland increase in the snow line elevation. Another proposed influence on dry valley climate is the advection of cold air into the valleys from McMurdo Sound [*Bromley*, 1985; *McKendry and Lewthwaite*, 1990, 1992]. The interaction of the cooler coastal air and the adiabatically warmed katabatic winds has been suggested to cause the spatial differences. To test this hypothesis, we performed a temporally synchronized analysis of the Taylor Valley wind and temperature behavior. When plotting Lake Fryxell wind speed against Lake Bonney wind speed in summer and winter (Figure 5), it is

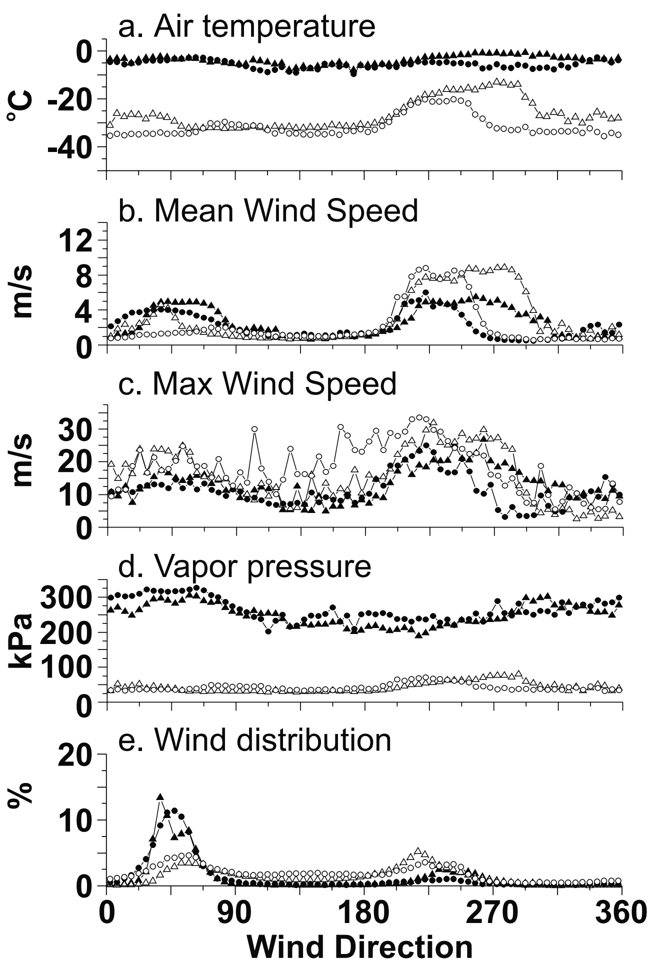

Figure 4. Summer (solid symbols) versus winter (open symbols) Taylor Valley comparison of (a) temperature, (b) average wind speed, (c) maximum wind speed, (d) vapor pressure, and (e) wind frequency by wind direction (5 degree averages). Triangles represent Lake Bonney data and circles represent Lake Fryxell data.

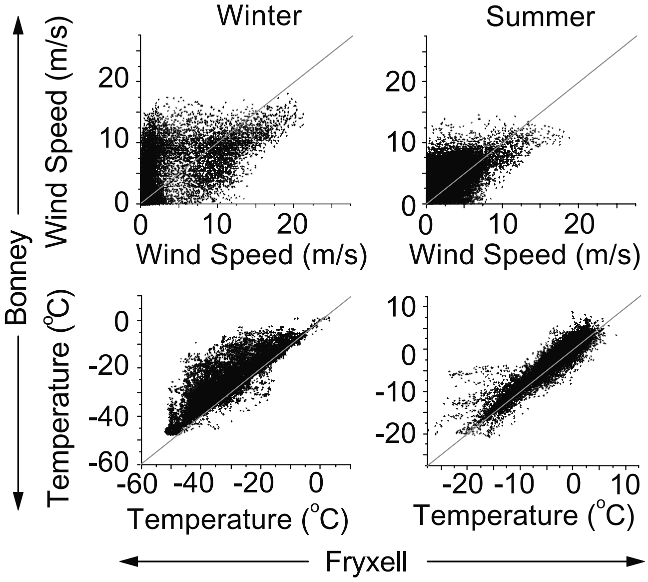

Figure 5. Plots comparing winter and summer Lake Fryxell versus Lake Bonney wind speed and temperature. Lines are 1:1.

clear that there are numerous cases where there is strong wind at Lake Bonney and calm conditions at Lake Fryxell. At the higher wind speeds, however, Lake Fryxell is the windier site, as katabatic winds gather momentum as they descend. This effect is also clearly shown when comparing temporally synchronous temperatures between the two sites (Figure 5). During the summer months, Lake Bonney has many extreme temperature anomalies, where the site is significantly (>15°C) warmer than Lake Fryxell at the same time. During the winter months, the higher elevation Lake Bonney is almost always warmer than Lake Fryxell, sometimes by more than 30°C! By inspecting individual windstorms we have observed that these wind and temperature anomalies are associated with a lag in the onset of katabatic wind events as they flow down valley. As Figure 6 shows, a typical winter katabatic event starts with increasing wind speed and temperature at Lake Bonney while conditions remain calm at Lake Hoare and Lake Fryxell. It isn't until an hour later that the wind conditions are observed changing at Lake Hoare and 2 hours and 20 min later that they start to climb at Lake Fryxell. At the time that Lake Bonney winds peak early in the storm in Figure 6, travel time alone should allow that wind (~16 m/s) to get to Lake Hoare in about 15 min, but Lake Hoare does not reach a corresponding peak until 2 hours later. The topographic obstacles in the valley may play some role in this delay, but it is curious that the barrier effect is intermittent, and sometimes even affects Lake Bonney. This is particularly evident in the region of the arrow in Figure 6 where Lake Bonney wind speed drops to calm conditions and then goes back up to katabatic speeds again. Also, during the calmer period (indicated by the arrow in Figure 6) at Lake Bonney, a backflow is evident with weak winds coming from the opposite direction of the katabatic flow. This behavior is very similar to that of katabatic wind cessation in other areas of coastal Antarctica, caused by what has been called a hydraulic jump, or Loewe's Phenomenon [*Lied*, 1964; *Pettré and André*, 1991; *Wendler et al.* 1993; *Targett*, 1998]. Hydraulic jumps in katabatic flow are believed to occur at the transition between shooting and tranquil flow. As air piles up near the coast, the katabatic wind is slowed and forward flow deflected upward, causing week backflow at ground level on the leeward side of the katabatic "front." In our case, depicted in Figure 6, the so-called stationary hydraulic jump is just upslope of the Lake Bonney station during the period of the arrow and migrates downslope toward the coast during the development of the katabatic storm. This causes the delay in the wind progressing through the valley. During katabatic events earlier in the season, the delay in winds progressing down valley is not as evident (Figure 7), which could be related to the presence of sea ice off the coast. *Pettré et al.* [1993] have suggested that the presence of sea ice allows for katabatic airflow to extend a considerably greater distance offshore, implying less piling up of air in the coastal region.. If our situation is a hydraulic jump, it is anything but stationary as we find abrupt wind cessation occurring throughout Taylor Valley. We present further evidence for, and variations of, this phenomenon below in the other valleys.

4.3. Wright Valley

[20] The Wright Valley wind regime is similar to Taylor Valley's in that it is bimodal, with strong warmer katabatic winds coming from the polar plateau, and lighter winds from the direction of McMurdo Sound (Figure 8). The winter westerlies are stronger, warmer, and more frequent at Lake Vanda than at Lake Brownworth. In the winter vapor pressures are higher in winds coming from the polar plateau, and in summer they are higher in onshore winds.

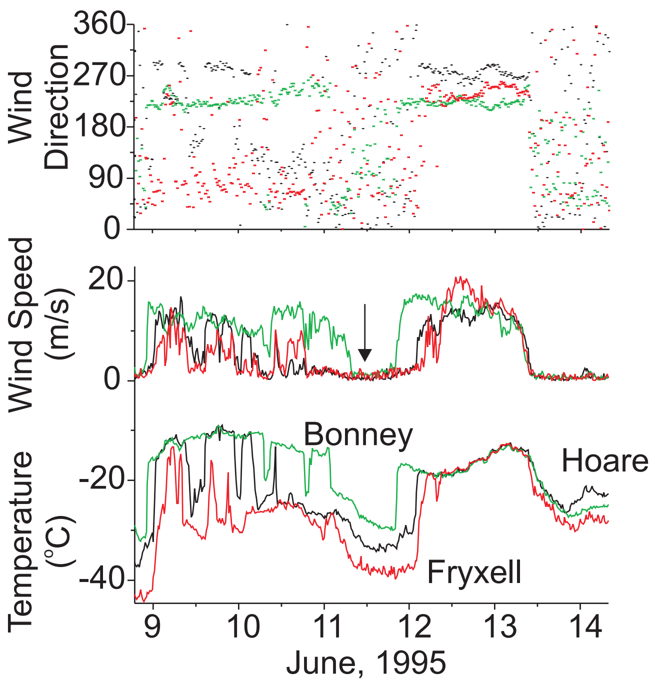

Figure 6. Comparison of air temperature, wind speed, and wind direction during a period of katabatic winds in June 1995 in Taylor Valley. Arrow points to period discussed in text when the katabatic seems to be deflected off the ground at Lake Bonney.

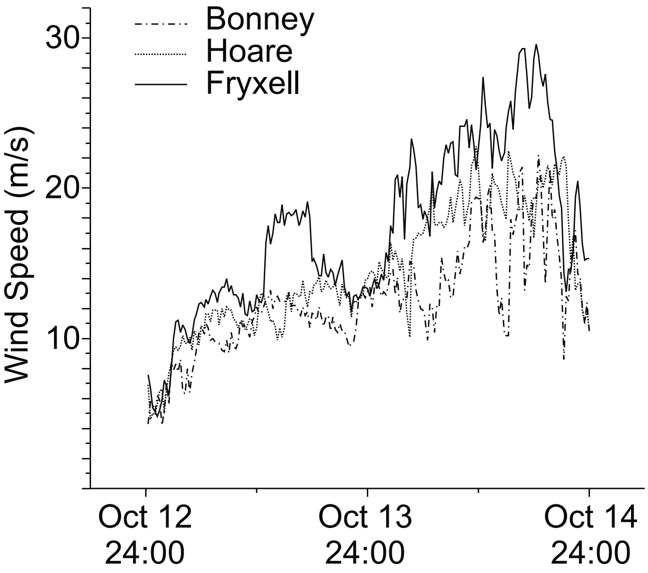

Figure 7. Katabatic event in Taylor Valley during spring 1999. This event produced the highest maximum wind speed in our record.

The broader and multinodal nature of the Lake Brownworth westerly wind speed distribution seems related to the strongest katabatic flow occasionally spilling over from Victoria Valley via a small mountain pass (Clark Valley) on the north side of the valley.

[21] When comparing Vanda and Brownworth on the same timescale (Figure 9), in the summer Lake Vanda is almost always warmer, sometimes by greater than 10°C. This corresponds to a normally higher wind speed during the summer at Lake Vanda. During the winter, however, large temperature differences can occur in both directions with Vanda sometimes being more than 25°C warmer than Brownworth, and Brownworth sometimes being more than 32°C warmer than Vanda. Similarly, it is more common to have high wind speeds at Lake Brownworth during the winter and Lake Vanda calm, than vice versa. By focusing on a small period of one winter, the cause for these differences becomes clear. Figure 10 shows that much of the time during the winter months, Lake Brownworth is experiencing katabatic winds from the direction of Lake Vanda, but Lake Vanda is calm. The katabatic winds appear to ride directly over Lake Vanda without touching the ground for part of the storm, and occasionally the katabatic flow lowers to affect the region of Lake Vanda. In other documented cases of hydraulic jumps described above, the katabatic dissipates at altitude, downslope of the jump. In this case, the katabatic wind is either displaced from the ground between the plateau and Lake Vanda by a hydraulic jump type phenomenon, or it is never allowed to touch the ground until past Lake Vanda. We propose that during periods where we see no wind at Lake Vanda, but strong westerlies at Lake Brownworth, a cold cell sits low in the Lake Vanda basin and prevents the relatively warm katabatic from touching down. Over time, and/or if the katabatic is sufficiently strong and turbulent, it is able to erode the cold cell and reach Lake Vanda. During periods where we see strong westerlies at Lake Vanda but not Lake Brownworth, we propose that the situation is similar to Taylor Valley in Figure 6 where either cold air pushing into the valley from the coast forces the katabatic upward and/or a hydraulic jump is formed.

4.4. Victoria Valley

[22] We have only one station in Victoria Valley at Lake Vida, and therefore can not do the same down-valley comparisons we have done for the other valleys. However, the single station at Lake Vida confirms and strengthens our conclusions about katabatic flow made for the other valleys.

[23] During the summer months at Lake Vida, winds are dominantly from the coast (Figure 11). Note also that compared to the other valleys, in Victoria Valley during the winter there is almost a complete absence of an easterly wind, and average wind speeds are lower from all directions in all seasons. Infrequent katabatic flows are observed from the southwest. During the winter, Lake Vida is a relatively cold, dry and calm location, with only infrequent katabatic winds (Figure 12). Furthermore, when comparing a typical Lake Vida winter with Lake Bonney in Taylor Valley it is

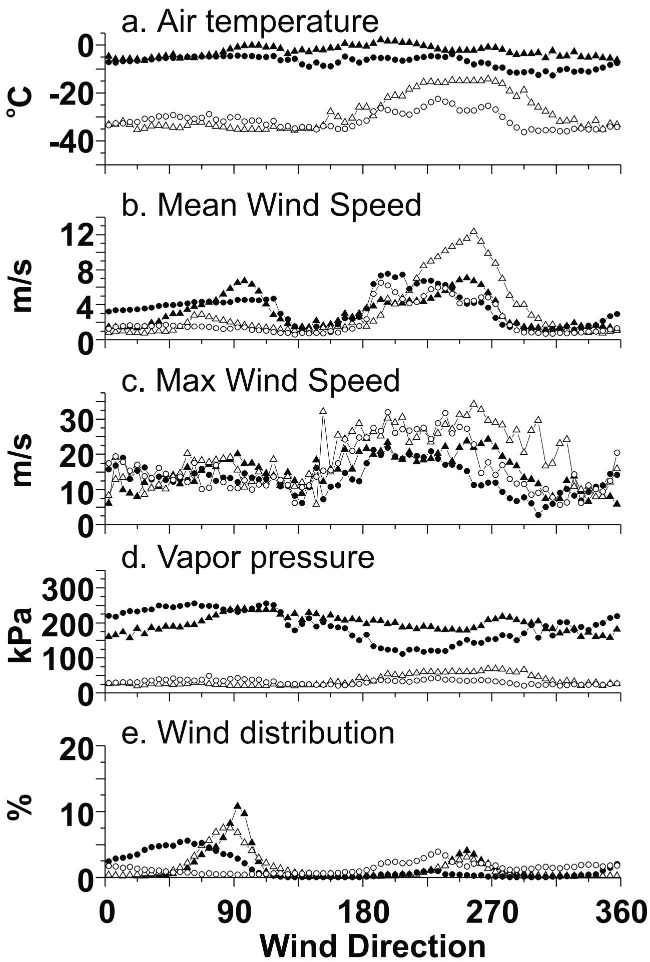

Figure 8. Summer (solid symbols) versus winter (open symbols) Wright Valley comparison of temperature, average wind speed, maximum wind speed, vapor pressure, and wind frequency plotted by wind direction (5 degree averages). Triangles represent Lake Vanda data and circles represent Lake Brownworth data.

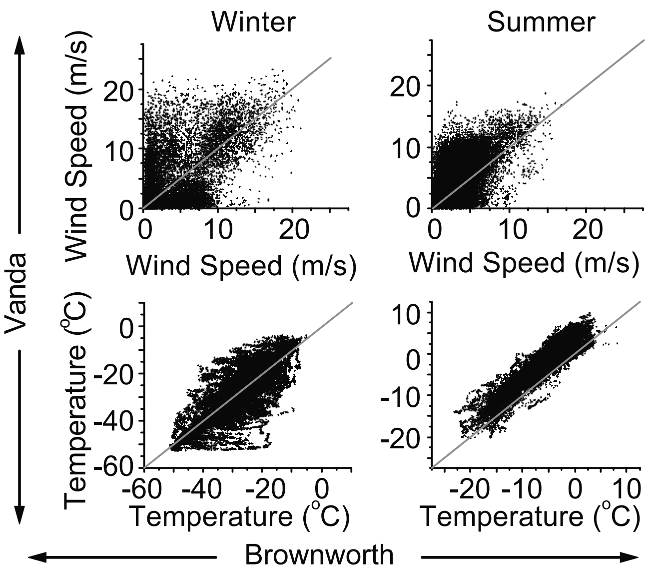

Figure 9. Plots comparing winter and summer Lake Brownworth versus Lake Vanda wind speed and temperature. Lines are 1:1.

obvious that Lake Vida experiences only the most severe katabatic winds (T. H. Nylen et al., Climatology of katabatic winds in the McMurdo dry valleys, Antarctica, manuscript in preparation, 2002). We hypothesize that conditions in Victoria Valley are such that a cold cell is allowed to form in the bottom of the valley (the location of Lake Vida station), which prevents all but the strongest katabatic flows from reaching the valley floor. This is analogous to the situation at Lake Vanda, but the barrier to katabatic flow at Lake Vida is much more effective. The reason for the strength of the barrier compared to Wright Valley may be related to the difference in topology. Like Wright Valley, Victoria Valley is somewhat bowl-shaped (i.e., lowest in the center), but is at a higher elevation with drainage valleys where katabatic flow can spill out of the valley and flow downhill (i.e., a path of lesser resistance over eroding into the cold cell). It is this lack of katabatic warming that allows Lake Vida to commonly reach temperatures below −50°C during the winter months, and provides this station with a significantly lower mean annual temperature than all others in our network (Table 1; Figure 2a). Although winter temperatures are extreme at this site, summer temperatures are similar to Taylor Valley, which is at a much lower altitude. Similar to Lake Vanda this region is broad and flat allowing for significant solar heating.

5. Summer Conditions and Temperature Modeling

[24] The strong influence of sporadic katabatic windstorms on the dry valley climate introduces a random component in the mean annual and seasonal temperatures. As a result there is significantly more variation in the mean annual temperatures (e.g., range of 5°C at Lake Hoare). Because katabatic winds occur more frequently in the winter months, most of the variation in the mean annual temperature comes from winter temperatures; at Lake Hoare the variation in winter temperatures over the data period is twice the variation in the summer temperatures. This variability makes predicting mean annual temperature based on geographic position (altitude and distance from the coast) difficult (Figure 13). However, summers experience fewer katabatic events, and because summer temperatures drive the local hydrological cycle, developing predictive models of summer conditions are of interest.

[25] We tested the relationship between summer temperature and geographic position for the period 13 November 1998 to 6 April 2000 when all stations were reporting and operating normally. Because the sites vary in elevation we have considered how the potential temperature, θ, varies with geographic position. The potential temperature is defined [e.g., *Peixoto and Oort*, 1992] as the temperature that a parcel of air would attain in a reversible adiabatic process if the parcel was displaced from a reference level (dlnT/dlnP = 0.286, with a reference pressure of 1000 mbar). In such a process, the parcel would follow the dry adiabatic lapse rate warming by 9.8°C km^{-1}. Figure 13 shows the mean summer potential temperature referenced to sea level as a function of shortest direct distance from the coast. It is interesting to note that the dependence is very closely linear with a slope of 0.09°C/km (r^2 = 0.992, $P <$ 0.0001) and the fit is best when the distance is considered as the shortest distance from the coast rather than the distance along the valley, although the trend is still the same with the latter (r^2 = 0.979, $P <$ 0.001). In addition if any temperature lapse rate other than the dry adiabatic (9.8 °C km^{-1}) is used to compute the potential temperature the linearity of the fit

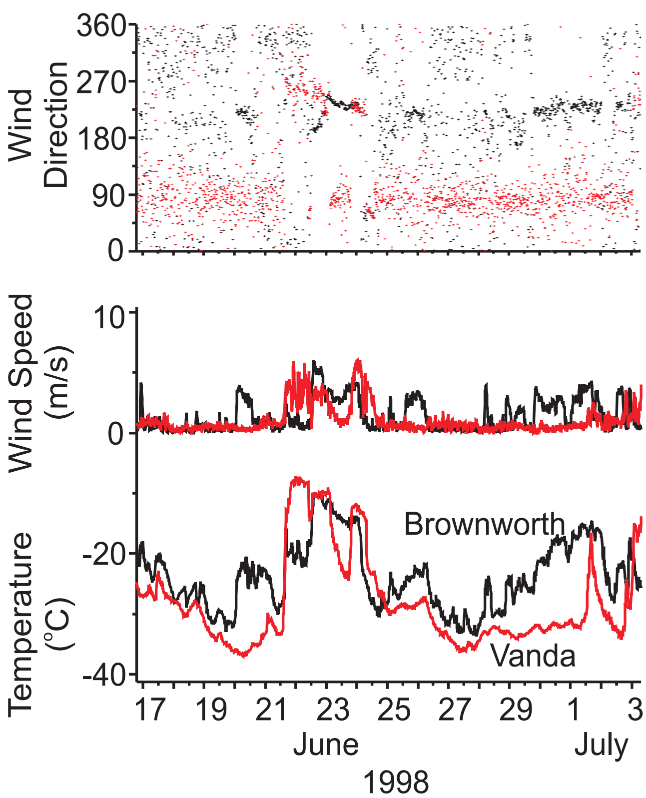

Figure 10. Comparison of Lake Brownworth and Vanda air temperature, wind speed, and wind direction during a period of katabatic winds in June/July 1998.

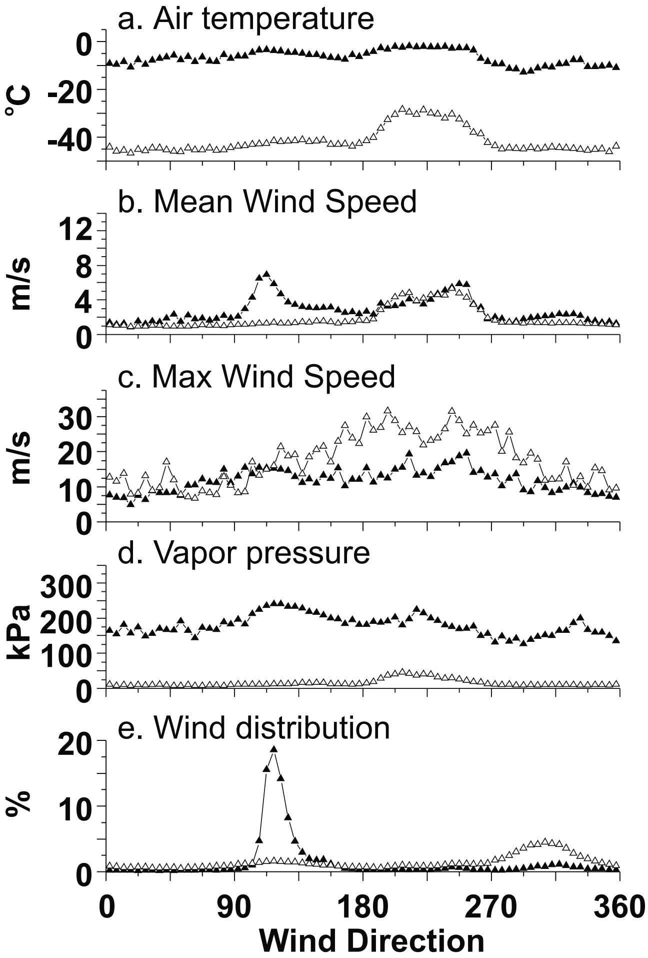

Figure 11. Summer (solid symbols) versus winter (open symbols) Victoria Valley (Lake Vida) comparison of (a) temperature, (b) average wind speed, (c) maximum wind speed, (d) vapor pressure, and (e) wind frequency plotted by wind direction (5 degree averages).

is degraded. During the same period, mean summer wind speed increases with distance from the coast at a rate of 0.04 m/s per km ($r^2 = 0.70$, $P = 0.019$: this improves to $r^2 = 0.91$, $P < 0.01$ when removing Lake Hoare Station which is blocked by Canada Glacier to the east). Furthermore, our analysis shows that the ratio of easterly:westerly wind frequency decreases from ~7 near the coast to ~2, 50 km inland ($r^2 = 0.76$, $P = 0.010$).

[26] The east-west gradient in summer temperatures in the dry valleys was first noted by *Bull* [1966] and discussed by *Keys* [1980]. Keys proposed two reasons for the observed gradient: the cooling effect of marine (easterly) winds which he reasoned were more frequent near the coast and decreased solar heating toward coastal sites. We have investigated both of these effects. As shown in Table 1, the total summer sunlight levels do not correlate with east-west position. Further, comparison of the noontime solar fluxes at all stations, a time when no topographic shadows are present at any site, also shows no east-west variations. These results show that decreased solar heating toward coastal sites is not an important effect. The east-west temperature gradient is correlated with occurrence of coastal winds. This is shown in Figure 14 in which we have plotted the total temperature difference between the eastern and western ends of the Taylor Valley as a function of direction of the wind in the western end of the valley. The observed temperature difference between the warm western end and the cooler eastern end is the area between this curve and the *x axis*. For most wind directions there is no systematic

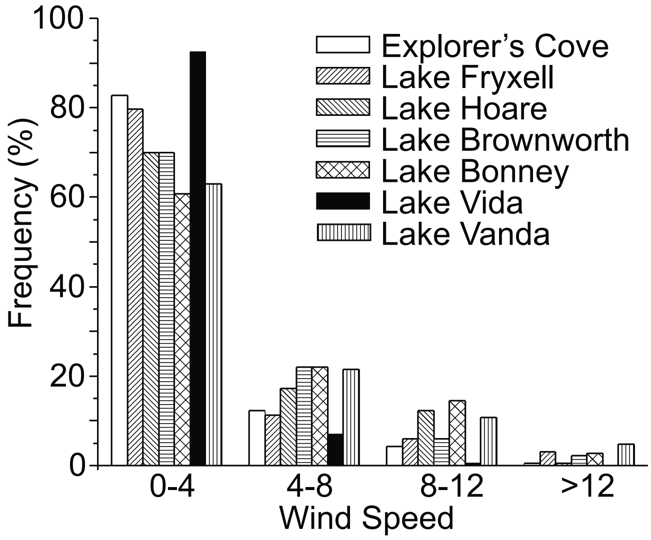

Figure 12. Frequency of winter wind speeds for all stations during 1999 and 2000.

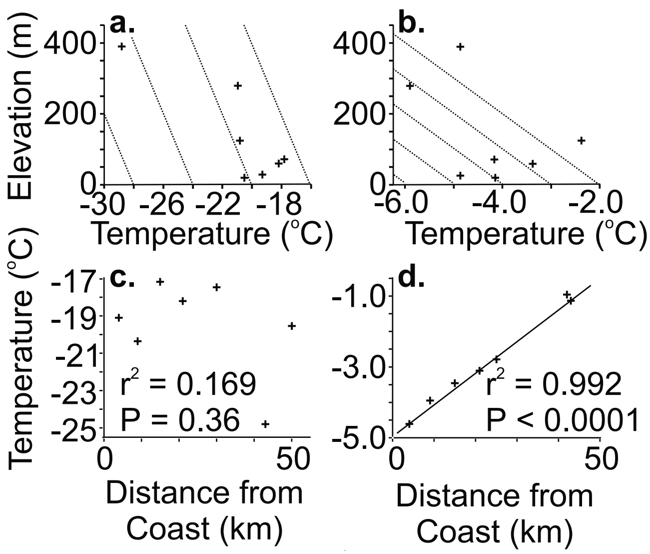

Figure 13. For period of common record at all stations, relationship between (a) elevation and mean annual temperature (for each station, average of all mean annual temperatures that can be calculated between 13 November 1998 and 6 April 2000), (b) elevation and summer temperature (average of temperatures for 1998/1999 and 1999/2000 summers), (c) distance from coast and annual temperature normalized to sea level, and (d) distance from coast and summer (DJF) temperature normalized to sea level. Lines in the elevation plots represent the dry adiabatic lapse temperature gradient for reference.

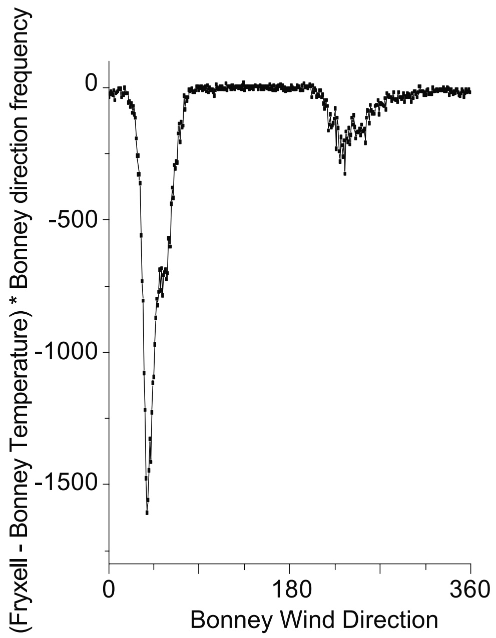

Figure 14. Plot of the difference between Fryxell and Bonney summer temperature weighted by Lake Bonney wind direction frequency versus wind direction at Lake Bonney (in 1° increments).

difference in summer temperatures between the east and west ends of Taylor Valley. There is only a systematic difference for wind blowing east up the valleys and for winds blowing west down the valley. The easterly winds are the coastal winds and they explain the majority of the cooling effect toward the coast. We note that this cooling effect is not simply due to easterly winds near the coast being more frequent than easterly winds further inland. This is clear from Figure 14 in that the *x axis* is the wind direction at the western extreme of the valley. From Figure 15 we see that during the summer there are considerable periods when the winds are easterly at both ends of Taylor valley (and interestingly, the second most common mode is to have a westerly wind at Lake Bonney and an Easterly wind at Lake Fryxell). The coastal winds must result in the cooling effect observed not by their variation in frequency between coastal and inland stations but due to the attenuation of their cooling effect as they move inland. Presumably this is due the movement of the cold coastal air mass over the relatively warmer dark valley surfaces. Similar results are observed in Wright Valley.

[27] The strong relationship between summer potential temperature and distance from the coast makes it well-suited as the basis for modeling summer temperature in the dry valleys. For the period the model is based on, mean summer potential temperature anywhere in the dry valleys can be calculated as

$$\theta = (0.09D - 4.9), \tag{1}$$

where θ is the predicted summer potential temperature in °C, and D is the distance from the coast in km. Since the potential temperature when D = 0 is the mean summer temperature at the coast, and since the mean summer potential temperature is related to mean summer temperature by the adiabatic lapse rate of 9.8°C km^{-1}, we can write an expression for the predicted mean summer temperature (T_p) as a function of altitude (Z) and distance from the coast as

$$T_P = (0.09D - T_c) - 10Z, \tag{2}$$

Or we can predict summer temperature from any other location in the valleys as,

$$T_p = T_m - 10(Z_p - Z_m) + 0.09(D_p - D_m). \tag{3}$$

These equations were tested on data not used in their construction, and have an accuracy of ±0.9°C when the prediction is based on one measured value. Accuracy improves to ±0.4°C when six other stations are used in equation (3) and the results averaged. In order to better visualize summer temperature variation in the region based on these equations, we draped equation (1) over a digital elevation model of the dry valleys region (Figure 16). Figure 16 should be interpreted with caution above the floor of the three valleys discussed here, since we have not tested its applicability at higher elevations. The impact of proximity to glacier ice on the model also needs to be tested.

[28] Other authors have attempted to model paleotemperature throughout the dry valleys using assumptions about mean annual temperature trends and elevation [*Marchant and Denton*, 1996; *Sugden et al.*, 1995], but these attempts were based on the limited published data available in the past. Our research clearly shows that mean annual temperature does not follow any predictable trend with elevation and distance from the coast due to the overwhelming influence of exposure to katabatic winds. However, a developed summer temperature model based on our data could be applied to paleoenvironments, using isolated summer temperature proxies to extrapolate to other regions of the dry valleys. We suggest that the relationship of

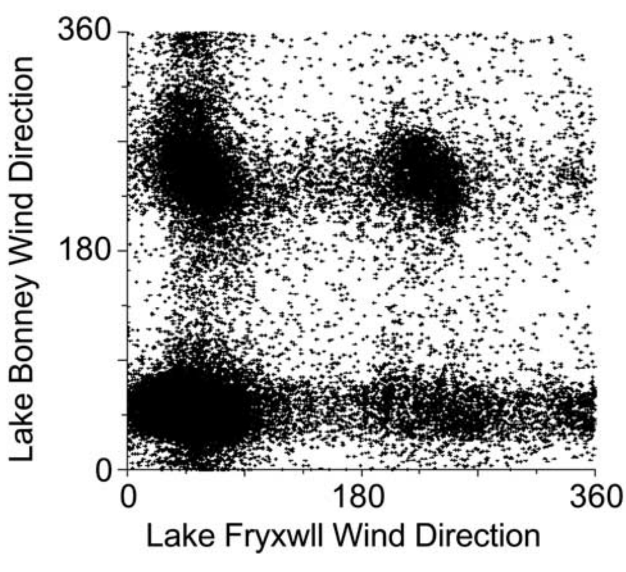

Figure 15. Lake Bonney versus Lake Fryxell wind direction during the summer (DJF) months.

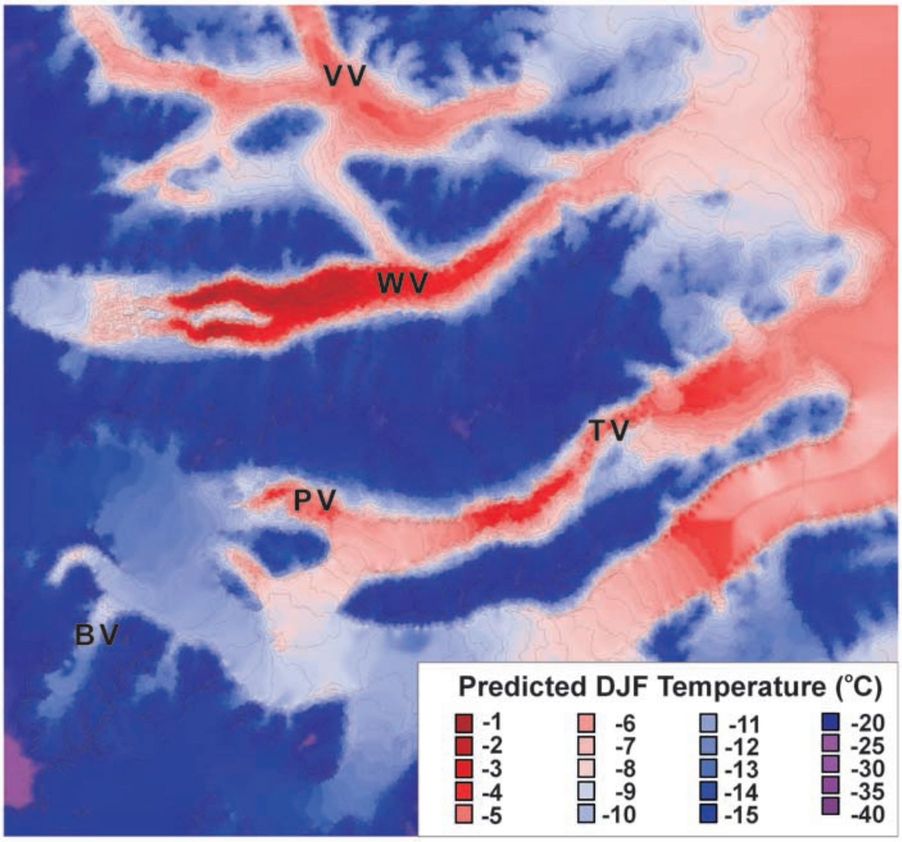

Figure 16. Modeled summer (DJF) temperature based on equation 1, and the United States Geological Survey's digital elevation model of the dry valleys region. Major valleys are indicated: Taylor Valley (TV), Wright Valley (WV), Victoria Valley (VV), Pearse Valley (PV), and Beacon Valley (BV). Ice covered regions have not been removed from this model, but likely the model over-predicts temperature at these sites.

increasing temperature with distance from the coast during the summer could play a role in the paradox of large glacial lakes occupying the dry valleys during the last glacial maximum [*Stuiver et al.*, 1981, *Hendy*, 2000]. During this time, the Ross Ice Shelf was blocking the seaward end of the dry valleys [*Hall and Denton*, 2000], effectively shifting the coast further away from the dry valleys. The current model would predict that this would increase summer temperatures in the dry valleys creating more melt from local glaciers.

6. Conclusions

[29] The data we have collected from a meteorological network in the McMurdo dry valleys of Antarctica is an unprecedented record of climate in the region. We have shown that the interaction between topography and air masses can greatly influence the microclimate. At any given time, temperature at two sites at near the same elevation in the same valley can vary by as much as 30°C. Mean annual temperature can differ between sites by over 10°C for the same period, yet the sites are only separated by <40 km distance and <300 m elevation (e.g., Lake Hoare versus Lake Vida for much of the record). Under normal alpine conditions, mean annual temperature is strongly controlled by altitude. In the dry valleys, however, the overwhelming influence on mean annual temperature is exposure to the warming effect of katabatic winds. Our observations suggest katabatic winds can be slowed and/or forced from the ground by phenomena that in some cases are similar to hydraulic jumps described for other coastal regions of Antarctica [e.g., *Lied*, 1964; *Pettré and André*, 1991; *Wendler et al.* 1993; *Targett*, 1998]. Although some of our observed phenomena do not follow the hydraulic jump model described in the literature, and suggest a different mechanism. Hydraulic jumps form a sharp boundary between strong katabatic conditions on the ground upslope (toward the continent) of the jump, and calm or gentle backflow conditions downslope (toward the coast). Although we note the occurrence of similar phenomena in Taylor and Wright Valleys, occasionally we find katabatic winds at the downslope stations, and not the upslope stations (especially in Wright Valley). Furthermore, Victoria Valley seems to be shielded from all but the strongest katabatic winds, allowing the valley bottom to become extremely cold in the winter. AVHRR imagery suggests that the katabatic winds ride over top of the cold cell created, and at least partially drain through Bull Pass and Clark Valley (see Figure 1 for locations). A more detailed treatment of these phenomena will be presented by

Nylen et al. (in prep), and future research will clearly benefit from more detailed measurements of pressure, temperature and wind in the valleys, combined with AVHRR observations.

[30] With the reduction of frequent katabatic storms in the summer, average temperature in summer (DJF) varies predictably according to the dry adiabatic lapse rate and distance from the coast. Summer temperatures are strongly controlled by the coastal winds which warm at a rate of 0.09°C km^{-1} as they move inland, and cool with inland elevation at the dry adiabatic lapse rate. This interaction of air masses in the summer creates a strong relationship between temperature and distance from the coast that can be used to model current and past summer temperatures in uninstrumented regions of the dry valleys.

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