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Spatiotemporal Impact of Snow on Underwater Photosynthetically Active Radiation in Taylor Valley, East Antarctica

Madeline E. Myers

Louisiana State University and Agricultural and Mechanical College

SPATIOTEMPORAL IMPACT OF SNOW ON UNDERWATER PHOTOSYNTHETICALLY ACTIVE RADIATION IN TAYLOR VALLEY, EAST ANTARCTICA

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Madeline Elizabeth Myers
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LIST OF ABBREVIATIONS

ASL	Amundsen Sea Low
AWS	Automated Weather Station
BOYM	Lake Bonney Meteorological Station
EXEM	Explorers Cove Meteorological Station
FRLM	Lake Fryxell Meteorological Station
HOEM	Lake Hoare Meteorological Station
LH	Lake Hoare
MCM LTER	McMurdo Long Term Ecological Research
MDVs	McMurdo Dry Valleys
PAR	Photosynthetically active radiation
PPR	Primary Productivity
RH	Relative Humidity
S PAR	Surface Photosynthetically Active Radiation
SWE	Snow Water Equivalent
TV	Taylor Valley
UW PAR	Underwater Photosynthetically Active Radiation
WLB	West Lake Bonney

ABSTRACT

The role of snow on underwater photosynthetically active radiation (UW PAR) in the McMurdo Dry Valleys (MDVs) has been understudied due to lack of a detailed snowfall record. Research has shown that a relationship between snow cover and UW PAR exists, but the extent has never been evaluated in great detail. Although annual snowfall values in the MDVs are low (3 to 50 mm water equivalent annually), trends of increasing snowfall on the continent under future warming conditions could lead to an increased role for snow in regulating UW PAR (and associated primary productivity). Here, I discuss evidence from the snowfall record, surface PAR, and UW PAR, of the influence of snowfall on UW PAR in the major lakes of Taylor Valley. This study aims to quantify the spatiotemporal impact of lake ice snow packs on UW PAR in Taylor Valley from field surveys, long-term UW PAR, and meteorological data. Lake Fryxell has the strongest seasonality to precipitation, which decreases inland. On average, Lake Fryxell also has the most days with snow cover on the lake ice. Lake Hoare is experiencing an increase in Fall snow persistence since the 2007 snow year. Snow less than 0.5 mm snow water equivalent (SWE) can suppress UW PAR by 40%. The calendar day that snow falls often determines whether phototrophs will switch from photosynthesis to respiration, which suggests the importance to seasonality in determining the impact of snow on photoautotrophs and lake-wide carbon budget.

INTRODUCTION

Solar radiation functions as an important regulator to aquatic ecosystems (Kirk, 1994). Radiation harnessed for photosynthesis falls between wavelengths of 350 to 750 nm and is referred to as Photosynthetically Active Radiation (PAR) (McCree, 1981). It roughly coincides with the spectrum of visible light. The radiation that reaches aquatic ecosystems is controlled by absorption and scattering associated with the mediums that it passes through such as the atmosphere, water column, and occasionally ice and snow.

Polar regions receive 24 hours of sunlight during the summer and complete darkness during the winter, and annually receive significantly less solar energy than the equator. Less solar energy allows for cold temperatures (more freezing degree-days) and some lakes to maintain an ice cover through much of the summer. In Antarctica, there are a number of lakes which keep an ice cover year-round. Snow accumulates on the lake ice surface and reduces the irradiance that reaches the ice surface, in some cases, to near zero.

In east Antarctica, the McMurdo Long Term Ecological Research (MCM LTER) project has supported research in the McMurdo Dry Valleys (MDVs) since 1992. MDV ecosystems are highly sensitive to small fluctuations due to the limited availability of water and energy (Moorhead and Priscu 1998). Both pelagic and benthic photosynthesis are light-limited (Lizotte and Priscu, 1992; Vopel and Hawes, 2006) and changes to the available radiation could initiate a lasting ecological response.

The MDVs are located along the continental margin of Antarctica in southern Victoria Land at 77°30’S and 162°E (Figure 1). Taylor Valley (TV) lies within the MDVs and has an average annual valley bottom air temperature range of -18°C to -20°C (Doran et al., 2002a) and only receives 3 to 50 mm snow water equivalent (SWE) annually (Fountain et al., 2010), making

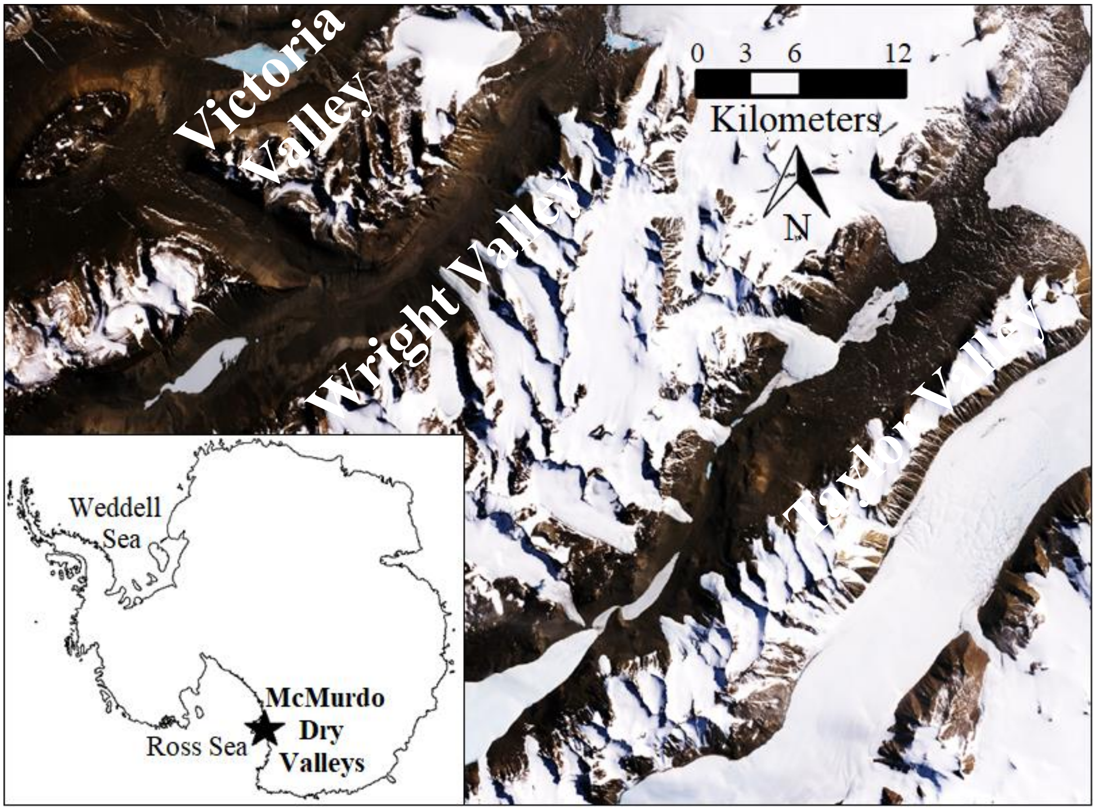

Figure 1. Location of the McMurdo Dry Valleys with Taylor Valley highlighted. Satellite imagery from Landsat 7's Enhanced Thematic Mapper plus (ETM+) in 1999.

it a polar desert. The Transantarctic Mountains buffer the MDVs from the East Antarctic Ice Sheet and allow them to remain ice-free with the exception of glaciers that flow from the surrounding mountains (Chinn, 1990). Ephemeral streams supply glacial melt to valley-bottom closed-basin lakes. Water input from the glaciers is balanced by evaporation and sublimation of the permanent ice cover on the lakes (Doran et al., 1994; Dugan et al., 2013) and the perennial moats that form during summer (Chinn, 1993). Moat ice is distinguishable from permanent lake ice by its smooth, flat texture.

Snow has been historically understudied in TV due to lack of a precipitation record and measurement difficulty. Although snow accumulation contributes minimally to the hydrologic budget (Chinn, 1981), it regulates the local radiation budget by increasing the albedo and blocking underwater radiation available for use by photoautotrophs. Upon deposition, snow is

redistributed by wind and is lost to the atmosphere by sublimation and evaporation and can persist for weeks (Eveland et al., 2013). Previous publications have acknowledged the reduction of UW PAR by snow (Priscu 1992, Adams et al., 1998, Fritsen et al., 1998, Howard-Williams et al., 1998, Fritsen and Priscu 1999), but the impact has never been evaluated in detail.

Although annual snowfall values in the MDVs are low, trends of increasing snow cover could augment its local impact. Reduced sea ice concentrations in the nearby Ross Sea under future warming conditions increase the surface area available for evaporation and therefore influences precipitation in the MDVs. Here, I quantify the spatiotemporal impact of snow on UW PAR in TV lakes from meteorologic, limnologic, camera, and satellite data. Our understanding of ecosystem dynamics within TV lakes is currently limited to a few sample sites each season. Establishment of a numerical relationship between a snow pack and UW PAR would enhance our interpretation of the aquatic ecosystem response to the changing climate.

BACKGROUND

2.1. Precipitation in Taylor Valley

Typically, precipitation falls as snow although rain occurs very rarely (Keys, 1980). The study of snow in the MDVs has historically been dismissed since it has little hydrologic importance (Chinn, 1981). The greatest accumulation of snow occurs at the coast (Bull, 1966; Keys, 1980; Fountain et al., 2010; Eveland et al., 2013). Keys (1980) previously noted a typical snowfall density of 80 kg m^{-3} at Lake Vanda located in Wright Valley of the MDVs and uses 100 kg m^{-3} to describe the 100 mm water equivalent estimated for the average annual precipitation in the McMurdo region. To my knowledge, no measurements of precipitation density in TV have been published. Katabatic winds coming from the Polar Plateau transport snow to the MDVs and resemble precipitation events (Nylen et al., 2004; Fountain et al., 2010). Dry conditions created from low precipitation relative to evaporation potential and katabatic winds encourage high ablation rates (Clow et al., 1988).

2.2. Controls on Snow Ablation Rates

Topography and regional microclimates create spatially heterogeneous ablation rates which decrease as summer progresses (Eveland et al., 2013). Within TV, the average relative humidity (RH) is 68% and typically decreases inland. Wind speed increases inland as well. The RH and wind speed gradient drive higher sublimation rates inland (Doran et al., 2002a). McMurdo Station, roughly 90 km east of TV across the McMurdo Sound, is typically foggier during the summer as the sea ice extent retreats toward the station (Doran et al., 2002a). Decline in sea ice extent due to global climatic changes could increase the RH of TV and therefore snow persistence.

2.3. Optical Properties of Taylor Valley Lakes

Snow cover is a major contributor to attenuation of light in ice-covered lakes (Hawes 1985; Bolsenga et al., 1996). Trodahl and Buckley (1990) note a transmission reduction of 30% by 18 mm snow cover on McMurdo Sound sea ice. Attenuation and scattering of light through the ice depends on: ice color, presence of wind-blown sediment, gas bubbles, and crystal structure of the ice (Howard-Williams et al., 1998). Transmission is greater under diffuse light than direct light (Priscu, 1992). The ice cover prevents surface turbulence from wind, therefore creating highly stratified lakes (Spigel and Priscu, 1998), which along with low turbidity contributes to the high transmission of light in the water column. Ice cover thickness varies between 3 and 6 m (McKay et al., 1985; Clow et al., 1988; Howard-Williams et al., 1998; Doran et al., 2002b, Obryk et al., 2016). Lake ice turnover typically takes 3 to 5 years as ice grows on the bottom and ablates from the top (Dugan et al., 2013). The nature of crystal growth along a vertical c axis enhances the penetration of solar radiation through the ice cover (Chinn, 1993).

The accumulation of detritus and the seasonal formation of melt lenses and bubbles decrease transmission through the ice (Fritsen et al., 1998; Fritsen and Priscu, 1999). Lake ice typically undergoes a seasonal whitening when it becomes isothermal at 0°C (Fritsen et al., 1998). Transmission is greatest in early summer when the ice is cold and completely frozen (Howard-Williams et al., 1998). With increased heating, scattering and internal absorption increase with the formation of light-scattering Tyndall figures and hoarfrost on bubbles. Further progression encourages more melt which erases cracks and light scattering features and transmission rebounds. Then, with the refreezing of the ice and formation of cracks and fissures, transmission declines as winter approaches. The spectral distribution of light entering the water

column is shifted to lower wavelengths since greater wavelengths attenuate more quickly (Palmisano and Simmons, 1987).

Low nutrient concentration in the trophogenic zone supports low phytoplankton densities which leads to low biologic attenuation of light (Howard-Williams et al., 1998). Attenuation due to sediment loads is low too due to the slow process of glacial melt (McKnight et al., 1998)

2.4. Spatial Variability of UW PAR in Taylor Valley

Average annual surface PAR (S PAR) in Taylor Valley ranges from 182 to 232 µmol photons m^{-2} s^{-1}. The maximum generally occurs at the coast and decreases inland (Doran et al., 2002a). Lake Hoare is the exception and receives the least due to topographic shading to the north and cloud coverage (Acosta, in revision). Underwater PAR (UW PAR), however, increases inland as ice thins due to warmer inland temperatures (McKay et al., 1985; Doran et al., 2002b). Doran et al. (2002b) note reduced underwater irradiance in the east lobe of Lake Bonney from cooler temperatures between 1986 and 2000, which increased the ice cover thickness. Doran et al. (2002b) also note a reduction of primary productivity by 9% per year associated with the increase in ice thickness. Accumulation of snow on the lake ice could encourage thicker ice covers by reducing ablation rates and further reduce UW PAR. Primary production in west lobe of Lake Bonney (WLB) was reduced by 23% during a flood year in 2002 due to stream induced water column turbidity, indicating the sensitivity of photoautotrophs to light disturbances. PAR was reduced the greatest at WLB due to higher gradient streams and resulting larger sediment loads (Foreman et al., 2004). Persisting snow covers could have the potential to create lasting changes to aquatic ecosystem dynamics of TV.

2.5. Physical and Biological Limnology of Taylor Valley

Taylor Valley lake ecosystems are largely dominated by microbial loop dynamics and nearly half of heterotrophic carbon demand is met by primary productivity (Takacs et al., 2001). Lakes Fryxell and Bonney are permanently stratified and vertical distribution of organisms is generally constrained by light availability and the nutrient concentrations at the chemocline (Lizotte and Priscu, 1991; Vick and Priscu, 2012). Lake Hoare, however, is not permanently stratified and exhibits a higher variability of Chl-a maximum depth because the lower limit is controlled by light availability (Roberts et al., 2004). Of the three lakes, Lake Bonney exhibits the most extreme bathymetric gradient. It has a surface area of 4.5 km^2 (Acosta, in revision) and maximum depth of 40 m (Dohli et al., 2015). Lakes Hoare and Fryxell are shallower and have a lake surface area of 2.27 km^2 and 6.82 km^2 (Acosta, in revision) and maximum depths of 20 m (Dohli et al., 2015) and 34 m (Spigel and Priscu, 1998), respectively. It is important to note that Lake Hoare has risen by about 1 m since that datum was collected (personal communication).

The response of pelagic autotrophs to light availability in East Lake Bonney has been extensively studied (Lizotte and Priscu, 1992; Thurman et al., 2012; Morgan-Kiss et al., 2016). Populations are vertically stratified and respond differently to photic disturbances (Lizotte et al., 1996). Lizotte et al. (1996) discuss the limiting factors for photosynthesis of the different communities. Shallow phytoplankton are typically more nutrient-limited, while deeper communities that live near the nutricline are more light-limited, as evidenced from photosynthetic quantum yields at depth for the progression of the Winter-Summer transition.

In Lake Hoare, production from phytoplankton equates to only 15% of benthic productivity (Moorhead et al., 2005). Similar to Lake Bonney, populations of benthic algal mats also have variable photosynthetic efficiencies depending on their depth (Hawes and Schwarz,

2000; Vopel and Hawes, 2006). The inherently static nature of benthic mats implies they may be more impacted by snow than pelagic phototrophs.

METHODS

3.1. Update and Evaluate Precipitation Data

Snowfall has been measured at 4 meteorological stations in TV using sonic rangers (Campbell Scientific SR50), weighing bucket gauges (Belfort), and a tipping bucket (Texas Electronics TE525MM) since 1994 (Figure 2). A Nipher Shield was mounted over the opening of the weighing and tipping buckets roughly 1 m above the ground. Sonic rangers record the decrease in vertical distance to the ground, yielding a snow depth. The weighing bucket records precipitation from a bucket on a digital scale. The tipping bucket captures and melts snow in an

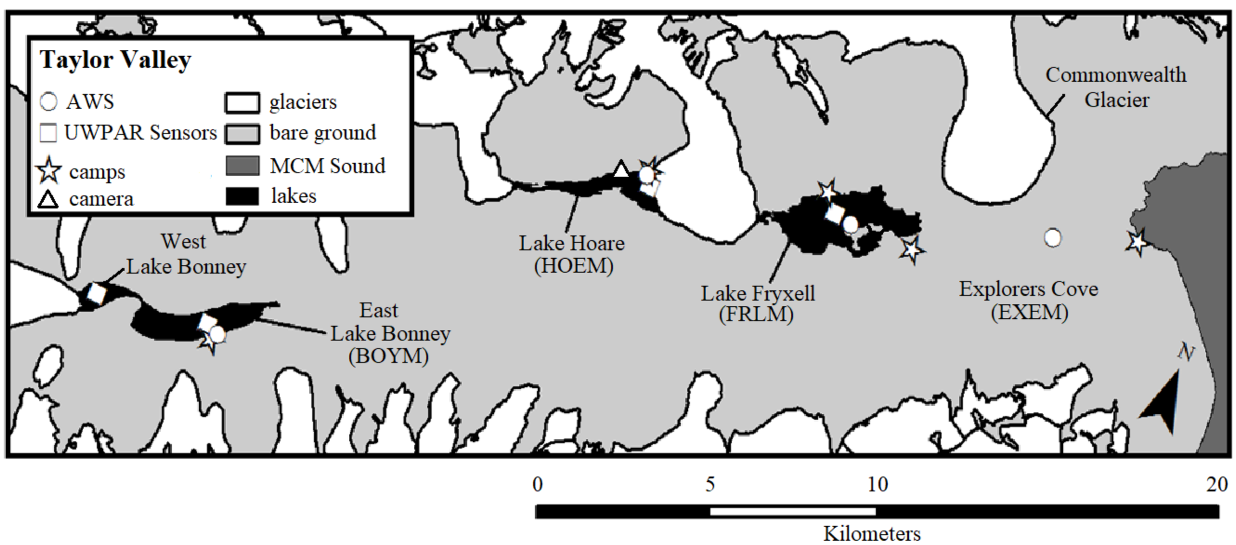

Figure 2. Location of measurement sites and study areas within Taylor Valley.

antifreeze solution. The additional volume from the snow tips the bucket and records 0.1 mm SWE. Data are telemetered and accessible from the MCM LTER website, http://mcm.lternet.edu/.

Daily averages of precipitation are calculated from data recorded every 15 minutes. Differences in daily averages less than 0.5 cm and 0.5 mm SWE for the sonic ranger and

weighing gauge respectively were removed based on the instruments' precision and the low signal to noise ratio. False readings due to snow or sand blown from katabatic winds are removed based on average wind speed exceeding 5 m/s and direction between 230° and 280°azimuth, recorded at the meteorological stations (Nylen et al., 2004). Statistical analysis of a decade of ground-truthed data indicate the climatology of precipitation. Therefore, precipitation during low RH (less than 40%), maximum wind speeds greater than 15 m s^{-1} or exceeding 30 mm SWE are removed. If the difference in recorded precipitation between instruments at the same station exceeds 5 mm SWE, those data are also removed. Station set-up and data processing details are explained in depth by Fountain et al. (2010). Sonic ranger distances were converted to mm SWE from measured snow density of 83 kg m^{-3}. Volume was derived from measurements of freshly fallen snow in a 0.5 m x 0.5 m clean, smooth surface. The snow was melted in a bag and weighed to calculate density.

Similar to water year in hydrological analyses, a "snow year" was defined from May 1 to April 30 of the following year, which roughly coincides with the final sunset of the season. Total measured precipitation was calculated for each snow year as the sum of differences in daily averages that exceed the threshold defined above. The use of a snow year allows better comparison to the UW PAR record. Snow years are divided into Spring, Summer, and Fall. Spring begins with first light and ends November 15. Fall begins February 15 and ends with the final sunset. Dates coincide with statistically distinct climate conditions (Obryk, personal communication). Seasonal means were calculated from seasons with over 75% data available.

Due to the low signal-to-noise ratio it was necessary to ground-truth precipitation measurements and recalibrate the weighing buckets. Accumulation was measured manually at each camp within TV during the 2018 snow year from a smooth surface. Weighing buckets were

tested by adding a known volume to the bucket and comparing that value to the value recorded by the instrument.

The meteorological snow record has been evaluated against camera images taken at Lake Hoare every 6 hours since October of 2007 (Figure 3). Total number of days with snow on bare ground was determined from visual inspection of the camera record. Any new accumulation of snow was considered an event. Persistence for each event was calculated by subtracting the end date from the initial date with snow on the ground for that event. Images where the camera was covered by snow were excluded.

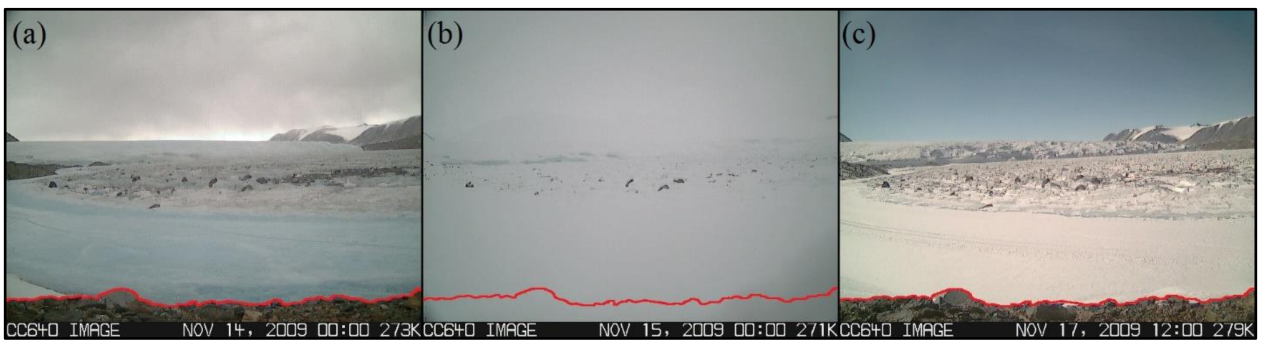

Figure 3. Camera images taken at Lake Hoare immediately (a) before, (b) during, and (c) following a Nov 15, 2009 precipitation event. Red line indicates edge of bare ground used for determining whether or not there was snow cover. Camera faces east. The location can be found in Figure 2.

Summer snow cover at Lake Hoare was reconstructed for the years prior to the establishment of the camera from glacier accumulation data. Accumulation measurements have been taken since 1993 for Commonwealth Glacier and data are accessible on the MCM LTER website. This study utilizes data from stake 23. Accumulation is typically measured between November and January each year. Here, I use the percentage of days with snow on the ground recorded between accumulation measurements. Simple linear regression of accumulation and the percentage of days with snow cover between those two measurements was used to derive the

relationship between accumulation and the percentage of snow cover days for the summer at Lake Hoare since 1993.

3.2. UW PAR Monitoring Station

UW PAR data and collection procedures are also available at the MCM LTER website. Figure 4 shows UW PAR monitoring station. Due to the dynamic nature of the ice cover, UW PAR is corrected from attenuation coefficients measured throughout the field season and pressure transducers attached to the UW PAR cage. Daily averaged UW PAR at 10 m depth was

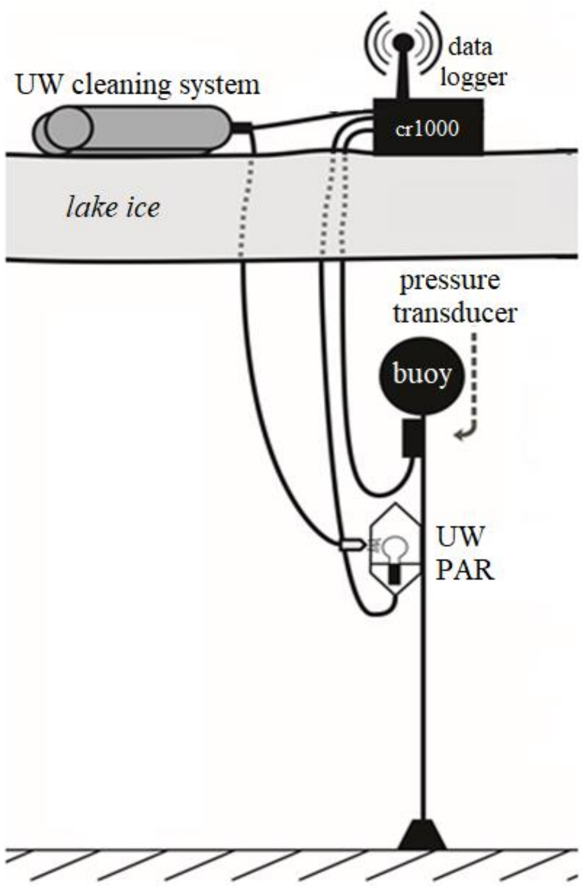

Figure 4. UW PAR monitoring station. UW cleaning system consists of 2-3 dive tanks that blow bubbles on UW PAR to prevent biofouling. Figure adapted from Dugan et al. (2013).

extended throughout the water column from average seasonal attenuation coefficients for each lake. From daily averaged UW PAR profiles, mean UW PAR for each lake is calculated by calendar day for the 2007 through 2016 snow years.

The effect of snow on UW PAR can be divided into two parts: (1) the initial blanketing effect during and immediately after precipitation and (2) the formation of snowpacks on the ice surface from ablation and redistribution by wind.

3.3. UW PAR During Precipitation Event

The impact of blanketed snow on UW PAR was evaluated allowing snow to accumulate on a flat quantum sensor (LI190 SB) inset into a piece of wood. Simultaneously, another LI190 SB measured PAR and kept free of snow accumulation. Snow depth was measured from the surface of the wood and transmittance was calculated by dividing PAR measured by the covered sensor by the background surface PAR. Mean UW PAR for each lake is multiplied by light transmission values to establish potential UW PAR suppression by calendar day from typical snow accumulations of 0.5, 1, and 2 cm snow falls. Values above 0.5 cm are derived from Perovich (2007).

3.4. Spatiotemporal Impact of Snowpack on UW PAR

The spatial control of a lake ice snow pack on UW PAR was evaluated from a UW PAR survey conducted during the 2018 snow year (Figure 5). The UW PAR regime varies between each lake of TV; however, logistical constraints limited the survey to Lake Hoare. We took vertical casts of UW PAR beneath a 6 m x 7 m tarp. The survey was conducted on December 17 and 18 between 8 and 11 AM to minimize variability in sun position. The two dates highlight variability associated with variable cloud conditions. Rather than drill separate survey holes, the

tarp was moved, which maintained equivalent ice conditions, including thickness which was recorded as well. We used agricultural-grade tarp to minimize transmission. UW PAR was recorded every 0.5 m from a depth of 17 m to the water surface. A vertical profile was taken every 1.2 m along the snowpack radius.

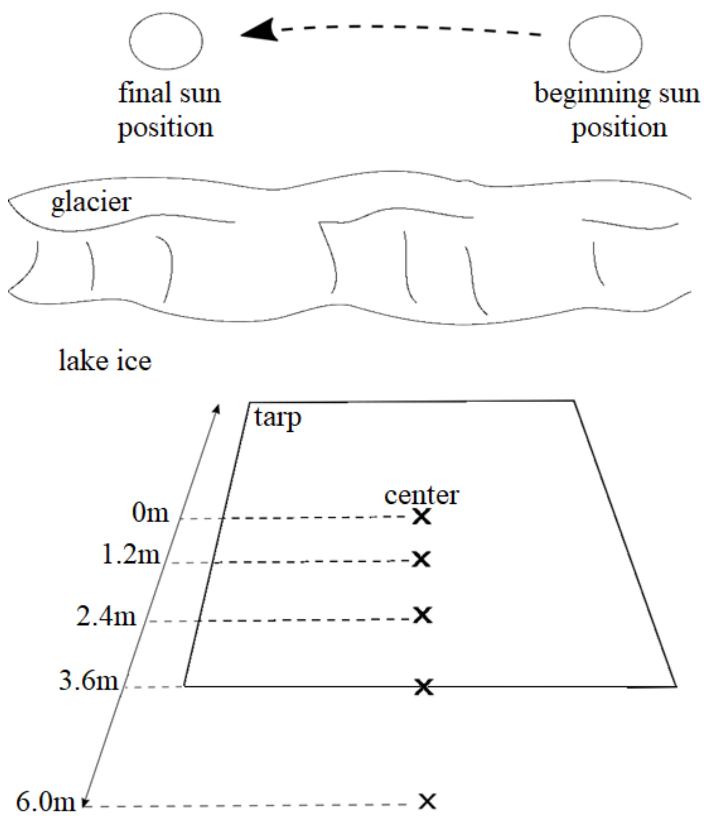

Figure 5. Schematic of UW PAR survey. "X"s indicate locations of survey holes in tarp. Not to scale.

RESULTS

4.1. Precipitation in Taylor Valley

Patterns of precipitation in Taylor Valley were determined from automated weather station (AWS) and camera data. During the 2018-19 field season, weighted gauges were calibrated. Snow density was measured to correct sonic ranger data to mm SWE. At the Lake Bonney met station (station code BOYM), the gauge recorded 9 mm SWE (16%) less than was added. Explorers Cove (EXEM) reported 31 mm SWE (57%) less than the volume added to the gauge; however, when comparing EXEM data to measured accumulation nearby, the values agreed within about 0.5 mm SWE. Although it snowed several times during the period observed from November 2018 to December 2019, snow only accumulated twice because it melted very rapidly. A very rare observation of rain mixed with snow was made on the morning of December 20^{th}, 2018. Accumulated snow at Lake Fryxell had densities of 82 and 84 kg m^{-3}. These measurements agree with previously published snow densities within the Dry Valleys (Keys, 1980).

Comparison with the previously published record allows for interpretation of AWS data in a historical context (Figure 6). Overlapping measurement types tend to agree across stations. BOYM shows the greatest agreement, likely due to the infrequency of precipitation events which would reduce measurement error. The greatest disagreement at BOYM is in 2004. The Fountain et al. (2010) weighted gauge measured 4-5 times more accumulation than the sonic ranger from the same study and the weighted gauge data from this study. It is likely erroneous due to the agreement of the other two sensors. The sonic ranger is typically lower than the weighted gauge where data are available. The disagreement from 2008 is attributed to two 4 mm SWE events

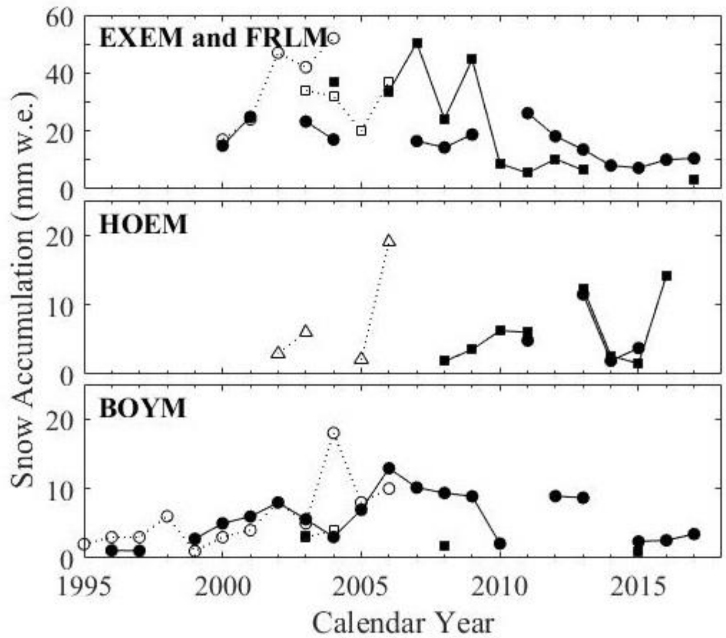

Figure 6. Snow accumulation by calendar year from Fountain et al., 2010 (open) and this study (closed). Symbology denotes weighted gauge (circles), sonic ranger (squares), and tipping bucket (triangles). FRLM only has a sonic ranger and EXEM a weighted gauge. The two are combined in the top plot. Years with less than 75% data available are excluded. Appendix A contains a table of errors for accumulation derived in this study.

recorded by the weighted gauge on January 10 and 11. The camera confirms that Lake Hoare received a few mm SWE on both days which disappeared the same day. Annual accumulation calculations from sonic ranger data based on daily averages may underestimate years with events with persistence less than 1 day. If snow both accumulates and ablates or sublimates within one day, then the daily average accumulation is likely about half of the actual accumulation recorded by the sonic ranger. Depending on the rate of accumulation and dissipation the daily average could actually be much less. This could result in an underestimation of precipitation where accumulation is the difference in daily averages.

A comparison of this new data set with the accumulation calculated by Fountain et al. (2010) shows that the agreement is variable at EXEM. Data from 2000 and 2001 agree within 2 mm SWE Data from 2003 and 2004, however is about 30 mm SWE higher than this study. One

explanation is missing data from January, 2003 although 30 mm SWE in one month is unlikely. One event shows up as 8 mm SWE on August 3, 2003 which Fountain et al. (2010) includes because the mean wind speed is less than 5 m s^{-1}; however, reprocessing of the wind data shows mean wind speed of 17 m s^{-1}, much higher than the katabatic threshold. There is another similar instance in 2004 around May 15 and June 8 where 33 mm SWE total are included and would have been removed with new wind speed considerations. For the two data points that do overlap, data from the sonic ranger at Lake Fryxell met station (FRLM) tend to agree within 5mm SWE Data quality at Lake Hoare met station (HOEM) do not allow for overlapping data with the historical record. Where data is available, measurement types agree within 1 to 2 mm SWE. To evaluate precipitation at Lake Hoare in a historical context, we use the camera record coupled with the long-term glacier mass balance record. General agreement between the historical record and measurement types suggest that precipitation recorded by the weighted gauge and sonic ranger in this study are accurate. The sonic ranger is less efficient at capturing precipitation with persistence less than 1 day, which are frequent occurrences within Taylor Valley. Disagreement between this record and historical data are primarily attributed to inaccurate processing of daily wind speeds.

FRLM experiences the greatest amplitude of variability for the Fall. Spring follows at about half of that for the Fall (Figure 7). HOEM and BOYM have similar, low variability when compared across seasons of around 1 mm SWE deviation from the mean. Precipitation volume during the Summer at FRLM is the most consistent between all stations and seasons and has an average deviation of 0.7 mm SWE The total accumulation appears to change on longer timescales than HOEM and BOYM. HOEM experienced consistently lower accumulation until

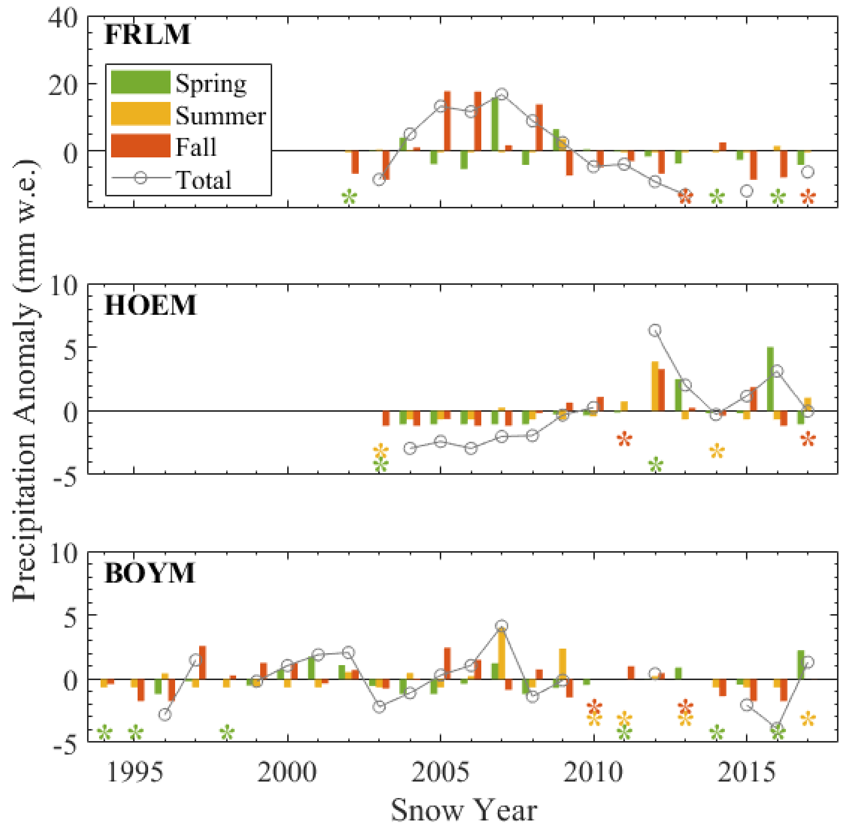

Figure 7. Precipitation anomaly at each lake AWS is separated by season indicated in color. Total precipitation anomaly is the total for all seasons, excluding winter. Asterisks indicate over 75% of data missing. Total excludes winter accumulation.

the 2010-11 season where interannual variability increased in Spring and Fall. Summer accumulation is consistently low across the entire record; however 2012-13 received anomalously high snow volume. Summer at BOYM maintains fairly consistent accumulation relative to the mean apart from the presence of two snowy summers in 2007 and 2009.

Table 1 highlights the seasonality of accumulation across each lake AWS. FRLM exhibits the strongest seasonality with over half of its precipitation occurring in the fall. It also receives the most snow: almost 4 to 5 times higher than BOYM and HOEM respectively. BOYM on average receives about 1 mm SWE more than HOEM, even when non-overlapping years are

Table 1. Mean annual snow accumulation (mm SWE) at each AWS for the duration of the record. Error represents the standard error of the mean.

Location	Spring	Summer	Fall	Total
FRLM	5.4 ± 1.6	0.5 ± 0.3	8.6 ± 2.6	14.6 ± 2.8
HOEM	1.0 ± 0.5	0.7 ± 0.4	1.2 ± 0.4	2.9 ± 0.7
BOYM	1.2 ± 0.2	0.6 ± 0.3	1.8 ± 0.3	3.9 ± 0.5

excluded. BOYM and HOEM experience similar seasonality although HOEM is only slightly weaker.

The camera at Lake Hoare (LH) reveals that there is a near tripling of the average snow cover days from about 50 to 120 days after the 2011 snow year. A snow cover heatmap (Figure 8) suggests that the increase in days with snow cover is primarily due to an increase during the

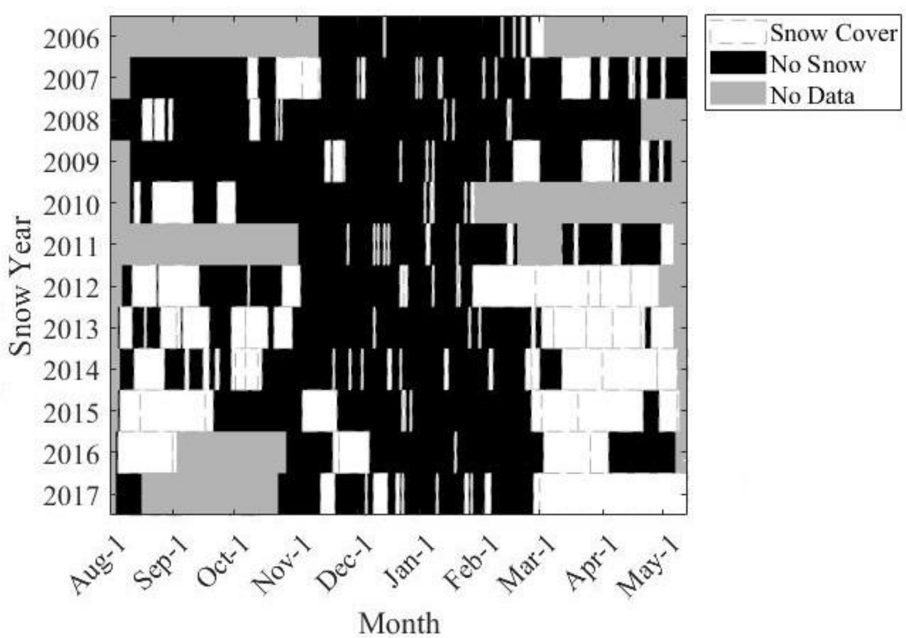

Figure 8. Snow cover record derived from the LH camera. Dashed lines around white boxes denote individual events.

Spring and Fall. Missing data from the Spring and Fall of snow years 2006, 2010, 2011, 2016, and 2017 may inaccurately portray low snow cover for those seasons. The increase in snow cover may have been more gradual. Annual snow persistence is derived from normalizing snow cover to the number of events and appears to be increasing. When broken down by season (Figure 9), it is clear that snow persistence is increasing, but only during the Fall. On average, snow cover lasts 3 days longer than Spring and 10 days longer than Summer. Low summer persistence has implications for how we analyze summer accumulation due to low signal-to-noise ratio and suggests that summer accumulation may be higher than what is recorded by the sonic ranger. Fall of 2018 had an anomalously high persistence due to precipitation on March 1 that lasted through last light. If we exclude the anomalously high persistence year, the slope of the least-squares trend line suggests Fall persistence is increasing by 1.1 day each year.

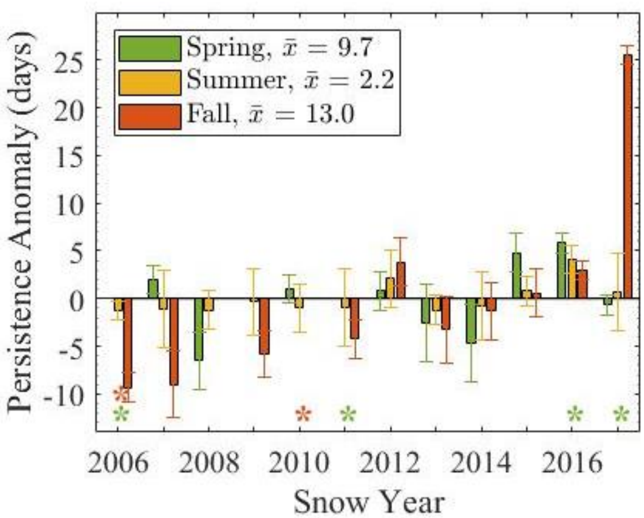

Figure 9. Persistence anomaly from the Lake Hoare camera is separated by season indicated in color. Asterisks indicate more than 75% of data missing. Sample means are given in the legend. Error bars are based on a temporal resolution of ± 0.5 days per event.

Empirical relationships rule out increased volume (Figure 7) and more snowfall events (Figure 8) as the drivers of the increase in Fall persistence, which suggests the driver is likely climatic although further analysis is required for attribution.

Linear regression of percentage of days with snow cover at Lake Hoare with accumulation measured on Commonwealth Glacier allows the analysis of summer snow cover in a historical context (Figure 10). Accumulation at Commonwealth Glacier and the percentage of days with snow cover at Lake Hoare are strongly correlated ($r^2 = 0.74$; $p < 0.001$). The long-term record reveals that summer snow cover at Lake Hoare is highly variable. Multi-year trends are present prior to 2005, followed by increased interannual variability up until 2013. The most recent 5 years of data show an increase in the fraction of days with snow cover.. An even longer record is required to determine if summer snow cover is increasing on longer timescales or if it will decline again, similar to 4-5 year trends of increasing and decreasing snow cover prior to

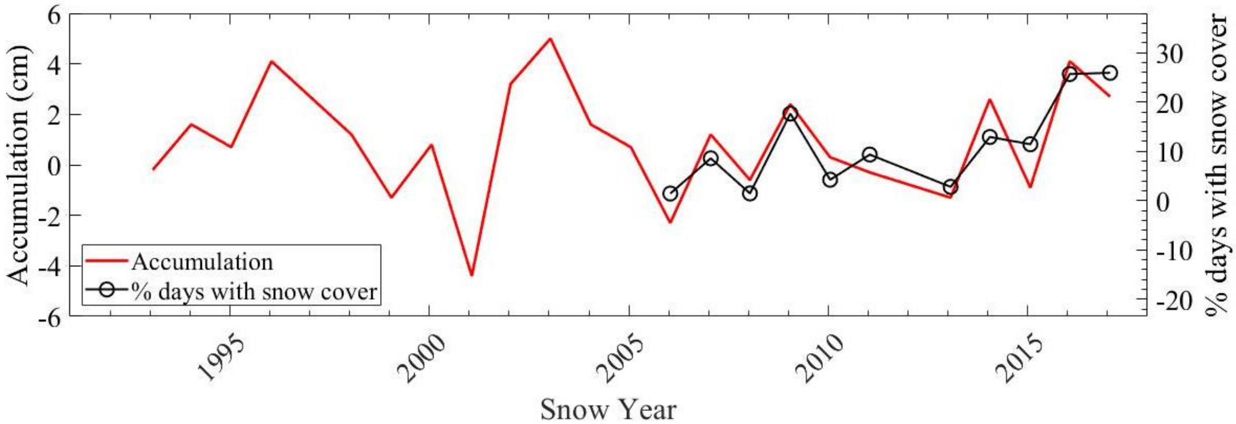

Figure 10. Percentage of days with snow on the ground between November and January plotted against accumulation measured during the same time period on Commonwealth glacier.

2006. For all stakes, the residual does not appear to follow a trend. The incorporation of other climatic factors would likely improve the snow cover estimates, however, for the purposes of this study accumulation on Commonwealth Glacier is a sufficient proxy for understanding variability in percent days with snow cover at Lake Hoare. Regression analysis indicates no correlation of snow cover with sea ice extent or mean temperature between mass balance measurements although there is a weak correlation with degree days above freezing ($r^2 = 0.25$; $p < 0.05$). Lack

of correlation with sea ice extent contradicts what would be expected since less sea ice would increase the potential moisture source for precipitation as well as increase RH which would increase snow persistence. The discrepancy may be explained by interannual variability of atmospheric patterns that control moisture transport pathways described by Patterson et al. (2005). It is necessary to examine snow cover days coupled with local sea ice extent and atmospheric variability for attribution.

Lake Fryxell, on average, has the most days with snow cover, followed by Lake Hoare. Lake Bonney has about half as many days with snow cover when compared to Lake Hoare (Table 2). During the Spring, all of the lakes have a similar number of days with snow cover.

Table 2. Mean annual snow cover (days) on each lake for the 2007 through 2016 snow years. Total number of days for each season is included in parenthesis. Error represents standard error of the mean.

Location	Spring (106)	Summer (92)	Fall (106)	Total (304)
Lake Fryxell	12.0 ± 2.6	23.5 ± 7.0	53.6 ± 37.8	64 ± 22.8
Lake Hoare	9.9 ± 2.3	22.2 ± 6.9	11.3 ± 3.8	47.9 ± 7.2
Lake Bonney	11.2 ± 3.9	14.2 ± 3.6	12.6 ± 5.0	25.2 ± 4.4

Transitioning into Summer, Lake Bonney has the least snow cover. Lake Fryxell and Hoare are most similar within 1 day and almost 10 days more than Lake Bonney. During the Fall, however, Lake Hoare behaves more similar to Lake Bonney. Their total snow cover days equate to only half of Lake Fryxell's during the same time period. The spatiotemporal heterogeneity of snow cover implies heterogeneity of the impact of snow on UW PAR.

4.2. Snow and UW PAR: Lake Blanketing

Mean UW PAR for each lake was derived between 2007 and 2016 (Figure 11). Ice thickness and optical properties variability is the primary contributor to the variability in light penetration depth across each lake under snow free conditions. During the time of this study, ice thickness averaged 4.2 m, 3.9 m, 3.7 m, and 4.9 m at West and East Lake Bonney, and Lakes Hoare and Fryxell respectively. Background UW PAR at Lake Fryxell is the lowest and appears to be the least affected by ice whitening. West Lake Bonney represents the other end member and has the highest UW PAR and greatest UW PAR reduction due to ice processes. The seasonal variability in UW PAR is important to consider when assessing the implications for snow in regulating photosynthesis due to variability in mean background values.

Snow was allowed to accumulate on a flat PAR sensor while background PAR was measured simultaneously. PAR transmission decreased at a rate of about 10% per mm up to 6 mm snow depth (Figure 12). Transmission values are consistent with Perovich (2007). The greatest variability in transmission occurred around 3 mm depth, likely owing to the low density, dendritic nature of the snow crystals.

At Lake Hoare, transmission was applied to mean UW PAR (Figure 11) to assess the role for snow in stopping benthic photosynthesis at habitation depths of 6 m, 10 m, and 13 m (Figure 13). Mat communities living at 6 m depth are least affected by snowfall across all calendar days and 13 m communities are the most affected. Irradiance only falls below compensation irradiances for 6m mats before October and after March for up to 2 cm of snow, although these dates are not so different from the start of the light season. In this case, snow may provide shelter from high summer irradiances. With up to 1 cm snow cover, for mats at 10 m depth,

compensation irradiances are met from mid-November through mid-February. With 2 cm snow cover, compensation irradiances are only met during mid- to late-November. Depending on

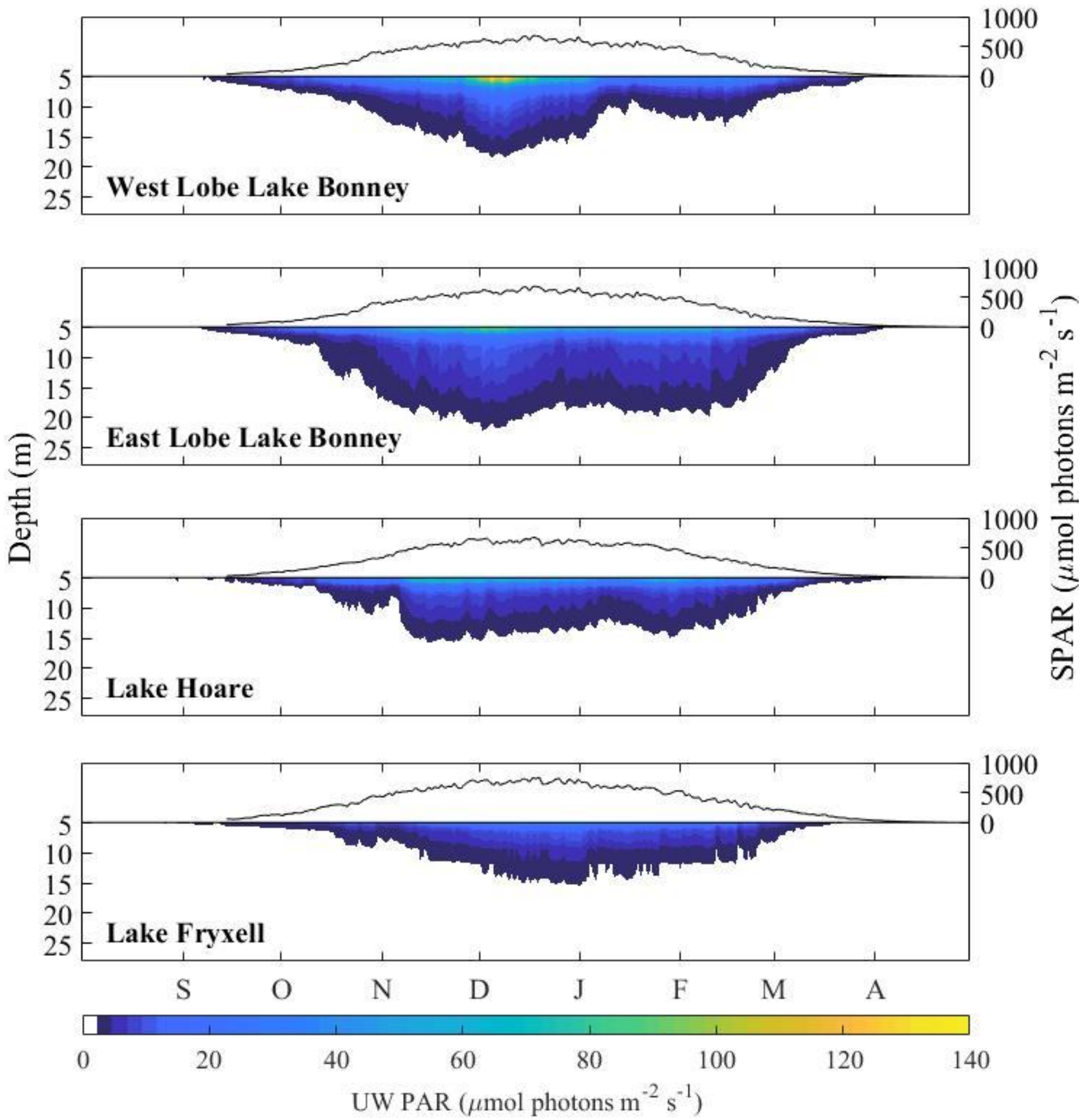

Figure 11. Mean UW PAR for each lake by calendar day calculated from 2007 to 2016. Depths where UW PAR is less than 0.5 µmol photons $m^{-2}s^{-1}$ are white. Mean surface PAR is indicated by the black line above the UW PAR plots.

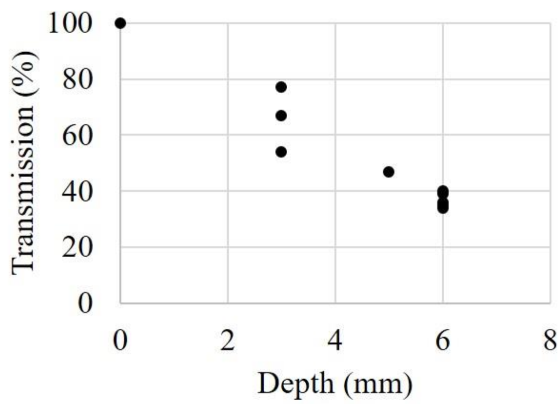

Figure 12. Impact of fresh snow on PAR transmittance during December 2018 at Lake Fryxell.

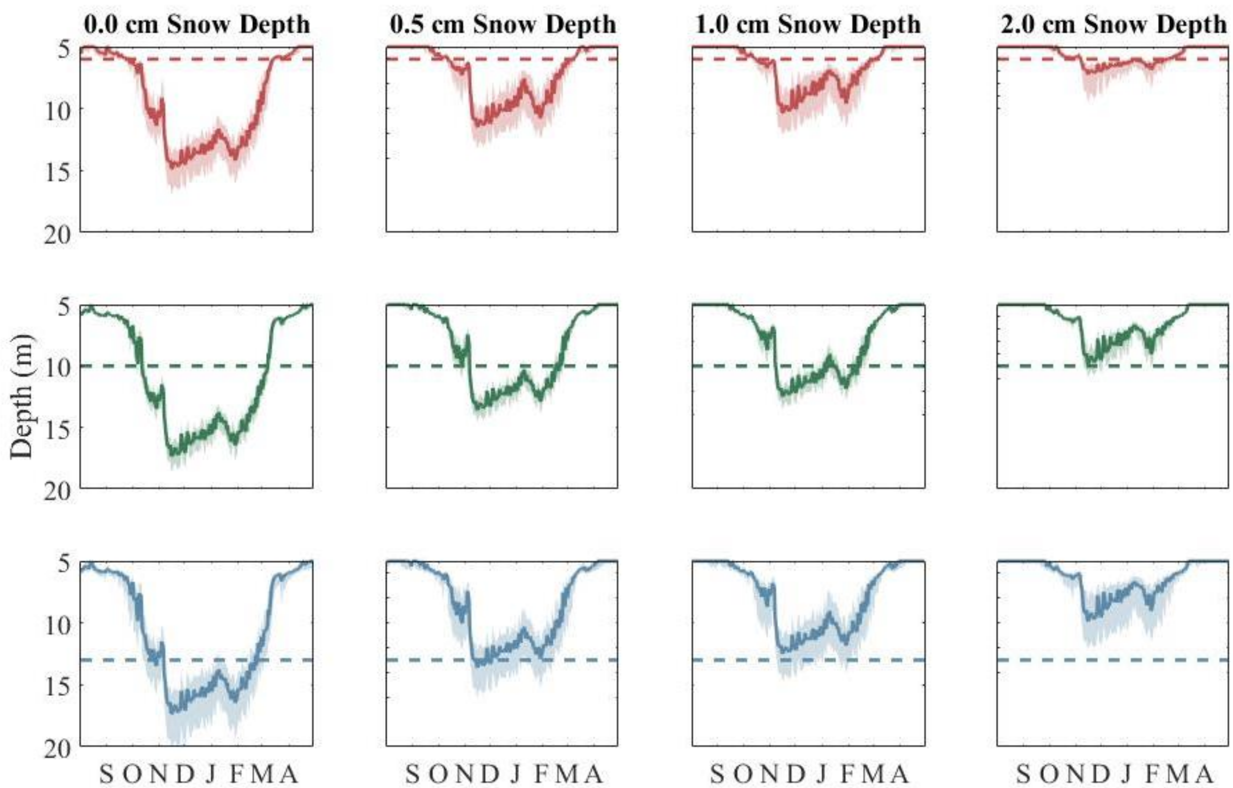

Figure 13. Potential penetration depth of compensation irradiance for different mat communities in Lake Hoare under different snow conditions. Compensation irradiances for mats living at 6 m, 10 m, and 13 m depth are 1.6 ± 0.6, 0.9 ± 0.2, and 0.9 ± 0.4 µmol photons $m^{-2}s^{-1}$ respectively (Hawes and Schwarz, 2000). Dashed line indicates habitation depth of the communities. Shading indicates standard error. Data is normalized to SPAR of 2165 µmol m^{-2} s^{-1}, consistent with maximum SPAR during survey.

background irradiance, 1 cm snow cover could stop benthic photosynthesis for 13 m communities at all times of the year. 0.5 cm snow cover is less important in encouraging respiration, although could suppress UW PAR below compensation irradiances before and after mid-November and mid-February respectively. When comparing Spring to Fall it is important to note that Spring snow is more likely to impact Fall snow due to the persistence of snow cover when S PAR is beginning to ramp up for the snow year.

When transmission is applied to East Lake Bonney, calendar day is critical in determining if light will impede pelagic photosynthesis (Figure 14). During peak underwater irradiance in December, accumulated snow reduces shallow UW PAR from over 60 to less than 20 μmol photons $m^{-2}s^{-1}$ under 2 cm of blanketed snow. At a depth of about 10 m, irradiance is reduced from about 10 to about 1.5 μmol photons $m^{-2}s^{-1}$ under similar snow conditions. For

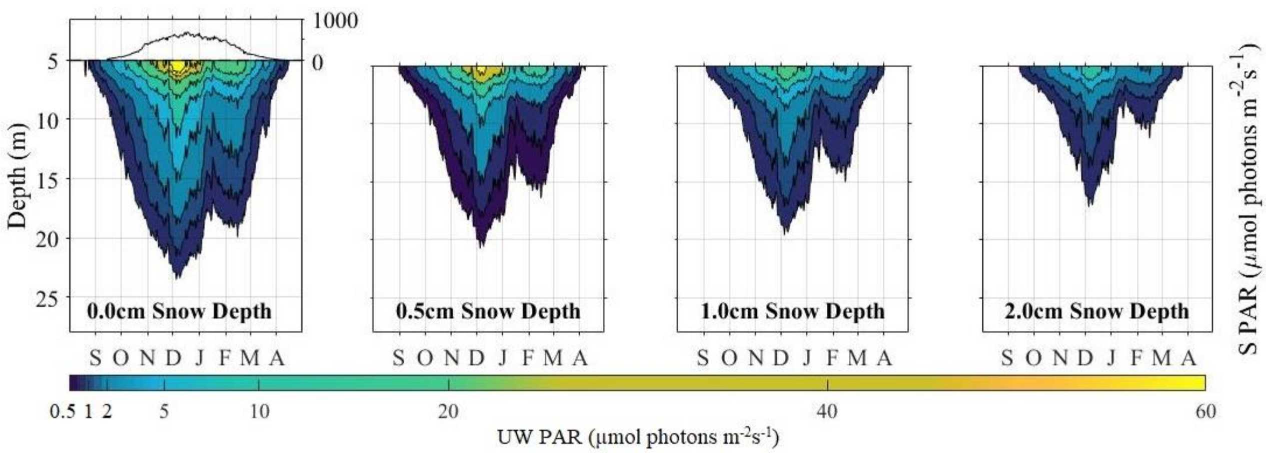

Figure 14. Potential mean UW PAR Lake Bonney under variable snow conditions (0 mm, 5 mm, 10 mm, and 20 mm depth). Contours begin at 0.5 μmol photons $m^{-2}s^{-1}$. Values for contour lines are indicated on the color bar. Mean annual S PAR is indicated in the first plot.

communities living at 17 m, UW PAR drops below 1 μmol photons $m^{-2}s^{-1}$ under only 0.5 cm blanked snow and below 0.5 μmol photons $m^{-2}s^{-1}$ under 2 cm snow. Depending on the time of year, amount of snow that falls, and background UW PAR for the snow year, 17 m communities

may be unaffected. For example, if it snowed after March 1, when UW PAR at 17 m depth is already below 0.5 µmol photons $m^{-2}s^{-1}$ photosynthesis would likely be unaffected. If it snowed before mid-October, however, snow could persist on the surface of the lake ice into the start of the UW PAR season and impede photosynthesis.

4.3. Snow and UW PAR: Snowpacks

A survey of UW PAR was conducted below a tarp with 1% light transmission to simulate snow cover. Under full sun conditions, the greatest impact of snow on UW PAR is at the center of the snowpack and within the first 10 m of the water column (Figure 15). Light tends to increase with depth up to about 10 m and then decreases, similar to what we would expect in a snow-free environment. At up to 1.2 m from the center, the UW PAR profile has a similar trend.

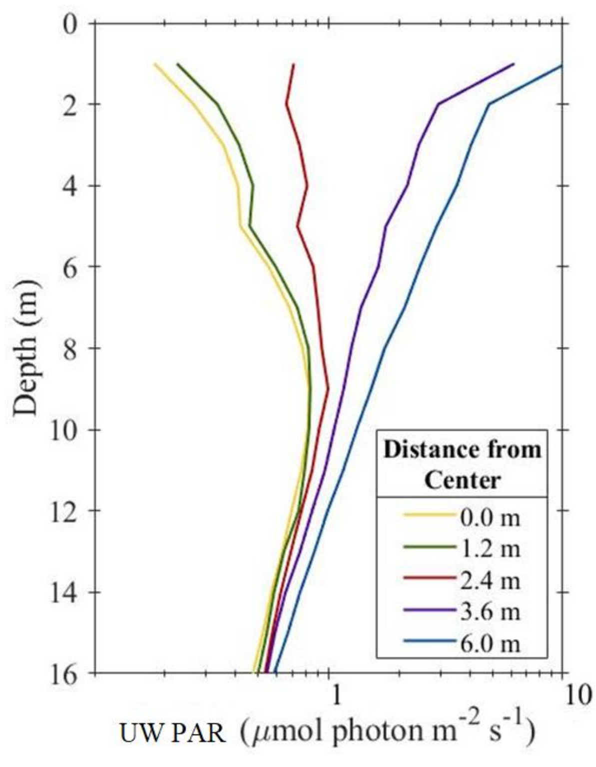

Figure 15. UW PAR casts sampled every 0.5 m depth at variable distances from snowpack center. Snowpack radius is 3.6 m. Ice bottom is at 4.36 m depth.

At 2.4 m from the center of the snowpack, UW PAR does not change very much with depth and begins to decline around 9 m. At the edge of the snowpack and 2.4 m from the edge, UW PAR appears to attenuate at a similar rate, although UW PAR is slightly greater further from the snowpack. Data from UW PAR casts were linearly interpolated (Figure 16). Deviation from the 6 m UW PAR cast was also calculated to determine the reduction of UW PAR by a snowpack (Figure 17). For a snowpack of typical size and transmission, the greatest reduction to PAR occurs within the ice cover and immediately below it. Even directly below the center of the snowpack, UW PAR is only reduced by 0.5 µmol photons $m^{-2}s^{-1}$ at 8 m depth. Results suggest

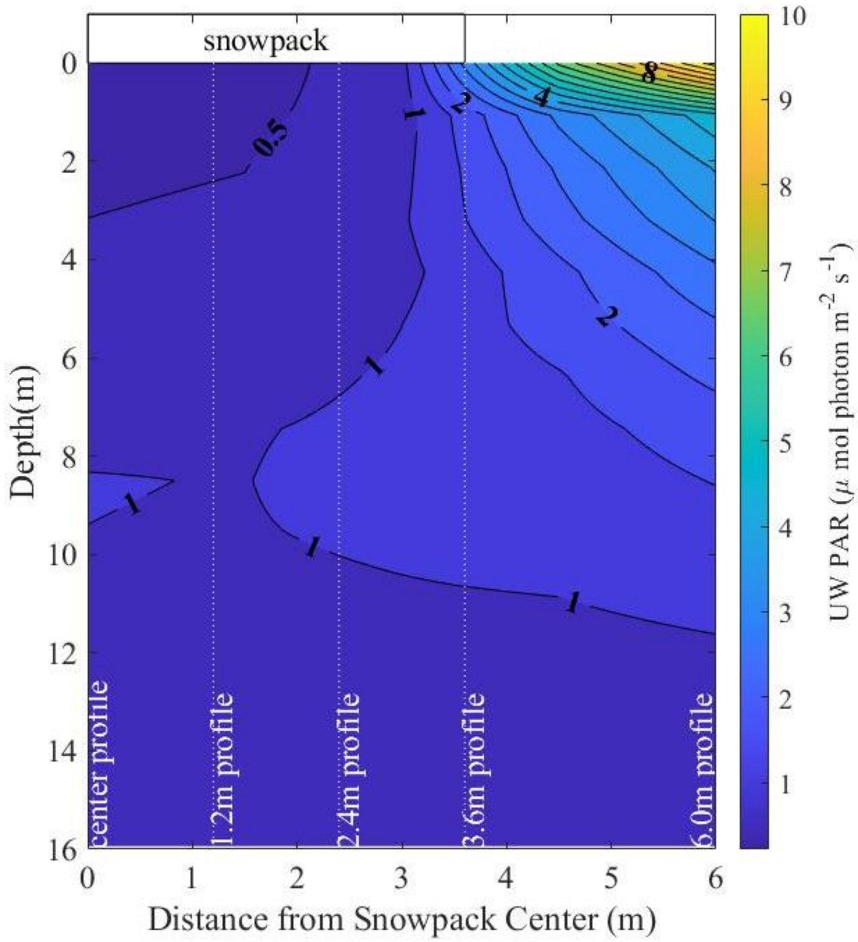

Figure 16. Spatially interpolated UW PAR below a tarp with radius 3.6 m. Data is normalized to SPAR of 2165 µmol m^{-2} s^{-1}, consistent with maximum SPAR during survey. Contours are every 0.5 unit of PAR. Ice bottom is at 4.36 m depth.

communities living above 8 m are likely to be the most impacted by snowpacks with deeper communities experiencing little to no change. Results come from one survey conducted at Lake Hoare.

4.4. Examples of Anomalous Snow: Large Snowpacks and High Volume

The 2017 snow year provides an example of a year with large, closely distributed snowpacks on Lake Bonney (Figure 18). Although UW PAR recorded at the permanent lake station was higher than mean UW PAR at that time of year, the snowpacks likely added to the spatial heterogeneity of UW PAR with implications for whole-lake primary productivity modeling. Further studies are necessary to fully understand the nature of larger snowpacks in controlling underwater

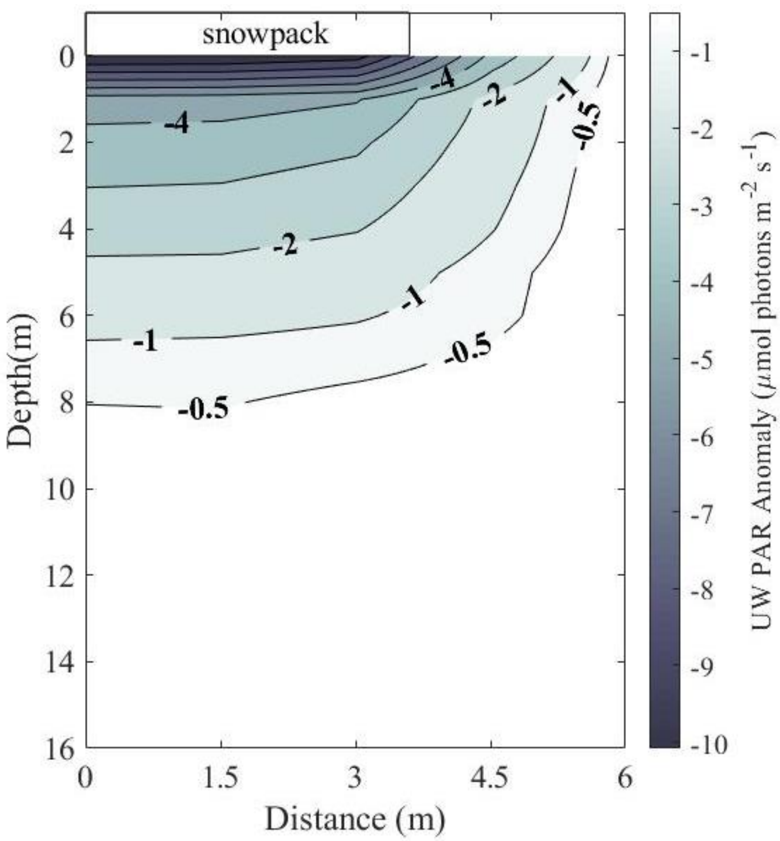

Figure 17. UW PAR deviation from 6m profile. Sample locations provided in Figure 12. Ice bottom is at 4.36 m depth. Contours are every 1 µmol photons $m^{-2}s^{-1}$.

irradiance, especially during years with a lot of persisting snowpacks.

During the 2016 snow year, all lakes received a significant amount of snow from November 22 through the 26th. Lake Bonney received 2 mm SWE Lake Hoare received 7.5 mm SWE and Lake Fryxell received 6 mm SWE. Figure 19 shows PAR around the time of the event for each lake. The spatial variability in UW PAR suppression duration is likely a result of the volume of precipitation that fell at each site and the spatial gradient in weather conditions

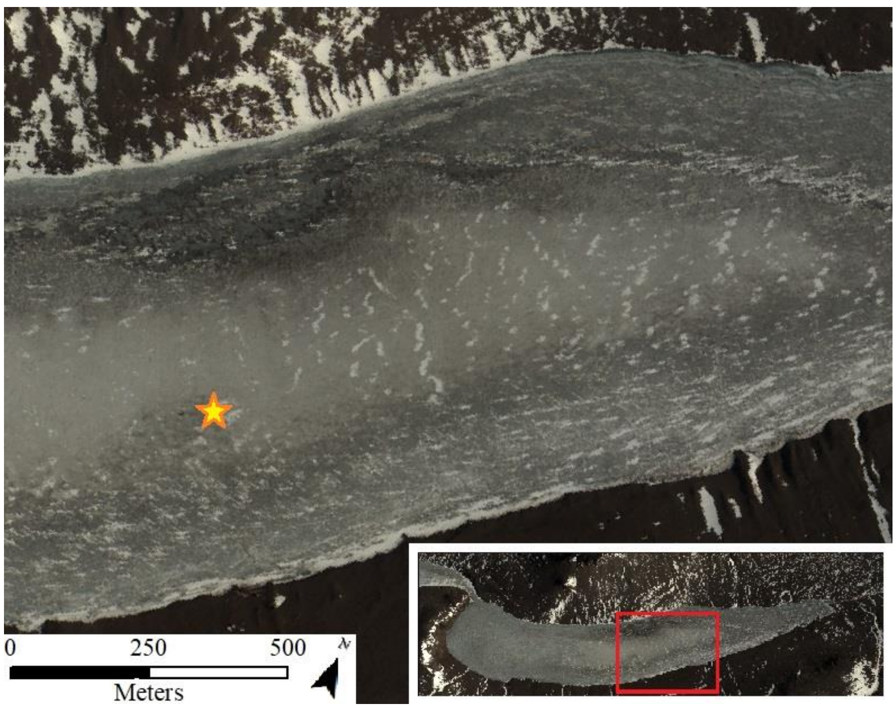

Figure 18. World View 2 image of Lake Bonney with snowpacks from 23 November, 2017. Image was orthorectified by the Polar Geospatial Center. Star marks the location of moored UW PAR sensor. Snowpacks are distinguishable from lake ice by their white appearance.

conducive of snow persistence on lake ice. Lake Bonney and Lake Hoare had the shortest persistence, both around 10 days. Lake Fryxell had the greatest snow persistence. Snow suppressed UW PAR for nearly 3 weeks. The percentage of UW PAR suppression follows a similar gradient. The greatest suppression was at West Lake Bonney (70%), followed by East Lake Bonney (84%). Lakes Hoare and Fryxell had a similar reduction to UW PAR at 90% and

91% respectively. Percent UW PAR reduction agrees with expected transmission values for East Lake Bonney. West Lake Bonney likely received less snow than was recorded by BOYM, which lies on the shore of East Lake Bonney. There is some disagreement with transmission values at Lakes Hoare and Fryxell. The anticipated volume of snow to fall based on UW PAR suppression is 6 cm from Perovich (2007). During that study, snow density was higher which could require less snow for a similar PAR suppression.

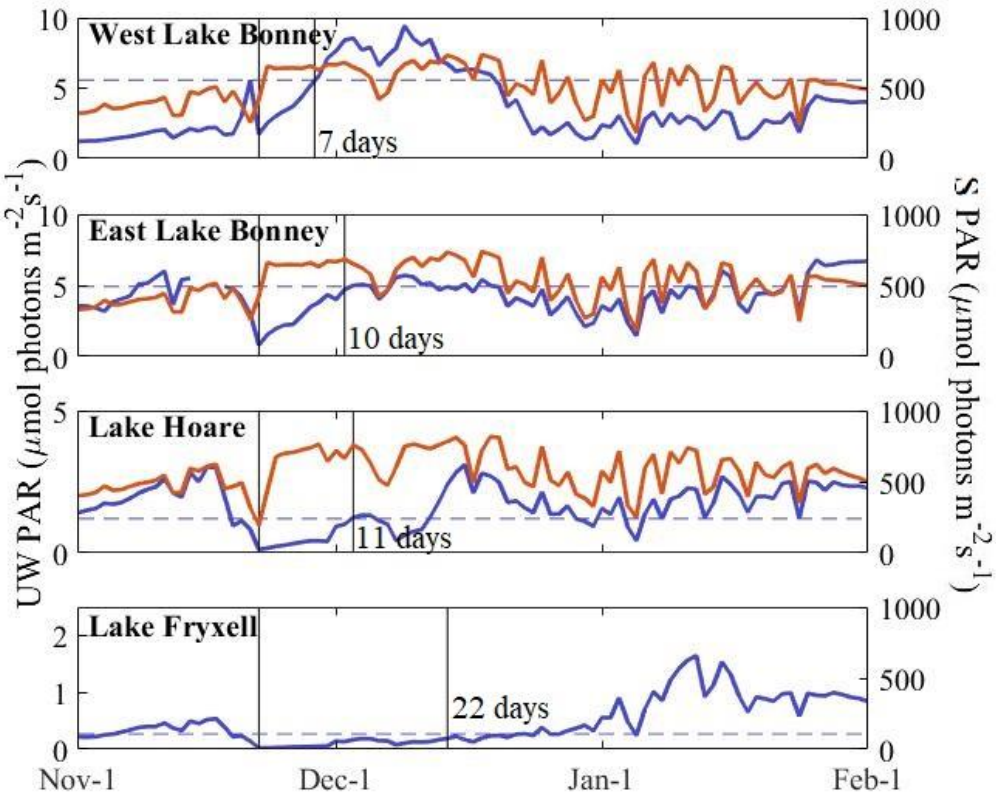

Figure 19. UW PAR suppression at all TV lakes after the 22 November, 2016 snowfall event. UW PAR is in blue, S PAR is in orange. Dashed line indicates UW PAR prior to precipitation. Vertical black lines indicate start and end of UW PAR suppression due to the snowfall event. UW PAR suppression duration indicated in each plot.

DISCUSSION

5.1. Seasonality of Precipitation

Lyons et al. (2000) suggests seasonal variability in the climatic controls at each lake. Lakes Hoare and Fryxell typically experience a marine climate, while Lake Bonney has a more continental climate. They suggest that Lake Hoare tends to shift closer to a continental climate as the season progresses. Results presented in Table 2 suggest a similar pattern for the average number of days with snow cover on each lake's surface. Snow volume does not exhibit a similar pattern although spatial trends in Fall accumulation provide evidence to suggest a shifting climate regime.

Seasonal variability of microclimates within TV could be caused by atmospheric teleconnections. Several studies suggest a seasonality of tropic-Antarctic teleconnections, however they disagree on the strength of it (Thompson and Solomon, 2002; Bertler et al., 2006; Fogt and Bromwich, 2006). Bertler et al. (2004) suggest these teleconnections influence the position of the Amundsen Sea Low (ASL). Furthermore, Patterson et al. (2005) suggest ASL position-driven changes in moisture transport pathways to the MDVs, thereby influencing katabatic events. Evidence from this study supports the importance of seasonality in analyzing the controls of climate on ecosystem structure and function, especially for attribution and projection of the ecosystem response to climate change.

5.2. Implications for Ecosystem Modeling

Due to logistical constraints, limnological studies in Taylor Valley are often limited to a single sample site at the center or deepest portion of the lake which is not always an accurate representation of mean lake ice transmission. In West Lake Bonney, percent transmission was

shown to vary between 1 and 6 (Obryk et al., 2014). UW PAR availability typically drives models for primary productivity where photosynthesis is light-limited (Lizotte and Priscu, 1991). It is necessary to understand the role of snow in reducing UW PAR to increase the accuracy of whole lake models of primary productivity (PPR).

Presently, little is known about the effect of snow on UW PAR in Taylor Valley Lakes although it has been mentioned as a UW PAR disturbance (Roulet and Adams, 1984; Howard-Williams et al., 1998; Fountain et al., 2010). This paper presents the first quantified relationship between snow and UW PAR in Taylor Valley, Antarctica. One of the MCM LTER hypotheses is to examine how climate variation alters connectivity among landscape units. Although precipitation is minor and infrequent, this study has shown days with snow cover are increasing and that even light precipitation events can reduce UW PAR below 0.5 μmol photons $m^{-2}s^{-1}$ at depths where PPR is typically greatest.

Organisms living within the water column have been known to adjust their vertical position in response to light variability (Thurman et al., 2012), some organisms are confined to lower depths due to their reliability on the chemocline (Lizotte and Priscu, 1991; Vick and Priscu, 2012). Depending on the calendar day that it snows, populations of vertically stratified pelagic organisms are likely to respond differently to snow cover.

In one study (Hawes et al., 2001), benthic primary production was modeled in Lake Hoare from experimentally derived photosynthesis-irradiance relationships, respiration rates, and a standard ice transmission and extinction coefficient. Information gained from this study represent the start of coupling precipitation with PPR models to project habitat loss and resultant decline in benthic PPR due to increasing snow cover. If snow cover increases during the

summer, like we are already seeing in the fall at Lake Hoare, we could see a shift from benthic- to pelagic-dominated PPR.

Lizotte and Priscu (1991) demonstrated that communities living at different depths have different photosynthesis-irradiance relationships and their rates max out at different irradiances (Figure 20). Shallow (5 m) phytoplankton have the lowest photosynthetic rates by irradiance and

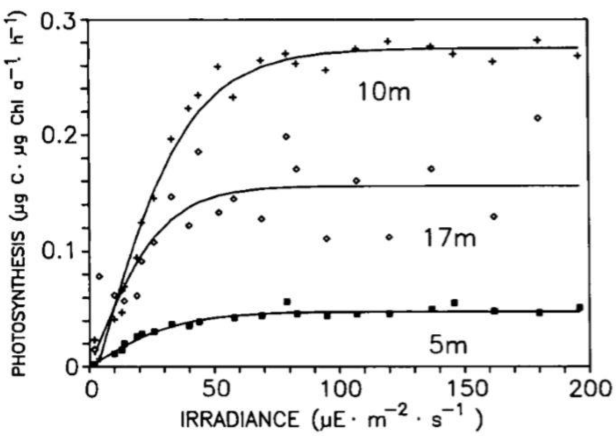

Figure 20. Photosynthesis-irradiance relationship for phytoplankton collected from Lake Bonney living at different depths. From Lizotte Priscu et al. (1991).

achieve maximum photosynthesis of 0.02 µgC · µg Chl a $^{-1}$ h^{-1} at about 40 µmol m^{-2}s^{-1}. In terms of carbon production, snow will have the least effect on these communities when assessing the amount that UW PAR is reduced and their rate of carbon production. Deeper communities living at 10 and 17 m have a more complex relationship. Phytoplankton residing at 10 m have the greatest photosynthetic rate by irradiance and achieve maximum photosynthesis of 0.25 µgC · µg Chl a $^{-1}$ h^{-1} at about 80 µmol m^{-2} s^{-1}. Deeper, 17 m populations achieve maximum photosynthesis (0.15 µgC · µg Chl a $^{-1}$ h^{-1}) at lower irradiance (50 µmol photons m^{-2} s^{-1}). Light penetration to 17 m depth is also low and strongly depends on surface processes affecting transmission. At 17 m depth, mean irradiance in East Lake Bonney rarely exceeds 2 µmol photons m^{-2} s^{-1}. Because it is

so low, the potential reduction to carbon production is lower for the organisms living at 17 m than those at 10 m.

Another consideration for the impact of snow on UW PAR is the role of snow in reducing albedo, which would slow melt generation from surrounding glaciers and slowing lake level rise. Snow can almost triple soil albedo depending on coverage (Bergstrom et al, manuscript in preparation). Because the Taylor Valley summers are typically right around 0°C, increases in albedo could tip conditions to be less favorable for melt generation. If this is the case, benthic communities would experience a two-fold areal habitat reduction due to snow cover. We could see reduced deep habitat controlled by shallower penetration of UW PAR above compensation irradiance and increased competition at shallower depths.

5.3. Applications for a High-Arctic Lake

A study from Belzile et al. (2011) examined PAR transmittance through snow and ice on a perennially ice-covered lake on Ellesmere Island, Canada where the ice cover is thinner (2 m) and snow depths are typically thicker (0.5 m) than Taylor Valley lakes. Although the ice cover thickness is about half, PAR transmission through the ice is similar (5.7-6.6%). The lake from this study, Lake A, typically receives 3 times more precipitation than the Taylor Valley annually. Their study presents results of snow conditions typical of Lake A, however it does not explore PAR reduction under shallower snow depths nor does it examine the seasonal variability in transmission properties of the ice cover.

Attenuation at PAR wavelengths decreases with snow depth (Perovich et al. (2007). Additionally, light transmittance through ice is greater under diffuse light conditions (Howard-Williams et al., 1998). Reduced snow cover on Lake A could would result in an overestimation of PAR reaching the water column. PAR predictions from singular transmission measurements

alone could further increase the error when calculating under-ice PAR in polar lakes, especially during the transition to and from the dark season. In polar regions where seasonal variability in solar radiation largely controls ecosystem processes, it is necessary to also include seasonal variability in precipitation, transmission, and background radiation. The incorporation of seasonality allows for a better understanding the role of snow in governing ecosystem processes which are highly sensitive to small climatic changes.

CONCLUSIONS

This study presents the first numerical evidence for the role of snow in reducing UW PAR and examines seasonal trends in precipitation across Taylor Valley. From the 20-year record of accumulation, no trend in precipitation volume is discernable at any weather station included in this study which is consistent with strong interannual variability typical of TV. Summer accumulation is most consistent at all lake AWS. Total precipitation at FRLM has been lower between 2010 and 2017 than prior to 2009. FRLM also exhibits the strongest seasonality. Over half of total precipitation during the light season occurs in the Fall. HOEM and BOYM receive similar volumes across all seasons.

Summer snow cover days at Lake Hoare have been increasing between 2013 and 2017, although this trend is not anomalous for the record spanning from 1993 to 2017. Summer snow persistence, however, has mostly remained unchanged throughout the 10-year record as has Spring persistence. Snow cover during the Spring tends to last about 1 week more than in the Summer. Fall persistence, contrastingly, has been increasing even if the anomalously high persistence from the 2017 snow year is excluded. Fall persistence is typically 3 days higher than Spring although this relationship may be biased by data from that anomalous season.

Light transmission through snow cover in TV is consistent with a previous study of light transmission through an alpine snowpack. Transmission typically declines by 10% for every mm of snow up to 6 mm depth. Thin, 5 mm snow cover has the potential to reduce UW PAR penetration depth by 1 to 7 m at all lakes. Increasing the snow cover thickness to 20 mm reduces the penetration depth by 7 to 12 m during peak radiation. Deep, 13 m mat communities at Lake Hoare are most impacted by snow cover. Benthic communities living at 6m depth in Lake Hoare are likely able to continue photosynthesis under up to 20 mm snow.

Pelagic autotrophs in Lake Bonney are affected differently depending on their vertical distribution in the water column. Shallow autotrophs residing above 10 m are likely unaffected by snow cover but could be impacted by a downstream response. Microbes living at 13 m are better adapted to punctuated light disturbances and are likely only to be affected if light is reduced continuously for weeks. Although deeper autotrophs are the most shade adapted and used to relying on other sources of energy, there may be a reduction to biomass in the Spring proceeding a snowy Fall.

Results from the snowpack survey at Lake Hoare suggest on current space and time scales, lake ice snowpacks are fairly insignificant at reducing UW PAR. Snowy seasons are likely more important at reducing productivity and biomass than individual precipitation events, as was observed during the 2017 snow year. If snow cover increases under future climate conditions, it will be necessary to better understand the role of snowpacks in altering the underwater light regime for improved models of whole lake productivity within Taylor Valley.

APPENDIX. ERRORS AND MISSING DATA

Table A1. Snow accumulation errors from this study. Error based on ±0.5mm SWE for each daily measurement.

Calendar Year	**EXEM** weighted gauge	**FRLM** sonic ranger	**HOEM** weighted gauge	**HOEM** sonic ranger	**BOYM** weighted gauge	**BOYM** sonic ranger
1996					0.5	
1997					2	
1998						
1999					2	
2000	2.5				3.5	
2001	8.5				3.5	
2002					3	
2003	2				1	1
2004	8.5	10			3	
2005					3	
2006		17			2.5	
2007	2.5	18			3	
2008	7	13.5		1	2	0.5
2009	5.5	9		3.5	2	

(table cont'd.)

Calendar Year	**EXEM** weighted gauge	**FRLM** sonic ranger	**HOEM** weighted gauge	**HOEM** sonic ranger	**BOYM** weighted gauge	**BOYM** sonic ranger
2010		4		2	1	
2011	4	6	0.5	2		
2012	7	4.5			4	
2013	5	1	2	2	1	
2014	2.5		2	1.5		
2015	2		0.5	2.5	1	0.5
2016	3			3.5	0.5	
2017	2	9			3	

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VITA

Madeline Elizabeth Myers received her bachelor’s degree from Louisiana State University in 2016. She was introduced to research in the geosciences as an undergraduate where she studied fault reactivation due to post-glacial rebound. The opportunity to participate in an Antarctic research cruise narrowed her interests and gave way to pursue a master’s degree studying snow and radiation. Upon completion of her master’s degree, Maddie plans to continue contributing to research within the cryosphere.