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Prediction of Ice-Free Conditions for a Perennially Ice-Covered Antarctic Lake

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Abstract Although perennially ice-covered Antarctic lakes have experienced variable ice thicknesses over the past several decades, future ice thickness trends and associated aquatic biological responses under projected global warming remain unknown. Heat stored in the water column in chemically stratified Antarctic lakes that have middepth temperature maxima can significantly influence the ice thickness trends via upward heat flux to the ice/water interface. We modeled the ice thickness of the west lobe of Lake Bonney, Antarctica, based on possible future climate scenarios utilizing a 1D thermodynamic model that accounts for surface radiative fluxes as well as the heat flux associated with the temperature evolution of the water column. Model results predict that the ice cover of Lake Bonney will shift from perennial to seasonal within one to four decades, a change that will drastically influence ecosystem processes within the lake.

1. Introduction

High-latitude lakes, especially those with perennial ice covers, are extremely sensitive to climate variability, particularly with regard to the dynamics of their ice covers. Owing to this sensitivity, ice thickness changes have been closely documented over the past several decades in both Arctic and Antarctic lakes (Adrian et al., 2009; Doran, Priscu, et al., 2002; Lehnherr et al., 2018; Mueller et al., 2009; Obryk, Doran, Friedlaender, et al., 2016; Obryk, Doran, Hicks, et al., 2016; Paquette et al., 2014; Vincent et al., 2008; Vincent et al., 1998; Wharton et al., 1989). For example, the ice-free area of a deep high-latitude Arctic Lake Hazen increased by 3 km^2/year over the last two decades in response to surface air temperature warming of only ~1 °C (Lehnherr et al., 2018), and shallow (<3 m deep) Alaskan lakes transitioned from winter grounded ice to floating ice as a direct response to increased surface air temperatures (Surdu et al., 2014). A shift from perennial to seasonal ice covers in the Arctic lakes showed that the transition is abrupt, rather than a gradual process (Mueller et al., 2009; Paquette et al., 2014), and results in a cascading ecological shift in the water column owing to wind-driven mixing and higher heat transfer (Lehnherr et al., 2018; Mueller et al., 2009; Vincent et al., 2008). However, a transition from perennial to seasonal ice covers has yet to be observed for the Antarctic lakes because Antarctic has not experienced the same warming the Arctic has (Grebmeier & Priscu, 2011; Salzmann, 2017).

Long-term ice thickness changes in the McMurdo Dry Valley lakes, Antarctica, have been measured systematically since the late 1970s (Castendyk et al., 2016; Doran, Priscu, et al., 2002; Obryk, Doran, Friedlaender, et al., 2016; Obryk, Doran, Hicks, et al., 2016; Wharton et al., 1989). These lakes have been perennially ice covered since at least 1903 when they were discovered by Robert Falcon Scott (Scott, 1905), and the ice thickness has been shown to vary over time. For example, lake ice thickness of perennially ice-covered Lake Hoare, Antarctica, McMurdo Dry Valleys (longest ice thickness on record in Taylor Valley, McMurdo Dry Valleys) decreased by ~2.5 m between 1977 and 1986 (Wharton et al., 1989) increased by ~1.4 m between 1986 and 1999 as a direct response to air temperature cooling (Doran, Priscu, et al., 2002) and decreased by over 2 m through 2016 (data available at www.mcmlter.org).

The lack of direct anthropogenic influence on Antarctic lakes makes them novel sentinels of climate change. Antarctic lakes are often located in closed basins, and as such, they integrate climate variability over a broad region (Adrian et al., 2009; Castendyk et al., 2016). Small changes in surface energy balance, such as changes in solar radiation, albedo, wind speed, cloud cover, or surface air temperature, often lead to large ecosystem responses (Doran, Mckay, et al., 2002; Foreman et al., 2004). These changes affect physical properties of the ice covers (thickness and optical properties) and consequently mediate ecological

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responses in the water column (Foreman et al., 2004; Obryk, Doran, Friedlaender, et al., 2016), many of which can be nonlinear (Gooseff et al., 2017).

Recent studies of the McMurdo Dry Valley lakes have shown ecological sensitivity to climate-driven changes in physical properties of the ice cover (Bowman et al., 2016; Foreman et al., 2004; Fountain et al., 2016; Gooseff et al., 2017; Obryk, Doran, Friedlaender, et al., 2016). Despite these dynamics, little is known how these light- (Morgan-Kiss et al., 2015) and nutrient-limited (Priscu, 1989, 1995) food webs will respond to future ice thickness decline under projected regional warming. Small changes in ice thickness in Antarctic lakes result in increased penetration of solar radiation with resultant increases in short-term rates of primary productivity (Gooseff et al., 2017; Obryk, Doran, Friedlaender, et al., 2016). However, as the ice continues to decline, nutrients are expected to become a limiting factor for phytoplankton growth (Dore & Priscu, 2001; Priscu, 1995). Consequently, long-term food web responses to changing penetrating solar radiation associated with ice thickness remain unknown (Obryk, Doran, Friedlaender, et al., 2016).

Ice cover thickness in perennially ice-covered Antarctic lakes is primarily a function of surface energy balance in addition to heat upwelling from the water column and geothermal flux (McKay et al., 1985; Obryk, Doran, Hicks, et al., 2016; Vincent et al., 2008). The variability in ice cover thickness is mainly driven by the surface air temperatures and responds to the changes caused by the natural and anthropogenic surface energy perturbations. Surface air temperature is a dependent variable and is driven by solar variability (Laepple et al., 2011). Recently, Obryk et al. (2018) attributed large solar radiation changes in the McMurdo Dry Valleys to the global anthropogenic sulfate aerosol contribution to the atmosphere. Large solar radiation variability drives the heat flux in the water column, which strongly influences long-term ice thickness variability (Obryk, Doran, Hicks, et al., 2016). Ice thinning allows greater penetration of the solar radiation flux to the liquid water column where the increased heat stored in the water column of deep lakes significantly contributes to ice melt at the ice/water interface (Obryk, Doran, Hicks, et al., 2016). The increase in heat storage causes a positive feedback mechanism resulting in a runaway abrupt ice cover disintegration, similar to that in Arctic lakes (Mueller et al., 2009; Paquette et al., 2014). The heat flux from the water column contributes to ice melt at the ice/water interface for several months after the onset of austral winter and associated lack of influence of solar radiation (Obryk, Doran, Friedlaender, et al., 2016).

Our study evaluates the stability of thick perennial ice on Antarctic lakes in response to climate change. Specifically, we used future climate scenarios to predict the ice thickness of the west lobe of Lake Bonney, Taylor Valley, Antarctica, a permanently ice-covered, chemically stratified lake (Figure 1). We then determined when the perennially ice-covered Antarctic lakes will experience complete ice loss associated with the changes of the surface energy balance. These results will provide a basis for the near-future biological studies of the lakes and of ecological trends. We utilized a high-resolution 1D ice thickness model coupled with the surface energy balance and the heat flux from the water column. For future climate scenarios, we use contemporary climate data to predict future ice thickness evolution by considering maximum and minimum trends of solar radiation, surface air temperature, relative humidity, and wind speed values based on a 16-year-long meteorological record (1996 to 2012). Finally, we developed an envelope of climate scenarios and associated response of ice thickness changes.

2. Study Site

The McMurdo Dry Valleys, Antarctica, is an ice-free polar desert located in East Antarctica (77–78°S, 160–164°E) with mean annual temperature at the valley bottoms ranging between −14.8 and −30.0 °C (Doran, McKay, et al., 2002) and annual precipitation less than 50 mm in water equivalent per year (Fountain et al., 2010). Exposed bare ground with lakes located in the topographic lows and local alpine glaciers on the valley slopes are the main characteristics of the region. Most of the McMurdo lakes are closed basin and are perennially ice covered with ice thickness ranging from 3 to 6 m (Doran, Priscu, et al., 2002; McKay et al., 1985). The hydrologic balance of the lakes is controlled by the water influx during the short austral summers when temperatures are high enough to melt nearby glaciers or permafrost and loss of water is through a combination of sublimation and evaporation of the ice covers (McKay et al., 1985; Obryk et al., 2017). Because of the delicate climate balance between summer and winter air temperatures, ice thicknesses and lake levels respond to small surface energy perturbations.

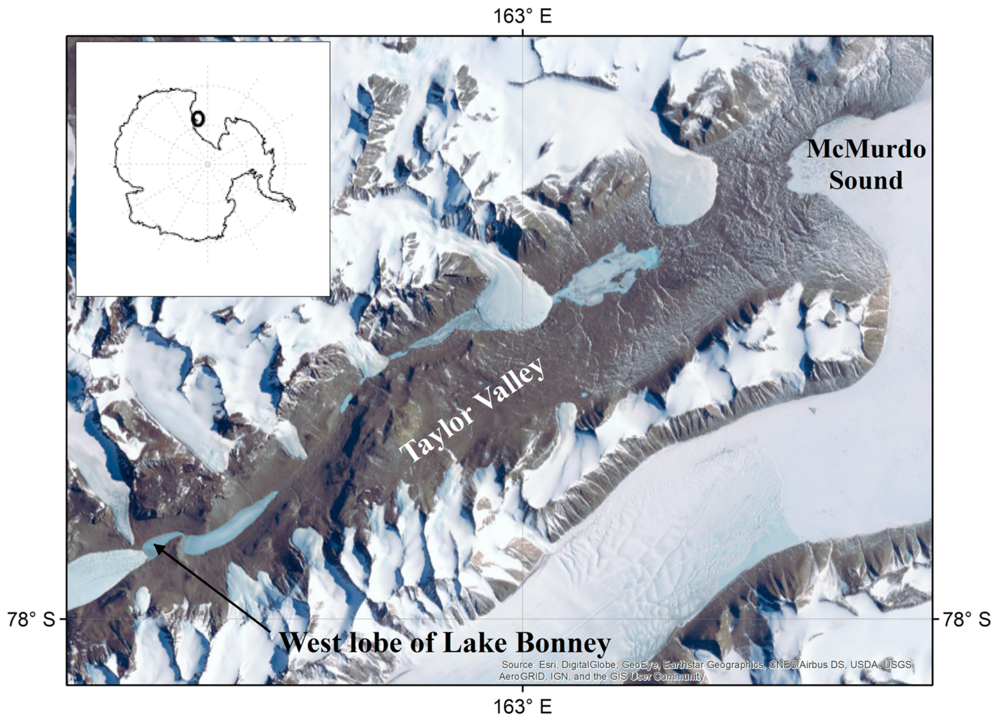

Figure 1. Map of Taylor Valley, McMurdo Dry Valleys, Antarctica.

The ice covers of dry valley lakes thin during the austral summers via surface sublimation or melt, which either percolates to the water column or evaporates, and melt at the bottom of the ice associated with the heat flux from the water column (Adams et al., 1998). Ice covers grow from the bottom down during austral winter. The bulk residence time of the ice in the ice covers is currently ~4 years based on the balance between summer ablation (0.47 to 0.89 m/year resulting from sublimation, evaporation, and melting) and winter ice growth (Dugan et al., 2013). Ice covers receive windblown sediment on the surface, which contributes to light attenuation. This sediment migrates to approximately 2-m depth within the ice cover as a result of melting caused by absorption of solar radiation (Jepsen et al., 2010). Consequently, ice covers have a distinct heterogeneous sediment layer at 2-m depth (Dugan et al., 2016; McKay et al., 1994; Obryk et al., 2014; Priscu et al., 1998).

Perennial ice covers also insulate the water column from wind-driven turbulent mixing, allow gas supersaturation, and decrease penetration of solar radiation by up to 99% in the most extreme cases (Howard-Williams et al., 1998; Prisu et al., 1996; Wharton et al., 1989). Despite the light attenuation due to the ice, the transparency of ice crystals due to their columnar growth and elongate vertical bubbles along the *c*-axis permits light penetration through a thick ice cover to the water column (Adams et al., 1998; Chinn, 1993), which allows seasonal phytoplankton growth and development of benthic microbial mats within the photic zone (Hawes et al., 2016; Lizotte & Priscu, 1992). The ice cover itself acts as an insulator trapping solar-derived heat in the water column (Spigel & Priscu, 1998). Heat within the water column is conducted upward through the ice cover and removed via sublimation of the ice (McKay et al., 1985). The high heat capacity of the water column, in conjunction with high deep water salinity in chemically stratified lakes, allows for the development of thermal maxima at depth (Obryk, Doran, Hicks, et al., 2016; Vincent et al., 2008). Deep (~>20 m) perennially ice-covered lakes are often highly stratified, with dense and deep hypersaline waters (Chinn, 1993; Spigel et al., 2018; Spigel & Priscu, 1998). The high salinity of the deep water column in Lake Bonney and other chemically stratified lakes inhibits seasonal mixing of the water column, with temperature having little to no influence on density-induced water mixing (Chinn, 1993; Spigel et al., 2018; Spigel & Priscu, 1998).

We focused on the west lobe of Lake Bonney, a ~40-m-deep lake located in the Taylor Valley, McMurdo Dry Valleys, Antarctica. Lake Bonney is located approximately 25 km from the coast (Figure 1). The west lobe of

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Lake Bonney is chemically stratified with a well-developed temperature maximum at 10 m (~3 °C) and a sharp chemocline at 15 m. Bottom water temperature reaches −4 °C and does not freeze due to a high concentrations of salts (Spigel & Priscu, 1998).

3. Methods

We use a 1D ice thickness model coupled with surface energy balance and heat fluxes from the water column driven by the penetrating solar radiation flux, developed by Obryk, Doran, Hicks, et al. (2016), which accurately modeled 16 years of ice thickness data for multiple lakes in the dry valleys on a centimeter resolution. Obryk, Doran, Hicks, et al. (2016) showed that long-term ice thickness modeling based on surface energy balance requires coupling with the water column due to heat storage at depth that upwells and can facilitate (hinder) ice decay (growth). Below we briefly describe the thermodynamic model; however, for a detailed model description, see Obryk, Doran, Hicks, et al. (2016). The model accounts for all surface radiative fluxes as well as heat fluxes from the water column (two 1D heat equations coupled at the ice/water moving boundary condition). Sensible heat from stream inflow is not included. The model requires inputs of solar radiation, air temperature, relative humidity, and wind speed. All other variables are calculated based on published equations. Due to a lack of cloud cover data for the McMurdo Dry Valleys, the model uses a random number generator to calculate daily cloud cover variability. This approximation was shown to sufficiently capture cloud influence on the ice thicknesses based on 16 years of ice thickness simulation at 12-hr intervals (Obryk, Doran, Hicks, et al., 2016). However, this introduces variability in the results, and for this reason, each modeled scenario considered in this paper was ran five times with lower and upper boundaries reported in Figure 2. The model simulation runs were stopped during the first seasonally ice-free year or after 50 years of ice thickness predictions. Simulations were not run after the ice melted, because the model does not account for physics associated with wind-driven turbulent mixing of the water column (ice-free lakes). Due to an inherit variability in the model (cloud cover randomization), the model can exhibit large variability of ice thickness with time (cumulative error) between replicate simulations (up to 0.5 m over 50-year simulations). Hence, we only considered near-future ice thickness simulations (≤50 years). The model was run at daily intervals.

No high-resolution meteorological predictions exist for the McMurdo Dry Valleys. Consequently, we made predictions based on past trends at the Lake Bonney meteorological station located on the south shore of Lake Bonney. Detailed station metadata are provided at www.mcmlter.org. Air temperature and solar radiation are the main drivers of ice thickness variability, and both have varied significantly over the past several decades (Gooseff et al., 2017; Obryk et al., 2018). For the future climate scenarios, we identified annually averaged years (January to December) in the meteorological record with the maximum and minimum air temperature, solar radiation, relative humidity, and wind speed values based on a 16-year-long record (between 1996 and 2012), summarized in Table 1. Years with incomplete record (missing >100 data points) were excluded from analysis. The selected years in Table 1 represent the most extreme annually averaged climatic spectrum for the region. The thermodynamic ice thickness model was run utilizing daily averaged meteorological data based on the identified years, as shown in Table 1, representing the most extreme climate spectrum. Nine iterations of a combination of solar radiation, surface air temperature, relative humidity, and wind speed data were used in the analysis and were looped during the simulations. These simulations encompassed the most extreme climate scenarios as well as highlight the influence of individual variables on the ice thickness variability.

The abovementioned approach allowed us to build a realistic envelope of climate scenarios based on the historical/empirical record. We did not attempt to model future climate for the McMurdo Dry Valleys; rather, we were interested in investigating the response of the ice thickness based on an existing meteorological record. Climate in the McMurdo Dry Valleys has undergone dramatic changes, and the scenarios derived in this study represent near-future possible ice thickness predictions based on the historical record.

4. Results

Ice thickness predictions of the west lobe of Lake Bonney ice cover show dynamic ice variability on variable timescales (Figure 2). The curves in Figure 2 represent daily ice thickness predictions based on a possible combination of years representing extremes of climate with respect to air temperature, solar radiation,

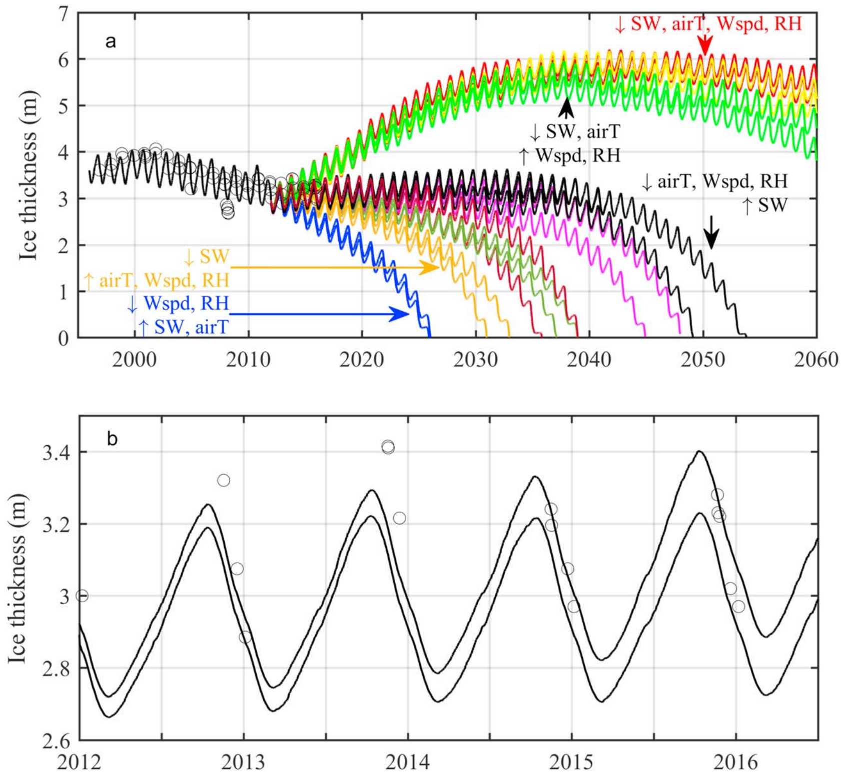

Figure 2. Ice thickness prediction for the west lobe of Lake Bonney (curves represent modeled seasonal ice thickness variability) and measured ice thickness data (circles). Each color represents a different combination of solar radiation, surface air temperature, relative humidity (RH), and wind speed. Due to inherit model variability, we show maximum and minimum simulation outputs for each climatic scenario based on five runs. (a) Modified figure from Obryk, Doran, Hicks, et al. (2016), which includes future ice thickness predictions (new data starts in 2012); (b) close-up of panel (a) showing ice thickness prediction along with measured data (circles). For clarity, only the best fit is shown in panel (b). Colors not identified in panel (a) represent the following combination of climatic variables: yellow (low solar radiation, surface air temperature, and RH and high wind speed), magenta (low surface air temperature and RH and high solar radiation and wind speed), green (low solar radiation, wind speed, and RH and high surface air temperature), brown (low surface air temperature and high solar radiation, wind speed, and RH).

relative humidity, and wind speed (Table 1). Ice thickness evolution based on the years with minimum values of both air temperature and solar radiation (red, yellow, and green curves in Figure 2a) exhibited ice growth and continuity of perennial ice cover. Changes in relative humidity and wind speed minimally influenced ice growth. Conversely, predictions when maximum values of either solar radiation or surface air temperature were considered resulted in complete ice disintegration within one to four decades (Figure 2). The effect of relative humidity and wind speed was pronounced when either solar radiation or surface air temperature was considered at their highest values. For example, considering increased solar radiation and surface air temperature but decreased relative humidity and wind speed resulted in the ice

Table 1
Mean Annual Values of Solar Radiation, Air Temperature, Relative Humidity (RH), and Wind Speed

	Max air temperature (°C)	Min air temperature (°C)	Max solar radiation (W/m^2)	Min solar radiation (W/m^2)	Max RH (%)	Min RH (%)	Max wind speed (m/s)	Min wind speed (m/s)
Year	1996	2004	2001	1999	2002	2008	1997	2006
Annual average	−16.2	−19.1	107.5	93.7	67.1	59.7	4.1	3.3

Note. The data are from between 1996 and 2012 at the Lake Bonney meteorological station. Annual averages were determined from 15-min increment data. Years with missing more than 100 data points were excluded from the analysis.

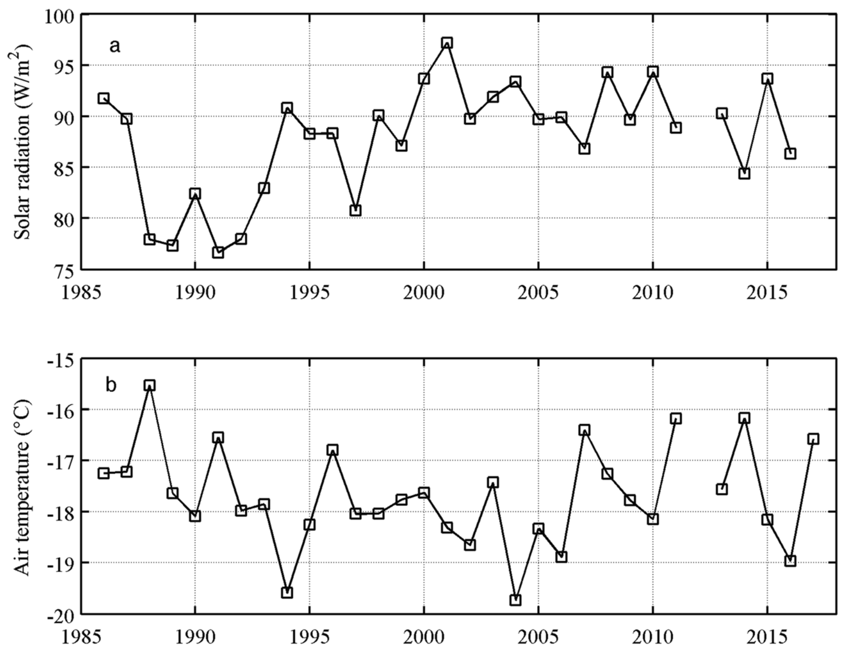

Figure 3. Annually averaged (a) surface air temperature and (b) solar radiation trends from a nearby Lake Hoare meteorological station. The Lake Hoare station has the longest continuous record.

disintegration within one decade (blue curve in Figure 2a). Simulation based on an either increased solar radiation or surface air temperatures only, regardless of a combination of relative humidity or wind speed, postponed yet resulted in full ice disintegration (orange, brown, dark green, magenta, and black curves in Figure 2a).

We tested our model prediction by starting model runs at the beginning of 2012 (end of simulations in Obryk, Doran, Hicks, et al., 2016) and overlap the results with recently obtained measurements of ice thickness (2012 to 2016; Figure 2). The black curve in Figure 2 shows the best fit to the most recent measured ice thickness data, where model prediction was run utilizing a combination of high solar radiation and low surface air temperature, relative humidity, and wind speed. The root mean square error between measured data and averaged ice thickness prediction (black curve) based on five simulations between 2012 and 2016 is 0.06 m, $n = 16$ (Figure 2b).

5. Discussion

We developed an envelope of climate possibilities based on climate extremes over a 16-year meteorological record to test ice thickness prediction on west lobe Lake Bonney. The climate scenarios with minimum air temperatures and solar radiation did not conform to the empirical ice thickness record of the past 5 years (Figure 2a) and exhibited rapid ice thickness growth and sustained perennial ice covers. However, climate scenarios that only considered either increased solar radiation or surface air temperatures resulted in a shift from perennial to seasonal ice cover. Considering increased solar radiation only while keeping all other variables (surface air temperature, relative humidity, and wind speed) at their historical lowest values, the ice covers are predicted to disintegrate in four decades. We view this as a maximum prediction for the longevity of perennial ice on McMurdo Dry Valley lakes.

Solar radiation in the McMurdo Dry Valleys has increased in the 1990s and remained relatively elevated since (Figure 3a), a trend attributed to geomorphic and ecological changes in the region (Fountain et al., 2014; Gooseff et al., 2017; Levy et al., 2018; Obryk et al., 2018). Surface air temperature has decreased until 2006 and exhibited high variability thereafter (Figure 3b). Data shown in Figure 3 are from a nearby Lake Hoare meteorological station, which has the longest continues record in the valley (meteorological stations throughout the valleys are highly correlated (Obryk et al., 2018)). The elevated solar radiation along with

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infrequent high surface air temperatures over the past decade (Figure 3) is consistent with the near-future perennial ice cover disintegration (Figure 2), as the only way to sustain perennial ice covers is to maintain both solar radiation and surface air temperature close to their historical minimum.

The predicted rapid ice thickness decline in Figure 2 is a consequence of a greater penetration of the solar radiation into the water column due to ice cover thinning. While surface air temperature plays an important role in the surface energy balance, surface air temperature is a dependent variable based on solar radiation in high latitudes (Laepple et al., 2011). Heat stored in the water column, associated with the solar radiation, has a positive feedback mechanism on the thickness of the ice covers by contributing to ice melt at the ice/water interface as a consequence of a greater heat flux from the water column (Obryk, Doran, Hicks, et al., 2016). The modeled rapid ice disintegration is consistent with previously observed shifts from perennial to seasonal ice covers on Arctic lakes (Mueller et al., 2009; Paquette et al., 2014). Our modeling results suggest that the heat accumulated in the water column, associated with recent ice cover thinning, acts as a positive feedback mechanism and is responsible for the future ice thinning/disintegration. The shift from perennial to seasonal ice cover is a result of legacy heat stored in the water column when ice cover is thin, and the below-ice solar radiation flux is thereby enhanced.

The thickness of the west lobe Lake Bonney ice cover varies in response to climate forcing; however, a shift from perennial to seasonal ice occurs only when a critical thermodynamic threshold between the surface energy balance and heat legacy (trapped heat) within the water column is reached, resulting in cascading ice disintegration (Mueller et al., 2009; Paquette et al., 2014). The chemically stratified lakes in the McMurdo Dry Valleys have been perennially ice covered for over a century based on empirical observations (Scott, 1905) and may have been ice covered for over a millennium based on geochemical evidence (Hall et al., 2017). Here we show that the ice thickness of Lake Bonney is prone to abrupt ice cover disintegration, similar to the Arctic lakes. While we assumed a static climate (looped selected meteorological data; Table 1) throughout the simulations, we expect the ice covers to become seasonally ice free earlier than predicted, unless unprecedented socioeconomic changes prohibiting global air temperatures rise above 1.5 °C are implemented (Millar et al., 2017), which would inhibit the positive feedback mechanism. If the surface energy balance remains the same as today, the Antarctic lakes can become seasonally ice free in less than four decades. We also note that our model is conservative in its projections in that it ran to zero ice thickness; however, the ice cover breakup will occur sometime before this as the perennial ice cover transitions to candled ice during its final stage of melt down. Candle ice enhances penetration of solar radiation; this would also cause ice-free conditions to occur earlier than our model predicts. The anticipated shift from perennial to seasonal ice covers will have unknown consequences on the lake food web.

6. Conclusions

Utilizing contemporary meteorological data from the McMurdo Dry Valleys, we predicted future ice thickness changes based on climatic extremes. The only climate scenarios capable of maintaining perennial ice covers required decrease in solar radiation and surface air temperatures. If either variable exhibits increased trends, the ice covers are predicted to shift from perennial to seasonal ice covers within four decades. Relative humidity or wind speed does not change the trend, rather they influence the duration of perennial ice cover persistence.

Our results emphasize the vulnerability of the perennially ice-covered Antarctic lakes to small surface energy perturbations and temperature evolution of the water column. Despite the thick perennial ice covers, their rapid disintegration is inevitable and consistent with observations in the Arctic. Our model predicts that the west lobe of Lake Bonney is on the verge of a thermodynamic-dependent threshold required for a shift from perennial to seasonal ice cover (heat flux from the water column offsets the surface energy balance). These results provide a basis for models describing the near-future ecosystem structure and functioning of the McMurdo Dry Valleys.

The McMurdo Dry Valleys have shown a transition from water storage in the cryosphere to the hydrosphere over the past decade due to an increased and persistent solar radiation (Levy et al., 2018). Decrease of both solar radiation and surface air temperature required to maintain perennial ice covers is highly unlikely under projected climate change, and our model results predict that the perennially ice-covered lakes in this region will become seasonally ice free within this century. Ours is the first study to provide an estimate when the transition from perennial to seasonal ice cover in McMurdo Dry Valleys would likely occur.

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