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Earth Sciences

Winter warming of McMurdo Dry Valleys soils

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Abstract

Continuous permafrost is present across the McMurdo Dry Valleys of southern Victoria Land, Antarctica. While summer active-layer thaw is common in the low-elevation portions of the Dry Valleys, active layers have not significantly thickened over time. However, in some locations, coastal Antarctic permafrost has begun to warm. Here, based on soil and meteorological measurements from 1993 to 2023, we show that wintertime soil temperatures have increased across multiple sites in the Dry Valleys, at rates exceeding the pace of summer soil warming. Linear warming trends over time are significant ($P < 0.05$) at six of seven soil monitoring sites. Winter warming is strongly correlated with increased numbers of down-valley wind events (Foehn/katabatics), but it may also be driven by increased incident longwave radiation at some stations (although winter longwave increase is not significant over time). While down-valley wind events increase winter warming, when down-valley wind events are excluded from the record, winter soil warming remains persistent and significant, suggesting that Antarctic soils are experiencing less cold winters over time in response to regional warming. Together, these observations suggest that some Antarctic permafrost may be approaching a transition to discontinuous permafrost in some regions as winter freezing intensity is reduced over time.

Key words: Antarctica, Foehn wind, katabatic wind, McMurdo Dry Valleys, microclimate, permafrost

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Introduction

Continuous permafrost is present from the near-surface to ~800 m depth across the McMurdo Dry Valleys (MDV; ~77–78°S, 160–164°E), the largest region of the terrestrial Antarctic that is not currently covered in ice sheets (Cartwright & Harris 1981, Harris & Cartwright 1981, Bockheim *et al.* 2007). Active layers form seasonally in most coastal and mid-elevation sites located within a few tens of kilometres of the coast in the coastal thaw and intermediate mixed microclimate zones (Bockheim *et al.* 2007, Marchant & Head 2007, Vieira *et al.* 2010, Fountain *et al.* 2014, Hrbáček *et al.* 2021). Active layers form as summer soil temperatures rise from winter cold values of ~ -30°C to -50°C to peak summer temperatures of 5–10°C or more (Doran *et al.* 2002, Fountain *et al.* 2014, Obryk *et al.* 2020). Given the extreme winter cold and the limited summertime warmth (both in terms of the short thaw season in November through February and the modest summertime surface temperatures), Antarctic permafrost is not widely considered to be imminently at risk for thaw in response to climate change (Chadburn *et al.* 2017).

Indeed, most studies of Antarctic permafrost and active-layer processes focus on summertime thaw and active-layer properties, monitoring circum-Antarctic active layers for evidence of warming and resulting enhancement of seasonal melting (e.g. Bockheim 1995, Guglielmin *et al.* 2003, Vieira *et al.* 2010). Active-layer thicknesses are variable across the MDV and are generally greater near the coast (45–70 cm), thinner inland (20–45 cm) and thin to vanishing along the edge of the polar plateau (< 20 cm; Bockheim *et al.* 2007). Where active-layer thickness has been monitored over time, MDV active layers show seasonal variability; for example, deeper thaw during the 2001–2002 'melt year' (Doran *et al.* 2008, Adlam *et al.* 2010). Active layers also show spatial heterogeneity, with thickening towards the north and towards the coast (Adlam *et al.* 2010, Hrbáček *et al.* 2023). MDV active layers show fine-scale spatial trends, with deeper thaw in seasonally wetted soils (Levy *et al.* 2011), within stream channels (Wlostowski *et al.* 2018) and even across small hydrological features such as water tracks (Levy *et al.* 2024) and across small patterned ground geomorphic features (Hrbáček *et al.* 2021). Importantly, despite this spatial and temporal variability in active-layer thickness, no clear pattern of active-layer thickening over time has been detected at any MDV site, although thickening of 0.3 cm/year is reported in northern Victoria Land (Adlam *et al.* 2010, Guglielmin *et al.* 2014, Carshalton *et al.* 2022, Hrbáček *et al.* 2023).

In the Arctic, summer warming, combined with reduced winter cooling, has thickened Northern Hemisphere active layers and warmed Northern Hemisphere permafrost (Smith *et al.* 2022); however, the extent to which Antarctic permafrost is warming beneath the active layer is not fully clear. Permafrost temperatures in boreholes measured during the 2007–2008 International Polar

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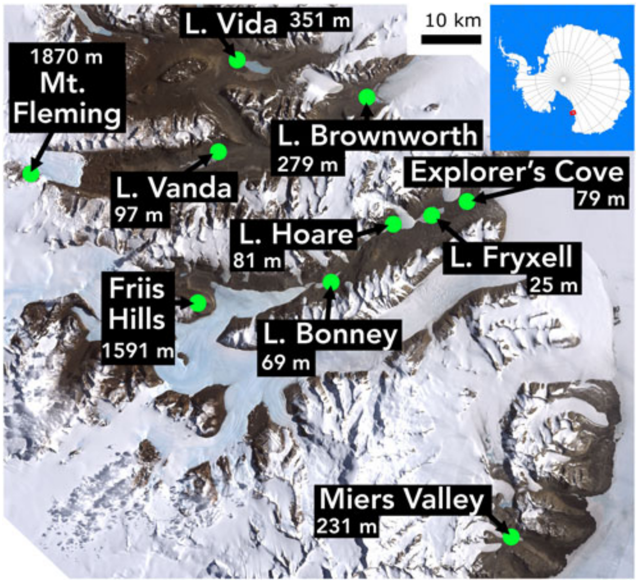

Figure 1. Location of the McMurdo Dry Valleys Long Term Ecological Research (MCM-LTER) Long-Term Automatic Weather Network (LAWN) automatic weather stations used in this study. Stations are located between ~77–78°S and 160–164°E in the McMurdo Dry Valleys. Base map is Landsat 7 image data (Bindschadler *et al.* 2008).

Year ranged from -13.3°C in northern Victoria Land, to -17.4°C to -22.5°C in the MDV, to -23.6°C at high-elevation sites such as Mount Fleming (Vieira *et al.* 2010). In places where both active-layer and deeper permafrost temperatures have been monitored, the active-layer thickness does not always increase in step with the temperatures of the underlying permafrost, with active-layer thickness and near-surface temperature tracking much more closely with end-of-summer shortwave insolation and air temperature than with top-of-permafrost temperatures (Guglielmin & Cannone 2012, Guglielmin *et al.* 2014). Indeed, permafrost and active layers can even change out of phase, with localized surface cooling (e.g. Doran *et al.* 2002) occurring alongside modest, 0.1°C/year warming of permafrost at depth (Guglielmin & Cannone 2012).

This potential mismatch between summertime active-layer conditions and the deeper temperature structure of underlying permafrost raises questions about the roles of air temperature, radiation and wind on the wintertime thermal regime of Antarctic permafrost and active layers. Is it possible that changes to Antarctic active layers and permafrost are occurring not during the well-monitored summer but during winter? Recent observations suggest winter weather events can lead to short-lived periods of extreme warmth (Barrett *et al.* 2024). During austral winter (i.e. April through September), ground surface temperatures are commonly colder than the air at monitoring sites in Beacon and University valleys in the upland stable zone of the MDV (Lacelle *et al.* 2016), consistent with radiative and conductive cooling of the soil surface. However, heat can be delivered to MDV surfaces, even in winter, by sensible heat flux from regionally warming air (Obryk *et al.* 2020), via sensible heat from compressively warmed katabatic/Foehn winds (Nylen & Fountain 2004, Speirs *et al.* 2010) and from incident longwave radiation from changing cloud cover. Winter clouds dramatically change incident longwave flux (e.g. Walsh & Chapman 1998), typically increasing it over clear-sky conditions by 20–30 w/m^2 (Curry *et al.* 1996), but in some cases nearly doubling incident longwave and increasing flux by 100 W/m^2 or more (Yamanouchi 2019). Is it possible that winter warming is occurring in the MDV, and that this warming could have implications for the long-term stability of MDV permafrost?

Here, we use a ~30 year record of soil and air temperature data, in conjunction with wind and longwave flux measurements

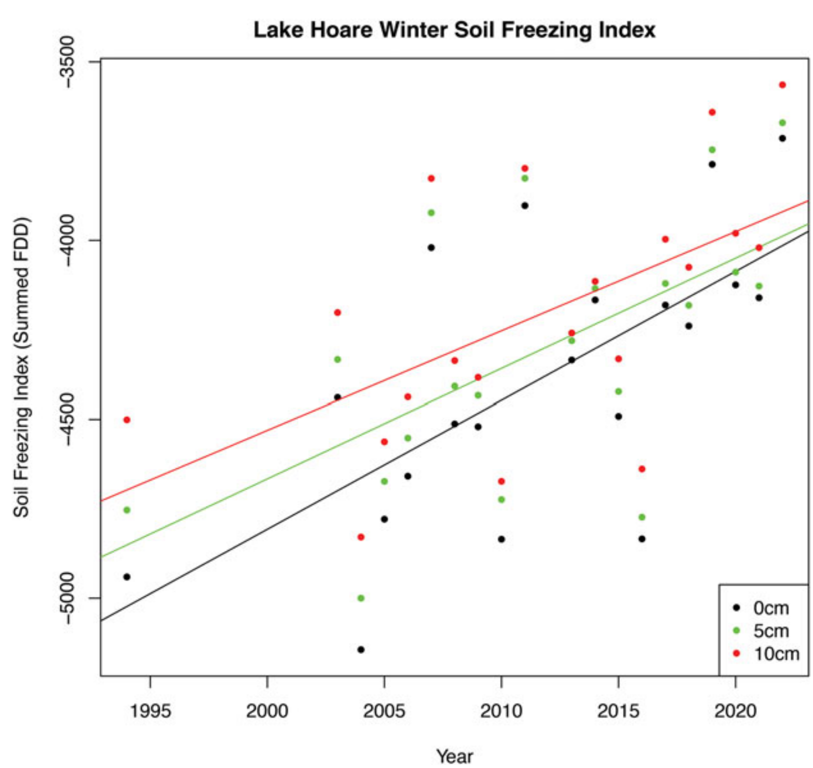

Figure 2. Soil freezing index over time at Lake Hoare. Soil freezing indices (total wintertime summed freezing degree-days (FDDs)) show a decrease in FDDs over time at all measured soil depths. Soil warming is ~36 fewer FDDs per year. Wintertime warming of soils is a robust signal at Lake Hoare ($R = 0.43$, $P < 0.002$).

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Table I. Rates of freezing index change at soil sites (0 cm). Slope is the number of freezing degree-days lost per year.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	33.77	0.0407	0.25	0.50
Lake Bonney	17.58	0.0104	0.27	0.52
Lake Brownworth	19.17	0.0039	0.33	0.58
Lake Fryxell	23.38	0.0069	0.28	0.53
Lake Hoare[a]	36.03	0.0016	0.43	0.66
Lake Vanda	10.83	0.2778	0.07	0.26
Lake Vida	19.75	0.0193	0.20	0.45

[a]Data plotted in Fig. 2.

Table II. Rates of air freezing index change at air temperature monitoring sites. Slope is the number of freezing degree-days lost per year.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	18.43	0.0522	0.18	0.42
Friis Hills	−6.78	0.5940	0.03	−0.17
Lake Bonney	22.16	0.0016	0.36	0.60
Lake Brownworth	17.63	0.0048	0.32	0.57
Lake Fryxell[a]	29.44	0.0004	0.41	0.64
Lake Hoare	11.66	0.0194	0.16	0.40
Lake Vanda	15.53	0.0193	0.19	0.44
Lake Vida	26.06	0.0047	0.28	0.53
Miers Valley	29.00	0.2845	0.13	0.35
Mount Fleming	−3.54	0.6980	0.02	−0.14

[a]Data plotted in Fig. 3.

from the McMurdo Dry Valleys Long Term Ecological Research (MCM-LTER) Long-Term Automatic Weather Network (LAWN), to understand the changing state of Antarctic active-layer soils during the winter freezing season. We address the following research questions: RQ1) Are Antarctic soils and air experiencing changes in wintertime temperature over time? RQ2) Is wintertime soil temperature correlated with other environmental variables that control surface energy balance, including wind run, air temperature and incident longwave radiation? RQ3) Are these environmental controls on winter surface energy balance changing over time? RQ4) Ultimately, is there a long-term climate trajectory in which refreezing no longer occurs at some sites during Antarctic winter?

Methods

All meteorological data analysed in this project were collected at MCM-LTER LAWN (Doran *et al.* 1995, 2002) stations in the MDV (Fig. 1) between 1993 and 2023 and are available for download at mcm.lternet.edu. The Lake Bonney, Lake Hoare and Commonwealth Glacier stations were installed in 1993; the Lake Fryxell, Taylor Glacier and Lake Vanda stations were installed in 1994; the Lake Vida and Explorer's Cove stations were installed in 1995; Lake Brownworth in 1996; Mount Fleming in 2006; Friis Hills in 2010; and Miers Valley in 2011. Lake Fryxell is at 25 m above sea level (a.s.l.), Lake Bonney is at 69 m a.s.l., Explorer's Cove is at 79 m a.s.l., Lake Hoare is at 81 m a.s.l., Lake Vanda is at 97 m a.s.l., Miers Valley is at 231 m a.s.l., Lake Brownworth is at 279 m a.s.l., Lake Vida is at 351 m a.s.l, Friis Hills is at 1591 m a.s.l. and Mount Fleming is at 1870 m a.s.l.

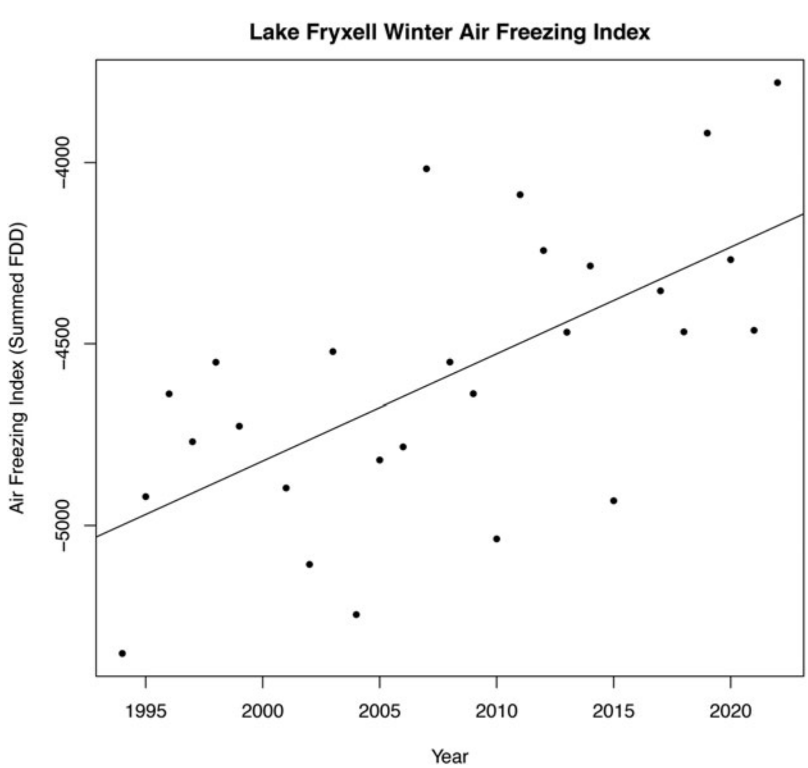

Figure 3. Air freezing index over time at Lake Fryxell. Air freezing indices (total summed wintertime freezing degree-days (FDDs)) show a decrease in FDDs over time. Air warming is ~29 fewer FDDs per year. Wintertime warming of soils is a robust signal at Lake Fryxell ($R = 0.64$, $P < 0.001$).

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In our analyses (described below), we used average daily measurements for air temperature, soil temperature at 0, 5 and 10 cm depth and incident longwave radiation, coupled with 15 min observations of wind speed and direction. Some stations collect both soil and air measurements: Lake Vida, Lake Vanda, Lake Brownworth, Lake Bonney, Lake Hoare, Lake Fryxell and Explorer's Cove. Other stations, including Friis Hills, Mount Fleming and Miers Valley, only collect air measurements (air temperature and wind speed and direction), in addition to other ecological variables not explored here (e.g. photosynthetically active radiation).

Data analysis methods

All MCM-LTER meteorological datasets used in this study were downloaded directly from the Environmental Data Initiative (EDI), using standard EDI Data Portal dataset ingestion scripts. We analysed daily average data from stations at Explorer's Cove, Lake Fryxell, Lake Hoare, Lake Bonney, Miers Valley, Lake Vida, Lake Brownworth, Lake Vanda, Friis Hills and Mount Fleming (Doran & Fountain 2023b–k). High-frequency, 15 min-resolution datasets were used for computations related to wind speed and direction (Doran & Fountain 2023l–t). Our full data

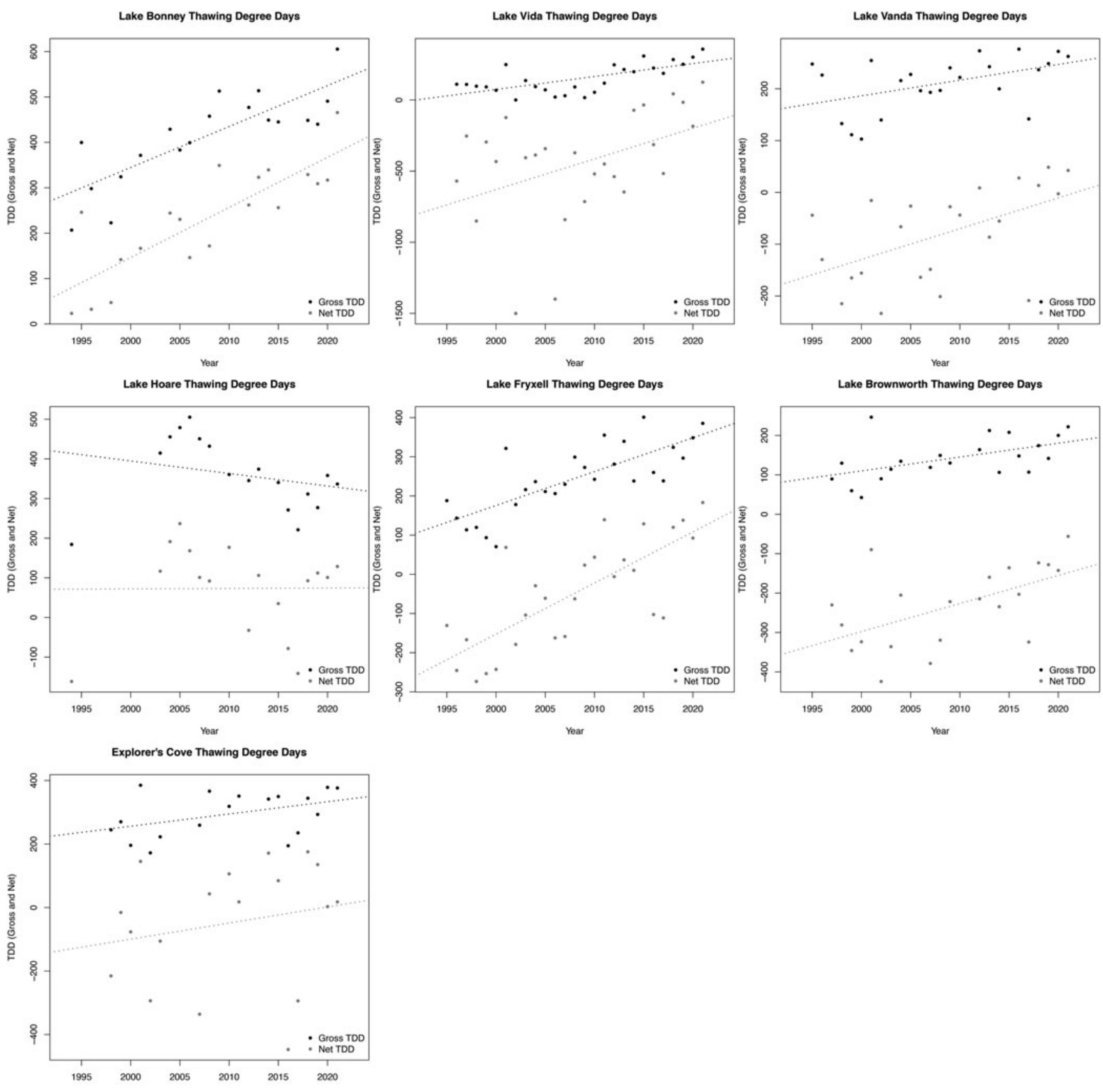

Figure 4. Thawing degree-days (TDDs) at soil monitoring sites. Soil TDDs are rising at all sites other than Lake Hoare in terms of both total positive degree-days (gross TDDs) as well as positive degree-days offset by days below freezing during summer (net TDDs). The steeper slopes of the net TDD lines may suggest a reduction in summer freezing days in the McMurdo Dry Valleys over time.

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Table III. Summer thawing degree-day (TDD) trends over time. Summer TDD slopes indicate the change in TDDs per year.

Site	Gross TDD slope	Gross TDD *P*-value	Gross TDD *R*	Net TDD slope	Net TDD *P*-value	Net TDD *R*
Lake Bonney	9.0219	2.5E-05	0.8110	11.0429	1.2E-05	0.8284
Explorer's Cove	3.8605	0.0759	0.4287	5.0781	0.4043	0.2094
Lake Brownworth	3.5156	0.0155	0.5209	7.1222	0.0087	0.5572
Lake Fryxell	8.6441	2.1E-06	0.7746	13.0470	4.8E-06	0.7575
Lake Hoare	−3.1606	0.3166	−0.2584	0.1156	0.9773	0.0075
Lake Vanda	3.0340	0.0253	0.4653	5.9406	0.0091	0.5312
Lake Vida	9.0995	0.0001	0.6792	21.5406	0.0319	0.4216

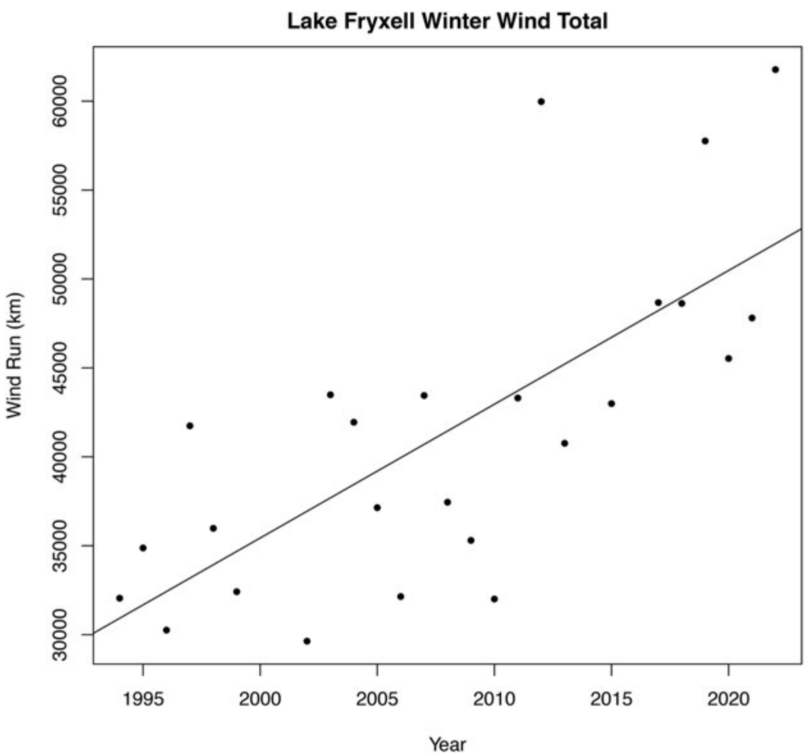

Figure 5. Total windiness over time at Lake Fryxell. Wind run is increasing significantly, by 8.71 m/s·day per year ($R = 0.73$, $P < 0.0001$).

analysis script can be found at our github repository: https://github.com/jslevy/mdvwinterwarming.

We analysed daily mean values of air temperature at 3 m, soil temperature at 0, 5 and 10 cm depth and incident longwave radiation (available from Lake Bonney and Commonwealth Glacier - the latter sited near the Lake Fryxell and Explorer's Cove stations; Doran & Fountain 2023a). The Lake Bonney longwave radiation data were used in the analysis of Lake Vanda, Lake Vida, Friis Hills, Mount Fleming and Miers Valley because these stations are close to the Lake Bonney station and reflect upland/inland sites, while the Commonwealth Glacier longwave radiation data were used in the analysis of Explorer's Cove, Lake Fryxell, Lake Hoare and Lake Brownworth, which are located closer to the Commonwealth Glacier station, and which are low-elevation/coastal sites.

Several dataset quality checks were applied to ensure compatibility between measurements at different locations and collected over different timeframes. Days with no measurements or

Table IV. Rates of change of wind run at air monitoring sites. Slope is the rate of change in wind run per year (km/year).

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	238.12	0.1277	0.12	0.35
Friis Hills	568.60	0.4478	0.07	0.26
Lake Bonney	246.09	0.1207	0.12	0.34
Lake Brownworth	168.35	0.2679	0.06	0.24
Lake Fryxell[a]	752.26	< 0.0001	0.53	0.73
Lake Hoare	341.35	0.0013	0.29	0.54
Lake Vanda	332.32	0.0905	0.12	0.35
Lake Vida	77.20	0.3167	0.04	0.20
Miers Valley	590.17	0.3200	0.11	0.33
Mount Flemming	1339.34	0.0873	0.32	0.57

[a]Data plotted in Fig. 5.

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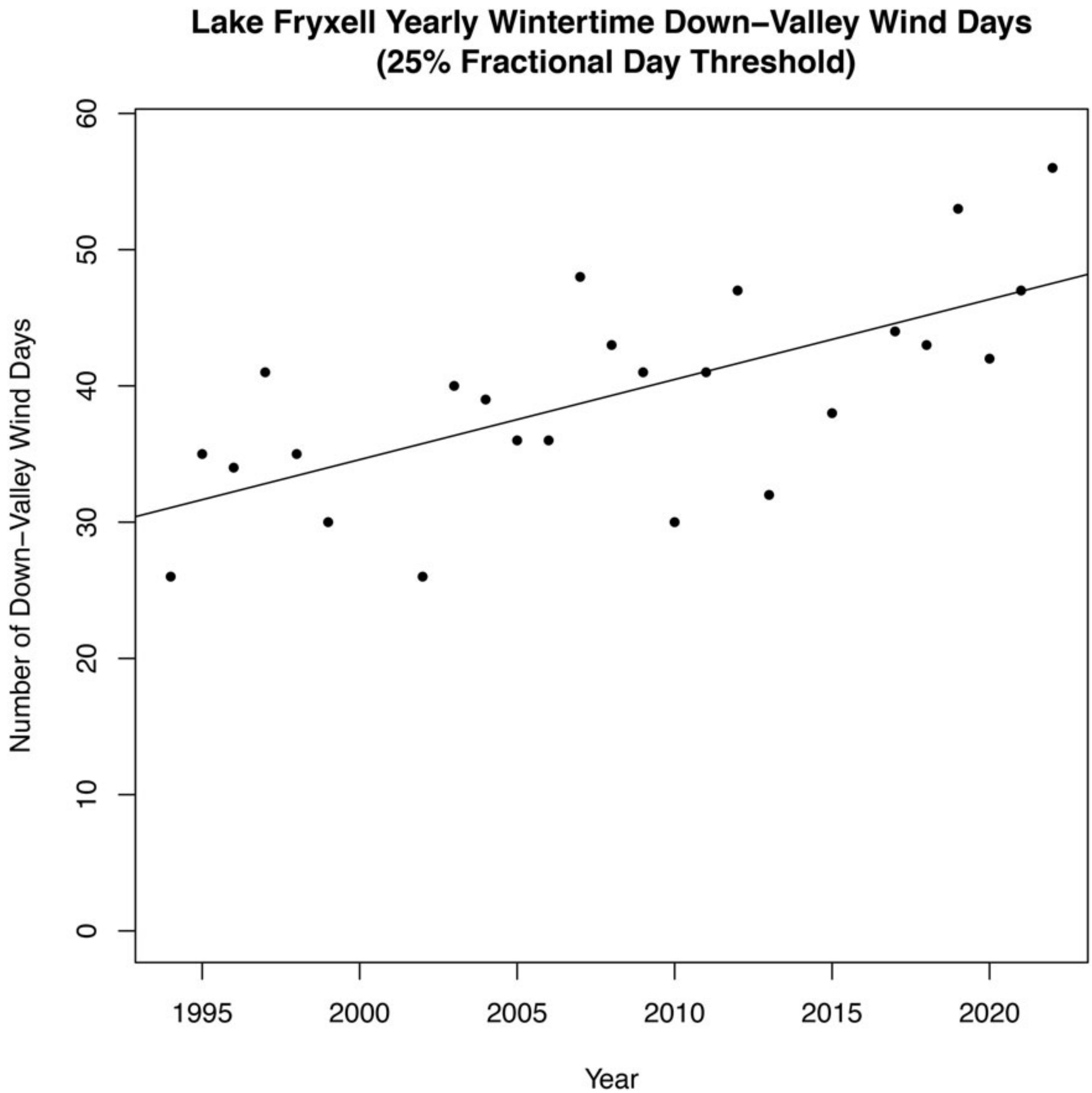

Figure 6. Down-valley wind days over time at Lake Fryxell. Down-valley wind days are increasing at Lake Fryxell (0.59 more down-valley wind days per year, $P < 0.002$, $R = 0.67$), counting wind days as those that meet our criteria for > 25% of the day.

Table V. Rates of change in number of down-valley wind days per year at wind monitoring sites based on a 25% fractional day threshold. Slope is the change in the number of down-valley wind days per year.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	0.27	0.2179	0.09	0.30
Friis Hills	0.54	0.6165	0.03	0.17
Lake Bonney	0.31	0.2498	0.07	0.26
Lake Brownworth	0.33	0.1572	0.10	0.31
Lake Fryxell[a]	0.59	0.0002	0.45	0.67
Lake Hoare	0.37	0.0235	0.16	0.41
Lake Vanda	0.53	0.0079	0.32	0.56
Lake Vida	0.16	0.2225	0.06	0.24
Miers Valley	1.30	0.1431	0.22	0.47
Mount Fleming	–0.38	0.6270	–0.03	–0.17

[a]Data plotted in Fig. 6.

incomplete measurements of air and soil temperature, wind speed and direction and incident longwave radiation were removed. Data were then filtered to include only winter months - here, days that fall between the 121st and 273rd days of the year (1 May through 30 September, or 29 April through 29 September on leap years). MDV winter was defined by Obryk *et al.* (2020) as April through September, but we exclude April data, during which latent heat could be released into soil by late-season freezing, especially in seasonal wetlands that can remain unfrozen through at least March (Kuentz *et al.* 2022). The winter data were then checked to ensure that over 90% of the days during the winter season were present for each year. If the year did not have data for more than 90% of the winter days, that year was removed from the analysis, following the approach in Obryk *et al.* (2020), to avoid comparison between years with differing numbers of measurements (this is especially important for calculations of freezing degree-days (FDDs), which are summative). Across all datasets and measurements, only ~2% of the data records (30 data records out of 1443) that reach the 90%

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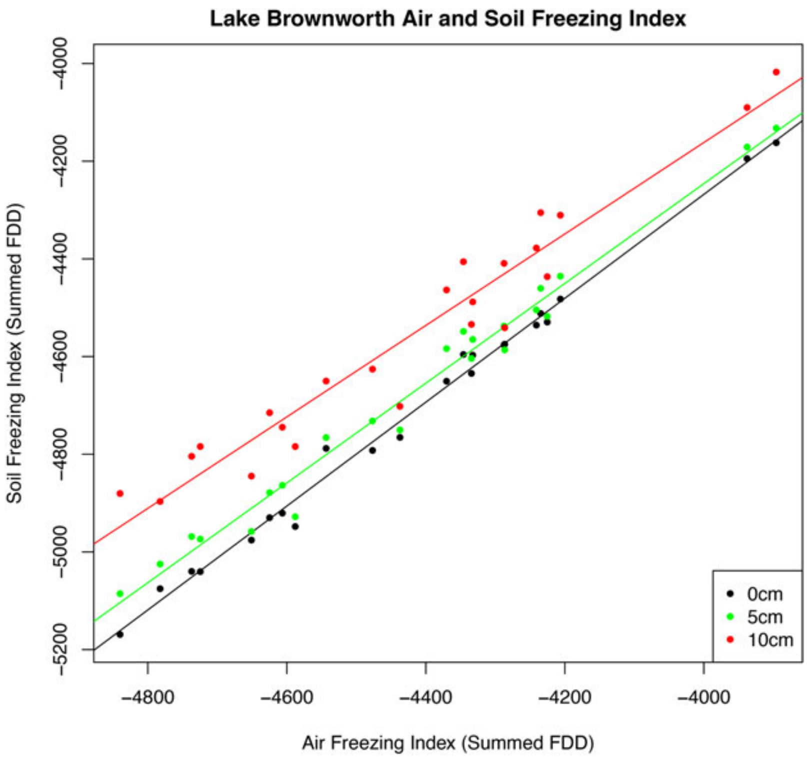

Figure 7. Soil and air freezing indices at Lake Brownworth. Air and soil freezing indices (summed freezing degree-days (FDDs)) are strongly and significantly correlated. At Lake Brownworth, warmer years reflect reduced freezing in soils.

wintertime daily measurement threshold do not have measurements for every single day during the winter months.

Using the verified datasets, annual summations of wintertime daily average values were calculated for each year and each dataset to determine changes in soil and air temperatures over time and to evaluate the role of environmental forcing variables (wind and longwave radiation). These wintertime yearly summations for the temperature, wind and longwave radiation data are referred to as air or soil freezing indices after Riseborough (2003) and Klene *et al.* (2001), wind run and radiation days, respectively. Freezing index is the sum of average daily temperatures during the winter, making it similar to FDDs, but differing in that it is not annualized. More negative freezing index values indicate colder winter temperatures. Soil freezing index is calculated for all soil depths (0, 5 and 10 cm), but only data from 0 cm are compared to air freezing index, wind run and longwave insolation, and only 0 cm data linear model statistics (*P* and *R*) are reported. Wind run (wind velocity multiplied by duration, summed over the winter months) is a measure of integrated windiness, while radiation days (mean daily longwave flux summed over winter months) is a measure of integrated infrared energy arriving at the soil surface.

Table VI. Relationship between air and soil freezing indices (0 cm) at all soil monitoring sites. Slope indicates the slope of the regression line between soil and air freezing index.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	0.97	< 0.0001	0.79	0.89
Lake Bonney	0.91	< 0.0001	0.93	0.96
Lake Brownworth[a]	1.06	< 0.0001	0.99	1.00
Lake Fryxell	0.93	< 0.0001	0.97	0.98
Lake Hoare	1.12	< 0.0001	0.96	0.98
Lake Vanda	0.93	< 0.0001	0.99	0.99
Lake Vida	0.64	< 0.0001	0.51	0.72

[a]Data plotted in Fig. 7.

In order to compute the number of days each winter in which down-valley winds (Foehn/katabatics) were present, we used high-frequency (15 min) wind data and processed them to identify candidate down-valley wind events. The first classification step was to identify wind records where the wind direction was broadly 'down-valley' - here, defined as winds blowing from between 150° and 360°. This overlaps with the wind direction range used by Nylen & Fountain (2014), expanding it slightly to include strong drainage winds resulting from southerly flows of air off of local plateaus and mountain peaks. In order to only capture down-valley wind events characterized by fast drainage/Foehn events, we filtered our dataset to only accept winds > 5 m/s, after Nylen & Fountain (2004). Every measurement record with down-valley direction and high speed was flagged as a candidate down-valley wind data record. In order to estimate the number of days per winter that down-valley winds were blowing, we classified a day as being a down-valley wind event if the percentage of down-valley wind records in that day exceeded 25% of the day, following the Speirs *et al.* (2010) 6 h threshold for classification of a MDV Foehn wind event.

The complement to the down-valley wind day dataset is a version of our temperature datasets for which the down-valley wind days have been removed. The freezing indices for air and for soil with the drainage wind days removed were calculated by summing all of the daily average temperatures on days that do not exceed the 25% threshold. The average daily temperature was then calculated by dividing this adjusted freezing index by the number of days not classified as down-valley wind days.

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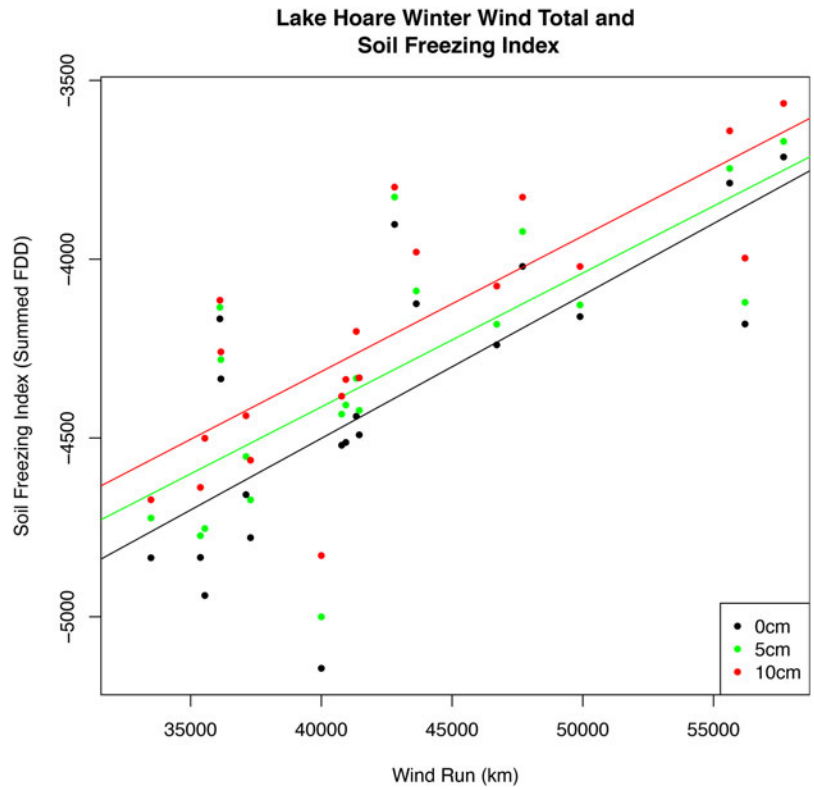

Figure 8. Soil freezing index and total windiness at Lake Hoare. Soil freezing index (summed winter freezing degree-days (FDDs)) and total windiness (wind run) are significantly correlated at both sites. Windier winters lead to winters with warmer soils.

For each environmental variable (e.g. soil freezing index, air freezing index, total windiness, etc.), we evaluated change over time and correlation between variables using simple linear regression analysis. All results are reported as the slope of those analyses, as well as the *P*-value of the slope and the correlation coefficient (*R*). *P*-values < 0.05 are considered significant. While it is possible to generate multiple linear regression models to explain a phenomenon such as winter soil freezing index, our goal was to evaluate the possible forcing processes that could have an effect on soil freezing index over time, not to generate an optimized statistical model for fitting soil freezing index.

Finally, we generated a pair of comparator/prediction calculations. The slope and *y*-intercept values from the linear regressions versus time created for the air and soil index data were used to calculate the predicted year of zero wintertime freezing for the study sites. In addition, while summer conditions are not the focus of this study due to their more complex thermal processes, including variable insolation and active-layer thickening, we also computed surface thawing degree-days (TDDs) measured at the soil sites. TDDs were computed using surface soil daily average temperatures from the same time period as the winter soil data. TDDs were summed from November through February, following the summer definition from Obryk *et al.* (2020). We report both net TDDs and gross TDDs: net TDDs are the summed daily temperatures from November through February, including days with sub-zero temperatures, while gross TDDs are the total positive degree-days from the summer.

Table VII. Relationship between soil freezing index (0 cm) and wind run at all soil monitoring sites. Slope indicates the slope of the regression line between soil freezing index and summed windiness.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	0.030	0.1808	0.13	0.37
Lake Bonney	0.023	0.0217	0.25	0.50
Lake Brownworth	0.027	0.0053	0.31	0.56
Lake Fryxell	0.026	5.00E-04	0.44	0.67
Lake Hoare[a]	0.040	2.00E-04	0.55	0.74
Lake Vanda	0.018	0.0361	0.25	0.50
Lake Vida	0.024	0.2874	0.05	0.21

[a]Data plotted in Fig. 8.

Results

The plots shown below provide one example of the data series or correlation calculated, typically a high-correlation, highly significant example.

Change over time at measurement stations

Total wintertime FDDs decreased significantly ($P < 0.05$) over time at all soil study sites except for Lake Vanda, which showed a non-significant ($P = 0.28$) decrease in freezing index (Fig. 2 & Table I). Here, and throughout the Results section, colder temperatures are reported as more negative freezing index values and warmer temperatures are shown as less negative values. This results in plots that show cold conditions at the base of the *y*-axis and warming temperatures over time rising on the *y*-axis, comparable to representations of measured temperature over time.

Rates of change of calculated soil freezing index at the study sites ranged from rapid warming of ~36 fewer FDDs per year on average (Lake Hoare) to ~18 fewer FDDs per year at Lake

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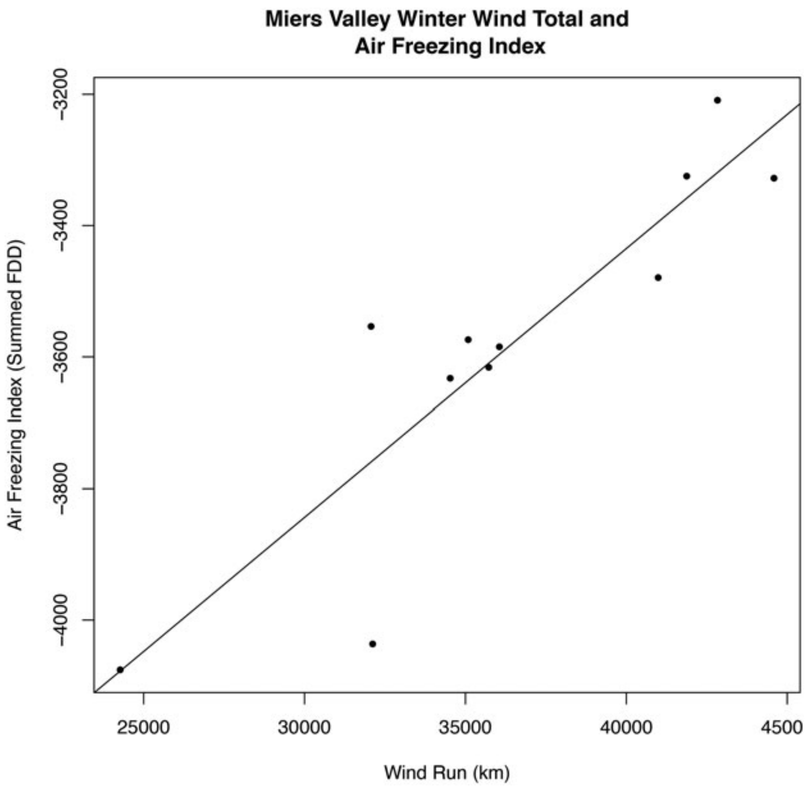

Figure 9. Air freezing index and total windiness at Miers Valley. Air freezing index (summed freezing degree-days (FDDs)) and wind run are significantly correlated. Windier years are years with warmer air temperatures.

Bonney. Correlation between freezing index and time is general strong, ranging from 0.66 at Lake Hoare to 0.45 at Lake Vida. In general, subsurface freezing indices for soils at 5 and 10 cm depths follow the same trend as surface freezing indices, showing fewer total wintertime FDDs over the measured record.

Concurrent with wintertime soil warming, wintertime air freezing index decreased significantly ($P < 0.05$) at all study sites except for Friis Hills, Mount Fleming, and Miers Valley; air warming at Explorer's Cove is marginally significant ($P = 0.0522$; Fig. 3 & Table II). At Friis Hills and Mount Fleming, linear fits to air freezing indices over time show a small but statistically non-significant increase in FDDs, while at Miers Valley, air FDDs are decreasing, but not significantly. Rates of change of calculated air freezing index at the study sites ranged from ~29 fewer air FDDs per year on average at Lake Fryxell and Miers Valley to ~12 fewer air FDDs per year at Lake Hoare.

Likewise, summer TDDs are increasing at most soil sites (Fig. 4 & Table III). Summer TDD increase is significant at all stations except Explorer's Cove, and summer TDDs are decreasing only at Lake Hoare (although the linear fit to the data is not significant). Soils are gaining between 3 and 9 TDDs per year (significant values only) when counted as gross increase in positive-temperature days, or between 6 and 21 TDDs (significant values only) when counted as net TDDs that include a reduction in the number of days with temperatures below 0°C or an increase in temperatures near 0°C.

In contrast to generally rising air and soil temperatures during winter, overall windiness, measured as wind run, is only increasing in the MDV significantly at Lake Fryxell and Lake Hoare (Fig. 5 & Table IV). At all other sites, wintertime total windiness is increasing over time, but not significantly.

The number of down-valley wind days are mostly increasing over time; however, the increase is not significant at all sites (Fig. 6 & Table V). Down-valley wind days determined by our algorithm are increasing significantly by ~0.3–0.6 days per year at Lake Fryxell, Lake Hoare and Lake Vida. All other sites, except Mount Fleming, show increases in down-valley wind days, though the trends are not statistically significant.

Measured wintertime incoming longwave radiation is increasing at Lake Bonney and Commonwealth Glacier, but the trend is not significant at either longwave measurement station. At Commonwealth Glacier, incoming longwave radiation is increasing during winter at a rate of 39 W/m^2·day per year ($P = 0.1036$,

Table VIII. Relationship between air freezing index and wind run at all air monitoring sites. Slope indicates the slope of the regression line between air freezing index and wind run.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	0.040	0.0091	0.32	0.57
Friis Hills	0.004	0.4834	0.06	0.24
Lake Bonney	0.031	0.0029	0.36	0.60
Lake Brownworth	0.025	0.0052	0.32	0.56
Lake Fryxell	0.033	< 0.0001	0.54	0.74
Lake Hoare	0.033	< 0.0001	0.51	0.71
Lake Vanda	0.022	0.0011	0.39	0.62
Lake Vida	0.073	0.0019	0.33	0.57
Miers Valley[a]	0.041	0.0002	0.79	0.89
Mount Fleming	−0.0004	0.9103	0	−0.05

[a]Data plotted in Fig. 9.

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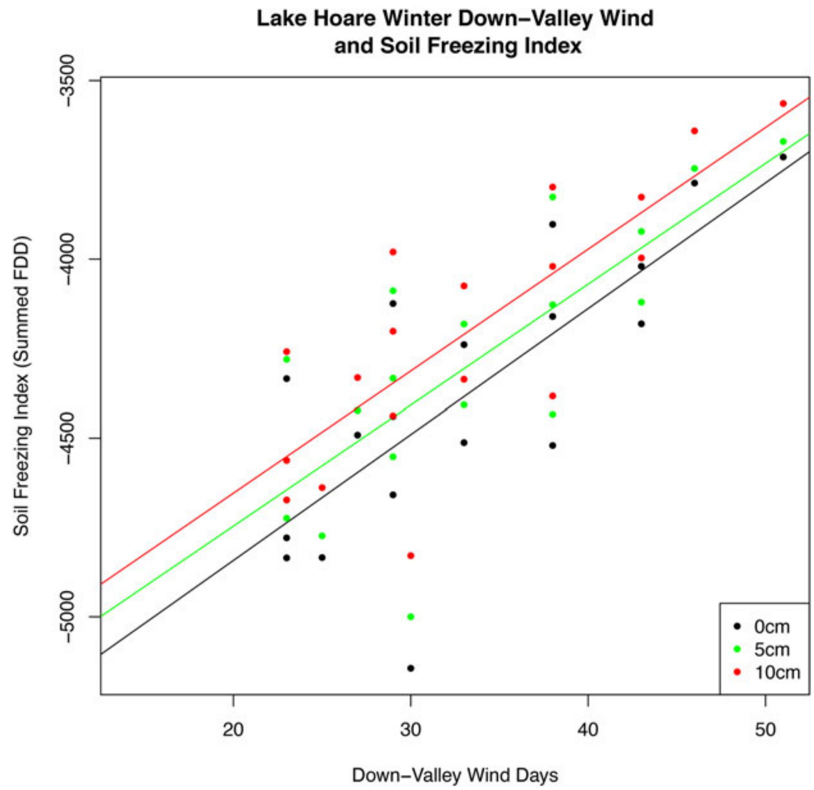

Figure 10. Soil freezing index and number of down-valley wind days (25% threshold) at Lake Hoare. Soil freezing index is strongly and significantly correlated with the number of down-valley wind days. Across the McMurdo Dry Valleys, all sites show warmer winter soils during years with more down-valley wind events, although the trend is not significant at all sites. FDD = freezing degree-days.

$R = 0.33$), while at Lake Bonney it is increasing 20.96 $W/m^2 \cdot day$ per year ($P = 0.6875$, $R = 0.11$).

Relationships between soil temperature, air temperature and possible environmental forcing variables

Wintertime air and soil surface freezing index values are strongly and significantly correlated at all sites (Fig. 7 & Table VI). Across all years of data collection, linear fits between air and soil surface freezing indices have slopes that range between 0.64 (Lake Vida) and 1.12 (Lake Hoare). Some sites regularly record air temperatures that warm faster than soil temperatures (slopes < 1), including Explorer's Cove, Lake Bonney, Lake Fryxell, Lake Vanda and Lake Vida, while other sites have soil temperatures that warm faster than air temperatures (slopes > 1), including Lake Brownworth and Lake Hoare (Table VI). At most stations, soil freezing index and air freezing index are strongly correlated, with R-values in excess of 0.96 at all sites except Explorer's Cove and Lake Vida.

Table IX. Relationship between soil freezing index and number of down-valley wind days (25% threshold) at soil monitoring sites. Slope indicates the slope of the regression line between soil freezing index and number of down-valley wind days.

Site	Slope	P-value	R^2	R
Explorer's Cove	27.36	0.0697	0.25	0.50
Lake Bonney	15.14	0.0170	0.26	0.51
Lake Brownworth	16.39	0.0061	0.32	0.57
Lake Fryxell	35.47	0.0001	0.52	0.72
Lake Hoare[a]	38.84	0.0002	0.58	0.76
Lake Vanda	13.29	0.1579	0.14	0.37
Lake Vida	22.51	0.0802	0.12	0.34

[a]Data plotted in Fig. 10.

Across soil monitoring sites, increased wintertime windiness is correlated with warmer soil temperatures (Fig. 8 & Table VII). The magnitude of soil freezing index decreases at all sites as wintertime total wind increases, a trend that is significant at all sites except Explorer's Cove and Lake Vida. Soil freezing index sensitivity to total windiness is variable across the study sites, with correlation R-values ranging from a high of 0.74 at Lake Hoare to 0.50 at Lake Bonney and Lake Vanda. At Explorer's Cove and Lake Vida, where the relationship between total windiness and soil freezing index is not statistically significant, R-values are also lower, at 0.37 and 0.21, respectively.

Air freezing index is strongly and significantly correlated with wintertime total windiness at valley-bottom air temperature monitoring sites but not at higher-elevation monitoring sites (Fig. 9 & Table VIII). Warmer air temperatures are correlated with greater total windiness at all sites other than Friis Hills and Mount Fleming. The correlation between warmer air temperature and windier winter conditions is strong, ranging from R-values of 0.57 at Explorer's Cove to 0.89 in Miers Valley.

In particular, larger numbers of down-valley wind days in a winter are correlated with warmer winter soil temperatures at most sites (Fig. 10 & Table IX). The magnitude of soil freezing index decreases significantly with increasing down-valley wind days at Lake Bonney, Lake Fryxell, Lake Hoare and Lake Brownworth. Down-valley winds are correlated with warmer soil temperatures at Explorer's Cove and Lake Vida, although the correlation is not significant.

As with total windiness, air freezing index is strongly and significantly correlated with the number of down-valley wind days at valley-bottom air monitoring stations (Explorer's Cove, Lake Bonney, Lake Brownworth, Lake Fryxell, Lake Hoare, Lake

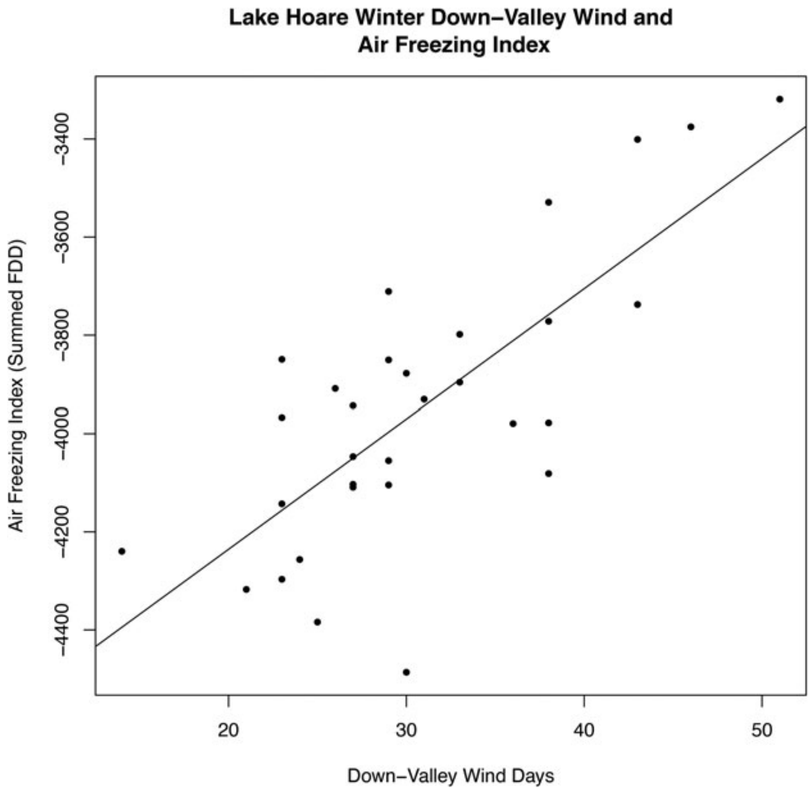

Figure 11. Air freezing index and number of down-valley wind days at Lake Hoare. Air freezing index is strongly and significantly correlated with the number of down-valley wind days. Across the McMurdo Dry Valleys, all sites show warmer winter air temperatures during years with more down-valley wind days, although the trend is not significant at all sites. FDD = freezing degree-days.

Vanda, Lake Vida and Miers Valley), while at higher-elevation sites (Friis Hills and Mount Fleming), the relationship is absent. As with soil freezing index, the magnitude of air freezing index decreases in years with more down-valley wind days, although the distribution is not uniform within the MDV (Fig. 11 & Table X). The correlation is strongest in Miers Valley and at Lake Hoare and Lake Fryxell, while further down Taylor Valley at Explorer's Cove the correlation is weaker.

Finally, downwelling (incident) longwave radiation strongly and significantly correlates with wintertime soil temperature at sites proximal to the Commonwealth Glacier longwave sensor, while sites compared to the Lake Bonney longwave sensor show correlations that are not significant. At all sites, years with greater wintertime incident longwave radiation are years with warmer wintertime soil temperatures (Fig. 12 & Table XI). Correlations between incident longwave radiation and soil freezing index are strong, ranging between 0.69 and 0.74 at sites with significant relationships.

Table X. Relationship between air freezing index and number of down-valley wind days at air monitoring sites. Slope indicates the slope of the regression line between air freezing index and number of down-valley wind days.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	32.67	0.0036	0.40	0.63
Friis Hills	3.83	0.3986	0.08	0.28
Lake Bonney	19.37	0.0025	0.39	0.62
Lake Brownworth	15.39	0.0061	0.32	0.57
Lake Fryxell	42.69	<0.0001	0.66	0.81
Lake Hoare[a]	25.33	< 0.0001	0.66	0.81
Lake Vanda	23.26	0.0010	0.44	0.66
Lake Vida	47.48	0.0003	0.42	0.65
Miers Valley	25.76	0.0005	0.75	0.87
Mount Fleming	−0.17	0.9685	0.0003	−0.01

[a]Data plotted in Fig. 11.

The relationship between incident longwave radiation and wintertime air freezing index persists at stations proximal to the Commonwealth Glacier longwave station, although the strength of the correlation between air freezing index and summed longwave radiation is generally less than for the relationship between soil freezing index and summed longwave radiation (Fig. 13 & Table XII). Air is warmer in winter at all stations in years with greater total longwave radiation flux; however, the trends are only significant at Explorer's Cove, Lake Fryxell and Lake Hoare (and are marginally significant at Miers Valley and Lake Brownworth).

At all stations, there is no relationship between the number of down-valley wind days in a year and the total incident longwave radiation that winter (Fig. 14 & Table XIII). Across measurement sites, some locations show an increase in longwave radiation in windier years, while others show a decrease (Fig. 14).

Discussion

Are Antarctic soils and air experiencing a change in wintertime temperature over time (RQ1)? Across all soil monitoring sites, wintertime soil surface temperatures are increasing with time, and at all but one soil site (Lake Vanda) linear fits to that warming are statistically significant ($P < 0.05$). Interestingly, summer TDDs are also increasing at most soil sites; however, the rate at which summer TDDs are increasing is less than the rate at which winter

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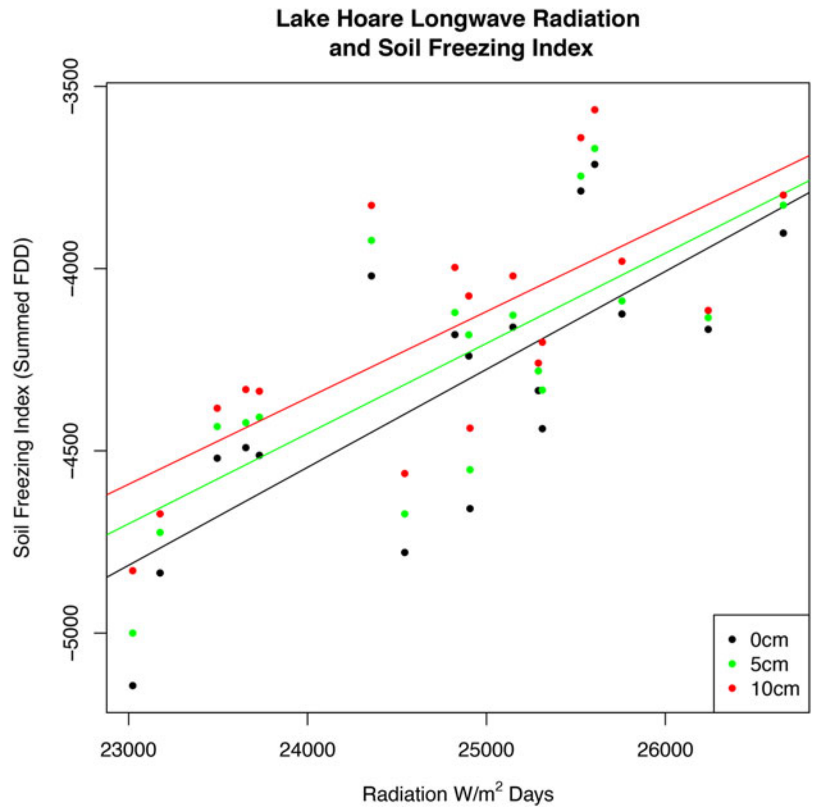

Figure 12. Soil freezing index and incident longwave radiation at Lake Hoare. Soil freezing index is strongly and significantly correlated with the total incident longwave. Across the McMurdo Dry Valleys, all sites show warmer winter soil temperatures during years with more longwave radiation, although the trend is not significant at all sites. FDD = freezing degree-days.

FDDs are decreasing. It is for that reason that we are focused on exploring potential drivers of winter warming to MDV soils.

What are the correlative relationships between wintertime soil temperature and other environmental variables that control surface energy balance - in other words, what could be driving soil warming (RQ2)? Soil temperatures and air temperatures are strongly coupled at MDV monitoring sites; however, some differences exist. At some sites, winter soil temperatures are slightly colder than air temperatures (e.g. Lake Brownworth), while at other sites, air temperatures are slightly colder than soil temperatures (e.g. Lake Vida). At all soil sites other than Lake Brownworth and Lake Hoare, the slope of the air-soil temperature correlation is < 1, meaning that winter warming (loss of FDDs over time) is greater in air than in the soil. At Lake Hoare and Lake Brownworth, the slope is > 1, suggesting that soils there respond faster to warming than the air. One possibility is that, at these two sites, additional heat might also be entering the soil not through the mechanisms measured by our meteorological sensors (e.g. by secular lake level rise; Bomblies *et al.* 2001, Doran *et al.* 2008), adding latent heat of fusion or increasing soil heat capacity.

Table XI. Relationship between soil freezing index and indecent longwave radiation. Slope indicates the slope of the regression line between soil freezing index and summed longwave radiation.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	0.27	0.0015	0.53	0.73
Lake Bonney	0.07	0.2501	0.10	0.32
Lake Brownworth	0.20	7.00E-04	0.48	0.69
Lake Fryxell	0.28	1.00E-04	0.52	0.72
Lake Hoare[a]	0.27	4.00E-04	0.55	0.74
Lake Vanda	0.07	0.2981	0.10	0.31
Lake Vida	0.12	0.1181	0.17	0.41

[a]Data plotted in Fig. 12.

Wintertime windiness is clearly a key mechanism for transferring atmospheric heat into MDV soils from Foehn/katabatic wind compression during down-valley wind events, but is all warming due to down-valley wind events (e.g. Nylen & Fountain 2004, Speirs *et al.* 2010), or are there multiple drivers of warming? Soil freezing index is strongly correlated with total wintertime windiness as well as number of down-valley wind events. At some stations, this relationship is clear and significant (e.g. Lake Hoare), while at others (e.g. Lake Brownworth), the slope of the relationship and the correlation coefficient are both lower, suggesting that at some sites drainage wind frequency is less deterministic of wintertime soil temperatures.

Accordingly, this raises the question of how important down-valley wind events are to soil warming. When down-valley wind days are removed from the datasets, there is no significant correlation at any station between soil freezing index and total wintertime windiness (Table XIV). Wintertime soil temperatures become invariant to total windiness. This suggests that it is the down-valley wind events that are advecting heat into soils during winter, and that winters with more down-valley winds transfer more heat into the soils. This conjecture is supported by the fact that when down-valley wind days are removed from the air temperature record, there is also no significant correlation between air freezing index and total wintertime windiness at any station other than Lake Vida, where the effect is comparatively small ($P = 0.02$, $R = 0.44$; Table XV). Part of the persistence

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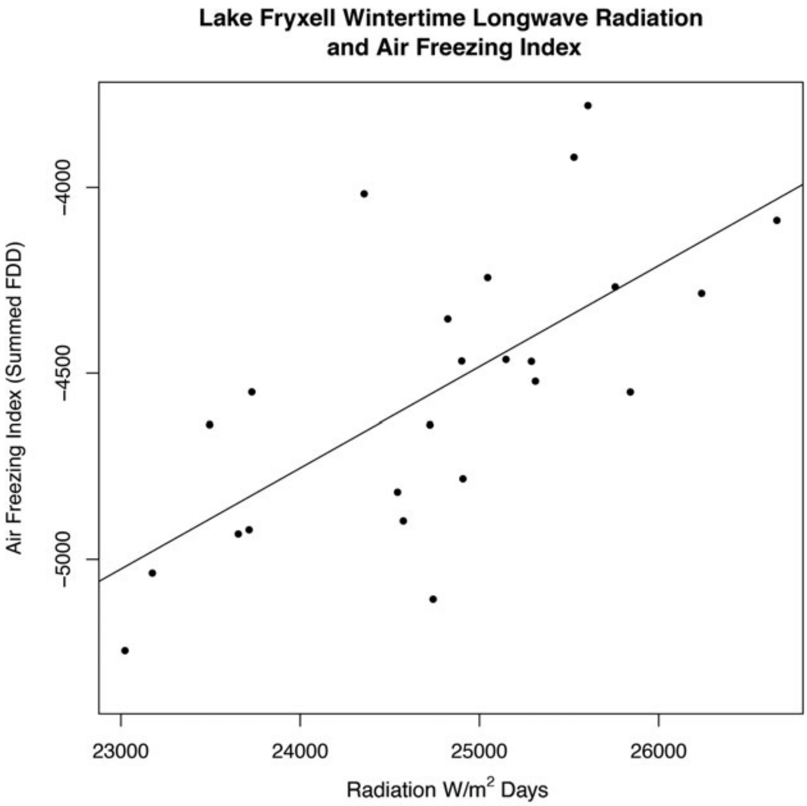

Figure 13. Air freezing index and incident longwave radiation at Lake Fryxell. Air freezing index is strongly and significantly correlated with the total incident longwave radiation. Across the McMurdo Dry Valleys, all sites show warmer winter air temperatures during years with more longwave radiation, although the trend is not significant at all sites. FDD = freezing degree-days.

of the correlation between winter air temperature and total windiness at Lake Vida may be that Lake Vida experiences some strong winds from out of the south-east, potentially related to air drainage off of Victoria Lower Glacier. If these south-easterly winds warm during descent and compression off the glacier, they may raise winter air temperatures while not being fully filtered out by our general down-valley wind flagging system, which is only designed to remove the strongest drainage winds from off the polar plateau from the west.

Other stations may also be undergoing changing winter wind regimes. Nylen & Fountain (2004) noted that the complex, curving and bifurcating terrain of many of the Dry Valleys can cause winds to 'skip' stations via hydraulic jumps (Doran *et al.* 2002), particularly in the mouths of the valleys, which are broad and open, affecting some stations but not others. Stations such as Lake Fryxell may be experiencing notably high rates of winter warming, and notably statistically significant changes over time, due to that station having the highest (statistically significant) rate of change in the number of down-valley wind days recorded at the station over time (0.59 per year). If more wind events are affecting the broad, open mouths of the valleys, these stations may be particularly susceptible to winter soil warming.

Table XII. Relationship between air freezing index and indecent longwave radiation. Slope indicates the slope of the regression line between air freezing index and summed longwave radiation.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	0.24	0.0008	0.48	0.69
Friis Hills	0.15	0.0632	0.53	0.73
Lake Bonney	0.06	0.3877	0.05	0.24
Lake Brownworth	0.18	0.0009	0.47	0.68
Lake Fryxell[a]	0.27	0.0003	0.46	0.68
Lake Hoare	0.20	0.0005	0.43	0.66
Lake Vanda	0.04	0.5165	0.03	0.18
Lake Vida	0.07	0.4338	0.04	0.21
Miers Valley	0.20	0.0563	0.64	0.80
Mount Fleming	0.07	0.3578	0.28	0.53

[a]Data plotted in Fig. 13.

But are down-valley wind events the only driver of winter warming in the MDV? Clearly, there is a limit on the amount of warming that down-valley wind events can cause owing to the limited number of wind events that can occur in a single winter season. Interestingly, despite the strong relationship between wintertime air/soil temperatures and the number and intensity of down-valley wind days, winter soil and air temperatures continue to show increases over time, even when down-valley wind days are removed from the dataset (Figs 15 & 16 & Tables XVI & XVII). This suggests that there is also wintertime warming in the MDV that is being driven by other heat sources, including incident longwave radiation or sensible heat from regional air warming. So, while down-valley wind events do warm the soil and air, they are not the only causes of winter soil and air warming over time.

What about snow - how might it be influencing our analysis of the instrumental record? Snow is a key insulator in Arctic soils, reducing wintertime freezing in soils despite cold overlying air temperatures (Klene *et al.* 2001, French 2007). Snow cover is notoriously difficult to measure in the MDV, particularly during winter, when it is blown as sediment over the land surface,

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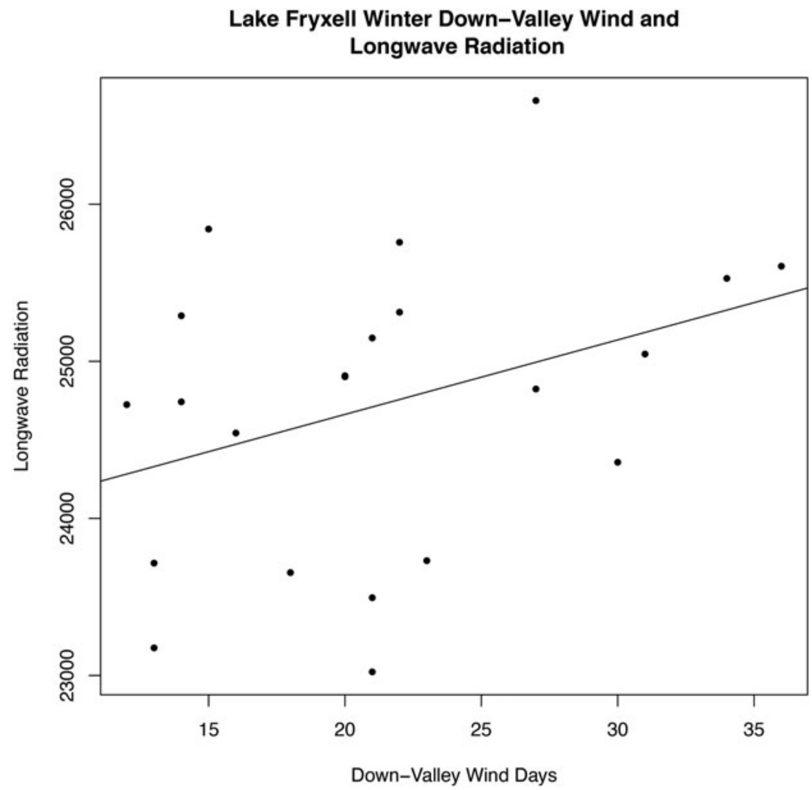

Figure 14. Incident longwave radiation and number of down-valley wind days at Lake Fryxell. Correlations between number of down-valley wind days and longwave radiation are generally positive; however, they are not significant at any site.

Table XIII. Relationship between incident longwave radiation and the number of down-valley wind days in a year. Slope indicates the slope of the regression line between longwave radiation and down-valley wind days.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	27.87	0.4933	0.03	0.18
Friis Hills	36.30	0.4436	0.15	0.39
Lake Bonney	−34.61	0.2935	0.09	−0.30
Lake Brownworth	−31.39	0.3279	0.06	−0.24
Lake Fryxell[a]	37.47	0.1920	0.08	0.29
Lake Hoare	29.66	0.1895	0.08	0.28
Lake Vanda	−68.90	0.1740	0.18	−0.42
Lake Vida	8.18	0.8984	0.001	0.03
Miers Valley	88.43	0.1031	0.53	0.72
Mount Fleming	−87.22	0.3544	0.28	−0.53

[a]Data plotted in Fig. 14.

producing drifts (Fountain *et al.* 2009). Snow is more aerially extensive in the mouths of the MDV than higher up in the valleys (Kuentz *et al.* 2022) - where the valleys widen at their mouths, wind velocities drop and snow can be deposited in winter. These two processes may in part explain the poor correlations between number of down-valley wind events and air/soil freezing indices at Explorer's Cove. This station may be simultaneously thermally insulated by comparatively thick winter snow drifts in some years while also experiencing less dramatic input of heat from down-valley wind events as they dissipate near the widening valley mouth.

Table XIV. Relationship between soil freezing index and total wintertime windiness when days with down-valley wind events are removed.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	0.07	0.2769	0.09	0.30
Lake Bonney	−0.02	0.6335	0.01	−0.11
Lake Brownworth	0.03	0.2856	0.05	0.23
Lake Fryxell	−0.02	0.7270	0.01	−0.08
Lake Hoare	−0.03	0.5926	0.02	−0.13
Lake Vanda	−0.017	0.7015	0.01	−0.10
Lake Vida	0.02	0.7720	0	0.06

Table XV. Relationship between air freezing index and total wintertime windiness when days with down-valley wind events are removed.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	0.08	0.1050	0.14	0.37
Friis Hills	−0.027	0.1334	0.23	−0.48
Lake Bonney	−0.01	0.7509	0.01	−0.07
Lake Brownworth	0.03	0.2484	0.06	0.25
Lake Fryxell	0.01	0.8970	0	0.03
Lake Hoare[a]	−0.02	0.6360	0.01	−0.09
Lake Vanda	−0.052	0.1889	0.08	−0.28
Lake Vida	0.13	0.0222	0.19	0.44
Miers Valley	0.07	0.3314	0.10	0.32
Mount Fleming	−0.002	0.9224	0	−0.04

[a]Data plotted in Fig. 16.

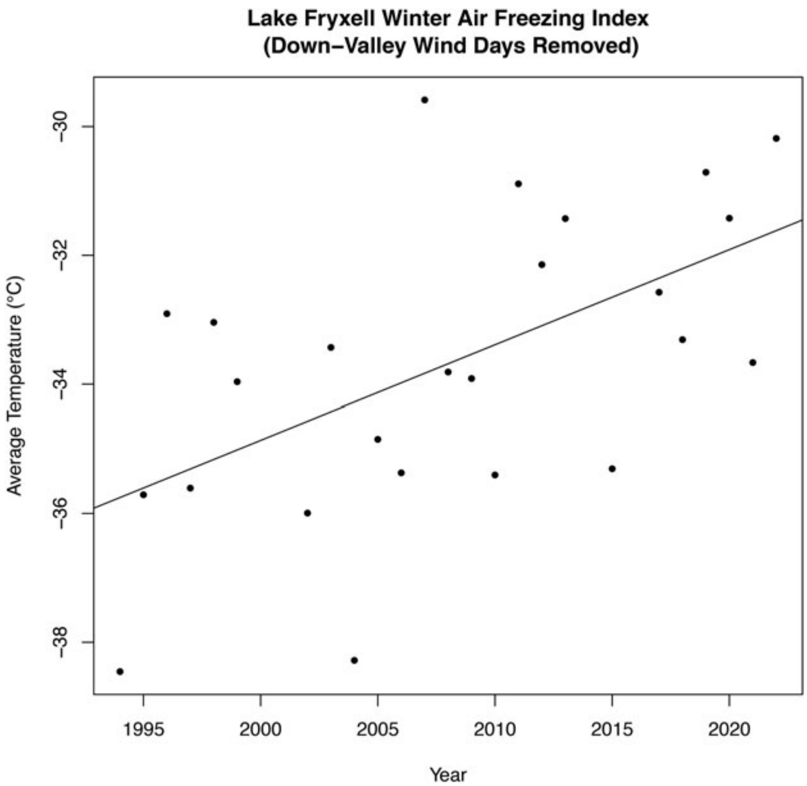

Figure 15. Air freezing index over time at Lake Fryxell when down-valley wind days are removed. Down-valley wind days are not the only cause of warming over time in the McMurdo Dry Valleys during winter.

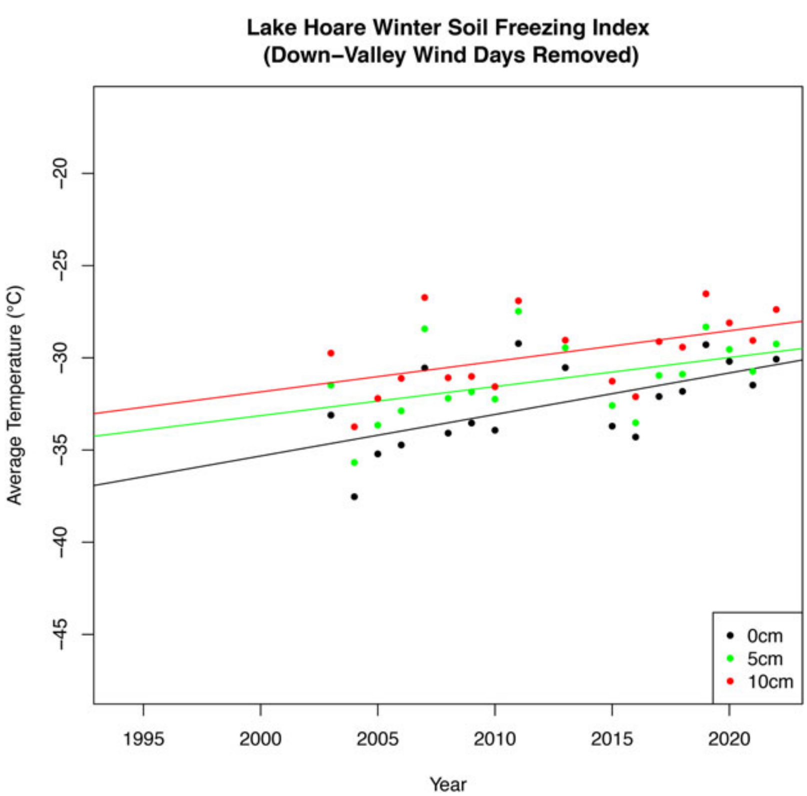

Figure 16. Soil freezing index at Lake Hoare when down-valley wind days are removed. Down-valley wind days are not the only cause of warming over time in the McMurdo Dry Valleys during winter.

If down-valley wind events, regional warming and increased longwave emission are all leading to winter warming of air and soil in the MDV, how do they interact - is there a trade-off between warming from wind *vs* warming from longwave radiation? We inferred that down-valley wind events and cloud cover leading to enhanced infrared might trade off, such that windy conditions would result in low ground-level relative humidity (Nylen & Fountain 2004) and potentially fewer clouds

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Table XVI. Air freezing index over time when down-valley wind days are removed. Slope indicates the slope of the linear model.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	0.10	0.1156	0.14	0.37
Friis Hills	−0.10	0.2247	0.16	−0.40
Lake Bonney	0.09	0.0373	0.20	0.45
Lake Brownworth	0.10	0.0100	0.28	0.54
Lake Fryxell[a]	0.15	0.0038	0.31	0.55
Lake Hoare	0.06	0.0301	0.15	0.39
Lake Vanda	0.05	0.3070	0.05	0.23
Lake Vida	0.14	0.0063	0.26	0.51
Miers Valley	0.06	0.6152	0.03	0.17
Mount Fleming	−0.01	0.9140	0.002	−0.05

[a]Data plotted in Fig. 15.

Table XVII. Soil freezing index over time when down-valley wind days are removed. Slope indicates decrease in freezing degree-days per year.

Site	Slope	*P*-value	R^2	*R*
Explorer's Cove	0.19	0.1296	0.18	0.43
Lake Bonney	0.11	0.0208	0.25	0.50
Lake Brownworth	0.10	0.0160	0.26	0.51
Lake Fryxell	0.10	0.0688	0.15	0.39
Lake Hoare[a]	0.23	0.0070	0.37	0.61
Lake Vanda	0.11	0.0398	0.27	0.52
Lake Vida	0.10	0.0904	0.11	0.33

[a]Data plotted in Fig. 16.

aloft. However, in fact, we observed a positive correlation between the number of down-valley wind days in a winter and the total incident longwave radiation at some sites (Fig. 14). This suggests that cloudier winters in the MDV may be winters in which more down-valley wind events occur. This is consistent with the interpretation of Speirs *et al.* (2010) that Ross Sea region winter cyclones are the driving factor in determining when down-valley wind events are triggered: large storms may bring winter clouds into the MDV, and the pressure differential from these storms could trigger Foehn-like down-valley wind events, potentially leading to enhanced incident longwave radiation during times of regional cloud cover.

Are the environmental controls on winter surface energy balance changing over time (RQ3)? Across all air temperature monitoring sites, wintertime air temperatures are rising significantly, except at Miers Valley, where the air warming is not statistically significant, and at the high alpine sites of Friis Hills and Mount Fleming, where non-significant cooling is observed. One possible explanation for the non-significant warming at Miers Valley and non-significant apparent cooling at Friis Hills and Mount Fleming could be that these stations were installed later than the valley-bottom stations (2010–2012 *vs* 1987–1995). Warming in the MDV after a decadal cooling trend began in earnest *c.* 2005 (Obryk *et al.* 2020), meaning these newer stations have missed part of the warming record. The exposed, mountain-top positions of the Mount Fleming and Friis Hills stations may also expose them to fewer down-valley wind events, reducing warming from that driver. At Lake Bonney and Commonwealth Glacier, incident longwave radiation is increasing over time, although the trend is not statistically significant. Intriguingly, wintertime down-valley wind events are increasing at most low-elevation sites, with statistically significant increases in the number of wind events per winter at Lake Hoare, Lake Fryxell and Lake Vanda and non-significant increases at all other sites except Mount Fleming. Together, these observations suggest that MDV active layers, and potentially underlying permafrost, are undergoing winter warming with fewer winter FDDs in the soil, while, concurrently, wintertime air temperatures are rising and wind events are becoming more common, perhaps in conjunction with increased longwave warming associated with cloudier winter sky conditions.

Ultimately, is there a long-term climate trajectory in which refreezing no longer occurs in soils during Antarctic winter (RQ4)? Taking the soil freezing index observations over time at face value (Table I) and extrapolating into the future - bearing in mind that there is a limit to which down-valley wind events can continue to drive warming, while also recognizing that regional air warming and potentially increased winter longwave radiation could continue to drive warming - it is possible to predict when freezing index values will reach zero, indicating an end to even seasonally frozen conditions in the MDV. Zero annual wintertime soil FDDs will be reached based on these extrapolations in 2133 for Lake Hoare, in 2148 for Explorer's Cove, in 2213 for Lake Fryxell, in 2255 for Lake Bonney and Lake Brownworth, in 2314 for Lake Vida and in 2433 for Lake Vanda. In order for permafrost to begin thawing, winter FDDs need not reach zero. TDDs in the MDV typically average < 500 for the warmest coastal sites (Fig. 4), rising only to ∼600 at Lake Bonney, and then only very recently (Fig. 4). If soil FDDs are decreasing at a rate of 20–30 per year (Table I), this suggests that a transition to seasonally frozen conditions rather than permafrost conditions could occur ∼20 years earlier than the linear model would predict. Together, these extrapolations suggest that permafrost in the MDV may be threatened with thaw over the long term, from thickening active layers during summer, but also from incomplete and waning wintertime freezing.

Conclusions

Analysis of wintertime air and soil surface/near-surface temperature records show that winter FDDs are generally decreasing in the MDV by 17.58–33.77 FDDs per year in soils (at statistically significantly changing stations), while summer TDDs are increasing only at a rate of 3–9 TDDs per year. Statistically significant winter soil warming was detected at all soil monitoring stations except Lake Vanda. Concurrently, winter air FDDs are also decreasing significantly at all air monitoring stations except Friis Hills, Miers Valley and Mount Fleming. Concurrently, wintertime incident longwave radiation measured at Commonwealth Glacier and Lake Bonney are increasing, but not significantly, and wintertime windiness (wind run and number of down-valley wind days) is generally increasing at the valley-bottom wind monitoring stations. Air and soil temperatures are strongly and significantly correlated. Likewise, windier years, especially years with more down-valley wind events, produce warmer winter soil and air temperatures.

However, winter warming of soils and air in the MDV over time cannot be explained entirely by an increase in the number, duration and/or intensity of down-valley wind events. When down-valley wind days are excluded from the temperature record, soils still show a reduction in FDDs over time. This suggests that MDV soils are experiencing winter warming from a combination of regional air temperature change, an increase in winter longwave flux, a combination of the two or from exogenous thermal inputs not measured by these meteorological stations.

Together, these observations suggest that, in concert with deepening of summer active layers, some MDV coastal permafrost may be at risk of thaw due to diminished winter cooling. Linear projections of winter freezing suggest that zero winter freezing could occur as soon as the early 2130s for Lake Hoare, and that near-surface freezing parity with TDDs could occur up to several decades earlier. It is possible that some MDV permafrost is on a trajectory to begin the transition from regionally continuous permafrost to discontinuous permafrost.

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References

Adlam, L.S., Balks, M.R., Seybold, C.A. & Campbell, D.I. 2010. Temporal and spatial variation in active layer depth in the McMurdo Sound Region, Antarctica. *Antarctic Science*, **22**, 10.1017/S0954102009990460.

Barrett, J.E., Adams, B.J., Doran, P.T., Dugan, H.A., Myers, K.F., Salvatore, M.R., *et al.* 2024. Response of a terrestrial polar ecosystem to the March 2022 Antarctic weather anomaly. *Earth's Future*, **12**, 10.1029/2023EF004306.

Bindschadler, R., Vornberger, P., Fleming, A., Fox, A., Mullins, J., Binnie, D., *et al.* 2008. The Landsat image mosaic of Antarctica. *Remote Sensing of Environment*, **112**, 10.1016/j.rse.2008.07.006.

Bockheim, J.G. 1995. Permafrost distribution in the southern circumpolar region and its relation to the environment: a review and recommendations for further research. *Permafrost and Periglacial Processes*, **6**, 27–45.

Bockheim, J.G., Campbell, I.B. & McLeod, M. 2007. Permafrost distribution and active-layer depths in the McMurdo Dry Valleys, Antarctica. *Permafrost and Periglacial Processes*, **18**, 217–227. DOI: 10.1002/ppp.588

Bomblies, A., McKnight, D.M. & Andrews, E.D. 2001. Retrospective simulation of lake-level rise in Lake Bonney based on recent 21-year record: indication of recent climate change in the McMurdo Dry Valleys, Antarctica. *Journal of Paleolimnology*, **25**, 477–492.

Carshalton, A.G., Balks, M.R., O'Neill, T.A., Bryan, K.R. & Seybold, C.A. 2022. Climatic influences on active layer depth between 2000 and 2018 in the McMurdo Dry Valleys, Ross Sea Region, Antarctica. *Geoderma Regional*, **29**, 10.1016/j.geodrs.2022.e00497.

Cartwright, K. & Harris, H.J. 1981. Hydrogeology of the dry valley region, Antarctica. *In* L.D. McGinnis, *ed.*, *Dry Valley drilling project.* Washington, DC: American Geophysical Union, 193–214.

Chadburn, S.E., Burke, E.J., Cox, P.M., Friedlingstein, P., Hugelius, G. & Westermann, S. 2017. An observation-based constraint on permafrost loss as a function of global warming. *Nature Climate Change*, **7**, 10.1038/nclimate3262.

Curry, J.A., Schramm, J.L., Rossow, W.B. & Randall, D. 1996. Overview of Arctic cloud and radiation characteristics. *Journal of Climate*, **9**, 1731–1764.

Doran, P. & Fountain, A. 2023a. Daily measurement summaries from Commonwealth Glacier Meteorological Station (COHM), McMurdo Dry Valleys, Antarctica (1993–2022, ongoing). DOI: 10.6073/PASTA/A5E6164ABB618444C0C2248B3D588F77.

Doran, P. & Fountain, A. 2023b. Daily measurement summaries from Explorers Cove Meteorological Station (EXEM), McMurdo Dry Valleys, Antarctica (1995–2022, ongoing). DOI: 10.6073/PASTA/188D48414868D5D1D2F1AD8EB3FDD198.

Doran, P. & Fountain, A. 2023c. Daily measurement summaries from Friis Hills Meteorological Station (FRSM), McMurdo Dry Valleys, Antarctica (2010–2022, ongoing). DOI: 10.6073/PASTA/DF200F01BAE8B7981BFFBD1142113BC9.

Doran, P. & Fountain, A. 2023d. Daily measurement summaries from Lake Bonney Meteorological Station (BOYM), McMurdo Dry Valleys, Antarctica (1993–2022, ongoing). DOI: 10.6073/PASTA/74468334923B397B4AC21D75562B89F1.

Doran, P. & Fountain, A. 2023e. Daily measurement summaries from Lake Brownworth Meteorological Station (BRHM), McMurdo Dry Valleys, Antarctica (1995–2022, ongoing). DOI: 10.6073/PASTA/07304DBA22D2AD3C940D9F95087A0307.

Doran, P. & Fountain, A. 2023f. Daily measurement summaries from Lake Fryxell Meteorological Station (FRLM), McMurdo Dry Valleys, Antarctica (1993–2022, ongoing). DOI: 10.6073/PASTA/6C38E01A1F8A9C73FD80CF8219384FF5.

Doran, P. & Fountain, A. 2023g. Daily measurement summaries from Lake Hoare Meteorological Station (HOEM), McMurdo Dry Valleys, Antarctica (1987–2022, ongoing). DOI: 10.6073/PASTA/A72B9F094B00BF3D53287E6325B13C97.

Doran, P. & Fountain, A. 2023h. Daily measurement summaries from Lake Vanda Meteorological Station (VAAM), McMurdo Dry Valleys, Antarctica (1994–2022, ongoing). DOI: 10.6073/PASTA/5D84678405F92FFC53F64585B27EFA2C.

Doran, P. & Fountain, A. 2023i. Daily measurement summaries from Lake Vida Meteorological Station (VIAM), McMurdo Dry Valleys, Antarctica (1995–2022, ongoing). DOI: 10.6073/PASTA/B603EFD83A02C5E237C1AB9F5E6059FD.

Doran, P. & Fountain, A. 2023j. Daily measurement summaries from Miers Valley Meteorological Station (MISM), McMurdo Dry Valleys, Antarctica (2012–2022, ongoing). DOI: 10.6073/PASTA/A6869B69F5CA60F161F051C62C23394D.

Doran, P. & Fountain, A. 2023k. Daily measurement summaries from Mount Fleming Meteorological Station (FLMM), McMurdo Dry Valleys, Antarctica (2011–2022, ongoing). DOI: 10.6073/PASTA/2DD5A722308CE4DB8855D6325FD48FE8.

Doran, P. & Fountain, A. 2023l. High frequency measurements from Explorers Cove Meteorological Station (EXEM), McMurdo Dry Valleys, Antarctica (1995–2022, ongoing). DOI: 10.6073/pasta/a28e9b87b2573d6ccb5e60a7b764b9d4.

Doran, P. & Fountain, A. 2023m. High frequency measurements from Friis Hills Meteorological Station (FRSM), McMurdo Dry Valleys, Antarctica (2010–2022, ongoing). DOI: 10.6073/PASTA/B2E8593758AD83C2FC1A8702E0391EF6.

Doran, P. & Fountain, A. 2023n. High frequency measurements from Lake Bonney Meteorological Station (BOYM), McMurdo Dry Valleys, Antarctica (1993–2022, ongoing). DOI: 10.6073/PASTA/D1FB2D06EAB04EC29BFA31B74E8D7E42.

Doran, P. & Fountain, A. 2023o. High frequency measurements from Lake Brownworth Meteorological Station (BRHM), McMurdo Dry Valleys, Antarctica (1994–2022, ongoing). DOI: 10.6073/PASTA/4AB14239B3692B0F9D1118F95FB68394.

Doran, P. & Fountain, A. 2023p. High frequency measurements from Lake Hoare Meteorological Station (HOEM), McMurdo Dry Valleys, Antarctica (1987–2022, ongoing). DOI: 10.6073/PASTA/055A5C55E59AE5338195E49092DB61CC.

Doran, P. & Fountain, A. 2023q. High frequency measurements from Lake Vanda Meteorological Station (VAAM), McMurdo Dry Valleys, Antarctica (1994–2022, ongoing). DOI: 10.6073/PASTA/C7FFDD11FD5E0F524A2139B84299A204.

Doran, P. & Fountain, A. 2023r. High frequency measurements from Lake Vida Meteorological Station (VIAM), McMurdo Dry Valleys, Antarctica (1995–2022, ongoing). DOI: 10.6073/PASTA/550FF8CD5DE3983DE8B704A872426162.

Doran, P. & Fountain, A. 2023s. High frequency measurements from Miers Valley Meteorological Station (MISM), McMurdo Dry Valleys, Antarctica (2012–2022, ongoing). DOI: 10.6073/PASTA/07DDF8AA9BE93D8071326C34697BB56B.

Doran, P. & Fountain, A. 2023t. High frequency measurements from Mount Fleming Meteorological Station (FLMM), McMurdo Dry Valleys, Antarctica (2011–2022, ongoing). DOI: 10.6073/PASTA/FFAF6EA76CF1ADE119716659483B1B62.

Doran, P.T., Dana, G.L., Hastings, J. & Wharton, R.A. 1995. McMurdo Dry Valleys Long-Term Ecological Research (LTER): LTER automatic weather network (LAWN). *Antarctic Journal of the United States*, **30**, 276–280.

Doran, P.T., McKay, C.P., Clow, G.D., Dana, G.L., Fountain, A.G., Nylen, T. & Lyons, W.B. 2002. Valley floor climate observations from the McMurdo dry valleys, Antarctica, 1986–2000. *Journal of Geophysical Research - Atmospheres*, **107**, 10.1029/2001JD002045.

Doran, P.T., McKay, C.P., Fountain, A.G., Nylen, T., McKnight, D.M., Jaros, C. & Barrett, J.E. 2008. Hydrologic response to extreme warm and cold summers in the McMurdo Dry Valleys, East Antarctica. *Antarctic Science*, **20**, 10.1017/S0954102008001272.

Fountain, A.G., Levy, J.S., Gooseff, M.N. & Van Horn, D. 2014. The McMurdo Dry Valleys: a landscape on the threshold of change. *Geomorphology*, **225**, 10.1016/j.geomorph.2014.03.044.

Fountain, A.G., Nylen, T.H., Monaghan, A., Basagic, H.J. & Bromwich, D. 2009. Snow in the McMurdo Dry Valleys, Antarctica. *International Journal of Climatology*, **30**, 10.1002/joc.1933.

French, H. 2007. *The periglacial environment,* 3rd edition. Chichester: Wiley, 376 pp.

Guglielmin, M. & Cannone, N. 2012. A permafrost warming in a cooling Antarctica? *Climatic Change*, **111**, 10.1007/s10584-011-0137-2.

Guglielmin, M., Balks, M. & Paetzold, R. 2003. Towards an Antarctic active layer and permafrost monitoring network. *In* M. Phillips, S. Springman & L. Arenson, *eds*, *Permafrost*. Lisse: Swets & Zeitlinger, 337–341.

Guglielmin, M., Fratte, M.D. & Cannone, N. 2014. Permafrost warming and vegetation changes in continental Antarctica. *Environmental Research Letters*, **9**, 10.1088/1748-9326/9/4/045001.

Harris, H.J. & Cartwright, K. 1981. Hydrology of the Don Juan basin, Wright Valley, Antarctica. *Dry Valley Drilling Project, Antarctic Research Series*, **33**, 161–184.

Hrbáček, F., Oliva, M., Hansen, C., Balks, M., O'Neill, T.A., de Pablo, M.A., *et al.* 2023. Active layer and permafrost thermal regimes in the ice-free areas of Antarctica. *Earth-Science Reviews*, **242**, 10.1016/j.earscirev.2023.104458.

Hrbáček, F., Vieira, G., Oliva, M., Balks, M., Guglielmin, M., de Pablo, M.Á., *et al.* 2021. Active layer monitoring in Antarctica: an overview of results from 2006 to 2015. *Polar Geography*, **44**, 10.1080/1088937X.2017.1420105.

Klene, A.E., Nelson, F.E., Shiklomanov, N.I. & Hinkel, K.M. 2001. The N-factor in natural landscapes: variability of air and soil-surface temperatures, Kuparuk River Basin, Alaska, U.S.A. *Arctic, Antarctic, and Alpine Research*, **33**, DOI: 10.1080/15230430.2001.12003416.

Kuentz, L., Levy, J. & Salvatore, M. 2022. Timing and duration of ephemeral Antarctic water tracks and wetlands using high temporal-resolution satellite imagery, high spatial-resolution satellite imagery, and ground-based sensors in the McMurdo Dry Valleys. *Arctic, Antarctic, and Alpine Research*, **54**, 10.1080/15230430.2022.2123858.

Lacelle, D., Lapalme, C., Davila, A.F., Pollard, W., Marinova, M., Heldmann, J. & McKay, C.P. 2016. Solar radiation and air and ground temperature relations in the cold and hyper-arid Quartermain Mountains, McMurdo Dry Valleys of Antarctica. *Permafrost and Periglacial Processes*, **27**, 10.1002/ppp.1859.

Levy, J.S., Fountain, A.G., Gooseff, M.N., Welch, K.A. & Lyons, W.B. 2011. Water tracks and permafrost in Taylor Valley, Antarctica: extensive and shallow groundwater connectivity in a cold desert ecosystem. *Geological Society of America Bulletin*, **123**, 10.1130/B30436.1.

Levy, J.S., Andrews, I., Guller, A., Johnson, J., King, I., Pfaff, E., *et al.* 2024. *Antarctic water track hydrology and geochemistry from drone and ground sensors: active layer wetland processes in a cold desert.* Presented at *12th International Conference on Permafrost.* Whitehorse, YT, 16–20 June.

Marchant, D.R. & Head, J.W. 2007. Antarctic dry valleys: microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars. *Icarus*, **192**, 10.1016/j.icarus.2007.06.018.

Nylen, T.H. & Fountain, A.G. 2004. *Climatology of katabatic winds in the McMurdo Dry Valleys, southern Victoria Land, Antarctica*, **109**, 10.1029/2003JD003937.

Obryk, M.K., Doran, P.T., Fountain, A.G., Myers, M. & McKay, C.P. 2020. Climate From the McMurdo Dry Valleys, Antarctica, 1986–2017: surface air temperature trends and redefined summer season. *Journal of Geophysical Research - Atmospheres*, **125**, 10.1029/2019JD032180.

Riseborough, D.W. 2003. Thawing and freezing indices in the active layer. *In* M. Phillips, S. Springman & L. Arenson, *eds*, *Permafrost*. Lisse: Swets & Zeitlinger, 953–958.

Smith, S.L., O'Neill, H.B., Isaksen, K., Noetzli, J. & Romanovsky, V.E. 2022. The changing thermal state of permafrost. *Nature Reviews Earth & Environment*, **3**, 10.1038/s43017-021-00240-1.

Speirs, J.C., Steinhoff, D.F., McGowan, H.A., Bromwich, D.H. & Monaghan, A.J. 2010. Foehn winds in the McMurdo Dry Valleys, Antarctica: the origin of extreme warming events. *Journal of Climate*, **23**, 10.1175/2010JCLI3382.1.

Vieira, G., Bockheim, J., Guglielmin, M., Balks, M., Abramov, A.A., Boelhouwers, J., *et al.* 2010. Thermal state of permafrost and active-layer monitoring in the Antarctic: advances during the International Polar Year 2007–2009. *Permafrost and Periglacial Processes*, **21**, 10.1002/ppp.685.

Walsh, J.E. & Chapman, W.L. 1998. Arctic cloud-radiation-temperature associations in observational data and atmospheric reanalyses. *Journal of Climate*, **11**, 3030–3045.

Wlostowski, A.N., Gooseff, M.N. & Adams, B.J. 2018. Soil moisture controls the thermal habitat of active layer soils in the McMurdo Dry Valleys, Antarctica. *Journal of Geophysical Research - Biogeosciences*, **123**, 10.1002/2017JG004018.

Yamanouchi, T. 2019. Arctic warming by cloud radiation enhanced by moist air intrusion observed at Ny-Ålesund, Svalbard. *Polar Science*, **21**, 10.1016/j.polar.2018.10.009.