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Key Points:
- Thirty years of meteorological observations between 1986 and 2017 from McMurdo Dry Valleys, Antarctica, are summarized
- Surface air temperatures decreased from 1986 to 2005 ±1
- Summer season is redefined using physically based processes and is applicable to other ice-free regions around Antarctica

Supporting Information:
- Supporting Information S1

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Climate From the McMurdo Dry Valleys, Antarctica, 1986–2017: Surface Air Temperature Trends and Redefined Summer Season

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Abstract The weather of the McMurdo Dry Valleys, Antarctica, the largest ice-free region of the Antarctica, has been continuously monitored since 1985 with currently 14 operational meteorological stations distributed throughout the valleys. Because climate is based on a 30-year record of weather, this is the first study to truly define the contemporary climate of the McMurdo Dry Valleys. Mean air temperature and solar radiation based on all stations were −20°C and 102 W m^{-2}, respectively. Depending on the site location, the mean annual air temperatures on the valleys floors ranged between −15°C and −30°C, and mean annual solar radiation varied between 72 and 122 W m^{-2}. Surface air temperature decreased by 0.7°C per decade from 1986 to 2006 at Lake Hoare station (longest continuous record), after which the record is highly variable with no trend. All stations with sufficiently long records showed similar trend shifts in 2005 ±1 year. Summer is defined as November through February, using a physically based process: up-valley warming from the coast associated with a change in atmospheric stability.

1. Introduction

The McMurdo Dry Valleys (MDVs) region, located in east Antarctica (77–78°S 160–164°E), is about 4,800 km^2 (Levy, 2012). The region abuts East Antarctic Ice Sheet to the west and Ross Sea to the east. The terrain is primarily ice free, largely covered with a sandy gravelly soil, dotted with perennially ice-covered lakes, and local alpine and a few outlet glaciers from the East Antarctic Ice Sheet. The soils are underlain by ice-cemented or dry permafrost (Marchant & Head, 2007). The ice-free landscape results from the Transantarctic Mountain Range, which blocks flow of the East Antarctic Ice Sheet, and creates a precipitation shadow. Snowfall in the valley bottoms reaches an annual maximum of ~50 mm water equivalent near the coast and much less inland (Fountain et al., 2010). Although precipitation occurs as snow, rain has been observed on rare occasions (M. Myers, 2019, personal communication, September 25, 2019). Snow accumulations on the valley floors largely sublimate before melting thus limiting infiltration into soils. As a consequence, this arid polar desert has one of the lowest erosion rates in the world ~1 m Ma^{-1} in the valley bottoms and ~0.06 m Ma^{-1} in perennially frozen landscapes at high elevations (Marchant & Head, 2007). Most of the lakes are in closed basins fed by ephemeral streams draining glacial melt in December and January. Water loss from the lakes is mostly through sublimation of the ice cover during the winter (Obryk et al., 2017). The MDVs host complex microbial ecosystems that respond to short- and long-term climate variability (Cary et al., 2010; Foreman et al., 2004; Gooseff et al., 2017; Tiao et al., 2012) and represent a climate extreme often used as an analog for exoplanetary studies (McKay et al., 2017; Mikucki et al., 2015; Obryk et al., 2014; Stone et al., 2010).

The longest weather record in the region is from nearby Scott Base, located on Ross Island approximately 100 km away from the MDVs. Between 1958 and 2000, Scott Base experienced a warming trend, albeit not statistically significant (Turner et al., 2005). The regional climate is coupled with the Southern Annular Mode (SAM), the main driver of atmospheric variability in the Southern Hemisphere (Fountain et al., 2016; Turner et al., 2005). In the MDVs, SAM was shown to influence the frequency of foehn winds, which, in turn, can influence seasonal surface air temperatures (Speirs et al., 2013).

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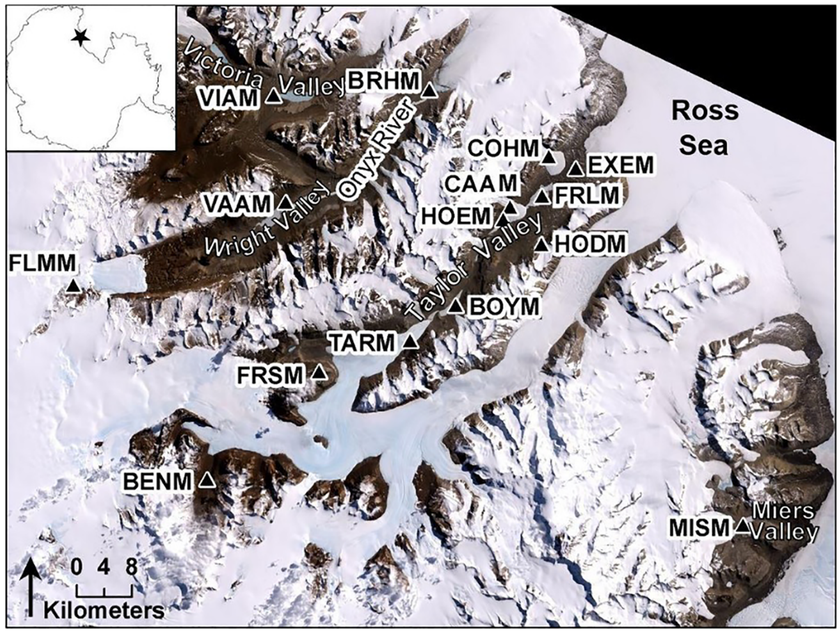

Figure 1. Landsat image of the McMurdo Dry Valleys region showing the location of the valleys and meteorological stations (labeled triangles). Elevations of individual meteorological stations are listed in Table 1. Inset shows the location of the McMurdo Dry Valleys within Antarctica.

In 1985, the first continuously operating meteorological station was installed at Lake Hoare (Clow et al., 1988), and in 1993 six additional stations were installed that formed a network of stations to monitor the spatial and temporal variations in weather (Doran et al., 1995). To date, the only comprehensive analysis of the MDVs weather, based on the seven meteorological stations, was by Doran, McKay et al. (2002) for the period of 1986–2000. They noted a range of mean annual surface air temperatures between −15°C and −30°C and mean annual solar radiation between 73 and 113 W m^{-2} depending on the valley. Doran, Priscu et al. (2002) showed a cooling trend of 0.7°C per decade over that time. In the summer of 2001–2002, an extremely warm 3-week period perturbed the physical and biological state of the region, consequences of which were observed for over a decade (Gooseff et al., 2017). During this time, lake levels increased significantly (Fountain et al., 2016), and for the first time in observational record, both undercutting and overcutting of stream banks occurred (Fountain et al., 2014; Sudman et al., 2017), in some cases exposing Pleistocene buried ice (Levy et al., 2013). Consequently, microbial communities responded to the influx of water and sediment in lakes and soils (Bowman et al., 2016; Foreman et al., 2004; Fountain et al., 2016; Gooseff et al., 2017; Obryk et al., 2016). Since Doran, McKay et al. (2002), individual climatic variables have been investigated including influence of drainage winds on regional climate (Nylen et al., 2004; Speirs et al., 2013), the atmospheric boundary layer (Katurji et al., 2013; Zawar-Reza et al., 2013), and drivers of solar radiation variability (Obryk et al., 2018). Updated surface air temperature and solar radiation were summarized through 2013, based on the longest operational meteorological station (Gooseff et al., 2017). Gooseff et al. (2017) found temperature cooled until the 2001–2002 summer season and found no statistically significant temporal trends afterward.

Here we update the weather summary of the MDVs with focus on surface air temperatures and seasonality. However, given that two stations (at Lake Hoare and Lake Fryxell) exceed the 30-year minimum record from which "climate" can be defined (World Meteorological Organization [WMO], 2019), we present the first climate analysis for the MDVs. Like Doran, McKay et al. (2002), the analysis is largely restricted to the valley bottoms. Our report differs from Doran, McKay et al. (2002) by including a new station in low elevation Miers Valley, four meteorological stations on different glaciers in Taylor Valley, and three high elevation stations (Figure 1). Although only data sets from two stations have sufficient length to provide a true climate record, as we will show, all but two high-altitude stations are highly correlated, effectively producing a climate summary for the region.

2. Data and Methodology

Meteorological data were obtained from 15 stations located throughout the MDVs (Figure 1), of which 14 stations are currently operational (Table 1). Stations were installed in different years with two before 1988, eight from 1993 to 1995, and one in 1997, 2000, 2010, and 2011. In the 1980s data were collected at 30-s intervals, averaged to 6-hr intervals and stored. Between 1993 and end of 1995, data were averaged between 10-min and 3-hr intervals between different stations; however, by November 1995 all stations averaged data to 15-min intervals (for a detailed list of date ranges and associated sampling intervals see www.mcmlter.org). Missing data due to either failed sensors/batteries or tipped over meteorological stations were not interpolated. Instead, monthly averages missing more than one continuous day were excluded from the analysis. Consequently, annual averages missing more than 1 month were also excluded.

Temperature data were collected at 3 m above ground level using Fenwal-type thermistors shielded in a Campbell Scientific 207 probe. Temperature was converted from voltage using a Steinhart-Hart equation, which yielded an error of ±0.02°C from −40°C to +60°C (Clow, unpublished data, 1991). At temperatures below −40°C, the error doubles for every 10°C temperature decrease. Solar flux was measured using Li-Cor LI-200 pyranometers, which are cosine-corrected silicon photodiodes, with a maximum uncertainty of ±5%. Wind was measured at 3 m above the ground using Met One model 014A and 024A for speed and direction, respectively, until they were replaced by RM Young aerovanes (Model 05103) in 1993. The Met One three-cup anemometers had a wind speed accuracy of 1.5% and direction accuracy of ±4% up to 45 m s^{-1}, with a starting threshold of 0.45 m s^{-1}. Installation of the RM Young aerovanes expanded the rating to 60 m s^{-1} with a wind speed accuracy of 2% and wind direction uncertainty less than 5°. The starting threshold for the RM Young aerovanes is 0.9 m s^{-1}. Relative humidity was measured using 207 Phys-Chem transducers housed with the temperature sensors in the nonaspirated radiation shields. Their accuracy was about ±5% at 25°C for the manufacturer-specified operating range of 12% to 100%. Relative humidity values below freezing point were corrected using vapor pressure over ice instead of water using the Steinhart-Hart temperature (Lowe, 1977). All sensors are on a 2-year manufacturers calibration schedule, eliminating the need for sensors drift calibration. Prior to 1993, sensors were calibrated irregularly.

Moving averages (running mean) were calculated based on a 13-term (month) moving filter (Brockwell & Davis, 2002) because unlike a 12-month filter, the 13-month filter eliminates the annual seasonality cycle. Pivot points in surface air temperature trends were determined based on nonparametric Pettitt test statistics (Pettitt, 1979), a commonly used test in hydrological and climatological studies (Kundzewich & Robson, 2000). A nonparametric Mann-Kendall test was used to determine existence of monotonic trends between the pivot point and beginning and end of the time series. If a trend was present, Sen's slope was used to compute linear rate of change, because it is insensitive to outliers, using a median of slopes (Gilbert, 1987).

Seasonal change in atmospheric stability was approximated using bulk Richardson number (R_b):

$$\boldsymbol{R_b} = \frac{\boldsymbol{g}\,\boldsymbol{\Delta z}\,\boldsymbol{\Delta\theta_v}}{\overline{\boldsymbol{\theta_v}}\,(\boldsymbol{\Delta U})^2}, \tag{1}$$

where g is gravity, Δz is layer thickness, $\Delta\theta_v$ is virtual potential temperature difference of the layer, $\overline{\theta_v}$ is average virtual potential temperature across the layer, and ΔU is difference in wind speed across the same layer (Stull, 1988). $\Delta\theta_v$ was calculated using surface air temperature (at 3-m height) and soil temperature (at 0-cm depth) sensors. Wind speed at the ground surface was assumed to be 0.

3. Results

Averages, minimums, and maximums of all measured climatic variables from all stations are summarized in Table 1. Differences between the last climate summary (Doran, McKay et al., 2002) and this analysis are shown in Table S1 in the supporting information. Since 1999, mean temperature and solar radiation increased by 0.3°C and 4 W m^{-2}, respectively. Surface soil temperature increased on average by 0.6°C and wind speed decreased by 1.5 m s^{-1}. Photosynthetically active radiation decreased by 2.7 μEinsteins m^{-2} s^{-1}. Mean air temperature and solar radiation in the MDVs, based on the record from the valley bottom stations only, was −19.6°C and 100.7 W m^{-2}, respectively.

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Table 1
Summary Climate Statistics for McMurdo Dry Valleys, Antarctica

		Terrestrial sites					
		Taylor Valley				Wright Valley	
		Explorer's Cove	Lake Fryxell	Lake Hoare	Lake Bonney	Lake Brownworth	Lake Vanda
Station code		EXEM	FRLM	HOEM	BOYM	BRHM	VAAM
Period of station record	start	21-Nov-97	28-Oct-87	12-Dec-85	24-Nov-93	9-Jan-95	24-Nov-94
	end	22-Nov-17	11-Dec-17	19-Feb-18	16-Nov-17	30-Nov-17	18-Dec-17
Station elevation, m asl		26	20	77	60	280	125
Distance from coast, km		4	9	15	25	21	43
Air temperature, °C	avg mean annual	−19.2	−20.0	−17.7	−17.3	−20.2	−19.5
	max mean annual	−16.9	−17.2	−15.3	−14.7	−18.6	−17.3
	min mean annual	−21.5	−23.0	−19.9	−19.2	−21.8	−22.0
	absolute maximum	11.6	9.9	10.0	10.6	10.7	10.7
	absolute minimum	−50.1	−60.2	−47.7	−48.3	−51.9	−53.7
Degrees days above freezing	mean annual	13.1	20.9	24.6	44.2	8.7	72.3
Soil temperature at 0 cm, °C	avg mean annual	−18.8	−19.2	−18.0	−16.5	−19.5	−19.2
	max mean annual	−16.7	−16.1	−16.0	−15.1	−18.0	−17.1
	min mean annual	−21.0	−21.1	−19.9	−18.0	−21.0	−21.3
	absolute maximum	24.7	24.9	25.7	31.1	18.0	21.6
	absolute minimum	−52.9	−52.3	−51.1	−50.9	−52.4	−54.5
Soil temperature at 5 cm, °C	avg mean annual	−18.5	−18.8	−17.7	−16.4	−19.6	−19.1
	max mean annual	−16.5	−16.2	−16.0	−15.1	−18.2	−17.2
	min mean annual	−20.7	−20.6	−19.7	−17.8	−20.8	−20.5
	absolute maximum	14.0	14.7	17.6	22.6	11.6	16.6
	absolute minimum	−46.4	−48.6	−47.1	−48.3	−49.4	−49.6
Soil temperature at 10 cm, °C	avg mean annual	−18.4	−18.5	−17.7	−16.4	−19.4	−19.1
	max mean annual	−16.4	−16.3	−16.0	−15.3	−18.2	−17.2
	min mean annual	−20.4	−20.2	−19.4	−17.6	−20.9	−20.7
	absolute maximum	10.3	12.0	11.2	19.6	8.2	11.4
	absolute minimum	−43.9	−45.0	−43.8	−47.4	−45.2	−48.5
RH, %	avg mean annual	75.7	71.3	65.7	63.5	70.0	60.1
	absolute maximum	100.0	100.0	100.0	100.0	100.0	100.0
	absolute minimum	6.2	13.0	6.8	0.6	6.3	1.8
Wind speed, m/s	avg annual vector	0.4	0.2	0.5	0.4	0.3	0.5
	avg mean annual	1.5	1.5	1.4	1.8	1.9	1.5
	absolute maximum	40.4	42.2	36.3	41.2	36.0	40.4
Wind direction, °	avg annual vector	83.2	81.8	244.2	249.9	194.8	178.5
Solar flux, W/m^2	avg mean annual	108.7	104.0	87.5	101.0	110.3	91.4
	max mean annual	117.7	113.6	97.3	107.9	118.1	101.6
	min mean annual	98.8	84.4	72.1	94.6	98.3	86.0
PAR, μeinsteins/m^2/s	ave mean annual	220.4	219.6	181.2	207.9	221.9	181.8
	max mean annual	232.2	238.2	195.2	263.5	229.1	194.4
	min mean annual	203.9	208.8	164.7	176.9	204.8	152.1

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Table 1
Continued

	Terrestrial sites		Glacial sites				High-altitude sites		
	Victoria Valley	Miers Valley	Taylor Valley						
	Lake Vida	Lake Miers	Taylor Gl	Canada Gl	Commonwealth Gl	Howard Gl	Friis Hills	Mt. Fleming	Beacon
Station code	VIAM	MISM	TARM	CAAM	COHM	HODM	FRSM	FLMM	BENM
Period of station record	24-Nov-95	28-Jan-12	21-Nov-94	1-Dec-94	20-Nov-93	20-Nov-93	21-Dec-10	8-Jan-11	27-Nov-00
	18-Dec-17	29-Dec-17	30-Nov-17	27-Nov-17	27-Nov-17	27-Nov-17	30-Nov-17	30-Nov-17	27-Dec-12
Station elevation, m asl	390	51	334	264	290	472	1,591	1,870	1,176
Distance from coast, km	42	5	33	13	5	9	47	80	68
Air temperature, °C	−26.8	−16.5	−17.2	−17.1	−17.6	−17.2	−22.5	−24.1	−21.5
	−23.4	−15.2	−15.1	−15.5	−16.0	−15.6	−21.8	−23.1	−20.7
	−29.6	−17.9	−18.7	−18.3	−19.4	−18.8	−23.5	−25.2	−22.3
	10.0	7.8	12.0	9.7	7.8	11.8	−2.8	−4.8	2.8
	−65.7	−41.6	−44.9	−45.6	−45.0	−43.9	−39.8	−46.3	−50.0
Degrees days above freezing	24.5	22.8	16.2	8.4	3.4	4.9	0.0	0.0	0.4
Soil temperature at 0 cm, °C	−25.1	−16.5							−18.0
	−21.0	−15.1							1.5
	−29.3	−17.9							−22.1
	23.4	15.7							23.3
	−59.8	−41.4							−49.8
Soil temperature at 5 cm, °C	−24.9								−21.2
	−21.0								−20.5
	−29.1								−21.8
	14.3								9.0
	−56.2								−45.9
Soil temperature at 10 cm, °C	−24.7	−16.2							−21.1
	−20.9	−14.9							−20.4
	−28.8	−17.5							−21.8
	10.6	6.8							6.0
	−55.5	−36.9							−44.6
RH, %	69.2	64.7	60.4	66.4	68.6	63.1	61.4	61.7	57.8
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	0.0	10.0	9.0	10.5	10.6	8.0	9.0	0.4	3.4
Wind speed, m/s	1.1	0.9	3.0	1.1	1.7	2.0	3.5	8.3	
	1.7	1.5	3.5	2.0	2.2	2.1	3.6	8.6	
	39.1	47.3	44.1	48.3	44.5	39.9	40.6	49.1	
Wind direction, °	133.9	161.6	265.3	245.1	336.8	184.7	199.3	213.8	
Solar flux, W/m^2	108.6	93.7	104.8	99.6	108.8	95.6			105.5
	122.4	99.2	109.1	110.8	115.5	104.7			113.9
	94.5	85.5	93.9	92.8	101.6	82.4			99.3
PAR, μeinsteins/m^2/s	210.1	193.2							197.5
	240.5	212.6							222.4
	182.3	178.2							155.5

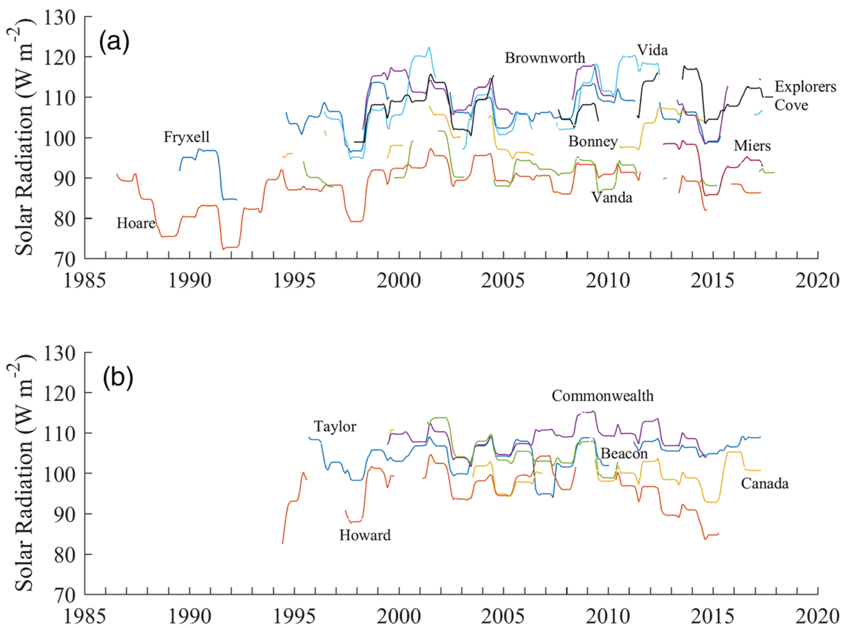

Figure 2. Monthly solar flux using (a) 13-term centered running mean, a valley bottoms and (b) glacial/high elevation sites. Friss Hills and mount Flemings did not record downwelling solar radiation.

3.1. Solar Radiation

The mean annual solar radiation flux in the MDVs ranged from 72.1 W m^{-2} at Lake Hoare station to 122.4 W m^{-2} at Lake Vida station (Table 1 and Figure 2). All stations exhibited similar patterns (Figure 2) and are highly correlated but with different means. Generally, the solar radiation increased from the beginning of the observational record until the early 2000s and it has remained relatively elevated since (Obryk et al., 2018).

3.2. Air Temperature

The maximum and minimum air temperatures recorded in the MDVs were 12.0°C at Taylor Glacier and −65.7°C at Lake Vida (Table 1), respectively. The mean annual air temperature on the valleys floors ranged between −14.7°C at Lake Bonney to −29.6°C at Lake Vida (Table 1). Within Taylor Valley, which has eight stations, the valley bottom mean annual temperatures ranged from −14.7°C to −23.0°C, in contrast to the four glaciers stations that ranged from −15.1°C to −19.4°C. High elevation sites ranged from −20.7°C to −25.2°C. With the exception of two high elevation sites (Friss Hills-FRSM and Mt. Flemings-FLMM), all stations exhibited similar trends but with different means (Figure 3). The order of mean annual temperatures among the valleys, using valley bottom stations, warmest to coldest is Miers Valley (1, −16.5°C) > Taylor Valley (4, −18.5°C) > Wright Valley (2, −19.8°C) > Victoria Valley (1, −26.8°C), where the integer is the number of stations and the decimal number is the mean annual temperature.

The time series of running mean air temperature for stations with sufficiently long records showed statistically significant cooling until 2005 ±1, a pivot point, after which no trend was detected (Table 2). Only six stations showed a statistically significant trend and each at different rates. The differences in cooling rates and timing of the pivot points are probably a result of the time series length and missing data. For example, Explorers Cove (EXEM) was missing data between the end of 2004 and the beginning of 2006; hence, the pivot point was detected at the end of 2004. The longest continuous record from Lake Hoare station showed cooling between 1986 and 2006 at −0.7°C per decade ($p < 0.01$), and we believe this station most accurately represents trends in the MDVs. Data from 1985 were excluded from the trend detection because only December values were recorded. After 2006, no trend was detected at the Lake Hoare station (Figure 4) or any other station. Running mean, standard deviation, and variance before and after the pivot at Lake Hoare were −17.9°C, 0.9, 0.8 and −17.3°C, 0.8, 0.7, respectively.

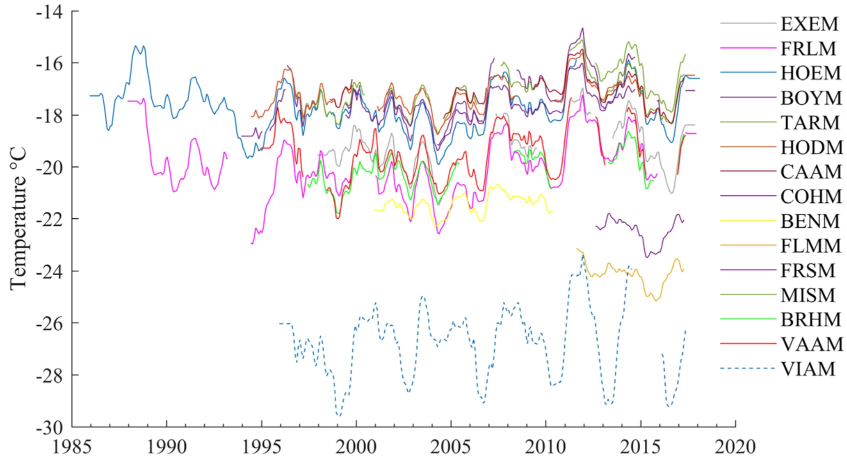

Figure 3. Monthly running mean temperatures in the McMurdo Dry Valleys based on a 13-term filter. Stations abbreviations are found in Table 1.

Previous analysis showed seasonally averaged cooling until 1999 at a rate of −0.7°C per decade, a cooling that was most pronounced in summer (December, January, and February) at −1.2°C per decade and fall (March, April, and May) at −2.0°C per decade (Doran, Priscu et al., 2002). For comparison purposes, we examined seasonal cooling rates until 2006, which were dominated by fall and winter (June, July, and August) at −1.3°C per decade (p = 0.07) and −0.9°C per decade (p = 0.53), respectively. Spring (September, October, and November) and summer (December, January, and February) showed lower cooling rates at −0.4°C per decade (p = 0.79) and −0.8°C per decade (p = 0.09), respectively.

3.3. Wind

The main axes of the valleys investigated in this study are northeast to southwest with the exception of the Miers Valley, which trends east to west (Figure 1). There are two primary wind regimes in the MDVs: northeasterly or on-shore winds and southwesterly. Southwesterly winds are predominantly foehn winds driven by the regional pressure differential (between valleys and Ross Sea) and topography (Speirs et al., 2010) and occasionally katabatics winds that descend from the Antarctic Plateau (Nylen et al., 2004). During the austral summers, the region experiences a higher frequency of northeasterly winds than in the winter, especially at the coastal sites (Figures 5 and S7). The inland sites can experience westerly winds while the coastal sites experience easterly winds (Figure S7). All stations exhibit southwesterly to northeasterly transition in November and northeasterly to southwesterly transition in February (supporting information Figures S1–S6). The maximum wind speed of 49.1 m s^{-1} was recorded at Mount Flemming, a high elevation site (Figure 1); however, a valley bottom site at Lake Miers recorded 47.3 m s^{-1}.

The highest frequency of strong winds (wind speed ≥10 m s^{-1}) was in Wright Valley (Lake Vanda) (Figure S8) with the majority of these occurring during the winter months (Figure S5). In adjacent Victoria Valley (Lake Vida), winter conditions were relatively calm and the station experienced the lowest frequency of wind speeds ≥10 m s^{-1} (Figures S6 and S8). Previously, this low frequency had been attributed to a formation of a cold cell at the bottom of the valley, which inhibits intrusion of westerly winds (Doran, McKay et al., 2002).

Table 2
Trend Statistics and Cooling Rates for McMurdo Dry Valleys, Antarctica

Station code	Station name	Pivot year	Cooling rate per year (°C)
BOYM	Lake Bonney	2006	
BENM	Beacon	2006	
BRHM	Lake Brownworth	2005	
COHM	Commonwealth	2006	−0.08
EXEM	Explorer's Cove	2004	−0.13
FRLM	Lake Fryxell	2006	−0.10
HOEM	Lake Hoare	2006	−0.07
HODM	Howard	2006	
VAAM	Lake Vanda	2006	−0.10
TARM	Taylor Glacier	2005	−0.06

Note. Only statistically significant (p < 0.01) pivot point statistics and cooling rates until the pivot point are shown.

3.4. Relative Humidity

For relative humidity, all sites have reached the saturation point and the lowest detectable limit of the sensors. Since Doran, McKay et al. (2002), all but the Lake Hoare station exhibited an increased relative humidity of 3% on average. In contrast, Lake Hoare station exhibited a decrease of 0.3% (Table S1).

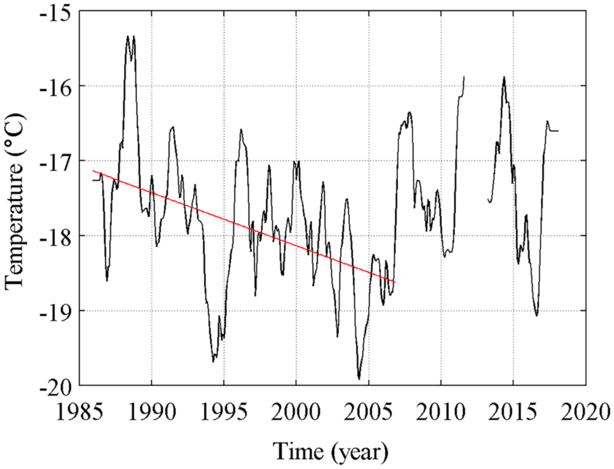

Figure 4. Monthly running mean surface air temperature from Lake Hoare meteorological station. Statistically significant surface air temperature cooling trend (in red) of −0.7°C per decade ($p < 0.01$) terminating in 2006, followed by warmer temperatures and no trend.

3.5. Relationships Between the Meteorological Variables

To investigate the relationship among climatic variables of solar radiation, surface air temperature, wind speed and direction, and relative humidity, we utilized principal component analysis (PCA) using monthly averaged data from Lake Hoare station. The first two principal components explain over 75% of variance (Figure 6a). Principal component (PC) 1 describes a relationship between solar radiation, surface air temperature, and wind direction (Figure 6b). Solar radiation is notably the independent variable that drives surface air temperature regime in this polar desert (positive correlation) (Lacelle et al., 2016). Wind direction is negatively correlated to both solar radiation and surface air temperature. Presence of solar radiation is responsible for the high frequency of thermally induced offshore breeze; the predominant wind direction during austral summer is from the northeast and the predominant wind direction during the austral winter is from the southwest. PC 2 describes a relationship between wind speed and relative humidity, where the two variables are negatively correlated (Figure 6b). An increased wind speed is associated with decreased relative humidity, a common observation associated with foehn winds (Nylen et al., 2004; Speirs et al., 2013) where air parcels descending from the polar plateau warm adiabatically and consequently decrease relative humidity.

3.6. Summer Season

Seasons are typically defined by astronomical events: the equinoxes and the solstices, associated with a recurrent phenomenon due to the change in the Earth's position relative to the Sun (Trenberth, 1983). Seasons are commonly grouped into 3-month averages coinciding with the beginning and end of calendar months. However, this definition might not align with the physical or ecological responses in polar regions where summers and winters are dominated by prolonged presence or absence of solar radiation. Continuous

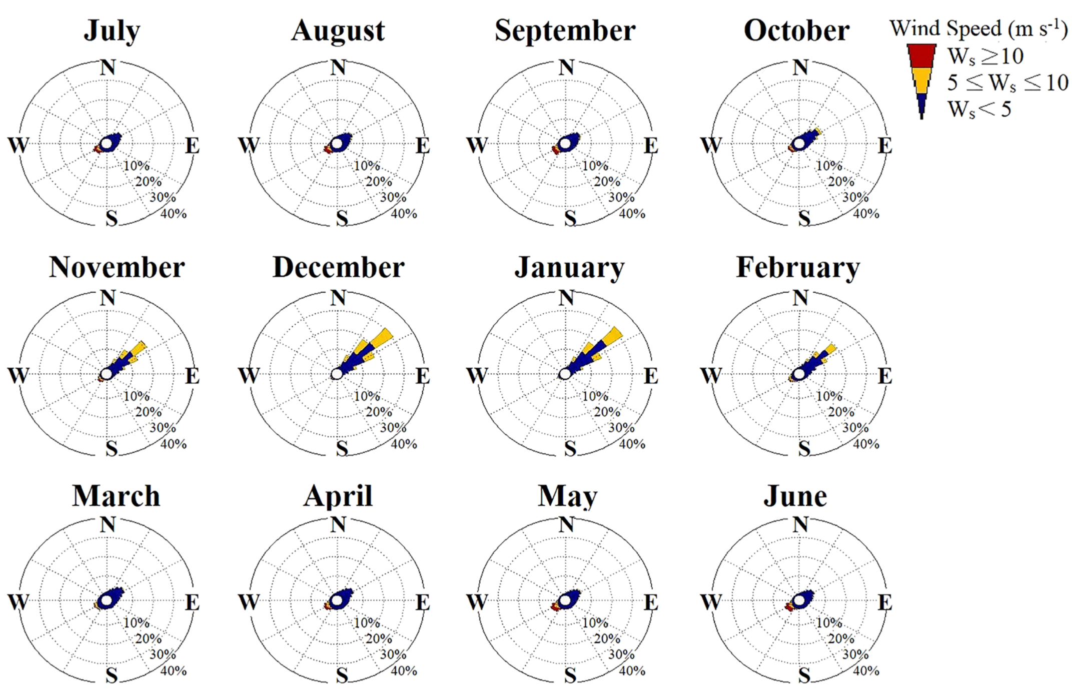

Figure 5. Wind rose diagrams from Lake Fryxell meteorological station, a typical wind pattern across all valley bottom stations (Figures S1–S6). The frequency of northeasterly winds is much higher in summer (November, December, January, and February).

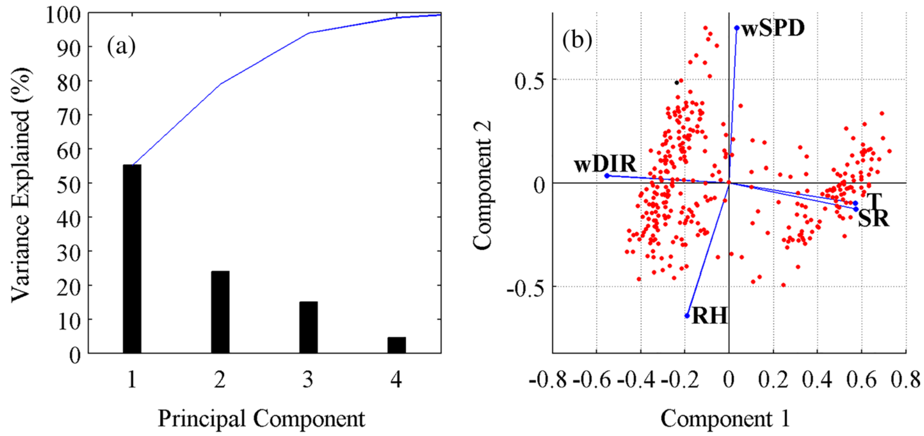

Figure 6. (a) Scree plot of variance explained by each principle component, the line is the cumulative variance explained. (b) A biplot of loadings and scores for each variable, where *T* is surface air temperature, SR is solar radiation, RH is relative humidity, wDIR is wind direction, and wSPD is wind speed.

solar flux in the MDVs is present between 19 August and 24 April. Here we defined summers based on valley-wide warming with distance from the coast. Previous work has shown that averaged summer air temperatures are highly correlated in the valleys with an upvalley trend of warmer temperatures (Bull, 1966; Doran, McKay et al., 2002; Ebnet et al., 2005; Fountain et al., 2014). In contrast, during the remaining parts of the year, that correlation breaks down as local inversions and a stable atmosphere develop, and reduced mixing causes high spatial variability in air temperatures (Doran, McKay et al., 2002; Nylen et al., 2004). Due to continuous solar radiation, the valleys bottoms heat up during summers and upvalley temperatures become correlated between the stations with distance from the coast. These conditons are unlike those in winters when inversions develop due to radiative heat loss when no solar flux is present (Nylen et al., 2004). To define summer, we use the correlation coefficient and p value of the linear regression of mean daily air temperature (averaged over the period of record and corrected for elevation) with distance upvalley (Figures 7a and 7b). To test the response of atmospheric stability on seasonal time scales, we compare our results in Figure 7a to bulk Richardson number (Figure 7d). Our calculation of bulk Richardson number (R_b) made several assumptions (see methods); however, the results corroborate with the only other atmospheric stability calculations in MDVs between 1986 and 1987 (Clow et al., 1988). Typically, values of $R_b > 0.2$ correspond to stable atmosphere. The results correspond well with the transition of up-valley warming, that is, summer (Figure 7a). Summer is therefore defined for the period of time that the daily regression is statistically significant, from 5 November to 20 February. Examining solar radiation, if summer is defined as months with average ≥100 W m^{-2}, then summer is defined as November through February (Figure 8).

4. Discussion

Solar radiation is not uniform across the stations due to topographic shading (Dana et al., 1998) and cloudiness (Doran, McKay et al., 2002). Topographic solar radiation models showed that the main driver of spatial variations in solar radiation is topography (Dana et al., 1998); cloudiness plays a secondary role. For example, cloud cover over Taylor Valley, based on proxy estimates and field observations, indicates more cloudiness in eastern Taylor Valley than in western Taylor Valley (Acosta, 2016; Doran, McKay et al., 2002). The long-term trends of solar radiation are similar across the stations but with different means (Figure 2). Long-term trends are related to atmospheric aerosol content from nonpolar sources rather than cloud cover (Obryk et al., 2018).

Similarly, long-term trends of surface air temperatures in the MDVs are similar but with different means (Figure 3). Annually averaged surface air temperatures cooled between 1986 and 1999 at −0.7°C per decade, a cooling that was attributed to decreased winds and less cloudy conditions (Doran, Priscu et al., 2002). Here we show that this cooling persisted until 2005 ±1 at all stations with sufficiently long record for the analysis but with different rates (Table 2). The cooling rates and their timing vary among stations due to the length of the time series or missing data, both of which can skew the analysis. We

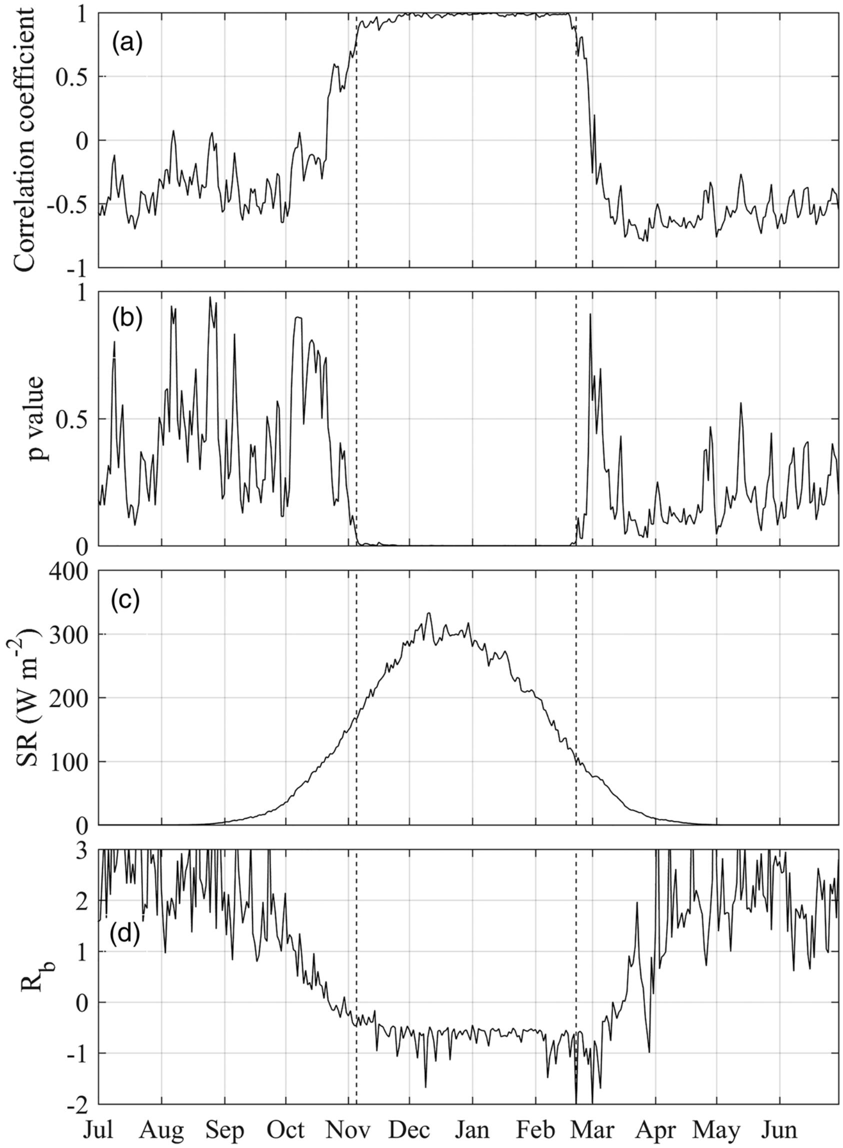

Figure 7. Time series (days) of (a) the correlation coefficient between distance from the coast and upvalley warming normalized to sea level and (b) its p value, (c) daily averaged solar radiation (SR), and (d) bulk Richardson number (R_b). Dashed vertical lines denote summer when the up-valley warming from the coast is statistically significant (between 5 November and 20 February). All data shown are averaged (daily values) over the period of record.

focused on Lake Hoare station because it has the longest continuous record and it was previously analyzed by Doran, Priscu et al. (2002). The Lake Hoare station showed statistically significant cooling at −0.7°C per decade ($p < 0.01$) until 2006 (Figure 4), a rate similar to Doran, Priscu et al. (2002). After 2006, no statistically significant trend was detected.

The Lake Hoare climate trend shift during 2005 ±1 differs from that of Gooseff et al. (2017) who detected the shift in the summer of 2001–2002. The disagreement can be reconciled by the differences in statistical approaches. We used running mean averaged air temperatures whereas Gooseff et al. (2017) used December, January, February averaged air temperatures. We also used a 4-year-longer data set.

In environmental studies, including meteorology and climatology, seasons are defined to coincide with calendar months (3-month average) to facilitate data compilation and to standardize seasonal comparisons. The most common definition for summer in the Antarctic literature is December, January, and February, often explicitly defined for dry valleys (Doran, McKay et al., 2002), Queen Maud Land, (Dale et al., 2015),

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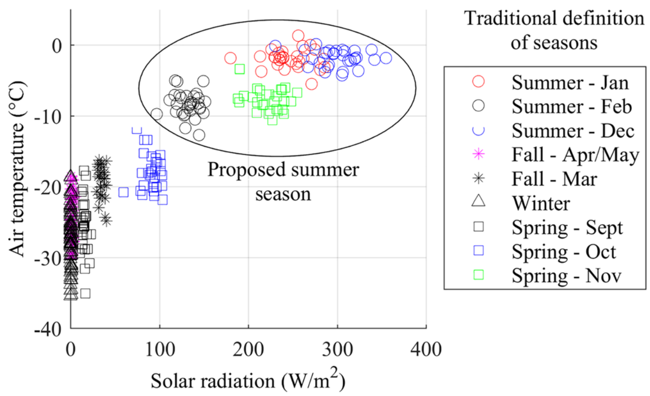

Figure 8. Relationship between solar radiation and monthly averaged air temperatures from Lake Hoare meteorological station. Legend represents traditional definition of seasons where circles are summers, asterisks are fall, triangles are winter, and squares are spring. Encircled points are November, December, January, and February reflecting newly defined summer season.

Ellsworth Land, (McKay et al., 2019), the Antarctic Peninsula (Marshall et al., 2006), and in a synthesis of Antarctic temperatures across the continent (Chapman & Walsh, 2007). However, there have been alternative definitions, including summer as December and January, Keys (1980) following Rusin (1964), and as November–February (Bromwich, 1989; Gibson & Trull, 1999; Kameda et al., 1997; Knox et al., 2016). This represents the second most common definition of Antarctic summer. Alternatively, Huybers and Denton (2008) used a vastly different approach to account for changing environmental conditions over long (10^4 years) time periods. They defined "summer duration" as the number of days in which the diurnal average insolation intensity exceeds 250 W m^{-2}. Defining summer in terms of an environmental variable such as light levels, temperature, and melting represents a completely different approach. From a hydrological perspective, December and January, are the most relevant months during which melt occurs. However, from an ecological perspective, defining summer between November and February is more appropriate due to increased biological activity. Lake ecosystems are active year-round and increased penetrating solar radiation enhances their productivity (Hawes et al., 2016). Soil fauna have been shown to respond to soil moisture more so than summer air temperatures (Andriuzzi et al., 2018). We reexamine the seasonal definitions for the MDVs based on air temperature correlation with distance from the coast as well as solar radiation, and we propose that summer lasts from November through February.

Since the MDVs' discovery in 1903 (Scott, 1905), numerous publications have documented up-valley warming with distance from the coast during austral summers (Bull, 1966; Doran, McKay et al., 2002; Nylen et al., 2004; Thompson et al., 1971). These observations have been corroborated by empirical models (Doran, McKay et al., 2002; Ebnet et al., 2005; Fountain et al., 2014; McKay, 2015). Summer averaged (December, January, and February) surface air temperatures warming, normalized to sea level using the dry adiabatic lapse rate (potential temperature), across all stations in MDVs are highly correlated with distance from the coast, $r^2 = 0.99$ (Doran, McKay et al., 2002). This relationship was shown to be valid at high elevation sites as well (Fountain et al., 2014). However, for stations distant from the coast, this warming might be driven more by solar radiation due to reduced cloud cover instead of the influence of coastal winds (McKay, 2015). We attribute the seasonal upvalley warming between November and February (Figure 7a) to solar radiation (Figure 7c), which is responsible for a shift from mostly stable (winter season) to unstable (summer season) atmosphere (Figure 7d) due to heating of the soil. The onset of summer requires a greater amount of solar radiation in order to overcome the latent heat. Conversely, the termination of summer is controlled by the latent heat released from the soils. Hence, the solar radiation difference between onset and termination of the summer season (Figure 7c).

The change in the atmospheric stability in this region is driven by the solar heating of the soils, which is a typical driver of an onshore sea breeze common to coastal areas globally (Thompson et al., 1971). The difference in the MDVs is continuous presence or absence of solar radiation on annual scales; during the summers thermally induced offshore breezes form (Clow et al., 1988; Colacino & Stocchino, 1978; McKendry & Lewthwaite, 1990; Thompson et al., 1971), a process that is moot during the winters (Figure 7). The seasonal change in atmospheric stability and the onset of up-valley warming is consequently reflected in the change of wind direction frequency, from primarily southwesterly to a combination of southwesterly and northeasterly during the austral summer (Figure 5), which is in agreement with the upvalley warming (Figure 7a). Summer heating of the soils occurs in other ice-free regions across Antarctica, and this revised definition of summer may be applied.

The summer season defined between November and February is further examined in relation to solar radiation and surface air temperature (Figure 8). Solar radiation had been shown to drive surface air temperatures on the Antarctic Plateau (Laepple et al., 2011), and the mean solar radiation in the MDVs is 102 W m^{-2}. Such definition of summer clusters November with December, January, and February (Figure 8), further supporting our analysis.

We defined MDVs summer as November through February. We propose that March and October are fall and spring, respectively, when the Sun sets and rises above the horizon and no significant surface changes occur during these months. Winter is defined as April through September.

5. Conclusions

This is the first study to provide climate assessment for the MDV region based on 30 years of weather observations (climate is defined based on a 30-year average). The mean annual air temperature and solar radiation in the MDVs varied between −14.7°C and −29.6°C and between 72.1 and 122.4 W m^{-2}, respectively. Air temperatures cooled between 1986 and 2006 at 0.7°C per decade (based on the longest continuous record at Lake Hoare station), a trend that was previously reported only until 2001. No apparent trend was detected afterward. The cooling trend could be attributed to decreased winds (Doran, Priscu et al., 2002), which have a profound influence on the regional climate (Speirs et al., 2013).

We redefine summer season based on a physical change: an up-valley warming driven by the solar radiation, expressed as a change in atmospheric stability associated with the predominant wind direction change. Based on the shift in atmospheric stability and associated up-valley warming from the coast and concurrent wind direction change, we propose to redefine summer season in the MDVs as between November and February. The newly defined seasons are based on physical observations and they also align better with ecosystem ephemerality (productivity) in the region. The seasonality defined based on the up-valley warming (i.e., atmospheric stability), driven by the solar radiation, is universal and is applicable to other ice-free regions in Antarctica because it is physically based.

Data Availability Statement

Data are available online (at www.mcmlter.org).

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