

Episodic basin-scale soil moisture anomalies associated with high relative humidity events in the McMurdo Dry Valleys, Antarctica

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Abstract: Outside of hydrologically wetted active layer soils and humidity-sensitive soil brines, low soil moisture is a limiting factor controlling biogeochemical processes in the McMurdo Dry Valleys. But anecdotal field observations suggest that episodic wetting and darkening of surface soils in the absence of snowmelt occurs during high humidity conditions. Here, I analyse long-term meteorological station data to determine whether soil-darkening episodes are present in the instrumental record and whether they are, in fact, correlated with relative humidity. A strong linear correlation is found between relative humidity and soil reflectance at the Lake Bonney long-term autonomous weather station. Soil reflectance is found to decrease annually by a median of 27.7% in response to high humidity conditions. This magnitude of darkening is consistent with soil moisture rising from typical background values of < 0.5 wt.% to 2–3 wt.%, suggesting that regional atmospheric processes may result in widespread soil moisture generation in otherwise dry surface soils. Temperature and relative humidity conditions under which darkening is observed occur for hundreds of hours per year, but are dominated by episodes occurring between midnight and 07h00 local time, suggesting that wetting events may be common, but are not widely observed during typical diel science operations.

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Introduction

In the McMurdo Dry Valleys (MDV) of Antarctica (~77–78°S, ~160–164°E), the presence of liquid water is considered to be a primary limiting resource in biological and geochemical processes (Campbell & Claridge 1987, Kennedy 1993, McKnight *et al.* 1999, Dickinson & Rosen 2003). Most MDV soils are exceptionally dry in the upper 3 cm, typically < 0.5 wt.% (Campbell *et al.* 1997), outside of hydrologically mediated groundwater-enriched regions such as stream and lake hyporheic zones (McKnight *et al.* 1999, Gooseff *et al.* 2016), water tracks and seeps (Lyons *et al.* 2005, Levy *et al.* 2011, Dickson *et al.* 2013, Gooseff *et al.* 2013), isolated efflorescent salt 'wet patches' (Levy *et al.* 2012, Gough *et al.* 2017, Bisson *et al.* 2018) and persistent snow bank margins where infiltration can occur (Gooseff *et al.* 2003, Fountain *et al.* 2009).

As a consequence of this extreme soil aridity, coupled with low organic matter content (Burkins *et al.* 2000) and abundant felsic fines (Bockheim 2010), MDV soils are commonly quite bright. Visible-wavelength-range soil reflectance is typically ~0.15–0.25 (Levy *et al.* 2014), but varies as a function of soil type and dominant lithology (Campbell & Claridge 1987). Wetted MDV soils darken abruptly as a function of soil moisture, with reflectance decreasing by 50–60% as soil moisture rises

from 0 to 5 wt.% (Levy *et al.* 2014). This produces characteristic spatial albedo patterns in MDV soils that are governed largely by landscape position and hydrological conditions (Lyons *et al.* 2000): locations of channelized or ponded soil moisture are dark, and dry hillslopes and other interfluves are predominantly bright. Even after snowfall events, widespread soil moisture enhancement is both rare and short-lived, as most snow that falls in the MDV sublimates (Fountain *et al.* 2009).

The strong spatial zonation of soil moisture into persistently wet and persistently dry areas has pronounced effects on ecosystem functioning and biogeochemical processes in the MDV. Soil moisture patterning drives soil primary production (Burkins *et al.* 2001), invertebrate (Nkem *et al.* 2005, Poage *et al.* 2008) and microbial (Ball & Levy 2015, George *et al.* 2021) habitat distribution and biologically relevant soil thermal regime (Levy & Schmidt 2016, Wlostowski *et al.* 2018). Soil moisture also controls geological and physical processes such as chemical weathering and solute transport, which in turn have feedbacks on MDV biological functioning and permafrost processes (Campbell & Claridge 1987, Dickinson & Rosen 2003, Gooseff *et al.* 2003, McKay 2009, Hagedorn *et al.* 2010, Levy *et al.* 2013, Toner & Sletten 2013).

Could other, unknown mechanisms also deliver moisture to MDV soils beyond the current understanding of MDV

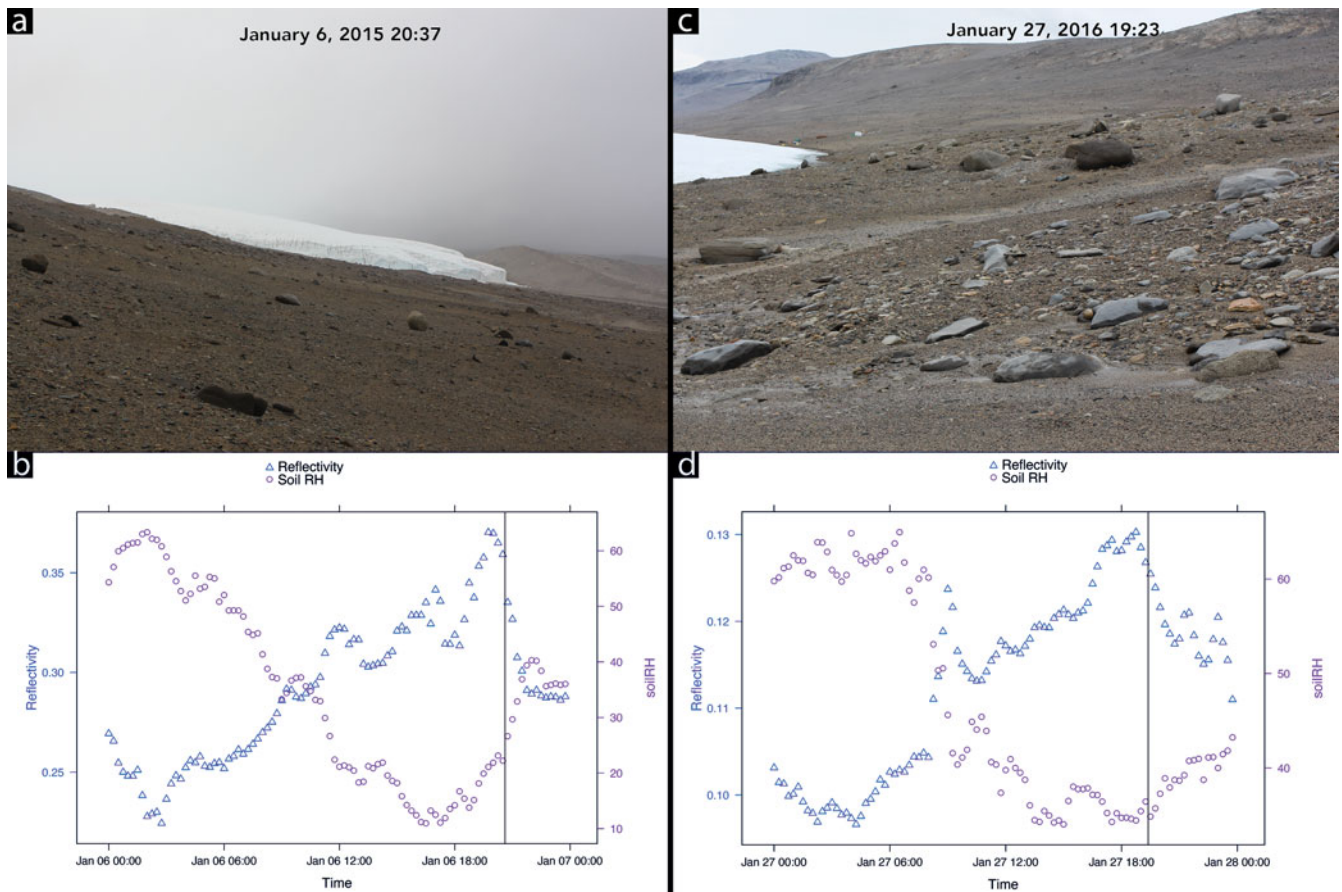


Fig. 1. Field observations of widespread soil wetting in the Lake Bonney basin that occurred in the absence of snowmelt. **a.** Field image looking west at 20h37 on 6 January 2015. **b.** Soil reflectivity (triangles) and soil relative humidity (RH; circles) measurements for 6 January 2015. Time of photograph is marked by the vertical line. Note the abrupt drop in soil reflectivity and the abrupt increase in soil RH. **c.** Field image looking east at 19h23 on 27 January 2016. Note that the soil is not uniformly darkened. **d.** Soil reflectivity and soil RH measurements for 27 January 2016. Time of photograph is marked by the vertical line. Note the abrupt drop in soil reflectivity and the abrupt increase in soil RH. Photograph credit: Joseph Levy.

groundwater budgets and spatial zonation patterns (Gooseff *et al.* 2013)? Field observations of enhanced soil moisture across wide spatial extents in the MDV outside of known soil moisture hotspots (Fig. 1) suggest that this may be the case. Anecdotal field observations consist of photographs and observations of dark, dampened soil across basin-scale spatial extents (e.g. broadly across the eastern Lake Bonney basin; Fig. 1). These dampened soil events are not associated with widespread snowfall or melt, although cloud cover, snow virga and high humidity conditions are associated with the field observations.

In this paper, long-term meteorological records are analysed to determine whether soil darkening reported anecdotally is recorded in the instrument record, whether it is associated with potential atmospheric forcing (relative humidity and/or temperature) and whether changes to soil reflectivity are consistent with the potential formation of widespread surficial soil solutions. Because long-term soil moisture measurements are not available across the

MDV, this study relies on reflectance as a stand-in for soil moisture, owing to the strong reflectance sensitivity to soil moisture for MDV sediments. Results from this investigation can provide a potential framework for determining drivers of soil moisture outside of hydrological focus regions should a network of regional soil moisture sensors be established.

Methods and data processing

Currently released McMurdo Dry Valleys Long Term Ecological Research (MCM-LTER) 15 min meteorological station data for the Lake Bonney station were accessed from <https://mcm.lternet.edu/>. Relevant datasets for this investigation are relative humidity, shortwave radiation, soil temperature, air temperature, snow height and precipitation (Doran & Fountain 2019), collected as part of the LAWN (Long-Term Automatic Weather Station)

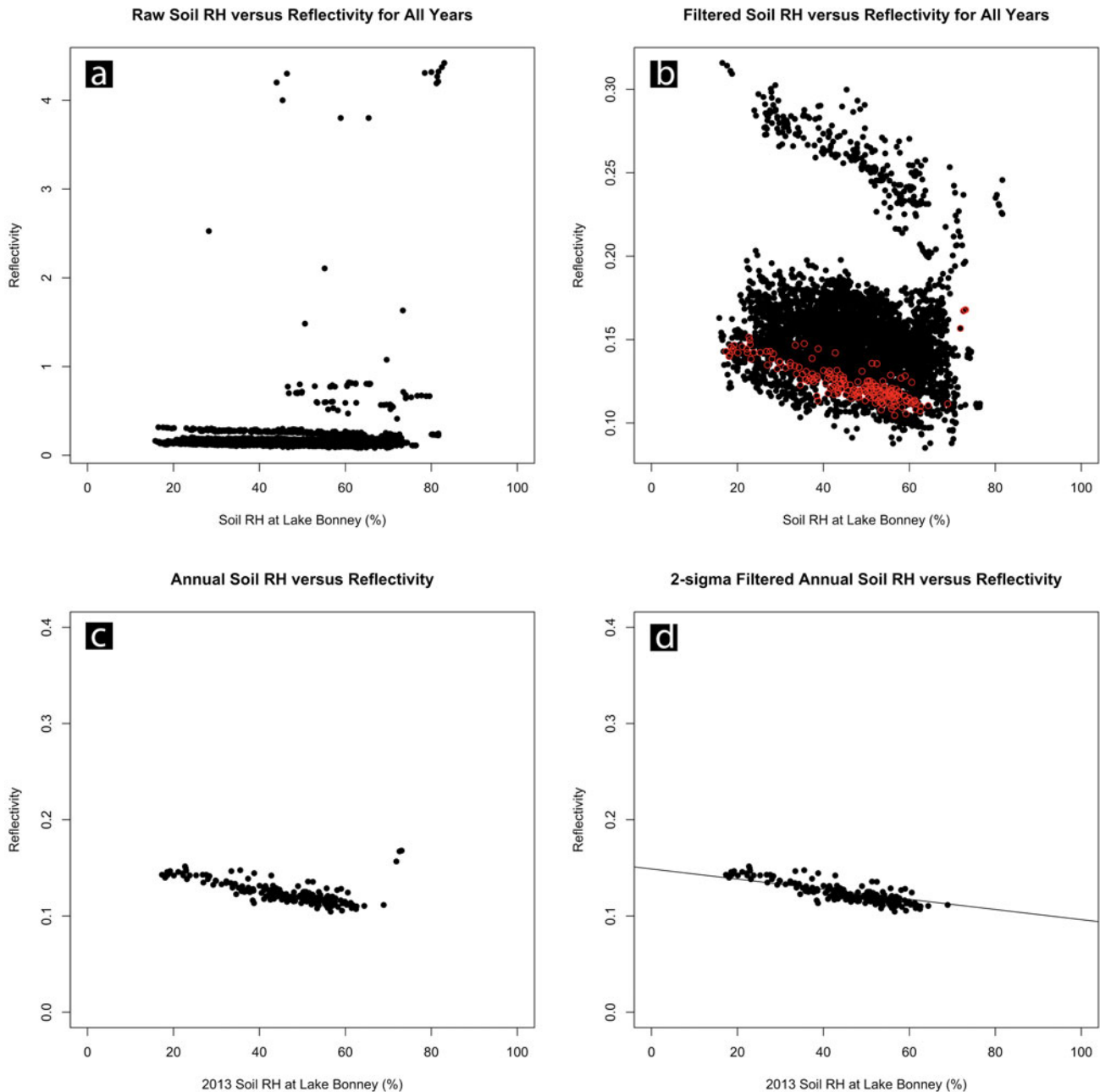


Fig. 2. Example data filtering process. **a.** Scatterplot of reflectivity and soil relative humidity (RH) for all records over all years. **b.** Reflectivity and soil RH data from January for all years after filtering to remove reflectance values exceeding 0.4. Data from January 2013 are shown in red. **c.** Reflectivity and soil RH data from January 2013, to which a linear regression model was fit to remove reflectance values associated with snowfall. **d.** Fully filtered reflectance and soil RH data for January 2013 and the resulting linear model fit to the filtered data. Note the removal of a small number of high-reflectivity points at the highest soil RH values removed by the filter.

network (Doran *et al.* 2002). The Lake Bonney LAWN station sits on sand- and pebble-dominated, gelisol-order soils with a pronounced desert pavement of coarse sands, pebbles and cobbles. Cryoturbation is limited at the site, leading most upper Taylor Valley soils to be classified as

typic anhyorthels (Bockheim *et al.* 2008). Soils at the site are dominantly Taylor-II/Bonney Drift glacial deposits, emplaced ~113–120 ky ago, which consist of poorly sorted sands and gravels, along with glaciofluvial and glaciolacustrine sands, silts, carbonates and organic matter

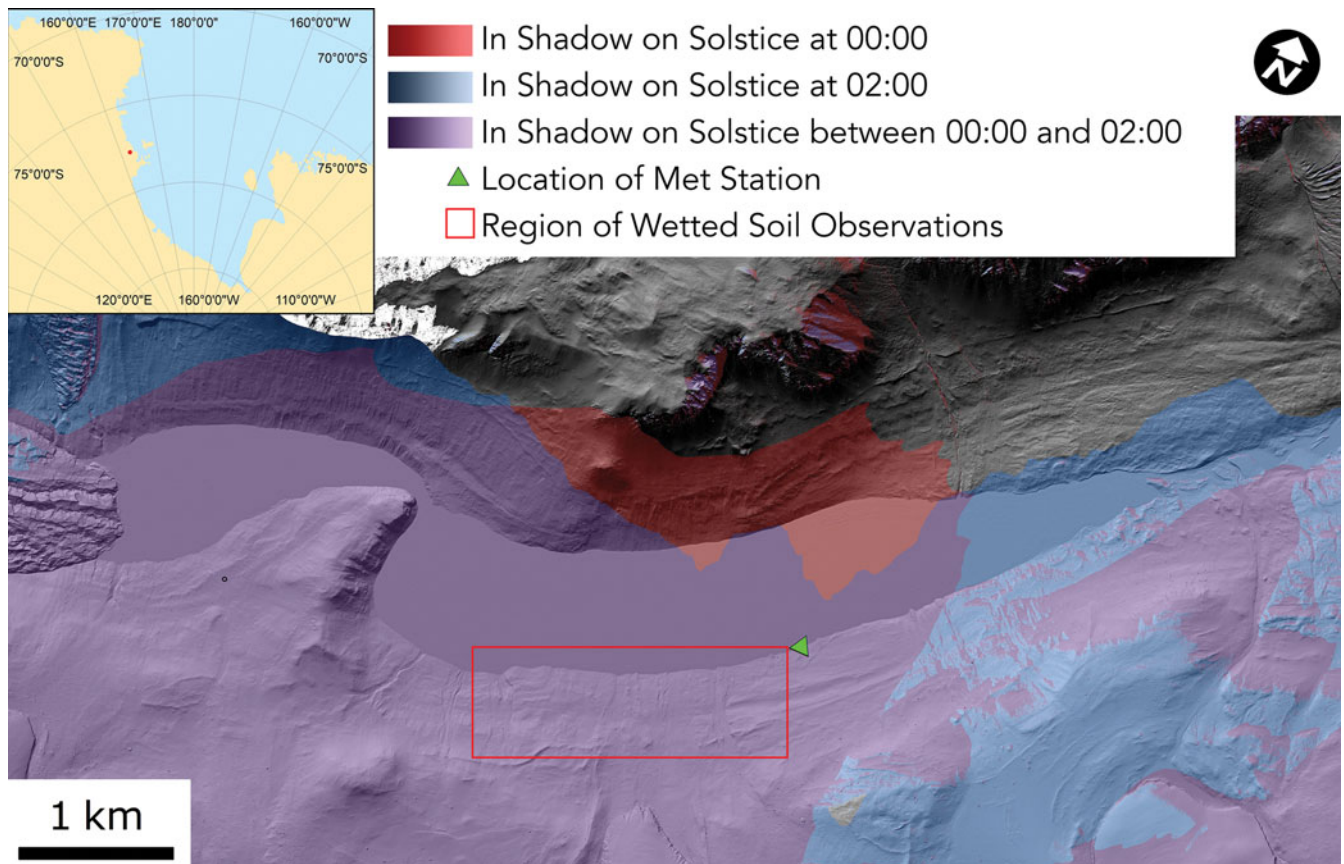


Fig. 3. Field setting for this study, showing Lake Bonney McMurdo Dry Valleys Long Term Ecological Research (MCM-LTER) meteorological station relative to maximum solar elevation (summer solstice) illumination conditions. The meteorological station is in shadow reliably between 00h00 and 02h00 during summer months. Uncoloured, greyscale regions are illuminated during this time range. Inset map shows the location of the field site in the Ross Sea sector of Antarctica (site is marked by a red dot). The base map is LIDAR hillshade from Fountain *et al.* (2017).

in places (Bockheim *et al.* 2008). Salts are common at the site, with visible salt efflorescences in the soil starting at 3 cm depth, and the soils support a column-integrated salt abundance of 1029 mg/cm^2 down to 70 cm depth (Bockheim *et al.* 2008). Ice-cemented soil is common at the site at depths > 45 cm, beneath dry-frozen permafrost, as active layer depths range from 20 to 45 cm (Bockheim *et al.* 2007).

Upwelling and downwelling shortwave radiation (W/m^2) are measured with Licor LI-200R pyranometers. For this project, surface reflectivity is defined as the unitless ratio of upwelling to downwelling radiation:

$$\text{Reflectivity} = \frac{\text{upwelling(reflected)shortwave/}}{\text{downwelling(incident)shortwave}} \quad (1)$$

A typical response curve for these hemispheric shortwave sensors is linearly increasing sensitivity from 400 to 950 nm, followed by a linear decrease in sensitivity to a cut-off at ~ 1100 nm. This produces

maximum errors of $\pm 5\%$ maximum and typical measurement uncertainties of $\pm 3\%$ (Doran & Fountain 2019). The Licor pyranometers are factory-calibrated against Eppley pyranometers and are typically replaced and refurbished every 2 years (Doran & Fountain 2019).

Air and soil temperature are measured using Fenwal Electronics-type UUT51J1 thermistors. Application of the Steinhart-Hart equation (Steinhart & Hart 1968) results in a fit that is $\pm 0.02^\circ\text{C}$ over the -40°C to $+60^\circ\text{C}$ range (Doran & Fountain 2019).

Relative humidity is measured using Vaisala HM70 relative humidity sensors, which replaced Phys-Chem 207 sensors in use in the earliest field seasons. Combined temperature and electrical uncertainty with these sensors results in a relative humidity accuracy of $\sim 5\%$ (at 25°C) over the humidity range of 12–100% (Doran & Fountain 2019).

A series of R scripts were used to process raw .csv-formatted data. All scripts are available for download at https://github.com/jslevy/mdv_albedo. Data processing and extraction are shown schematically in Fig. 2.

Table 1. Summary of reflectivity change as a function of changing soil relative humidity by year.

Year of record	Slope	Intercept	<i>P</i> value	Minimum reflectance	Maximum reflectance	Percentage change	Year
1	-5.12E-04	0.146	2.31E-03	0.085	0.161	47.1	1995
2	-7.29E-04	0.190	1.31E-32	0.139	0.180	22.9	1996
3	-5.73E-04	0.182	8.27E-21	0.134	0.191	29.8	1997
4	-4.30E-04	0.193	3.05E-14	0.151	0.189	20.3	1998
5	-6.25E-04	0.206	6.51E-50	0.155	0.203	23.9	1999
6	-5.76E-04	0.185	2.61E-53	0.144	0.181	20.4	2000
7	-2.52E-04	0.143	7.59E-12	0.113	0.144	21.4	2001
8	-6.65E-04	0.164	1.30E-55	0.106	0.162	34.5	2002
9	-5.16E-04	0.179	6.77E-20	0.136	0.171	20.6	2003
10	-7.24E-04	0.198	2.22E-09	0.141	0.183	23.1	2004
11	-7.54E-04	0.192	6.37E-27	0.138	0.192	28.4	2005
12	-4.45E-04	0.164	1.04E-12	0.122	0.167	27.0	2006
13	-9.77E-04	0.198	2.83E-10	0.125	0.171	26.7	2007
14	-7.38E-04	0.173	2.37E-15	0.121	0.180	32.7	2008
15	-9.30E-04	0.180	5.18E-18	0.126	0.167	24.6	2009
16	-6.19E-04	0.188	3.08E-34	0.139	0.183	24.3	2010
17	-9.12E-04	0.198	1.88E-33	0.131	0.187	29.7	2011
18	-5.33E-04	0.164	1.38E-15	0.105	0.172	39.0	2012
19	-7.89E-04	0.159	1.46E-56	0.105	0.152	31.0	2013
20	-5.81E-04	0.162	3.19E-58	0.111	0.159	29.8	2014
21	-1.57E-03	0.332	7.93E-64	0.199	0.316	36.9	2015
22	-6.36E-04	0.139	3.54E-96	0.096	0.135	29.1	2016
23	-6.80E-04	0.162	1.98E-24	0.103	0.154	33.0	2017
24	-4.73E-04	0.158	5.44E-03	0.138	0.142	2.5	2018
Mean	-6.76E-04	0.181	3.23E-04	0.128	0.177	27.4	-
Median	-6.30E-04	0.180	4.14E-21	0.129	0.172	27.7	-

Because surface albedo can vary as a function of solar zenith angle (Briegleb *et al.* 1986, Yang 2008), data were filtered to only include observations when direct-beam incident radiation is zero (i.e. the station is in shadow). This minimizes the effect where at high solar zenith angle (low sun elevation) albedo appears to rise due to increased scattering from the surface. Considering only diffuse illumination also reduces the impacts from sky anisotropy and sensor anisotropy. In practice, sensor station data were filtered to include only values collected during the month of January (when field observations of widespread soil wetting have occurred; Fig. 1) and between 00h00 and 02h00 local time when the Lake Bonney station is in full shadow (Fig. 3). See the 'Discussion' section for an analysis of the impacts of measuring indirect and reflected light.

Relative humidity data were reprocessed to determine the equivalent relative humidity for air in contact with and in thermal equilibrium with the soil surface, here termed 'soil relative humidity'. Soil relative humidity was calculated by determining total atmospheric vapour pressure measured at 3 m elevation (relative humidity \times saturation vapour pressure for air temperature recorded at 3 m) using the Magnus equation in the Huang (2018) formulation, and then determining the saturation vapour pressure for air in equilibrium with the soil surface temperature. Soil relative humidity is the ratio between the water vapour pressure measured at 3 m elevation and the saturation vapour

pressure of air that has the same temperature as the soil surface:

$$\text{Soil relative humidity} = (p_{\text{vap},3\text{m}})/(p_{\text{vap,sat,ground}}) \quad (2)$$

where $p_{\text{vap},3\text{m}}$ is water vapour pressure measured at 3 m elevation and $p_{\text{vap,sat,ground}}$ is saturation vapour pressure for air at the same temperature as the soil surface.

Data were then further filtered to remove reflectance artefacts and reflectance points that were dominated by the presence of snow. Data points with reflectivity in excess of maximum MDV soil albedo (~ 0.4) were removed. Anomalously high reflectance values could result from snow on the ground, objects in the upwelling radiation sensor field of view, stray light reflected off illuminated snowy surfaces, *etc.*

In order to account for changes in apparent reflectivity owing to year-to-year changes in measurement parameters (e.g. the level or geometry of the upwelling sensor, soil roughness in the upwelling sensor field of view, changes to sensor position over time, changes to the distribution of objects in the hemispheric field of view, *etc.*), the full record was subdivided by year (Fig. 2). Observations recorded when snow was on the ground in the reflected radiation sensor footprint typically show a small number of comparatively high reflectivity value outliers associated with very high relative humidity conditions (in excess of $\sim 70\%$ relative humidity). To remove these snow-

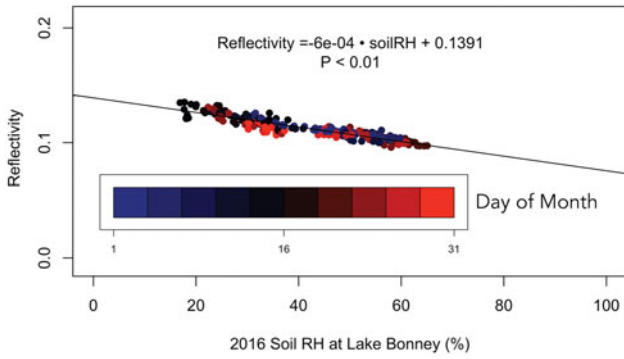


Fig. 4. Reflectivity vs soil relative humidity (RH) for January 2016. Data points are coloured by day of the month. The highest reflectivity values occur mid-month, and no clear reflectivity progression exists through time that could indicate confounding effects from solar elevation change over the course of the month. Comparable figures for all years can be found in the Supplemental Material.

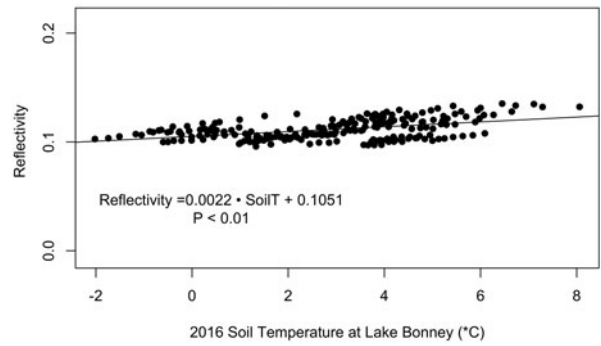


Fig. 5. Reflectivity vs soil temperature for January 2016. Linear point clusters show cooling trends on single-day timescales.

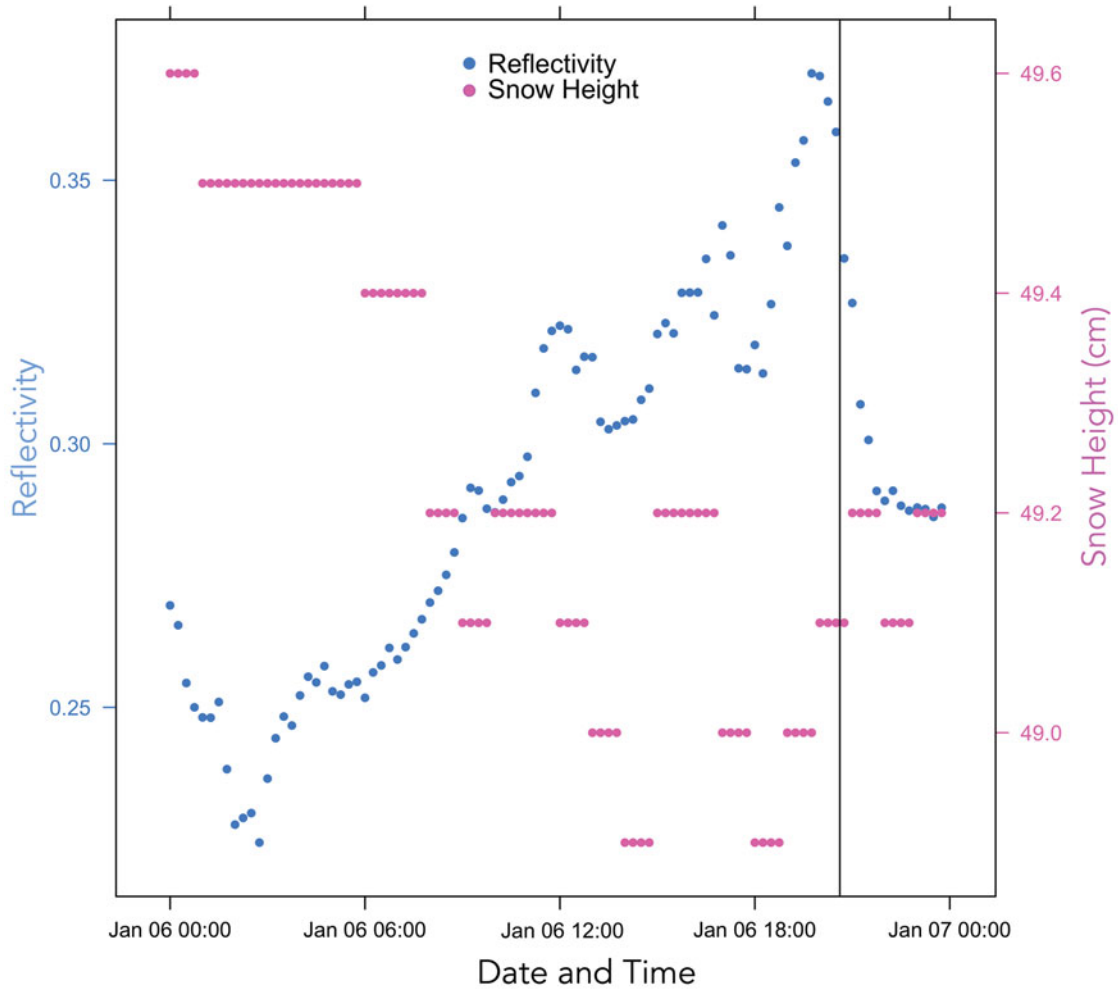


Fig. 6. Soil reflectivity and ultrasonic ranging-derived snow height for 6 January 2015 (see Fig. 2). Time of the photograph in Fig. 2 (when snow on the ground is absent) is marked by the vertical line. Reflectivity changes appear largely anti-correlated with apparent snow height, but snow height variability is below the measurement precision of ± 5 cm. No snow was present on the ground at the meteorological station during this interval.

influenced observations, a linear model testing for correlation between soil relative humidity and reflectance in each year was fit to the data and a filter was applied that rejected observations for which measured reflectance was more than two standard deviations above the linear model's predicted reflectance. In practice, this removes a small number of high-reflectivity outliers associated with the highest relative humidity measurements that are interpreted as snow-related observations.

Annual data that had been filtered for snow-related observations were used for subsequent analysis steps. A linear model testing for correlation between soil relative humidity and reflectance was fit to the filtered data. The slopes, intercepts and *P* values of the linear models are reported for each measurement year in Table I. A linear model testing for correlation between soil temperature and reflectance was also fit to each year's observations.

Results

Reflectivity at the Lake Bonney study site varies linearly with soil relative humidity (Fig. 4). The median highest reflectivity over all years is 0.172 and the median reflectivity minimum is 0.127, a 27.7% difference between maximum and minimum observed reflectivity. Raw measured relative humidity at 3 m spans ~20–80%, while soil relative humidity spans ~20–60% owing to soil temperatures commonly exceeding air temperatures during shadowed, night-time conditions, reducing the soil relative humidity by increasing the soil saturation vapour pressure.

Reflectivity is inversely correlated with soil relative humidity in all sampling years (Table I). A linear fit to soil relative humidity and reflectance datasets gives a median decrease of 6.3×10^{-4} in reflectivity per 1% increase in relative humidity, with a median intercept reflectance value of 0.18 at 0% relative humidity. Linear models are strongly statistically significant, with median *P* values much less than 0.001. Reflectivity shows no pattern with day of month, a proxy for solar elevation (Fig. 4). High and low reflectivity values are determined over the full course of the month, with no clustering of values by day.

A slight positive correlation exists between soil temperature and reflectivity over the sampling years, with comparably low *P* values relative to the relative humidity linear models (Fig. 5). The range of soil temperatures over which reflectivity varies with soil relative humidity is ~-4 to +8°C.

When snow height measured using sonic ranging is compared to reflectivity on days of interest determined by field observations of widespread soil darkening, no clear relationship exists that exceeds the ± 5 cm uncertainty threshold of the snow height sonic ranger observations (Fig. 6). Below the uncertainty threshold,

snow height measurements on 6 January 2015 are anti-correlated with surface reflectivity.

Discussion

The strong linear relationship between soil relative humidity and decreased soil reflectivity may be an indication of soil darkening due to increases in soil moisture content. If so, these observations suggest that widespread soil wetting may occur under high relative humidity in some regions of the MDV. Such a process could function as a basin-scale moisture source that could affect biogeochemical processes in these cold desert soils. The growth of humidity-controlled soil porewater solutions over hourly timescales has been observed in highly saline water tracks (Dickson *et al.* 2013), around the periphery of highly saline ponds (Gough *et al.* 2017) and in isolated saline soil patches (Levy *et al.* 2012), as soil salts deliquesce and vapour enters deliquescent brines, increasing the size of the brine droplets. However, the instrumental observations reported here are the first that suggest that anomalous episodes of high soil moisture content (sufficient to cause observable surface darkening) may occur away from hypersaline microenvironments in more typical MDV soils.

Instrumental considerations and error sources

Is it possible that the observed reflectivity changes are a result of a process other than soil moisture development? Critically, the reflectance signal does not appear to be a change associated with changing sky albedo. Field observations suggest that it is commonly overcast and cloudy when MDV relative humidity is high and apparent soil wetting occurs. 'White sky' ground albedo under cloudy or overcast conditions is higher for most surfaces than 'blue/black sky' albedo under clear skies, (e.g. Marion 2021). A sky albedo change in the record would tend to increase apparent reflectivity under overcast conditions rather than decrease it as observed here.

Another potential confounding factor that could drive reflectivity observations could be changes to sensor positioning or height or objects in the hemispheric field of view. For example, reflectivity is notably higher in 2015 than in any other year (see Fig. 2b, as well as Supplemental Material). In this year, reported outgoing (reflected) shortwave radiation values are commonly approximately two times greater than measured values in other years in the record (> 200 vs ~ 100 W/m²). Likewise, some years (e.g. 2017 or 2012) show a bifurcated reflectance record, with two linear trends of decreasing reflectivity with increasing soil relative humidity. These bifurcated records commonly show clustering in time (e.g. early or late in the month of

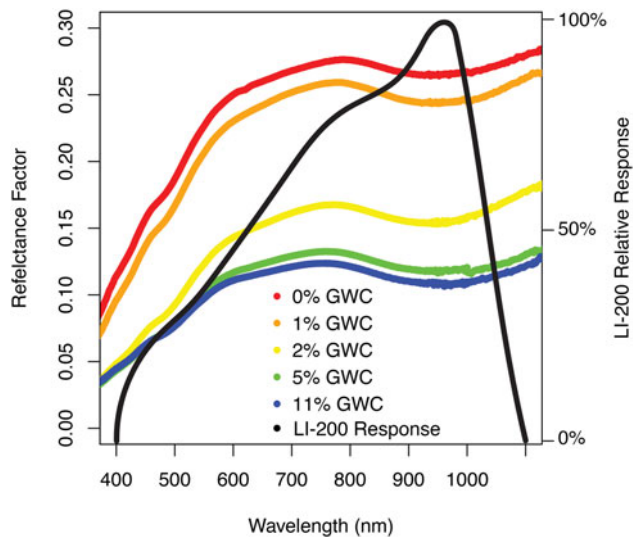


Fig. 7. Reflectance factor for dry and wetted McMurdo Dry Valleys soils over a soil moisture range from 0 to 11 wt.%, determined *via* gravimetric water content (GWC) determination reported by Levy *et al.* (2014), compared to the LI-200 relative response.

January), suggesting that changes to the sensor field of view may change calculated reflectivity by a few percent. Importantly, however, in all of these cases, decreasing soil reflectivity is observed in all years in association with increasing relative humidity, regardless of the absolute reflectance value. This suggests that the reflectance change observed here is largely insensitive to absolute calibration of the sensor or changes to the sensor footprint (e.g. roughening during station servicing).

The strong linear relationship between soil relative humidity and reflectivity is notable because it is measured by ratioing downwelling solar irradiance with reflected irradiance. The LI-200R probe carries a manufacturer's warning that the measured irradiance (W/m^2) may not be accurate if the sensor is used to measure obstructed light, light under cloud cover, artificial light, light filtered through glass or reflected light (<https://www.licor.com/documents/d3ckr4kis42388to96i96e0ukwru0p69>).

The accuracy change may occur under reflected light conditions due to the difference between the incident solar spectrum and the reflected light ground spectrum. A photodiode on the LI-200 converts irradiance to electrical current, which is then converted to voltage that is measured by the Campbell Scientific data logger. The LI-200 is calibrated against the surface solar spectrum such that the summed photodiode spectral sensitivity times the incident solar spectral irradiance across the ~ 400 – 1100 nm range of the sensor is proportional to the integrated total solar radiance reaching the ground. The photodiode has non-uniform sensitivity and is more sensitive to longer wavelengths in the visible to

near-infrared range, reaching a peak sensitivity between 900 and 1000 nm (Fig. 7). Because the constant of proportionality between current and irradiance is set during calibration and because the photodiode has variable spectral sensitivity but no spectral resolution, light entering the sensor will produce a larger change in apparent (measured) irradiance when that light has a wavelength in the range that the photodiode is more sensitive to and will produce a smaller change when the light has a wavelength in the low-sensitivity range.

The change in reflectance in MDV soils in response to wetting is non-uniform as well. When water is added to MDV soils, the largest reduction in reflectance occurs at the 1.4 and 1.9 μm water absorption features, although broad darkening occurs across the near-infrared and into the visible (Fig. 7) (Levy *et al.* 2014). Within the spectral range of the LI-200 sensor, the soil reflectivity reduction due to wetting is small in the low-sensitivity range of the photodiode (e.g. 400–500 nm) and is larger in the high-sensitivity range (600–1000 nm). This means that the largest changes to the measured irradiance from the soils occur where the LI-200 sensor is most sensitive to change and also where the soil reflectivity change is large. This means that the soil irradiance change from wetting is very measurable using an LI-200 (high sensitivity \times large signal). However, the output current from the photodiode calibrated using the solar spectrum may be larger in terms of absolute irradiance (W/m^2) than the integrated spectral irradiance ($\text{W}/\text{m}^2/\text{nm}$) would be if the reflectivity change were measured with an instrument with a uniform spectral response and greater spectral resolution. The enhanced sensitivity of the LI-200 in a spectral range where the reflectance change is large has the potential to increase the apparent darkening of the soil during episodes of dampness.

This enhanced reduction in reflected irradiance from the soil may be partially offset in the reflectivity calculations presented above by reductions in the downwelling irradiance measured during diffuse light conditions. Water vapour in the atmosphere absorbs some power in the 700–1100 nm range. The spectral distribution of solar radiation power is markedly different on cloudy and clear days, as clouds absorb solar radiation in the near-infrared (Gates 1965). However, the spectral distribution of solar radiation can also show reductions in near-infrared irradiance at low sun angles when atmospheric scattering results in more opportunities for water vapour absorption. Because the incident radiation in the reflectivity calculations (Eq. (1)) is entirely diffuse radiation, some reduction in the incoming solar irradiance is expected at the 700–1100 nm range. This is where the LI-200 is most sensitive and also where darkening in soils occurs during wetting. The consistent and linear reduction in reflectivity as a function of soil relative humidity indicates that the reflectivity drop in

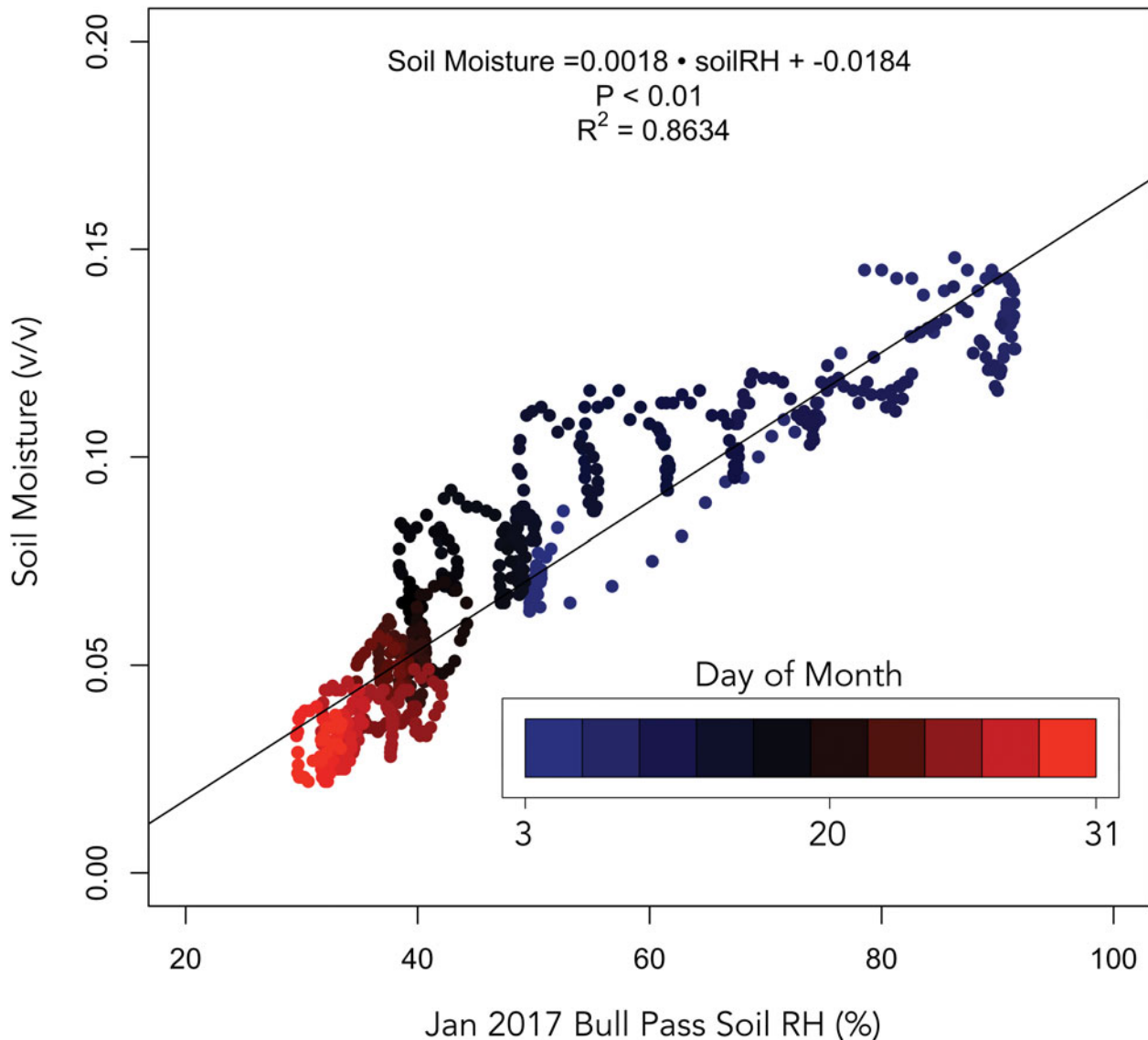


Fig. 8. Measured soil moisture (volume percent, or m^3 water per m^3 soil) vs soil relative humidity (RH) measured at the Bull Pass US Department of Agriculture Soil Climate Research Station. Soil moisture content and soil RH are strongly correlated during January 2017.

the soils at high relative humidity is greater than the irradiance drop from atmospheric absorption during diffusive lighting conditions.

Taken together, these changes to incident and reflected light at the site suggest that reflectivity change is occurring in the soils as a function of soil relative humidity, but that the absolute irradiance change may be different from the value determined by the factory calibration that assumes a solar spectrum distribution of spectral irradiance. Because the sensitivity of the LI-200 is high in the spectral region where albedo change in wetted soils is most pronounced, the reported upwelling irradiance change at high relative humidity should be considered a maximum change. The actual reflected power flux may be lower, but it still sets useful upper

bounds on the reflectivity change at the site. This type of semi-quantitative use of LI-200 sensors to measure reflected irradiance is a common application when weight, power or sensor distribution are limited (e.g. Canisius *et al.* 2019).

Soil hydrological implications

If soil reflectivity is changing as a consequence of rising soil moisture, what processes could cause this change? Soils could grow darker as soil moisture rises as a consequence of several mechanisms, including distributed soil salt deliquescence (Gough *et al.* 2017), capillary condensation in fine-grained soils or salts (Wierzchos *et al.* 2012) or growth of unfrozen water droplets bound

to soil matrix grains. It is notable that soil relative humidity and reflectivity follow a strong linear correlation; in none of the records is a steep reflectivity drop-off observed that might indicate abrupt phase change or deliquescence at a threshold relative humidity value. Gradual albedo change in response to changing relative humidity may be more consistent with the growth and interconnection of existing soil porewater droplets, which could form in response to deliquescence of soil salts (Gough *et al.* 2017) or could persist as either seasonally unfrozen matrix-bound water or capillary condensation deposits in fine-grained soil particles. Merging of these droplets into thin films sufficient to darken the soils could be an incremental process, resulting in the linear decrease in reflectivity. Continuous wetting is observed in MDV soils exposed to high-humidity conditions (e.g. Levy *et al.* 2015), growing increasingly voluminous soil solutions at decreasing exponential rates, even after initial brine droplet formation has ceased.

A model in which high relative humidity causes the growth of pre-existing water droplets is consistent with the observed spatial pattern of soil darkening during high-humidity events (e.g. Fig. 1). Darkening of the soil is widespread over the whole Lake Bonney basin hillslope during the observed events; however, some soil regions remain light-toned - notably, the coarse-grained wind tails adjacent to cobbles and boulders. If the coarsest-grained sediments at the site remain undarkened, this suggests that any water or brine droplets in these soils had not grown large enough during the imaged albedo change event to coat the grains or to fully link between sand and granule grain boundaries, resulting in no change to the reflectance properties of the coarsest soils in the scene.

This interpretation is consistent with direct soil moisture and soil relative humidity measurements collected at other MDV long-term meteorological stations, such as the US Department of Agriculture (USDA) Soil Climate Research Stations (Seybold *et al.* 2009). At the Bull Pass USDA station, January soil relative humidity is strongly correlated with soil moisture content (Fig. 8). This station directly measures these two values at 2 cm depth, along with downwelling shortwave radiation, but does not measure upwelling (reflected) shortwave radiation, so the data cannot be filtered for high-albedo snow events as the MCM-LTER station data can be. In addition, the USDA stations log hourly *vs* at 15 min increments, reducing our ability to assess whether soil relative humidity leads or responds to soil moisture change at this station.

Importantly, snowfall and snowmelt are not implicated in the observed darkening events. During days of interest, no snowfall is measured that exceeds the ± 5 cm uncertainty of the sonic ranging instrument on the meteorological station (Fig. 6). The apparent change in snow height shown in Fig. 6 is below this uncertainty.

Furthermore, apparent snow accumulation in the sonic ranger record (Fig. 6) is inconsistent with the measured reflectivity of the surface - reflectance decreases when the snow appears to be accumulating, which is inconsistent with the high albedo of fresh snow. A more probable explanation is that relative humidity is incompletely accounted for in the sonic ranger calibration and that increasing relative humidity and decreasing air density are providing an erroneous surface elevation change signal.

If albedo change at the Lake Bonney weather station results from the formation of soil porewater solutions, how much soil moisture might be involved? Time-resolving surface soil moisture measurements that could evaluate this albedo-based inference are rare in the MDV; however, field plans for 2022–2023 include the installation of soil moisture sensors at some MCM-LTER long-term weather stations (R.F. Brown & P. Doran, personal communication 2021). Such sensors could directly test the prediction that soil moisture anomalies develop in MDV soils during episodes of high relative humidity. This is especially true if soil moisture sensors include soil electrical conductivity measurements, which could be used to detect the growth of intergranular brine solutions at small spatial scales that might challenge soil moisture detection *via* time domain reflectometry (Wierchos *et al.* 2012).

Existing hyperspectral reflectance measurements of MDV soils provide one possible constraint on the magnitude of soil moisture growth that could be associated with these albedo reduction events. Taking into account the broad-band visible reflectance factors (equivalent to spectral reflectance or reflectivity per nanometre) that were determined for wetted and dried MDV soils under laboratory conditions (Levy *et al.* 2014), the $\sim 28\%$ reduction in reflectance observed in this study suggests that soils could be transitioning from dry conditions (reflectance of ~ 0.18 at < 0.5 wt.% water content) to surficial soil moisture contents of 2–3 wt.%. While this soil moisture content is small by the standards of saturated and unsaturated groundwater systems in the MDV (Cartwright & Harris 1982, Gooseff *et al.* 2003, 2013, Harris *et al.* 2007, Levy *et al.* 2011, 2013), it is considerably greater than the < 0.5 wt.% soil moisture common to MDV soils that dominate interfluvial areas in the MDV (Campbell *et al.* 1997). As noted in the previous subsection, this estimated soil moisture value should be considered a maximum.

Seasonal implications

How might soil porewater conditions change over the course of the summer and how might that impact the detectability of these pore solutions? It is notable that the soil relative humidity linear model reproduces background reflectivity (~ 0.18) as soil relative humidity approaches zero. In contrast, the linear model relating reflectivity to soil temperature does not have background

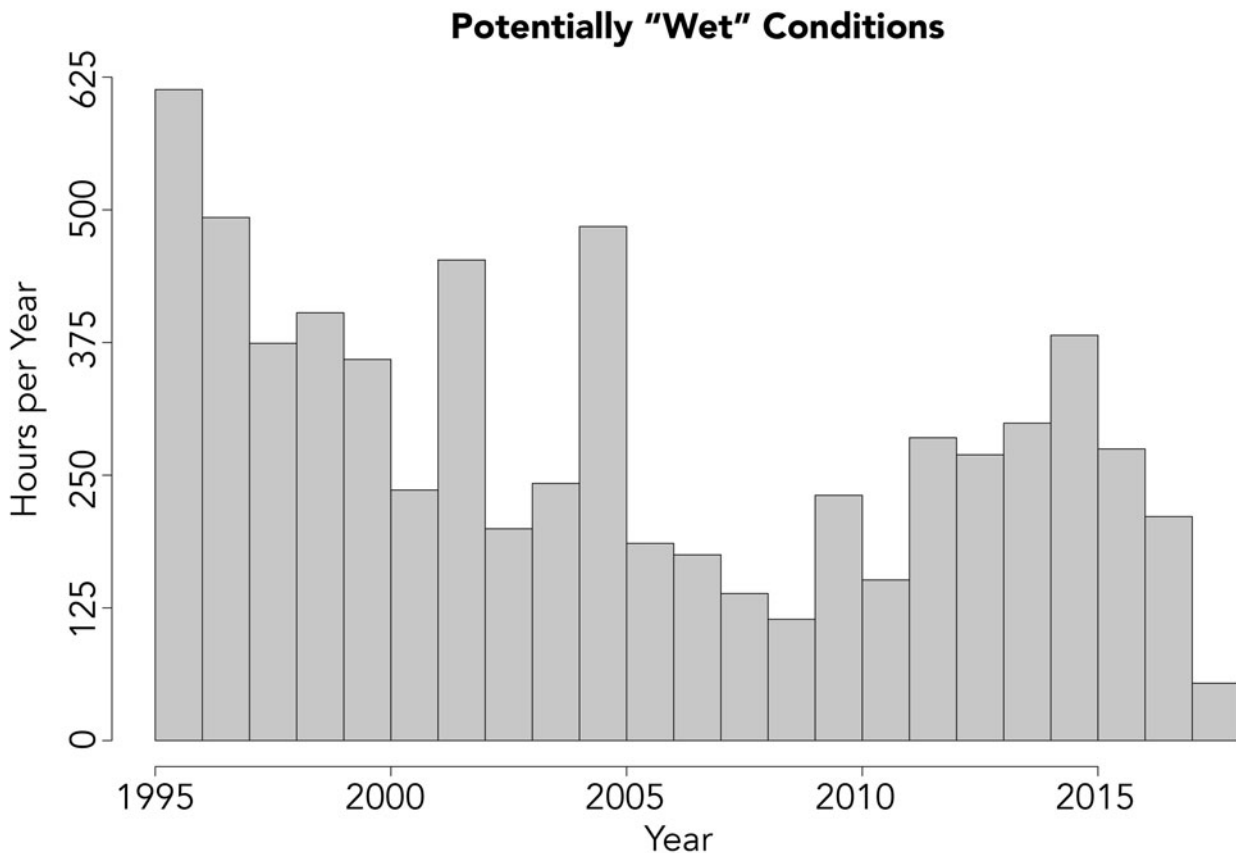


Fig. 9. Hours per year when potentially dampened/darkened soil conditions could occur based on Lake Bonney meteorological station 15 min readings filtered to include only those measurements for which temperature is between -4°C and $+8^{\circ}\text{C}$ and for which soil relative humidity is $> 50\%$.

reflectivity as its y -axis intercept- instead, it produces a median reflectance intercept of ~ 0.11 at the coldest measured soil temperatures. This makes intuitive sense because of the absence of possible mechanisms that could cause temperature change in soils to impact their reflectivity (with the possible exception of frost formation, which would both be recorded in the relative humidity data and would push reflectivity values higher at low soil temperatures, not lower as is observed). However, soil temperature analysis does provide a useful range of measured temperatures over which humidity-correlated albedo change occurs: -4°C to $+8^{\circ}\text{C}$.

Taking -4°C to $+8^{\circ}\text{C}$ as the temperature range over which albedo change occurs, the meteorological station data can be re-filtered to determine when and for how long soils might be in their low-reflectivity, presumed dampened state. Soil relative humidity is $> 50\%$ and soil temperature is between -4°C and $+8^{\circ}\text{C}$ during 61% of January night-time measurement records. Across the full year of meteorological station observations, these temperature and relative humidity conditions persist in $\sim 6\%$ of all snow-free observations. Over the course of a year,

potentially dampened conditions may be temporally extensive, summing to weeks per year of anomalously high soil moisture contents (Fig. 9).

Are there other possible sources of water vapour that could be contributing to soil dampening and darkening? Water vapour fluxes are generally upwards in the MDV during summer, from subsurface permafrost and ground ice to the atmosphere, as buried ice warms and vapour pressure above the ground ice grows (Hagedorn *et al.* 2007), except for when snowfall reverses the vapour gradient (McKay 2009, Kowalewski *et al.* 2011). It is possible, then, that vapour flux from ice-cemented permafrost or from buried ground ice is contributing moisture to surface soils and altering their reflectivity. However, two lines of evidence argue against this being a dominant factor: 1) the rapidity with which reflectivity changes in response to relative humidity change (e.g. Fig. 1) suggests that atmospheric forcing rather than diffusive processes from beneath the soil surface is controlling the timing of reflectivity change, and 2) dry-frozen permafrost is present in the upper 70 cm of the soil column in the Lake Bonney basin, suggesting

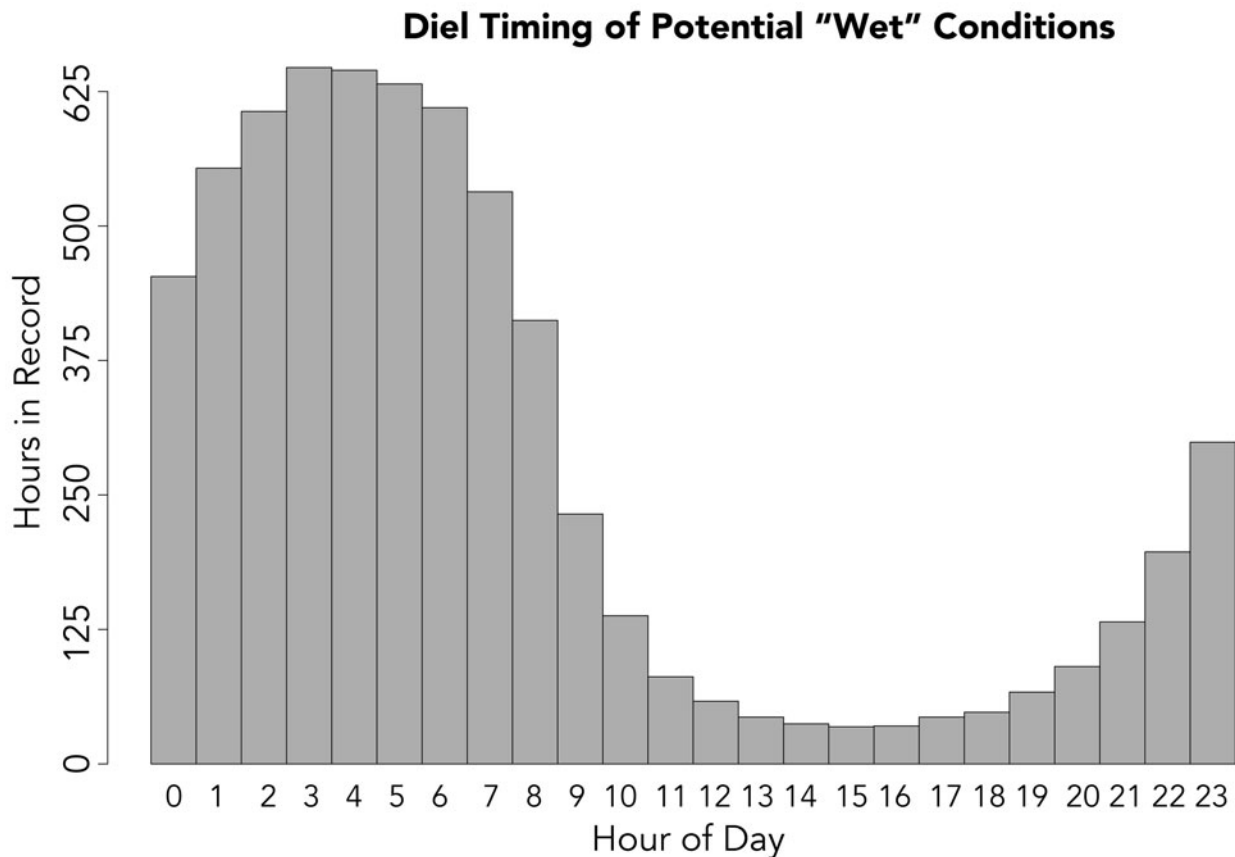


Fig. 10. Hours during the whole Lake Bonney instrumented record when potentially dampened/darkened soil conditions could occur based on Lake Bonney meteorological station 15 min readings filtered to include only those measurements for which temperature is between -4°C and $+8^{\circ}\text{C}$ and for which soil relative humidity is $> 50\%$. Data are binned by the hour of the day during which potential wetting and darkening could occur.

that most water has already been removed from near-surface soils at the sites were reflectivity anomalies are observed (Bockheim *et al.* 2008).

Periods of atmospherically controlled soil moisture anomalies in the MDV could have regional consequences on biogeochemical processes operating in this cold desert ecosystem. Enhanced soil moisture conditions could enhance moisture availability to both microorganisms and soil invertebrates, expanding the duration of the summer during which both primary production and respiration could occur (Poage *et al.* 2008). Soil wetting, particularly during shadowed night-time periods, could help make sense of anomalous night-time CO_2 fluxes (Ball *et al.* 2009), as wet soils have small but positive CO_2 fluxes that could be enhanced by soil dampening (Ball & Virginia 2015). Dampened soils could also alter the thermal state of MDV soils, increasing thermal diffusivity (Levy & Schmidt 2016) or altering habitat suitability and organismal thermal stress (Wlostowski *et al.* 2018). Episodic soil wetting at the basin scale as shown in Fig. 1 and implied by the meteorological station data could provide intragranular thin films of water that could drive salt migration on MDV

slopes (Wilson 1964, Dickinson & Rosen 2003), advecting solutes or driving grain-surface geochemical reactions such as ion exchange (Toner & Sletten 2013). Finally, episodic soil wetting could enhance clay swelling and/or freeze-thaw cycling that could promote soil cryoturbation and enhance the formation of inflated desert pavements in otherwise highly arid soils (Bockheim 2010).

Given the potential for widespread soil moisture anomalies in the MDV triggered by high-humidity episodes to produce regional enhancement in soil moisture and the extreme water limitation known to limit biogeochemical processes, why might this process not have been widely described before now? One factor is that remote sensing observations of the MDV that could detect spatially widespread reflectivity reductions are limited to low-cloudiness to cloud-free observing conditions. If reflectivity reduction events are associated with high relative humidity and cloudy or overcast conditions, it is probable that they could not be observed by orbital sensors. A second factor could relate to the timing of the reflectivity anomalies. The meteorological conditions described above (soil relative humidity $> 50\%$

and soil temperature between -4°C and $+8^{\circ}\text{C}$) associated with dampened soils occur overwhelmingly during late night and early morning time periods when soil surfaces are shadowed and soil relative humidity rises (Fig. 10). These are the times when most MDV field teams have returned to stations or camps and are not typically conducting sampling or observations. Taken together, this suggests that MDV soil processes may be occurring on episodic or diel timescales during which observation and sampling either cannot occur (due to cloud cover) or are not occurring (due to human factors). This constitutes a notable observational gap and strongly motivates regional, autonomous ground-based or aerial monitoring of soil moisture conditions.

Conclusions

Multi-year measurements made under conditions of diffuse illumination during night-time shadowing at Lake Bonney show a linear decrease in soil reflectivity that is strongly correlated with increased relative humidity. If this reflectivity signal results from the wetting of soils or growth of soil porewater solutions that are driven by atmospheric fluxes of water vapour into the soil surface, it could represent a hitherto undescribed source of regional soil moisture at the basin scale. Median reflectivity change (27.7% decrease) is consistent with darkening due to the wetting of soils from the MDV background value of < 0.5 wt.% to a maximum of 2–3 wt.%. Reflectivity change is observed during mid-summer (January) and is independent of solar elevation or zenith angle. Rapid reflectivity change occurs over quarter-hours to hours and is associated with increasing soil relative humidity. High-humidity, warm (-4°C to $+8^{\circ}\text{C}$) conditions associated with reflectivity reductions are common during the summer (61% of records between 00h00 and 02h00 during January), but they also occur throughout the summer, providing hundreds of hours of potentially dampened conditions. These conditions occur mostly between 00h00 and 07h00 and commonly under cloudy conditions, which may have limited their detection or description in the past.

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Author contributions

JL conceived of the project, conducted the data analysis and is responsible for writing of the manuscript.

Supplemental material

Twenty-three supplemental figures will be found at <https://doi.org/10.1017/S0954102021000341>.

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