Weather whiplash in a terrestrial polar ecosystem following the March 2022 Antarctic weather anomaly

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Author contributions: J.E.B., B.J.A., P.T.D., M.R.S., and M.N.G designed the research; J.E.B., B.J.A., P.T.D., M.R.S. M.D.S., K.F.M., S.N.P., A.W., and M.N.G performed the research and analyzed data; J.E.B., B.J.A., P.T.D., H.A.D., K.F.M., M.R.S., and M.N.G wrote the paper.

Key Points:

- An atmospheric river caused extreme weather in the Antarctic Dry Valleys in March 2022 with temperatures 25°C above average conditions.
- Record fall temperatures drove mobilization of liquid water and reactivated biota at a time when organisms are entering winter dormancy.
- Biotic responses to unseasonable warm and wet conditions may influence diversity and life-history characteristics of biotic communities.

Keywords: Atmospheric river, climate variability, polar desert, polar desert, weather whiplash

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Abstract

Record high temperatures were documented in the McMurdo Dry Valleys, Antarctica, on March 18, 2022, exceeding average temperatures for that day by nearly 30°C. Satellite imagery and stream gage measurements indicate that surface wetting coincided with this warming more than two months after peak summer thaw and likely exceeded thresholds for rehydration and activation of resident organisms that typically survive the cold and dry conditions of the polar fall in a freeze-dried state. Such events may be a harbinger of future climate conditions characterized by warmer temperatures and greater thaw in this region of Antarctica, which could influence the distribution, activity, and abundance of sentinel taxa. Here we describe the ecological responses to this weather anomaly reporting on meteorological and hydrological measurements across the region and on biological observations from Canada Stream, one of the most diverse and productive ecosystems within the McMurdo Dry Valleys.

Plain Language Summary

An atmospheric river event in March 2022 led to record warm temperatures over much of Antarctica. Here we report the ecological and hydrological responses to these extraordinary temperatures. The McMurdo Dry Valleys are unique among other regions of Antarctica that experienced this extreme weather event because contemporary observations of ecosystem responses to unseasonable weather can be anchored to a 30-yr record of meteorology, stream flow, and soil community data supported by the National Science Foundation Long Term Ecological Research program. As such weather anomalies are expected to be more common in future Antarctic climate regimes our insights are broadly relevant to the scientific community seeking to predict future ecosystem and organismal responses to ongoing climate change.

1 Introduction

Climate change is contributing to greater frequency of extreme weather (Casson et al. 2019, IPCC 2022,), and Polar Amplification predicts that such events will be especially evident in the Arctic and Antarctic (Biskaborn et al. 2019). Polar regions experienced record heat waves in March 2022; in the Arctic, temperatures reached 30ºC above average and sea-ice extent was the lowest on record for this typically cold month (Vargin et al. 2022, Patel 2022). In the Antarctic, record temperatures were documented by multiple research stations on the polar plateau in continental East Antarctica; most notably, Vostok and Concordia stations recorded high temperatures more than 40ºC above average conditions on March 18, 2022 (Patel 2022). This weather anomaly was driven by an intense atmospheric river advecting subtropical heat and moisture deep into the Antarctic interior (Wille et al. in press).

Record high temperatures were also documented in the McMurdo Dry Valleys of Antarctica in the third week of March 2022 (Fig. 1). Unlike stations on the polar plateau, this region is a landscape mosaic of glaciers, arid soils, streams, and perennial ice-covered lakes, and is the focus of a U. S. National Science Foundation-supported Long Term Ecological Research (LTER) project that has monitored meteorology, hydrology, and the resident organisms and ecosystems for over 30 years (Gooseff et al. 2017). The extreme climate of terrestrial Antarctica limits biodiversity in this region to microbes, including cyanobacterial mats, and a few taxa of invertebrates such as rotifers, tardigrades, and nematodes that survive in a freeze-dried state during the cold and dry conditions that characterize this region (McKnight et al. 2007, Lee et al. 2019). The McMurdo Dry Valleys can thus uniquely illustrate the hydrological and ecological responses to this extreme weather event of March 2022.

Weather whiplash describes rapid shifts between contrasting weather conditions, such as the occurrence of unseasonable warm events in winter before a return to more typical cold temperatures, or similar variation during seasonal transitions in spring and fall (Loeke et al. 2017). Unseasonable weather events can challenge biota, especially plants and invertebrates, because of the physiological stress experienced by poikilothermic organisms during freeze-thaw cycles (Knox et al. 2017, Switanek et al. 2017). In this report we describe the ecological significance of the March 18, 2022 Antarctic weather anomaly, focusing on the Canada Stream Antarctic Specially Protected Area #131 (ASPA) in Taylor Valley, an area of active hydrology (McKnight et al. 1997) and regionally high floral and faunal diversity (Schwarz et al. 1992 & 1993). Here, the responses of microbial mats and soil invertebrates exemplify the potential influence of extreme weather on sentinel taxa for this region. We hypothesize that weather whiplash events will have significant effects on activity, life history, and diversity of resident biota because of the physiological stress associated with freeze-thaw, particularly during critical seasonal transitions.

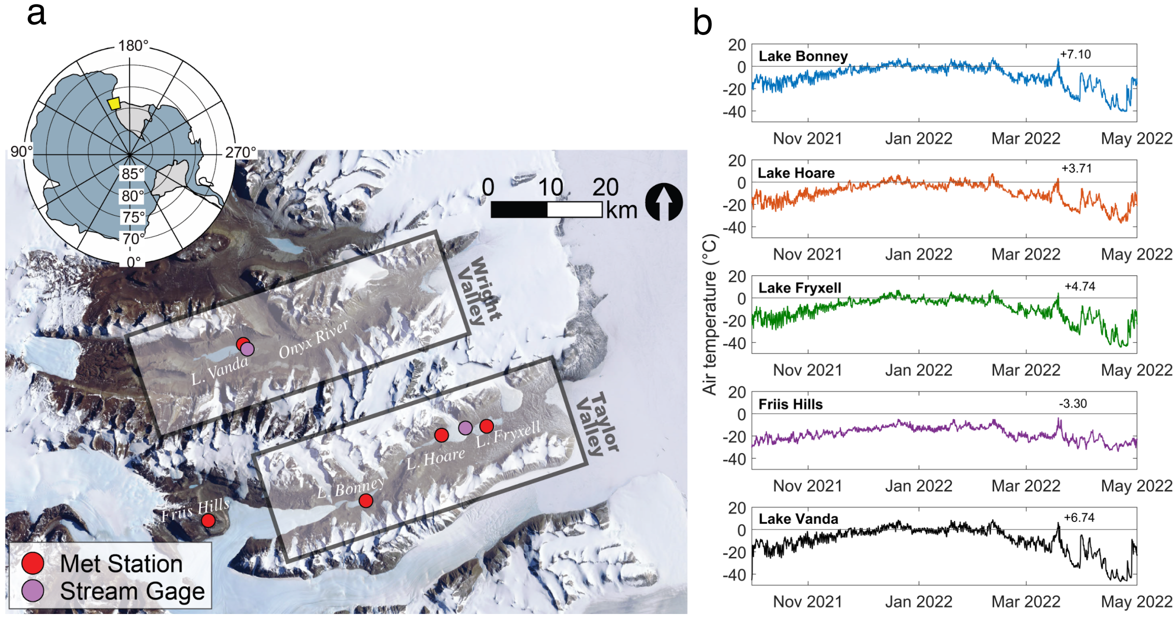

Figure 1. Map of the McMurdo Dry Valleys, Antarctica (a) and the location of meteorological stations where air temperature was recorded at Lake Bonney, Lake Hoare, Lake Fryxell, the Friis Hills, and Lake Vanda (b).

2 Material and Methods

2.1 Site Description

The McMurdo Dry Valleys (78°S, 162°E) are the largest (4500 km^2) ice-free area on the Antarctic continent (Levy 2013) with a landscape comprised of glaciers, exposed soils and rock, ephemeral stream channels, and closed-basin ice-covered lakes (Gooseff et al. 2017). The McMurdo LTER program has reported mean annual air temperature of -19°C, with extreme cold in the winter (< – 40°C) and typical temperatures just above the freezing point of water in the summer months (Obryk et al. 2020). The Canada Stream flows into the western end of Lake Fryxell at the terminus of the Canada Glacier in eastern Taylor Valley (McKnight et al. 1997). This ASPA has particular biological significance because of the high moss, cyanobacteria, and invertebrate abundance and diversity (Schwarz et al. 1992 & 1993), and high rates of primary productivity (Power et al. 2020, Salvatore et al. 2021).

2.2 Meteorological Observations

Meteorological data were selected from five automated weather stations located in the McMurdo Dry Valleys (Figure 1). Initiation of measurements at these stations varied from 1987 to 2010, but the main weather stations in Taylor and Wright Valleys have an average record length exceeding 30 years. For a detailed description the frequency of data collection, averaging, storage, and the post-processing of temperature records see Obryk et al. 2020. Air temperature data were collected at three m above ground using Fenwal-type thermistors shielded in a Campbell Scientific 207 probe. Wind is measured at 3 m above the ground using a RM Young aerovane Model 05103 (SI Fig. 4). The RM Young aerovanes has a wind speed accuracy of 2% up to wind speeds of 60 m s^{-1}, with a starting threshold of 0.9 m s^{-1}; wind direction uncertainty is less than 5°.

Mean summer (Nov - Feb), March, and average air temperatures at 3 m height for March 18th were calculated from the entire record to May 1, 2022 (Table 1). Additionally, we calculated the standard deviation for March 18th daily temperatures (σ) over the entire record, the difference between the maximum March 18th, 2022 and the long-term average March 18th air temperature (δT), and a March 18th 2022 deviation metric was expressed as $\delta T / \sigma$ following the approach of Schar *et al*. (2002). Exceedance frequency plots of daily maximum air temperature and wind speed were calculated using the long-term meteorological records from Lake Fryxell and Lake Bonney stations. From a 14-day window centered on a given date, exceedance frequency was calculated as the number of days exceeding a given air temperature and wind speed divided by total observations (approximately n = 427).

2.3 Stream hydrological observations

Stream records are described in detail by (Wlostowski et al. 2016). The stream discharge and water temperature data presented here were collected with CR10x data loggers at the Canada Stream gage in Taylor Valley and the Onyx River at Lower Wright gage in neighboring Wright Valley. Stream stage and water temperature were measured and recorded at both sites at 15-minute intervals. Stream stage is measured using Accubar Sutron Corporation pressure transducers. Discharge data was developed from stage data using a rating curve relationship between stream stage and discharge created in AQUATIC Informatics AQUARIUS timeseries software. Stream temperature is measured using Campbell Scientific CS547A conductivity probes.

2.4 Remote Sensing

We use the methodology of Salvatore *et al.* (2023) to generate topographically normalized surface albedo products using two WorldView-2 images acquired on March 14, 2022 (10300100CF2E9A00), and March 20, 2022 (10300100CF5E1E00). Assuming no significant changes to the composition of the surface between these two images, the only two factors that could result in a darkening of the surface are: (1) the introduction of shadows from clouds or surface topography; and (2) the addition of water. Like Salvatore *et al.* (2023), we use a 1-meter lidar-derived digital elevation model (Fountain et al. 2014) to first predict and then remove the influence of topographic shading from the surface albedo products. As there are no clouds or cloud-derived shadows observed in the areas of interest in either image, the only reason to observe darkening of the landscape between the acquisition of these two WorldView-2 images is because of increasing soil moisture. Once water content values were derived for all pixels in both images using the lab-derived relationship from Salvatore *et al.* (2023), the March 14 values were subtracted from the March 20 values to generate an image showing the difference in soil moisture content before and after the March 18, 2022, warming event.

We calculated the normalized differential vegetation index (NDVI), as:

$$NDVI = (\rho NIR - \rho Red)/(\rho NIR + \rho Red)$$

where ρNIR and ρRed are the spectral reflectance measurements acquired in the near-infrared 770–895 nm, band 7 and red 630–690 nm, band 5, respectively. NDVI is a common vegetation index used for determining whether an image contains photosynthesizing vegetation and has been successfully used in the Canada Stream area (Power et al. 2020, Salvatore et al. 2021).

2.4 Soil invertebrate enumeration and analyses.

Four replicate soil samples were collected on Dec. 25, 2022 from 1 m^2 plots at 15 pre-determined GPS coordinates selected from the albedo-surface water model to include areas that exhibited significant surface water content in the March 20^{th} image, areas that did not show significant surface water content in the March 20^{th} image, and validation sites that were positioned outside of the stream channel and riparian zone. The top ten cm of soil was collected into a WhirlPak© bag using a trowel. Gravimetric water content of all soils was measured by mass loss after drying at 105°C for 24 hours. Soil invertebrates were extracted from soils using a modified sugar-centrifugation extraction procedure (Freckman and Virginia 1997) and identified using inverted microscopy. The nematode genera *Eudorylaimus* and *Plectus* include cryptic species that we do not distinguish morphologically (Adams et al. 2006), but recent evidence has confirmed that *Scottnema lindsayae* is a single species within the McMurdo Dry Valley region (Jackson 2022). A fourth nematode taxa *Geomonhystera antarcticola*, relatively rare in the McMurdo Dry Valleys, has been reported in soils under microbial mats and moss and from sandstone derived soils that host cryptoendolithic communities of cyanobacteria (Adams et al. 2014). Tardigrades, rotifers, and the occasional flatworm are noted and counted but not further identified in routine enumeration.

Mortality was calculated as the ratio of dead to live nematodes and fecundity was calculated as the ratio of live juvenile to live female nematodes identified in the sample. Samples with zero observations in the denominator were excluded form analyses. Abundance of live organisms and life history trait data for soil invertebrate communities were analyzed using non-parametric comparisons (*e.g.*, Wilcoxon Rank Sum tests) between the wetted and unwet soils, and non-linear regressions over the full range of soil moisture conditions.

3 Results

Air temperatures recorded by McMurdo Dry Valleys LTER automated meteorological stations (Obryk et al. 2020) on March 18, 2022 rose above freezing and exceeded mean temperatures by an average of 25°C and three to four standard deviations of the mean (Table 1). Soil temperatures followed the same temporal trends and reached or exceeded 0°C at the three main Taylor Valley meteorological stations (SI Fig. 1). The Lake Bonney meteorological station recorded the highest regional temperature of +7.10°C at 14:00 local time on March 18 (Fig. 1b). This temperature exceeded the previous high March temperature of +2.82°C recorded at this station in 1996, and the long-term average for March by 26.36ºC and 3.57 standard deviations of the mean (Table 1).

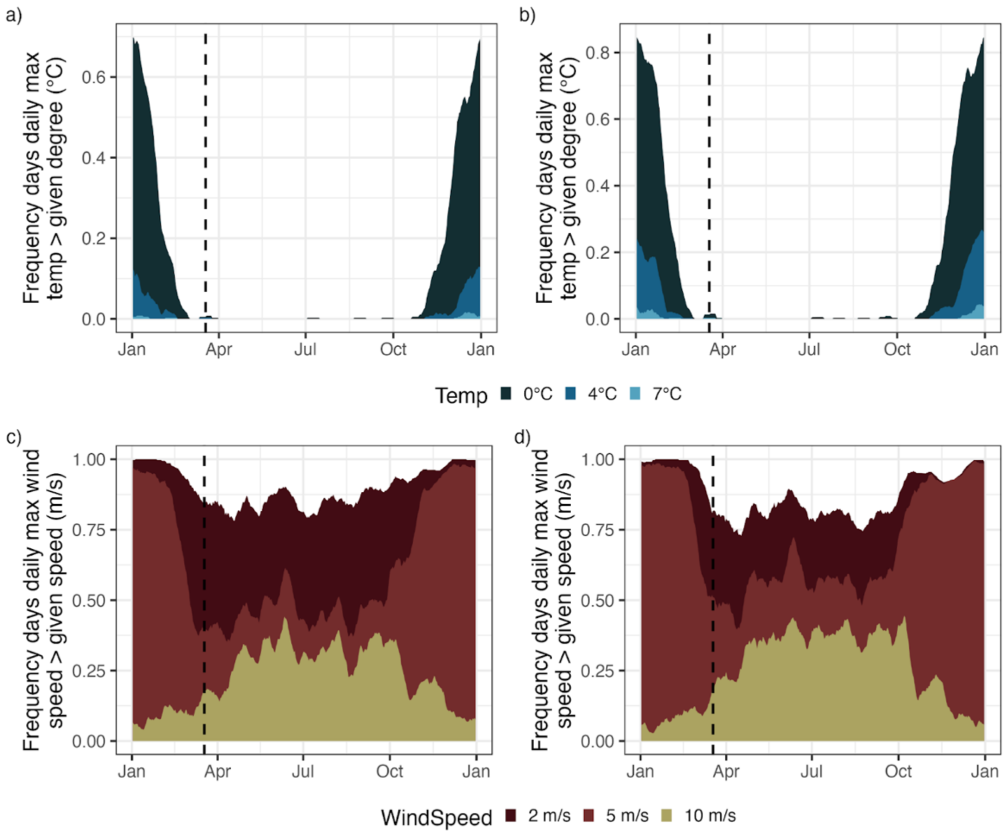

Figure 2. Frequency of daily maximum air temperature exceeding 0, 4, and 7°C during a given 2-week window at (a) Lake Fryxell and (b) Lake Bonney meteorological stations from 1994-2022. Frequency of daily maximum wind speed exceeding 2, 5, and 10 m/s during a given 2-week window at (c) Lake Fryxell and (d) Lake Bonney meteorological stations from 1994-2022. Dashed line indicates March 18th.

Air temperatures above +7°C are unusual in the McMurdo Dry Valleys even during the peak of summer insolation in Dec. and Jan. (SI Fig. 2) and are exceptionally unlikely during the austral fall based on the 30-year records for the Lakes Bonney and Fryxell meteorological stations (Fig. 2a & b). At the Lake Bonney station, situated close to the Polar Plateau, high temperatures were associated with sustained westerly foehn winds of 10 m s^{-1} through March 17, and 20 m s^{-1} on March 18th (SI Fig. 3), a time of year when strong wind events are not especially prevalent (Fig. 2 c & d). Notably, there was a transient decrease in temperature coinciding with a 75-minute drop in wind speed and change in wind direction, with easterlies prevailing for this range of time, before westerly winds increased again and temperatures reached their maximum (SI Fig. 3).

Multispectral satellite imagery shows significant surface darkening in the vicinity of Canada Stream in the Lake Fryxell basin between images acquired on March 14 and March 20, 2022 (Fig. 3a). Salvatore *et al*. (2023) have recently developed a model for estimating surface soil moisture from topographically-corrected remotely-sensed surface albedo in the McMurdo Dry Valleys. This model uses a decade-long image baseline and high-resolution airborne lidar data to quantify the reflectance associated with topographic changes and those associated with surface albedo. Microbial mat communities in these wetted areas also exhibited increases in the Normalized Difference Vegetation Index (NDVI) between images collected on March 14th and March 20th (Fig. 3b) when predicted soil moisture content accounted for 30% of the variation in NDVI values (linear regression r^2=0.30, p=0.035).

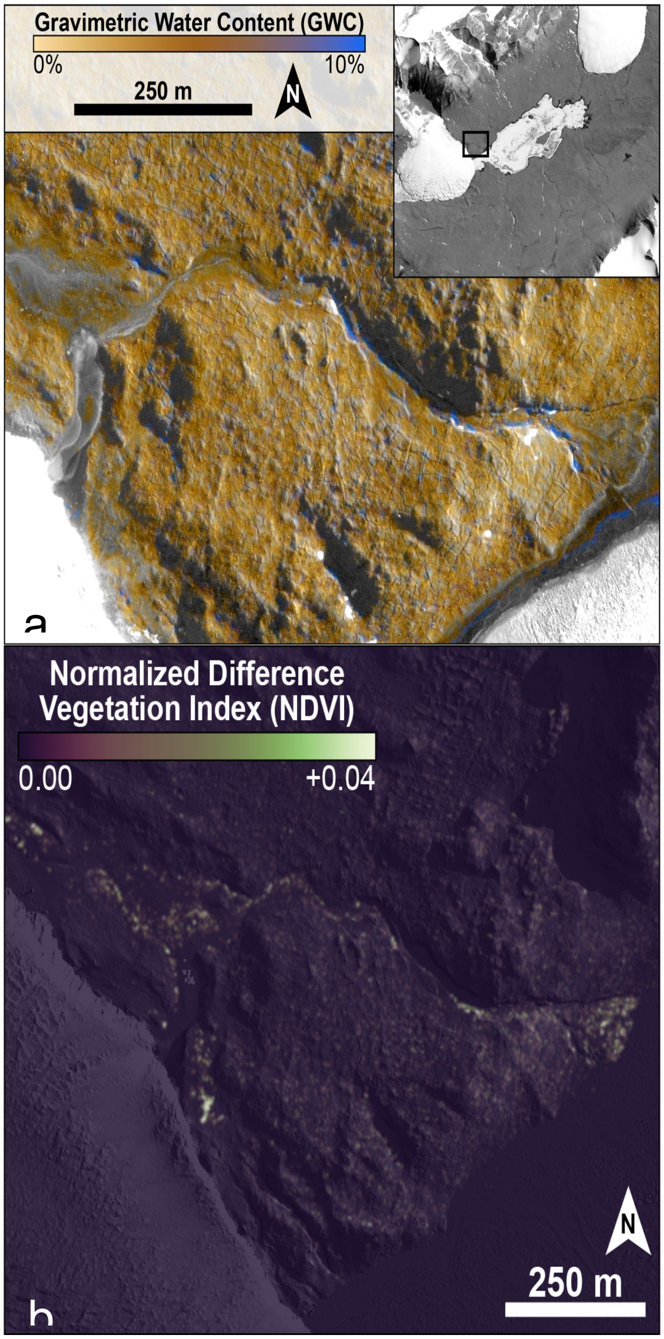

Figure 3. A subset of WorldView-2 image 10300100CF5E1E00 over the Canada Stream of Taylor Valley acquired on March 20, 2022. Both the inset and the primary basemap are panchromatic images, while the colors represent the surface soil moisture content derived from the instrument's visible/near-infrared multispectral capabilities (a). NDVI from the same image illustrates areas of significant microbial mat spectral activity (b.). Imagery © Maxar Technologies.

Stream gages on both the Canada Stream and Onyx River in neighboring Wright Valley recorded temperatures above freezing and increases in stream discharge on March 18, 2022 (Fig. 4, SI Fig. 4). Streamflow in the McMurdo Dry Valleys is dominated by glacial melt, occurring 8-10 weeks per year with no observations of flow outside the summer season. Activation of the Canada Stream in March 2022 is outside the range of observations for this time of the year (Fig. 4a). These stream gage measurements corroborate the interpretation of remotely sensed data and indicate that the Canada Stream experienced significant mobilization of liquid water in surface soils and sediments, resulting in moisture levels of up to 0.15 gravimetric water content.

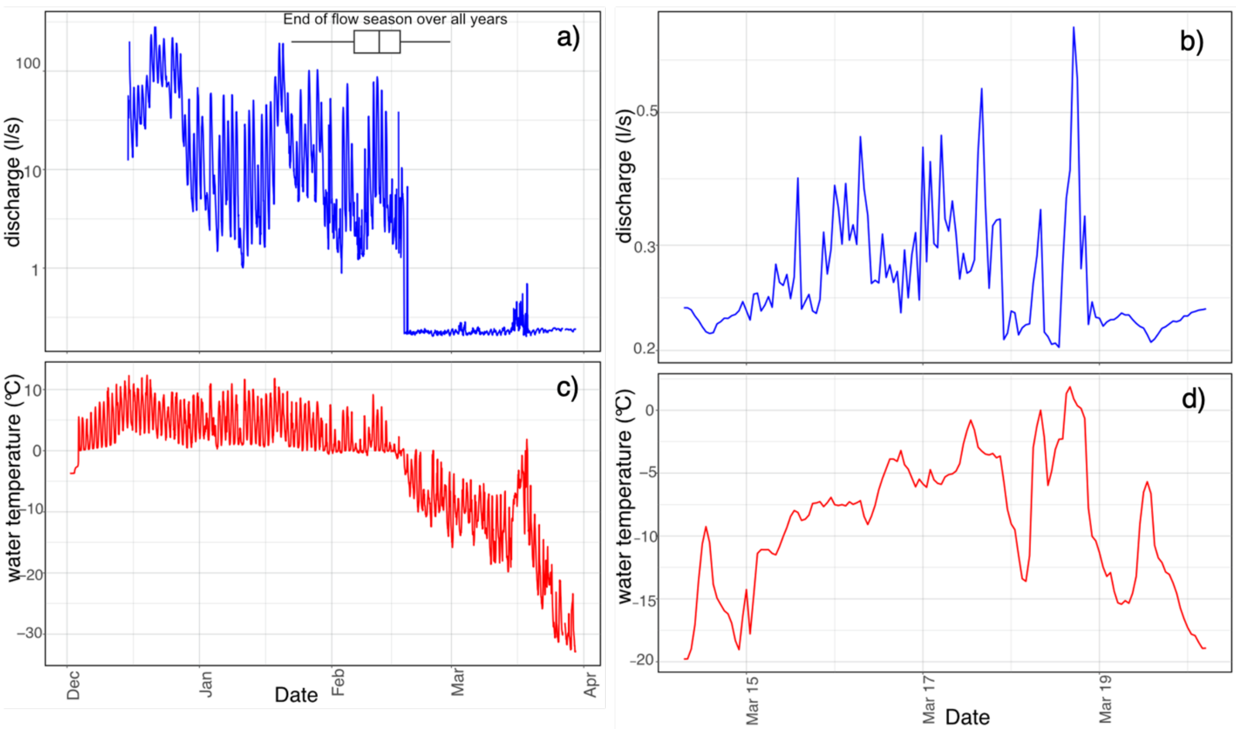

Figure 4. Stream discharge during December 2021 to April 2022 (a), and for March 14-March 20 2022 (b.), and water temperature for December 2021 to April 2022 (c), and for March 14-March 20 2022 (d.) for the Canada Stream in Taylor Valley, Antarctica.

Invertebrate populations in soils collected on December 25, 2022 ranged from zero to over 12,000 individuals per kg soil, generally increasing with average water content (Fig. 5a). Invertebrate communities were dominated by the endemic nematode *Scottnema lindsayae* in the driest soils where we observed relative abundances of 67-99% of this species. Moderately wet soils hosted more even communities consisting of multiple taxa, including rotifers, tardigrades, and the nematode taxa *Eudorylaimus* spp and *Geomonhystera antarcticola* (Fig. 5b). Invertebrate communities were less diverse and were numerically dominated by the nematode genus *Plectus* and rotifers in the wettest stream sediments (Fig. 5b). *Scottnema* was the only taxa examined that experienced significant demographic variation between wet and dry sites, with both greater mortality and fecundity in the wetted soils in samples collected nine months after the March 18th event (SI Fig. 5).

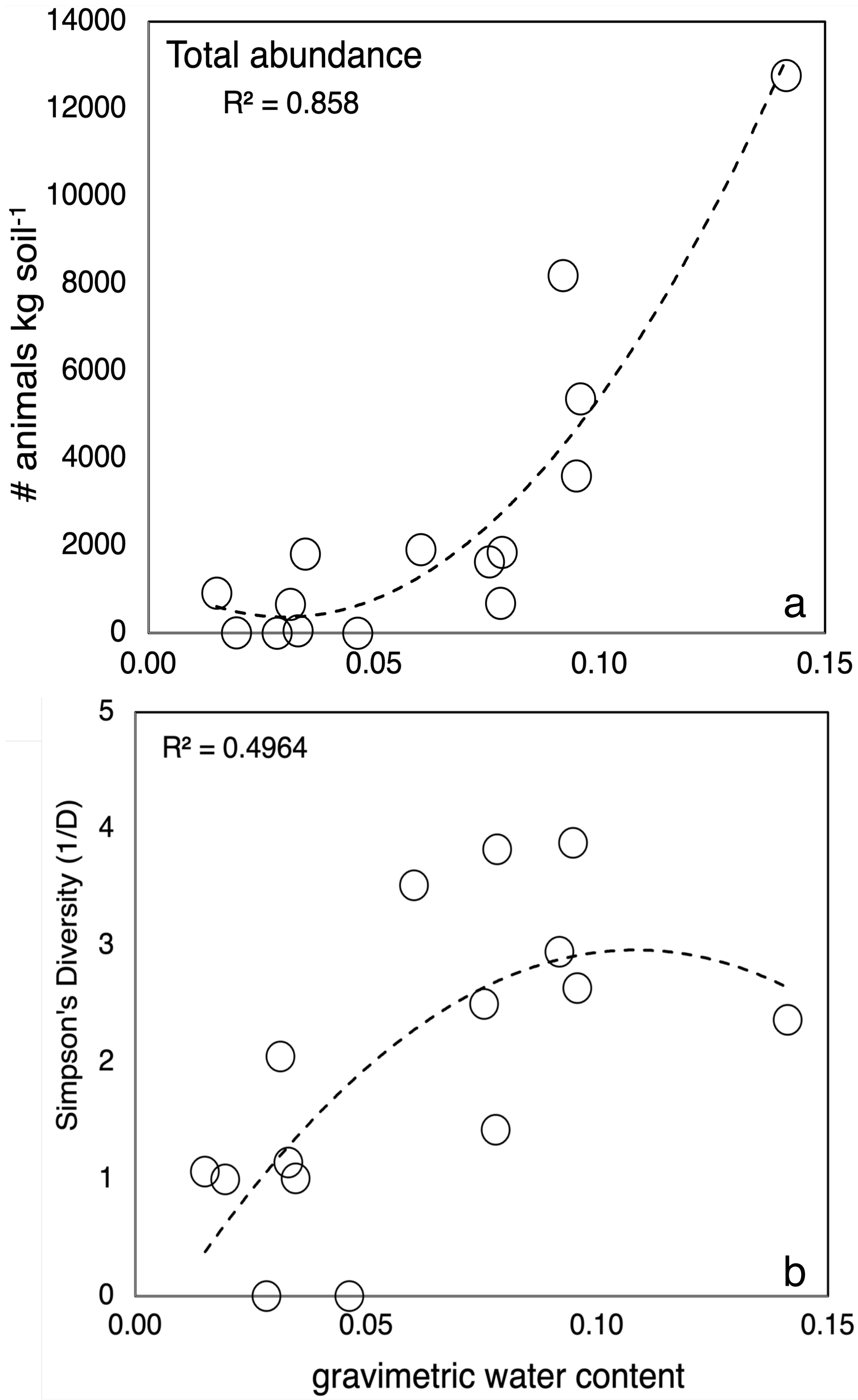

Figure 5. Total abundance (#/kg soil) of nematodes, tardigrades, and rotifers (a) and Simpson's Diversity (b) for soil and sediments collected from the Canada Stream Antarctic Specially Protected Area.

Discussion

Meteorological, satellite, and stream gage data indicate that the McMurdo Dry Valleys experienced a significant and unseasonable warming event on March 18, 2022, generating liquid water in soils and sediments above the threshold required for the rehydration and activation of sentinel taxa. Treonis *et al.* 2000 reported a moisture threshold for nematodes emerging from an inactive freeze-dried state, *i.e.*, anhydrobiosis, of ~ 0.02 gravimetric water content. Similarly, rapid rehydration and production of microbial mats in a relict stream channel were observed following a reactivation experiment (McKnight et al. 2007). Our multi-spectral albedo model indicates that liquid water content exceeded this water content threshold in the Canada Stream ASPA, and the changes in NDVI and soil invertebrate populations together illustrate significant biotic responses to this pulse of liquid water.

Soils in the Canada Stream ASPA host biotic communities with ranges in relative abundances and population densities similar to previous reports within and near riparian zones of streams or lake margins (Schwarz et al. 1993, Ayres et al. 2007). We found that abundance of soil invertebrates was positively correlated with average soil water content across all locations sampled, and that the driest soils supported the lowest abundance and diversity of invertebrates (Fig. 5). The greatest diversity occurred in areas where satellite imagery indicates significant increases in soil moisture between March 14 and March 20, 2022 (Fig, 5b). However, these same soils also exhibited higher mortality for *Scottnema* populations ($p = 0.039$, SI Fig. 5a), suggesting that autumnal wetting was physiologically challenging to these organisms. *Scottnema* is a free-living microbial-feeding soil nematode well-adapted to arid soils and is an abundant and widely distributed metazoan throughout continental Antarctica (Adams et al. 2006, Caruso et al. 2019). Late-season rehydration and activation of these soil organisms, followed by rapid re-freeze, has a high metabolic cost (Knox et al. 2017) that potentially contributes to the greater mortality observed, but this stress may be offset by higher rates of recruitment in *Scottnema* populations the following summer ($p = 0.012$, SI Fig. 5b). These results suggest that weather anomalies may influence life-history trade-offs for resident biota, and that activation of these organisms following unseasonable warming and wetting could have important ecological implications for the composition and activity of biotic communities in the McMurdo Dry Valleys (Barrett et al. 2008, Andruizzi et al. 2018).

These high March temperatures and the associated wetting in the McMurdo Dry Valleys are an example of summer-like temperatures reoccurring in fall, interrupting autumnal cooling and the seasonal transition to winter. Polar night (*i.e.*, 24-hour darkness) begins in early May at this latitude (SI Fig. 2), but average daily temperatures drop significantly beginning in February and are typically inhospitable to active biology in surface soils and sediments by early March (Fig. 1). The 2022 March warming occurred during a critical transition time in the hydrological and ecological calendar when temperatures are typically below freezing but solar radiation is still sufficient to support photosynthesis (Hawes and Schwarz 1999). This is in contrast to mid-winter, when air temperatures above freezing can occur, but PAR is zero (*e.g.*, Fig. 2 & SI Fig. 2); a scenario that likely elicits different responses from microbial mat communities. Additionally, the sign of temperature variation matters, as a similar magnitude cooling event in a transitional season may not have any discernible effect on inactive, freeze-dried resident biota.

This range of temperature variation and weather whiplash may be inherent to the climate regime of this region. For example, in contrast to the record warm March temperatures reported here, Solomon (2001) described how Robert F. Scott's South Pole Party faced unusually cold temperatures in March of 1912 that may have contributed to their demise.

Analogous weather whiplash in temperate climates include extremely cold spring temperatures associated with Polar Vortex conditions following mild winters, which often result in high mortality of deciduous plants and significant economic damage (IPCC 2022, Casson et al. 2019, Gu et al. 2008). Additionally, drought followed by extreme precipitation (Burt et al. 2018), can alter soil microbial communities and their activity, resulting in mobilization of soil nitrogen and carbon pools (Loecke et al. 2017, Osburn et al. 2021). There are many documented cases of extreme weather events driving ecological responses in the Arctic, *e.g*., (Christensen et al. 2021), but due to limited human and automated observations, fewer such events have been described in the Antarctic even though the influence of extreme weather on sentinel taxa is expected to be a significant driver of future biodiversity patterns. For example, a "flood" event during a record warm summer in 2001/2002 and the responses of terrestrial and aquatic ecosystems has been well documented for the McMurdo Dry Valleys (Gooseff et al. 2017). More recently, intense rainfall along the Adélie Coast of East Antarctica during the 2013/2014 summer resulted in 100% mortality of the Adélie penguin chick cohort in that region (Ropert-Coudert et al. 2014). Rain was also documented in Taylor Valley in 2018/2019 for the first time (SI V1and SI Table 1) and climate models predict a future where this may become less exceptional (Vignon et al. 2021, Maclennan et al. 2022).

Model forecasts predict increased occurrence of atmospheric rivers by the end of the century under mid-warming scenarios (Payne et al. 2020). Atmospheric rivers are associated with enhanced precipitation and the extreme temperatures of East Antarctica in March 2022 (Wille et al. in press). After decades of the McMurdo Dry Valleys not demonstrating significant response to anthropogenic greenhouse warming (Doran et al. 2002, Gooseff et al. 2017), the March 18, 2022 weather anomaly may be a portent of future climate with warmer temperatures and greater thaw, characteristics of a changing climate regime in this region of Antarctica and new drivers of organismal and ecosystem dynamics.

Acknowledgements

The authors declare no financial conflicts of interest with the results of this paper. This work was supported by the National Science Foundation (grants #2046260, 1744785, 1637708, and 1027284) and Antarctic Support Associates, Leidos.

Open Research

As part of the requirements of the National Science Foundation's Long Term Ecological Research Program and reflecting our own commitment to open and discoverable data our data are accessible through the Environmental Data Initiative (Doran et al. 2022a & b, and Doran et al. 2023 a, b & c).

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Table 1. Mean daily summer (NDJF) air temperature, mean monthly March air temperature, mean daily March 18th temperature for the entire record and standard deviation (σ), mean daily March 18th 2022 air temperature, maximum March 18th 2022 are temperatures, the difference between maximum and average March 18th temperatures (δT) and the number of standard deviations above the average temperatures experienced on March 18th, 2022 (δT/σ) for meteorological stations in the McMurdo Dry Valleys (Fig. 1)[16-20].

Station	Mean summer temp. °C	Mean March temp. °C	Mean March 18th temp. °C	σ March 18th temp. °C	Mean 3/18/2022 temp °C	Maximum 3/18/2022 temp. °C	δT	δT/σ	Start of record
Lake Bonney	-3.80	-18.88	-19.26	7.38	0.98	7.10	26.36	3.57	11/24/1993
Lake Hoare	-4.97	-18.98	-20.00	5.97	-2.85	3.71	23.71	3.97	11/11/1987
Lake Fryxell	-5.03	-20.47	-20.83	6.44	-4.32	4.74	25.57	3.97	12/7/1993
Friis Hills	-14.19	-22.75	-23.33	5.67	-9.71	-3.30	20.03	3.54	12/21/2010
Lake Vanda	-2.95	-21.35	-22.88	9.13	1.31	6.74	29.62	3.24	11/24/1994
Mean							**25.06**	**3.66**	