HYDROLOGIC RESPONSE TO FOEHN WINDS

IN THE MCMURDO DRY VALLEYS,

SOUTHERN VICTORIA LAND, ANTARCTICA

by

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ABSTRACT

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Hydrologic response to foehn winds in the McMurdo Dry Valleys, Southern Victoria Land, Antarctica

Thesis directed by Professor Michael Gooseff, Ph.D

In the McMurdo Dry Valleys (MDVs), foehn winds are a principal vector of landscape connectivity that facilitate movement of materials between glaciers, streams, soils, lakes and other parts of the ecosystem. While previous publications show that turbulent, warm and dry foehn winds indirectly relate to an increase in lake level rise via an increase in degree days above freezing (DDAF), the direct quantified impact of foehn winds to streamflow and lake level rise remains unclear. The MDVs are the largest ice-free region of Antarctica, which experience minimal precipitation. Valley bottoms contain permanently ice-covered closed basin lakes filled with meltwater from outlet glaciers via stream channels. In Taylor Valley, several meteorological stations and lake monitoring stations record average measurements of weather conditions and lake conditions on 15 to 20-minute intervals. In this thesis, the meteorological definition of foehn winds is refined and hydrologic response to foehn winds is evaluated. During the austral summer streamflow season (November - February), foehn winds are predicted to increase meltwater generation and closed-basin lake level rise. Past publications have shown that foehn wind events contribute to lake ice sublimation year-round, whereas melt does not typically occur in non-summer months. Analysis of non-summer lake ice ablation utilizing recent lake stage and ablation data is also explored herein. Although a significant correlation was not found, summer foehn winds appear to promote above average daily lake level rise given sufficient air temperatures. Daily average lake level rise is greater for longer periods (i.e., 4-day average daily rise > 3-day average daily rise, etc.) indicating that there is at least a 4-day post-foehn impact on lake level rise during the summer. Lake ice ablation in non-summer months is shown to have a significant relationship with increasing foehn wind occurrence and wind-run. Because foehn winds are expected to increase with global warming, these hydrologic relationships aid in predicting the future of the McMurdo Dry Valley ecosystem in a warming world.

DEDICATION

I am grateful for the interminable support of my family and friends, the students and faculty of the University of Colorado, Civil, Environmental and Architectural Engineering Department, the Hydrology, Water Resources and Environmental Fluid Mechanics program, the Institute for Arctic and Alpine Research, the McMurdo Long Term Ecological Research Program, contractor staff of McMurdo Station, the tenacity of past and future Asgard Rangers, the help of Johanna Speirs of the University of Queensland, my research committee and the Gooseff Lab Group.

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1. INTRODUCTION

1.1. Foehn Wind Mechanics - General

Foehn winds result from topographic modification of airflow leeward of mountain barriers. They are characterized by high gusts, turbulence, warm temperatures and low relative humidity (McKendry & Lethwaite 1990; Speirs *et al*., 2010; Speirs *et al*., 2013). During orographic lifting (Figure 1), air parcels cool at the dry adiabatic lapse rate (DALR) of 9.8°C km^{-1} or the saturated adiabatic lapse rate of 4–6° C km^{-1} (Speirs et. al, 2010). While rising, moisture removal and cloud formation may occur given moisture availability of the air parcel (Seibert *et al*., 1990; Speirs *et al*., 2010). Unobstructed air cresting a mountain ridge forms large-amplitude waves known as 'mountain wave activity'. If low-level winds are blocked by terrain barriers, air can be forced to descend leeward slopes (Klemp and Lilly 1975; Flamant *et al*., 2002; Jiang *et al*., 2005; Speirs *et al*., 2010). During descent, air compresses, warms at the DALR, and relative and absolute humidity are reduced (Barry and Chorley 2003; Speirs *et al*., 2010; Steinhoff *et al*., 2013; Obryk *et al*., 2017). These descending warm winds are known as "foehn winds" and occur in mountainous regions around the world including the McMurdo Dry Valleys of Antarctica.

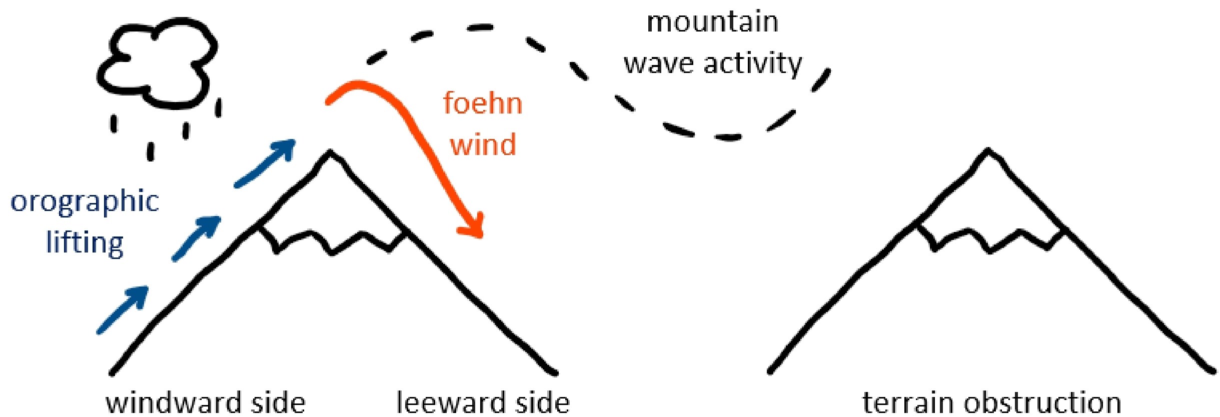

Figure 1 : Sketch of general foehn wind mechanics.

1.2. Setting

In eastern Antarctica (77–78°S 160–164°E), the McMurdo Dry Valleys (MDVs) are situated in the Transantarctic Mountains, bounded by the McMurdo Sound/Ross Sea to the east and the East Antarctic Ice Sheet to the west (Nylen *et al*., 2004; Levy *et al*., 2012). The greater MDVs cover a total area of 22,700 km^2, of which 4,500 km^2 make up the largest ice-free region in Antarctica and contain three large northeast–southwest trending valleys (the Victoria, Wright and Taylor Valleys) (Levy, 2013) (Figure 2, Appendices A and B). Valley floor elevations vary from 0 - 400 m above sea level and the surrounding mountain bands rise to 2,500 m (Nylen *et al*., 2004). The MDVs are a polar desert in which elevated outlet glaciers feed ephemeral meltwater streams running down-valley into closed basin lakes along the valley-bottom. These lakes are covered by a thick, permanently frozen layer of ice, except the lake perimeter which thaws for a portion of the summer and is known as the lake 'moat'.

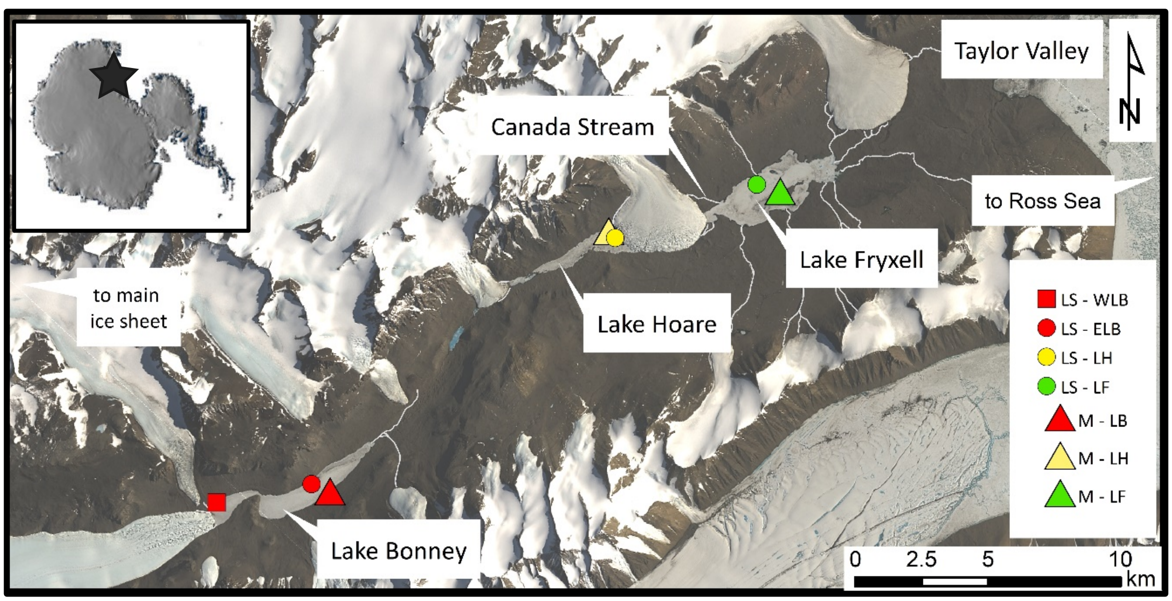

Figure 2: Map of Taylor Valley showing meteorological stations (M) and lake stations (LS) for Lake Fryxell (LF), Lake Hoare (LH), Lake Bonney (LB), and the east/west lobes of Lake Bonney (ELB, WLB). Lake Bonney has one meteorological station and two lake stations, which are further explained in the 'Data' section. The MDVs are indicated by the black star on the continent inset. Additional maps of the entire continent and the central MDVs are found in the Appendix.

Winter consists of April through September; Fall and Spring are March and October, respectively; Summer consists of November through February (Obryk *et al.*, 2020) and is also considered the "flow season" herein for the period of intermittent streamflow in a given 12-month period (Figure 3). The MDVs receive solar radiation only in the months of August – April (Nylen *et al.*, 2004). The 12-month period is split into "flow" and "non-flow" periods in this thesis, which will refer to summer and non-summer months.

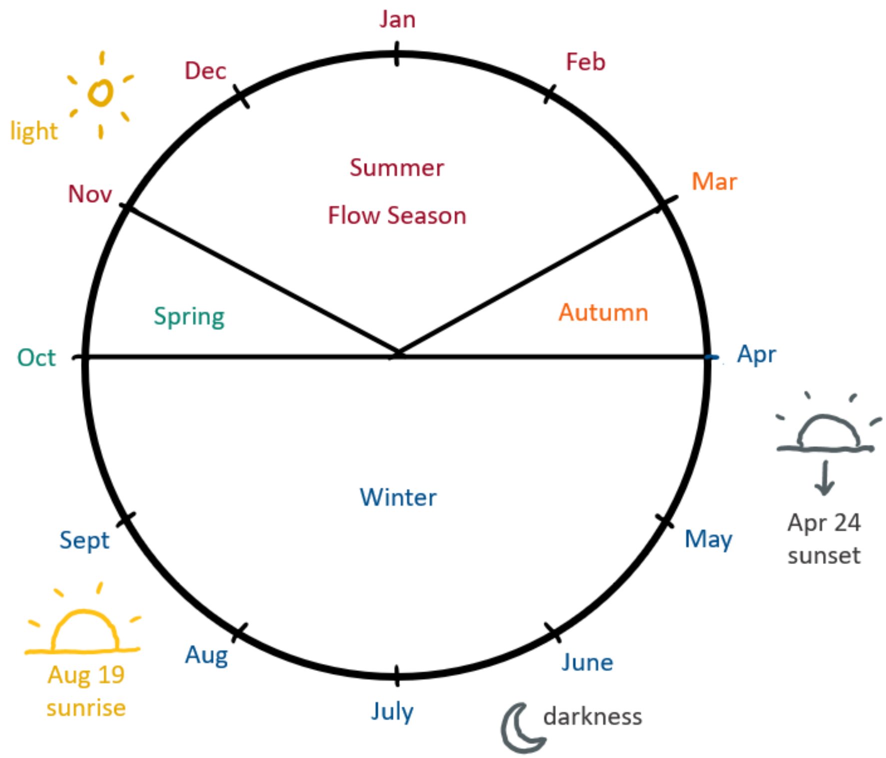

Figure 3: A typical year in the MDVs. The calendar year starting in the middle of the flow season can cause statistical complications about what happens on an annual basis, because streamflow from summer to summer has high variability. The 12-month period must be considered appropriately. Additionally, seasons of varying lengths are an important consideration for statistical comparison.

1.3. Meteorological Statistics

Precipitation in the MDVs is minimal: Rainfall rarely reaches the valley floor, and only then as trace amounts (Keys, 1980). Annual snowfall ranges from 3 - 50 mm water equivalent (Fountain *et al.*, 1999; Fountain *et al.*, 2010). Shallow subsurface water is associated with streams, lakes and water tracks (Gooseff *et al.*, 2013), and is disconnected from deeper aquifers. However, additional evidence suggests groundwater beneath a deep, substantial permafrost layer (Mikucki *et al.*, 2015). Lakes receive almost all water from glacial melt, and lake level rise can be an indicator of collective streamflow and meltwater generation within a water basin.

Regional wind regime is characterized by up- or down-valley topographically channeled airflow. During summer, thermally generated easterly winds dominate (McKendry and Lewthwaite, 1990; Doran *et al*., 2002; Nylen *et al*., 2004; Doran *et al*., 2008; Speirs *et al*., 2010; Speirs *et al*., 2013; Steinhoff *et al*., 2013). Analogous to sea/lake breeze circulations elsewhere, differential surface heating between the low-albedo valley floors and the high-albedo ice and water surfaces to the east induce offshore sea breezes heading southwest (up-valley) in summer months, but far less prominently in winter (Obryk *et al*., 2020; Speirs *et al*., 2013; Clow *et al*., 1988; Colacino & Stocchino, 1978; McKendry & Lewthwaite, 1990; Thompson *et al*., 1971). These up-valley sea breezes typically range from 2.5 to 5.3 m s^{-1} (Nylen *et al*., 2004). Average annual wind speeds range from 1.4 to 3.5 m s^{-1} in Taylor Valley (Obryk *et al*., 2020). Mean annual surface air temperature ranges from -17.1 to -20.0°C with a maximum of 12.0°C and a minimum of -60.2°C (Obryk *et al*., 2020). Average annual relative humidity ranges from 60.4% to 71.3% (Obryk *et al*., 2020).

1.4. Foehn Wind Mechanics – McMurdo Dry Valleys

Low-pressure synoptic scale cyclones in the Amundsen/Ross Sea region off the coast of Marie Byrd Land pull air from elevated inland regions down toward the coast (Appendices A and B) (Brinkmann *et al*., 1971; Doran *et al*., 2008; Speirs *et al*., 2010; Speirs *et al*., 2013). Air travels from the main ice sheet toward the valleys over mountainous terrain exhibiting mountain wave activity, low level wind is topographically obstructed by rows of mountains and valleys, and foehn winds are directed northeast and downward through the MDVs to the Ross Sea. Foehn winds have been modeled to travel from Taylor Glacier through Taylor Valley but can avoid Lake Bonney by passing over the Kukri Hills to enter the valley, and then head downward toward the coast (Speirs *et al*., 2010, Speirs *et al*., 2013, Steinhoff *et al*., 2013). In the past, foehn winds in the MDVs have reached speeds as high as 40 m s^{-1} (Doran *et al*., 2002, Nylen *et al*., 2004, Doran *et al*., 2008), but more recently maximum recorded wind speed of low elevation sites is 49.1 m s^{-1} (Obryk *et al*., 2020). Foehn winds in the MDVs have caused surface air temperature increases of >50°C (Steinhoff *et al*., 2013) and decreases in relative humidity as high as 30% (Clow *et al*., 1988; Nylen *et al*., 2004). Single events last from a few hours to a week in length. Foehn frequency at each site is explained in detail in the Results section.

1.5. Foehn Wind Significance – McMurdo Dry Valleys

Foehn winds are a major climatological feature of the MDVs with their frequency and duration affecting regional temperature records and trends. Regional weather/climate analyses and predictions in the MDVs are incomplete without consideration of foehn wind influence (Nylen *et al*., 2004; Speirs *et al*., 2013). Foehn wind events in winter are more significant in magnitude and frequency than those of summer (Nylen *et al*., 2004), due to greater cyclonic activity in winter (Simmonds *et al*., 2003; Speirs *et al*., 2010; Speirs *et al*., 2013). However, meltwater generation, streamflow and lake level rise occur predominantly in summer months when air temperatures rise to near and above freezing, and foehn activity is especially important (Steinhoff *et al*., 2013).

Foehn wind events are accompanied by other changes to meteorological parameters, such as air temperature and relative humidity. Summer foehn winds in the MDVs have been observed to raise maximum surface air temperature by 4.8°C and significantly increase seasonal degree days above freezing (Doran *et al*., 2008). Winter foehn events have been observed to increase surface air temperature as much as 50°C, but despite this increase, temperatures typically do not exceed freezing in winter months (Nylen *et al*., 2004; Doran *et al*., 2008; Speirs *et al*., 2013; Steinhoff *et al*., 2013; Obryk *et al*., 2017). Temperature variability within a summer foehn event is primarily dependent on the airmass from which the foehn event originates, rather than dynamics of the foehn event itself (Steinhoff *et al*., 2013). Windward air masses containing more moisture content gain more enthalpy when adiabatically rising, subsequently creating warmer foehn winds on the leeward side of the mountain ridge (Steinhoff *et al*., 2013).

Foehn wind frequency largely controls air temperatures from June through August (Nylen *et al*., 2004), and there is a strong correlation between seasonal mean air temperature and foehn frequency (Speirs *et al*., 2013). Elevated surface air temperature due to foehn winds has been observed to remain for days after foehn winds subside and temperatures return to normal, likely due to warming from surface sensible heat fluxes as a result of the foehn (Nylen *et al*., 2004; Steinhoff *et al*., 2013, Speirs *et al*., 2013). Accordingly, they have also contributed to a dramatic increase in degree days above freezing (DDAF) (Obryk *et al*., 2017), prolonged melt season (Obryk *et al*., 2017), glacial ablation (Welch *et al*., 2003), meltwater generation (streamflow) (Welch *et al*., 2003; Doran *et al*., 2008; Obryk *et al*., 2017), the formation of proglacial lakes (Obryk *et al*., 2017), increased lake level rise (Doran *et al*., 2008, Obryk *et al*., 2017), lake ice ablation (Dugan *et al*., 2013) and surface moisture evaporation (Speirs *et al*., 2008). While foehn winds have been tied to the hydrologic responses above, streamflow and lake level rise have not been quantified as responses to individual foehn events in the austral summer. The impacts of foehn winds on lake ice ablation during the winter have been discussed by Dugan *et al*. (2013) amongst others. In this thesis, metrics of foehn wind events are related to lake level rise during the austral summers and lake ice ablation during non-summer months.

Foehn wind events promote the melting and sublimation of ice. Melt primarily depends on solar radiation and low wind speeds. (Clow *et al*., 1988; Hoffman *et al*., 2008; Steinhoff *et al*., 2013). A paradox of foehn events is that synoptic scale cyclones provide cloudy conditions, but also promote foehn wind events that clear cloud cover over the MDVs (Steinhoff et al., 2013). These changes in cloud cover affect incident solar radiation, and therefore the surface energy balance and melt. High wind speeds encourage sublimation rather than melt. While foehn winds cause sublimation year-round, a crucial time period for melt is the few days after a summer foehn event has subsided, perhaps in a warm, calm period between foehn cessation and the next bout of sea breezes, when warming effects of the foehn event remain. In summer, mid-foehn periods can also be important for meltwater generation if windspeeds are low enough (Steinhoff *et al*., 2013).

Outside of hydrology, foehn winds have contributed to rock weathering (Selby *et al*., 1973), sand dune morphology (Speirs *et al*., 2008), aeolian transport of sediment and biological materials (Ayling & McGowan, 2006; Speirs *et al*., 2008; Sabacka *et al*., 2012; Diaz *et al*., 2018), and biological productivity (Fountain *et al*., 1999; Foreman *et al*., 2004). Aside from rare, wandering seals, penguins and skua, lifeforms in the MDVs consist of bacteria, algae, moss, nematodes, rotifers and tardigrades (McKnight *et al*., 1999). The biological communities in lakes, streams, rocks and soils such as algal mats and microbes, amongst many other lifeforms, respond to the influx of water and sediment in this region, (Bowman *et al*., 2016; Foreman *et al*., 2004; Steinhoff *et al*., 2013; Fountain *et al*., 2016; Gooseff *et al*., 2017; Wlostowski *et al*., 2019) making foehn winds of interest to biologists seeking to predict the fate of life in the MDVs in response to climate change.

Regional climate of the MDVs is coupled with the Southern Annual Mode (SAM), which is the main driver of atmospheric variability in the Southern Hemisphere (Fountain *et al*., 2016, Obryk *et al*., 2020). An increase in greenhouse gases in the atmosphere leading to a decrease in the ozone layer and a more positive (southern trending) SAM is predicted to cause more cyclonic activity off the coast of Marie Byrd Land, which in turn would cause more foehn wind activity in the MDVs (Speirs *et al*., 2013), thereby affecting all of the hydrologic, physical and biologic processes listed above.

1.6. Naming Convention

Foehn winds in the MDVs are often misinterpreted as adiabatically warmed katabatic winds draining from the polar plateau, or foehn winds which were instigated by katabatic winds (Speirs *et al*., 2010). Although synoptically driven winds in the MDVs may have a small katabatic component, katabatic winds do not instigate foehn wind events (Speirs *et al*., 2013), the MDVs do not lie in a katabatic convergence zone (Clow *et al*., 1988; Speirs *et al*., 2013) and katabatic activity in summers is not possible due to insufficient surface temperature inversions (Steinhoff *et al*., 2013). Past publications have interchangeably referred to foehn winds as “katabatic”, “warm strong westerlies”, “down-valley winds”, and “drainage winds”, amongst other titles (e.g. Nylen *et al*., 2004; Doran *et al*., 2008; Speirs *et al*., 2010; Steinhoff *et al*., 2013; Obryk *et al*., 2017). “Foehn” and “föhn” are interchangeable more accurate titles for these wind events, and similar wind phenomena have many different names around the world.

1.7. Purpose of this Thesis

Nylen *et al*. (2004) provided meteorological statistics for foehn winds in the MDVs. In this past study, data from several meteorological stations from 1999 were compared, as well as data from the Lake Hoare Met Station from 1989 to 2001. Statistical analysis regarding foehn wind behavior has not been updated with recently acquired data prior to this thesis. Additionally, advances have been made in statistically identifying foehn wind events via meteorological data (Speirs *et al*., 2010; Speirs *et al*., 2013). These methods have been analyzed and some updates are provided.

This thesis serves to update some of the statistical analyses reported by Nylen *et al*. (2004) with updated datasets and defining metrics described in Speirs *et al*. (2010 and 2013). Foehn winds have been known to largely control lake ice sublimation in winter months (Dugan *et al*., 2013) and increased streamflow and lake level rise in summer months (Doran *et al*., 2008; Obryk *et al*., 2017). An additional purpose of this document is to provide a preliminary exploration of quantifying the hydrologic response of foehn winds in winter and summer months. Meteorological data has been spatially paired with lake stage data for this investigation.

2. METHODS

2.1. Data

Lake monitoring stations are maintained by the MCMLTER at various lakes throughout the MDVs. Pressure transducers moored to the lake bottom deliver information to dataloggers sitting atop lake ice. These systems are explained in full detail in Dugan *et al*. (2013) and Doran (2020). This study has considered lake stage and lake ice ablation data from lake stations at Lake Fryxell, Lake Hoare, and the east/west lobes of Lake Bonney.

Over 15 year-round meteorological ("met") stations have been deployed in the MDVs by the MCMLTER, of which 14 are currently operational (Obryk *et al*., 2020). Stations have been installed at various times since 1993 and vary in data frequency (Figure 4). These systems are explained in full detail in Obryk *et al*. (2020) and Doran (2019). This study utilizes the met stations at Lake Fryxell, Lake Hoare and Lake Bonney, all of which are installed on soil. Considered data from these stations include air temperature, wind speed, wind direction and relative humidity (all at 3m above ground level). Missing data was not interpolated and seasonal records with insufficient data were not considered (Table 1). Locations for each data source are shown in Figure 2 and described in Table 2 below.

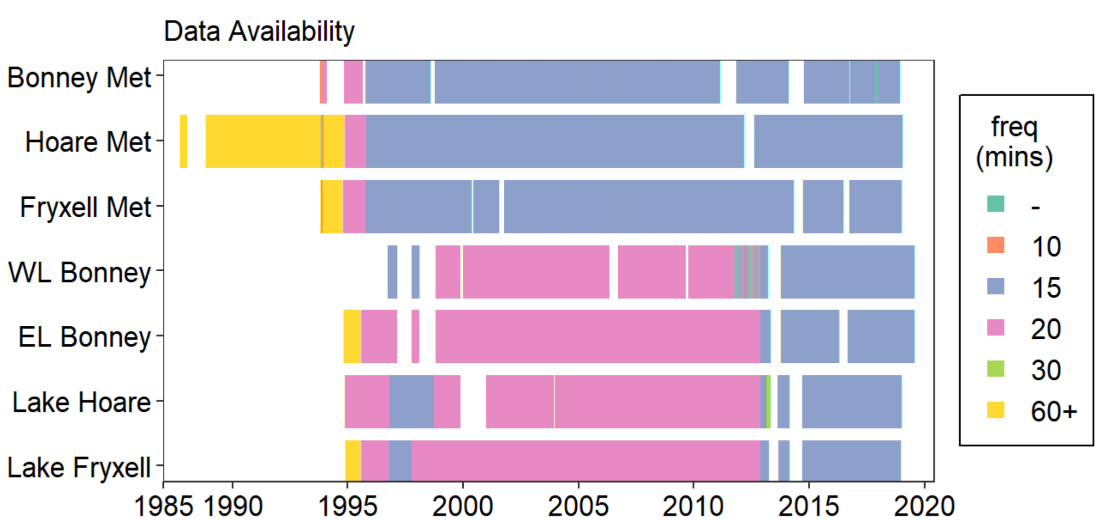

Figure 4: Data availability of windspeed and lake stage from meteorological stations and lake stations, respectively. Frequency of collected data in minute intervals is shown by color.

Table 1: Data used in this study.*											
Year	Paired Meteorological Data & Lake Stage Data								Met Data Only		
	Summer				Fall, Winter, Spring				Annual		
	F	H	ELB	WLB	F	H	ELB	WLB	F	H	B
1994	-	-	-	-	-	-	-	-	√	-	-
1995	-	-	-	-	-	-	-	-	√	-	-
1996	-	-	-	-	-	-	-	-	√	√	√
1997	√	√	-	-	√	-	-	-	√	√	√
1998	√	√	-	-	√	-	-	-	√	√	-
1999	-	-	√	-	√	√	-	-	√	√	√
2000	-	-	-	-	-	-	-	-	-	√	-
2001	√	√	√	-	-	√	√	-	-	√	√
2002	-	√	√	-	-	√	√	-	√	√	√
2003	-	-	-	-	-	√	-	-	√	√	-
2004	√	-	√	-	-	√	-	-	√	√	√
2005	√	√	√	-	√	√	√	-	√	√	√
2006	√	√	-	-	√	√	-	-	√	√	√
2007	-	√	√	-	√	√	√	-	√	√	-
2008	-	-	√	-	√	√	√	-	√	√	√
2009	-	-	√	-	-	-	√	-	√	√	√
2010	√	√	√	-	-	-	√	-	√	√	√
2011	√	√	√	-	√	√	-	-	√	√	-
2012	√	√	√	-	√	-	√	-	√	-	√
2013	-	-	-	-	-	√	√	-	√	√	√
2014	-	√	√	-	-	-	-	-	-	-	-
2015	√	√	-	√	√	-	-	√	√	-	√
2016	√	-	√	-	-	√	-	-	-	√	-
2017	√	-	-	-	√	√	√	√	√	√	-
2018	-	-	-	-	√	√	√	-	√	-	-

* Data usage shown for each location: Lake Fryxell (F), Lake Hoare (H), East Lobe of Lake Bonney (ELB), West Lobe of Lake Bonney (WLB). When solely using meteorological data for annual analyses, Lake Bonney (B) is used. Because Meteorological data is paired with lake station data in summer and non-summer analyses, both datasets need to contain usable data for the same timeframe at a given location for successful analyses. Data for each location and timeframe were plotted for visual inspection. Because data availability varies across 12-month period, usable seasons of data vary between summer, non-summer and annual analyses. Seasons with sufficient missing or blatantly erroneous data were discarded. Meteorological data cited in Doran & Fountain, 2019 and Doran, 2020.

Table 2: Meteorological Station & Lake Station Locations				
Location	Latitude °S	Longitude °E	Elevation (m) asl	Season Installed
Met Station: Lake Fryxell	77.611	163.170	20	1987/1988
Met Station: Lake Hoare	77.625	162.900	77	1985/1986
Met Station: Lake Bonney	77.714	162.464	60	1993/1994
Lake Station: Lake Fryxell	77.609	163.132	(varies)	1994/1995
Lake Station: Lake Hoare	77.628	162.910		1994/1995
Lake Station: East Lobe, Lake Bonney	77.712	162.435		1994/1995
Lake Station: West Lobe, Lake Bonney	77.719	162.284		1996/1997

Also maintained by the MCMLTER are 18 currently operational stream gauges which measure water temperature, specific conductivity and flow depth (which is used to calculate flow rate via rating curves). Several stream datasets were initially considered in this analysis but were later replaced by lake stage data. Lake stage is a reasonable indicator of total net meltwater flowing into a given basin because lake volume is made up almost entirely by stream inflow (less any evaporation of streamflow and lake water along the lake margins). In theory, streamflow at a single gauge may show response to increased glacial melt feeding the stream, but lake stage data provides an integration of all in-flow within a given basin (including direct glacial melt and streams that are not gauged). Compared to streamflow data, lake stage is generally less variable and contains less missing data within a given flow season. Three hydrographs of summer streamflow are shown in Figure 5 to display high variability of streamflow at a single site across three consecutive summer seasons. Taylor Valley was chosen for this study because foehn winds are prevalent in this region, and the three main lakes in Taylor Valley are available for paired lake stage and meteorological data analysis. The abundance of paired data sources in foehn wind prone areas such as this are not found elsewhere in the MDVs. Additionally, identifying foehn winds at glacier met stations is possible but can be more difficult due to down-glacial winds and otherwise more variable wind direction at higher elevations (Nylen *et al*., 2004; Speirs *et al*., 2010).

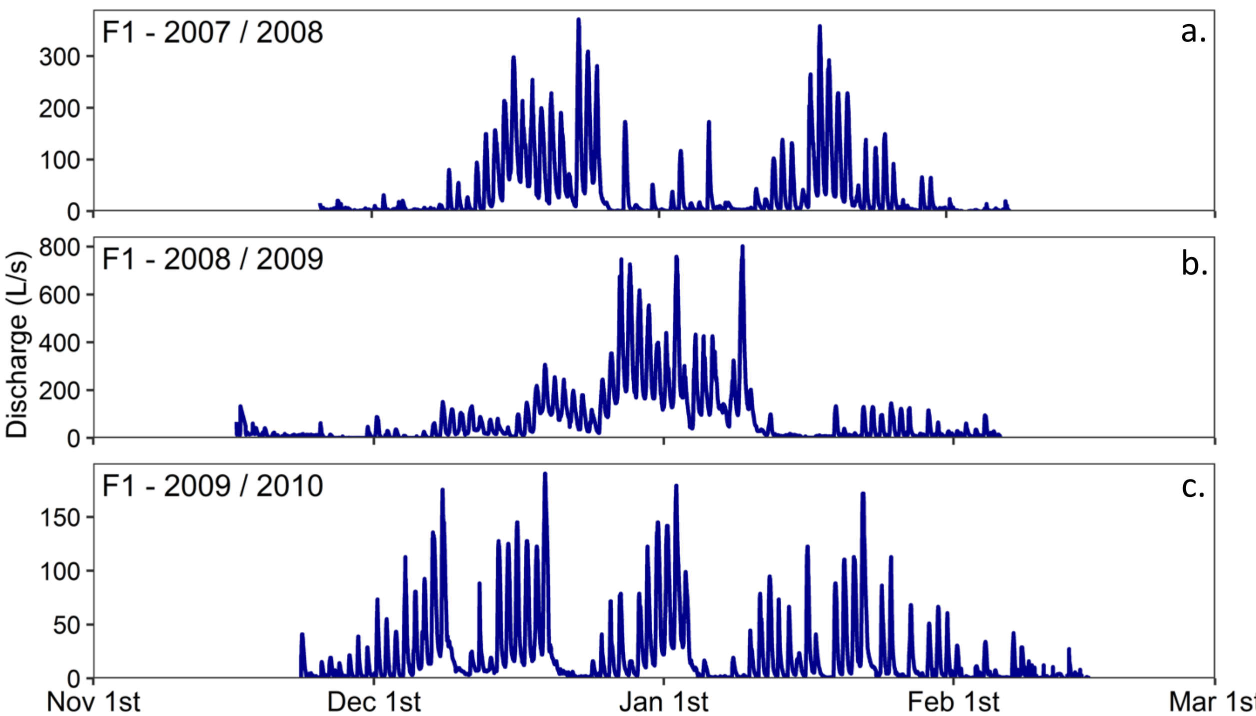

Figure 5: Summer hydrographs for Canada Stream at the F1 gauge for a) 2007/08, b) 2008/09 and c) 2009/10 flow seasons. Note the variability in discharge on the y-axis scale at the same location over three consecutive summer seasons. Streamflow data from Gooseff & McKnight (2019).

2.2. Evolution of Foehn Identification

The first step in this analysis is properly identifying the start (onset), middle (duration) and end (cessation) of foehn wind events. Identification of foehn winds by statistically analyzing MCMLTER meteorological data has evolved with different metrics in various publications through time. Selected publications have been included in Table 3. A minimum windspeed of 5 m s^{-1} has been described by Clow *et al*. (1988) and is accepted by all subsequent analyses. Foehn wind direction is generally described as 'down-valley', which Nylen *et al*. (2004) defines as an azimuth range of 180°-315° (180°-360° at Lake Vida). Windspeed of ≥ 5 m s^{-1} and a wind direction within 180°-315° (180°-360° at Lake Vida) will be referred to as "basic requirements" hereafter. Nylen *et al*. (2004) commented on foehn winds causing increased air temperature and decreased relative humidity, but this was not numerically included in identification metrics. Nylen *et al*. (2004) refers to foehn wind frequency as a percent of a total season because onset and cessation of foehn events is not identified.

Table 3: Evolution of Foehn Identification

Publication	Wind-speed	Wind Azimuth	Air Temperature	Relative Humidity	Duration	Onset & Cessation
Clow *et al*. (1988)		“down-valley”	***	-	-	***
Nylen *et al*. (2004)		180°-315° *	***	***	-	-
Speirs *et al*. (2010) Speirs *et al*. (2013) Steinhoff *et al*. (2013)	≥ 5 m/s	180°-315° *	≥1.0°C hr^{-1}	≤-5% hr^{-1}	≥ 6 hrs**	✓
Obryk *et al*. (2017)		180°-360°	-	-	> 6 hrs	-
updated method		180°-315°	≥1.0°C hr^{-1} OR >-1.5° C	≤-5% hr^{-1} OR <30%	≥ 6 hrs	✓

*Excepting Lake Vida **Used to constitute a foehn day ***Discussed; not implemented

Speirs *et al*. (2010 and 2013) built upon basic requirements for foehn events with explicit onset, minimum duration and the concept of the “foehn day”. Onset of a foehn event is identified as (1) satisfied basic requirements, (2) an air temperature increase of at least 1.0°C hr^{-1} and (3) a relative humidity decrease of at least 5% hr^{-1}. After onset, only basic requirements apply to the duration of the event. However, foehn events are required to be at least 6 hours long, of which at least 80% of points satisfy basic requirements (personal communication with Johanna Speirs). This 20% tolerance allows for noise in wind speed and wind direction data, as well as interruptions to foehn events by sea breezes.

Cessation is not explicitly defined but can be inferred as the time when less than 80% of points within a foehn event satisfy basic requirements after 6 hours. In practice, requirements by Speirs considerably reduce the amount of points in a given season identified as “foehn” compared to that of Nylen *et al*. (2004) and Clow *et al*. (1988) due to “onset” requirements to start an event. See additional information in the Discussion section and subsequent figures. Steinhoff *et al*. (2013) explicitly quotes using the foehn identification metrics of Speirs *et al*. (2013). Obryk *et al*. (2017) uses modified basic requirements and a minimum duration of 6 hours but does not discuss onset or cessation metrics. Three distinct sets of identification metrics will be referred to as the ‘Nylen method’, identifying an approach from Clow *et al*. (1988) and Nylen *et al*. (2004); the ‘Speirs method’ identifying the approach from Speirs *et al*. (2010 and 2013) and Steinhoff *et al*. (2013); and the 'updated method', referring to the approach established in this research and used in subsequent analyses.

The updated method provided in this thesis implements the Speirs method with three additions to both tighten and ease constraints as an attempt to improve foehn identification. In identifying onset, two qualifiers are added to relax requirements for change in air temperature and change in relative humidity. An "air temperature increase of at least 1.0°C hr^{-1}," and a "relative humidity decrease of at least 5% hr^{-1}" were implemented by comparing data from 30 minutes before and after a given time. This can lead to identification problems when a string of foehn events increases air temperature and/or decreases relative humidity and the following foehn event cannot satisfy the required change in these metrics for another onset. In other words, if temperature is already high (above freezing) another foehn event may not be able increase it by another 1.0°C hr^{-1}. Additionally, if relative humidity is already low (~<30%), another foehn event may not be able to decrease relative humidity an additional 5% hr^{-1}. This does not negate the validity of a given event and should be considered in requirement metrics.

Because foehn winds have been attributed to a decrease in relative humidity of up to 30% (Clow *et al*., 1988; Nylen *et al*., 2004), the required decrease in relative humidity has been ignored if relative humidity is already 30% or lower. Relative humidity is ≤ 30% for 4.8% of all data at the three locations (Figure 6). Because glacial runoff and ablation increase sharply as air temperatures rise above -1.5°C in this region (Ebnet, 2005), the requirement for an increase in air temperature of at least 1°C hr^{-1} has been ignored if the air temperature is already ≥ -1.5°C. Air temperature is ≥ -1.5°C for 9.8% of all data at the three locations (Figure 6), which is less of a restriction than the threshold for relative humidity. However, this value of -1.5°C is important to consider for melt response.

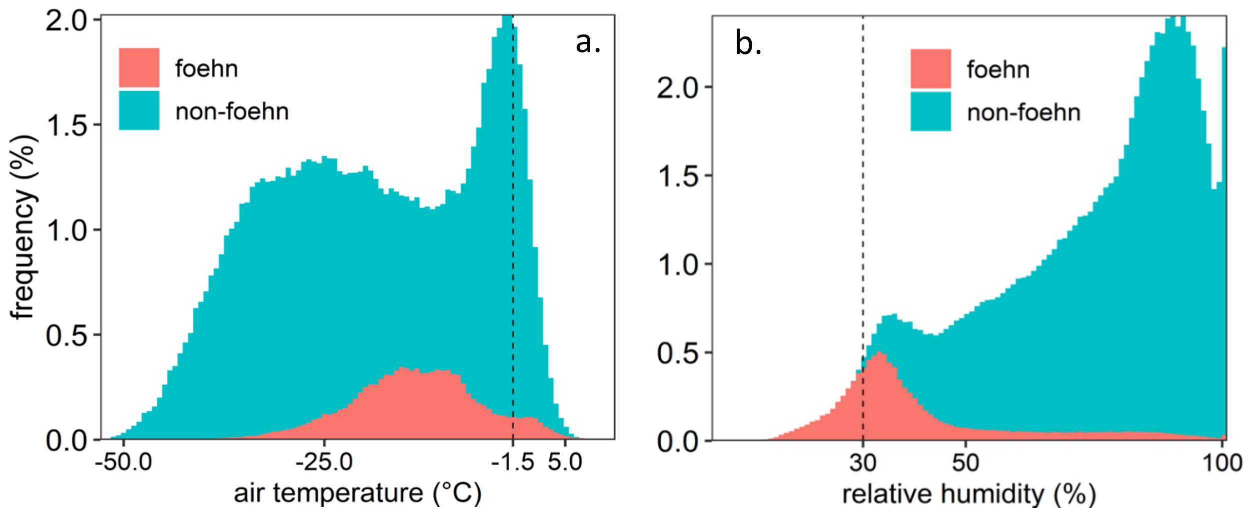

Figure 6: Histograms of a) surface air temperature and b) relative humidity for combined data at Lake Fryxell, Lake Hoare and Lake Bonney meteorological stations. Chosen thresholds of -1.5°C and 30% are shown, respectively, with a dotted line. Datapoints are colored by whether or not they are flagged as foehn or non-foehn (based on the updated method) and do not consider the warm period after a given foehn event.

Lastly, the inferred method from Speirs *et al*. (2010 and 2013) to identify cessation of a foehn event is defined by the moment in which the event fails to satisfy basic requirements for 80% of the elapsed time. It has been found that noise in windspeed and wind direction often allow the majority of a foehn event to successfully satisfy basic requirements, and the given 20% tolerance of basic requirement failure creates a “tail” of failing points in an identified event (Figure 7). In these instances, it is believed that event duration is over-estimated and these datapoints should not be considered as part of the given event. To remediate this, if basic requirements are not satisfied at the end of an identified event, points are marked ‘non-foehn’ backwards in time until basic requirements are satisfied, thus reducing the duration of the given event. This increases strictness of foehn identification, but also considers foehn interruption. Foehn events are often interrupted at eastern sites for brief periods of sea breezes (Steinhoff *et al*., 2013) and it is crucial to distinguish one event with a brief interruption from two distinct events.

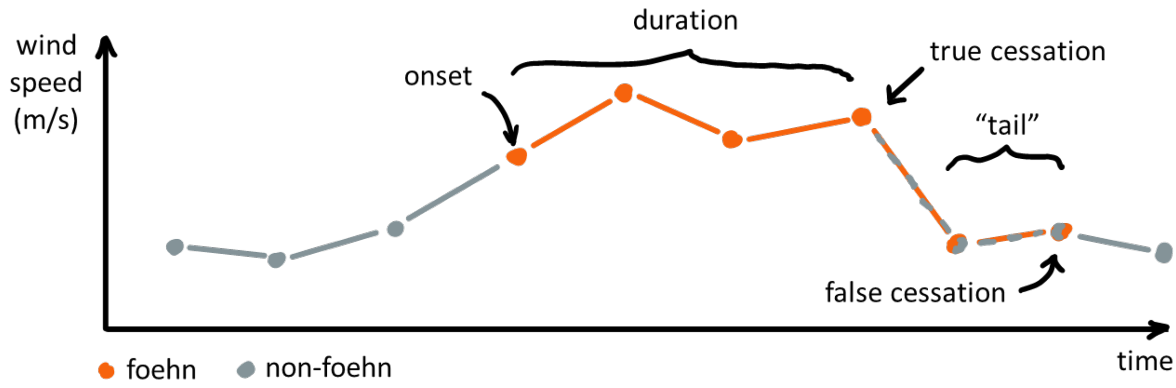

Figure 7: A simplified sketch of datapoints outlining a foehn wind with various identifiers. Typically, datapoints from meteorological stations are on a 15-min frequency, and foehn events occupy far more datapoints that what is shown due to the minimum 6-hour duration requirement.

2.3. Metrics of Foehn Wind Events

When attempting to analyze hydrologic records to uncover responses to foehn winds, a major task is identifying metrics of foehn winds as standalone events and as a collective set of events throughout a given season. This allows a magnitude of foehn influence to be compared to other aspects of the ecosystem such as the magnitude of streamflow or lake level response. As an attempt to identify foehn influence in a given timeframe, the concept of a "foehn day" was introduced (Speirs *et al*., 2010; Speirs *et al*., 2013) as a calendar day that experiences ≥ 6 hours of basic requirements after identified onset as described above. This explicitly excludes events that numerically satisfy constraints for less than 6 hours. Shorter events such as these are difficult to distinguish as foehn or down-glacial winds. The foehn day concept does not consider the length of a foehn wind occupying a calendar day (15 minutes to 24 hours). Nor does it distinguish foehn events that raise surface air temperatures in small or large magnitudes (1°C - 50°C), foehn events that raise or do not raise air temperatures above freezing, or events that have lower or higher velocity windspeeds (5 m s^{-1} – 40 m s^{-1}). The day simply *is* or *is not* a 'foehn day'. Nonetheless, the foehn day is a useful concept as shown in Speirs *et al*. (2010 and 2013).

Additionally, foehn winds can be compared using the metric of wind-run, which is the integration of windspeed with respect to time for a foehn event (Figure 8a). Foehn warming influence can be identified by degree days above freezing (DDAF), which is the integration of air temperature above 0°C with respect to time for a foehn event (Figure 8b). Wind-run and DDAF of foehn events solely quantify windspeed and air temperature respectively. Obryk *et al*. (2017) have correlated summer foehn winds quantified by wind run with general (non-foehn specific) summer DDAF, ($r^2 = 0.83$, $P < 0.001$, $n = 18$). Doran *et al*. (2008) have correlated summer DDAF with increased lake level rise using five seasons of data ($r^2 = 0.82$, $P = 0.035$). Thus, there is an expected indirect connection between foehn event wind-run, general summer DDAF, and summer lake level rise. A distinction of this work is researching the correlation of the magnitude of a single foehn wind event and its individual impact to lake level rise, rather than a seasonal analysis considering general DDAF. In summer seasons, we have quantified foehn winds by DDAF, but use -1.5°C rather than 0°C as a minimum threshold because Ebnet *et al*. (2005) noted a sharp increase in glacial melt above this threshold in this region. In this thesis, DDAF with a low threshold of -1.5°C rather than the commonly used 0°C will be referred to as '$DDAF_{-1.5}$'. Wind-run is used to quantify non-summer foehn events when temperatures above freezing are not applicable.

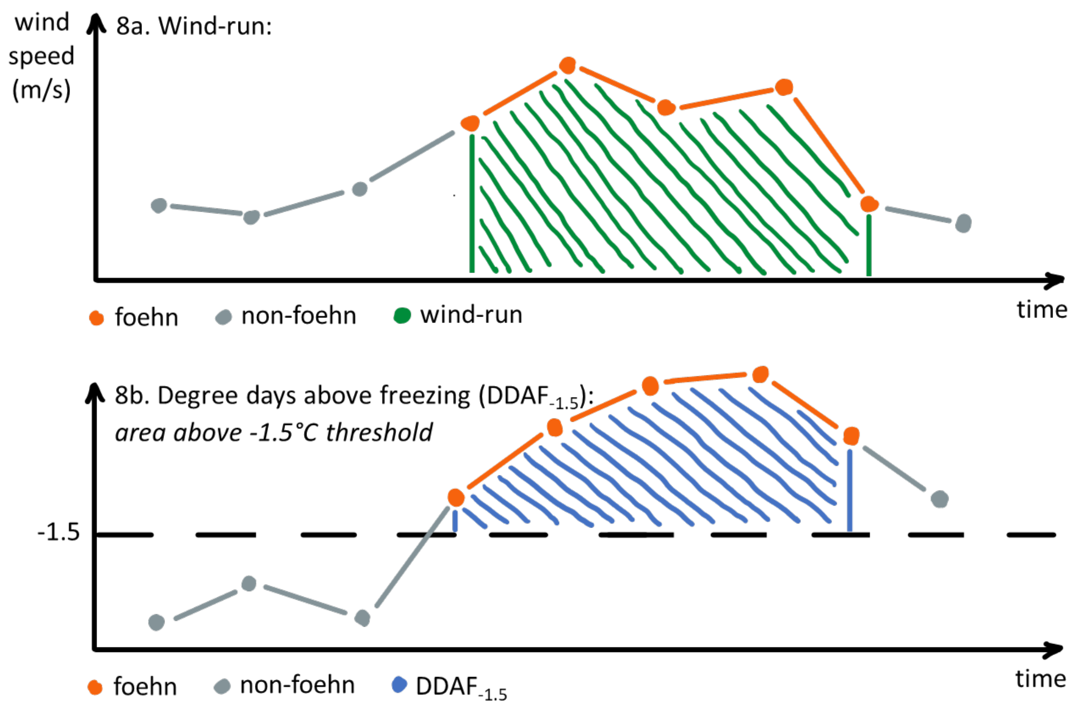

Figure 8: Concept sketches of a) wind-run and b) DDAF$_{-1.5}$ as integrations of windspeed with respect to time and air temperature above -1.5°C with respect to time, respectively.

2.4. Quantifying Lake Level & Post-Foehn Warming

The timeframe after foehn cessation is interrogated in this thesis for increased lake stage. It is hypothesized that in the austral summer, a foehn event provides warm air, promoting glacial melt, and in the following days the generated melt is delivered to the appropriate lake via streamflow. It is additionally hypothesized that a foehn event of greater magnitude creates more subsequent melt and lake level rise. Because stream lengths in Taylor Valley are highly variable (Doran *et al*., 2008), the amount of time for a pulse of glacial melt to register as lake level rise is variable across different stream lengths and is not known. Thus, "post-foehn" time windows of 24, 48, 72 and 96 hours are used in analysis and have been normalized for daily rise (i.e. 96-hour rise has been divided by 4) (Figure 9). The change in lake level in these arbitrary time windows after foehn cessation is quantified as the stage at the last available datapoint in the time window minus the stage at the time of foehn cessation.

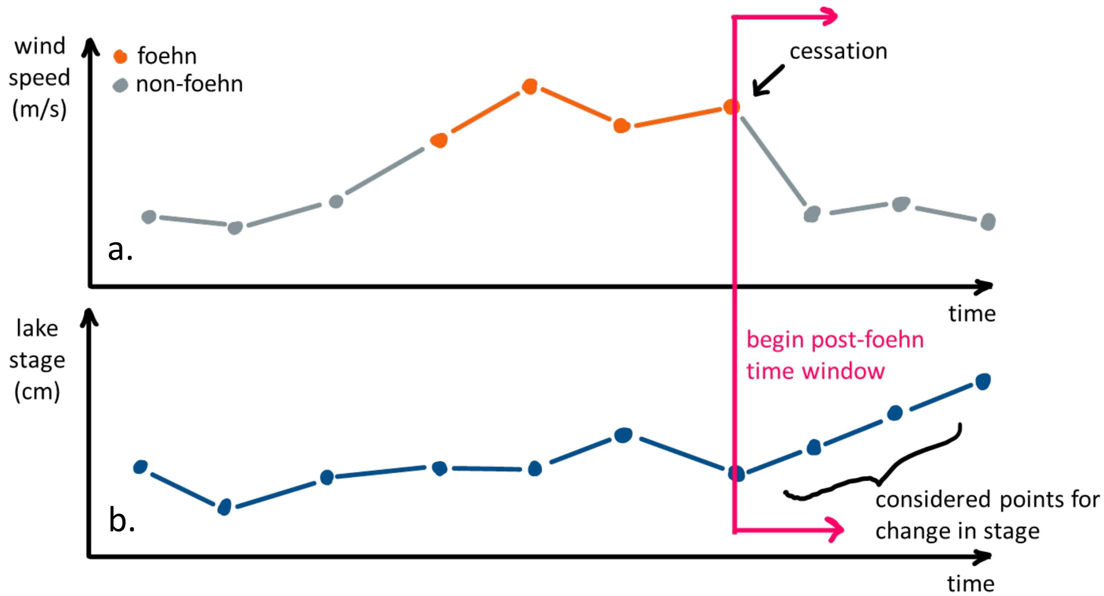

Figure 9: Concept sketch for the quantification of change in lake stage post-foehn event, based on a) windspeed, and b) lake stage. The post-foehn time window extends forward in time 24, 48, 72 or 96 hours for multiple analyses.

Within this summer analysis of foehn winds and lake stage rise, a "control" has been calculated which represents the average lake stage rise for times unaffected by foehn winds. This value is calculated by taking an entire meteorological record and determining which timestamps are unaffected by foehn events. This is carried out 4 times, with the assumption that a foehn event affects local climate while it is occurring, and 24, 48, 72 or 96 hours after it ends. Times labeled "unaffected" are then used to calculate change in lake level in a 24-hour period. This non-foehn daily change in stage is averaged over the entire record. Because this is carried out four times (one for each time window length), 4 values are calculated for each location.

2.5. Lake Ice Ablation

Lake ice sublimation data is provided by MCMLTER lake stations. Total ablation for a non-flow season between March 1st and October 31st at a given lake was initially calculated as the difference between reported ablation at the start and end of this time window. However, this analysis was abandoned and should be avoided due to the potential problem described in Dugan *et al*. (2013). As explained in full detail in Dugan *et al*., (2013), direct ablation data is acquired by pressure transducers (for data, metadata and equipment details, see Doran, 2020) suspended in lake water beneath the lake ice, and erroneously high ablation data is possible in winter months when ice accretes to the bottom of the ice cover. This increases buoyancy of the ice cover and elevates the pressure transducer. To avoid this, the difference in lake stage is instead used to calculate seasonal ablation as is implemented in Dugan *et al.* (2013). This is acceptable because winter change in lake level can be attributed to sublimation directly (Dugan *et al*., 2013). Lake inflow from precipitation and streamflow is negligible if not zero in winter months, and there is no outflow for these lakes. This change in stage value is compared to the fraction of seasonal foehn wind run divided by total wind run for the given season and is shown in the Results & Discussion section. Similar to other datasets used in this thesis, seasons with insufficient data were not used. We have also compared change in lake stage with the fraction of total foehn time over total time in the given season.

3. RESULTS & DISCUSSION

3.1. Foehn Frequency

As determined by the updated method, foehn winds generally occur 5-9 times per summer season and 27-41 times in a 12-month period (Table 4). Note that seasons vary in length, and the number of foehn events in a given season also varies accordingly.

Table 4: Average number of foehn events at each site.

	Summer Nov - Feb	Autumn Mar	Winter Apr - Sept	Spring Oct	Annual
Lake Fryxell Met	5	2	17	3	27
Lake Hoare Met	5	3	29	4	41
Lake Bonney Met	9	3	24	5	41

The number of foehn events is identified to be increasing through time at Lake Fryxell, but not Lakes Hoare or Bonney (Figure 10) (r^2: 0.24, p-value: 0.03; Lake Hoare r^2: 0.12, p-value: 0.15; Lake Bonney r^2: 0.20, p-value: 0.11). The specific number of foehn events occurring in a given timeframe is difficult to accurately quantify in data analysis or in the field. The difference between multiple individual foehn events and one long event with interruptions is defined only by the arbitrary 80% tolerance as described in the Methods section. Should future work decide to explore alternatives to this 80% metric, the number of foehn events occurring seasonally or annually is expected to change.

Annual foehn wind-run (Figure 11) is shown to be a more statistically significant metric than foehn frequency (Figure 10) when exploring long term trends of foehn presence in the MDVs. Annual foehn wind-run varies greatly and generally increases through time. This trend is statistically identified at Lakes Fryxell and Hoare, but not Lake Bonney (Lake Fryxell: r^2: 0.22, p-value: 0.045; Lake Hoare: r^2: 0.23, p-value: 0.040; Lake Bonney: r^2: 0.03, p-value: 0.563). It is anticipated that foehn winds will increase in the future with increased global warming (Section 1.5).

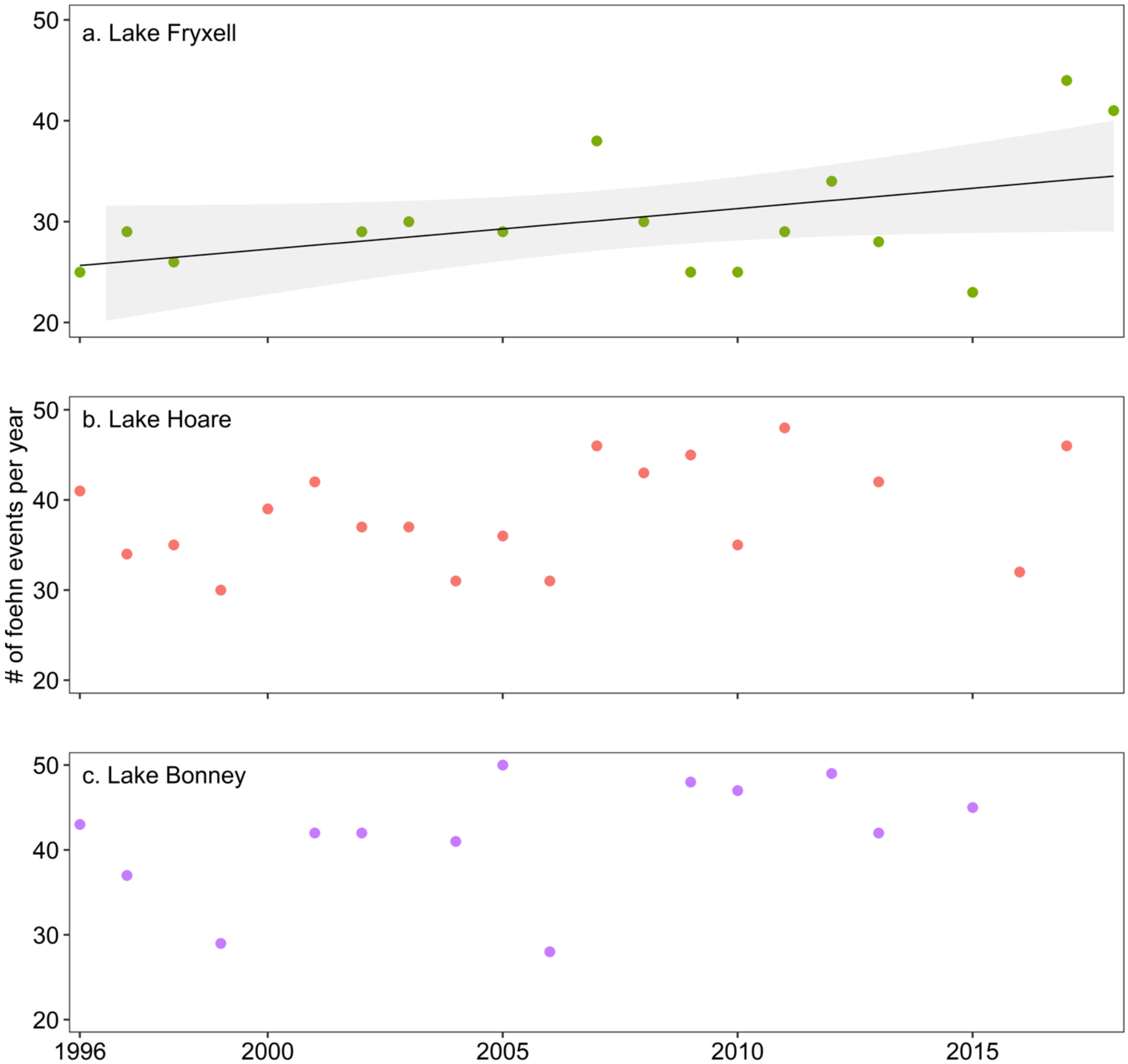

Figure 10: Annual foehn event count through time from meteorological stations at a) Lake Fryxell, b) Lake Hoare, and c) Lake Bonney, plotted with data from years shown in Table 1. Lake Fryxell is shown with a trendline and 95% confidence interval due to its more reliable statistics. Lake Fryxell r^2: 0.24, p-value: 0.03; Lake Hoare r^2: 0.12, p-value: 0.15; Lake Bonney r^2: 0.20, p-value: 0.11.

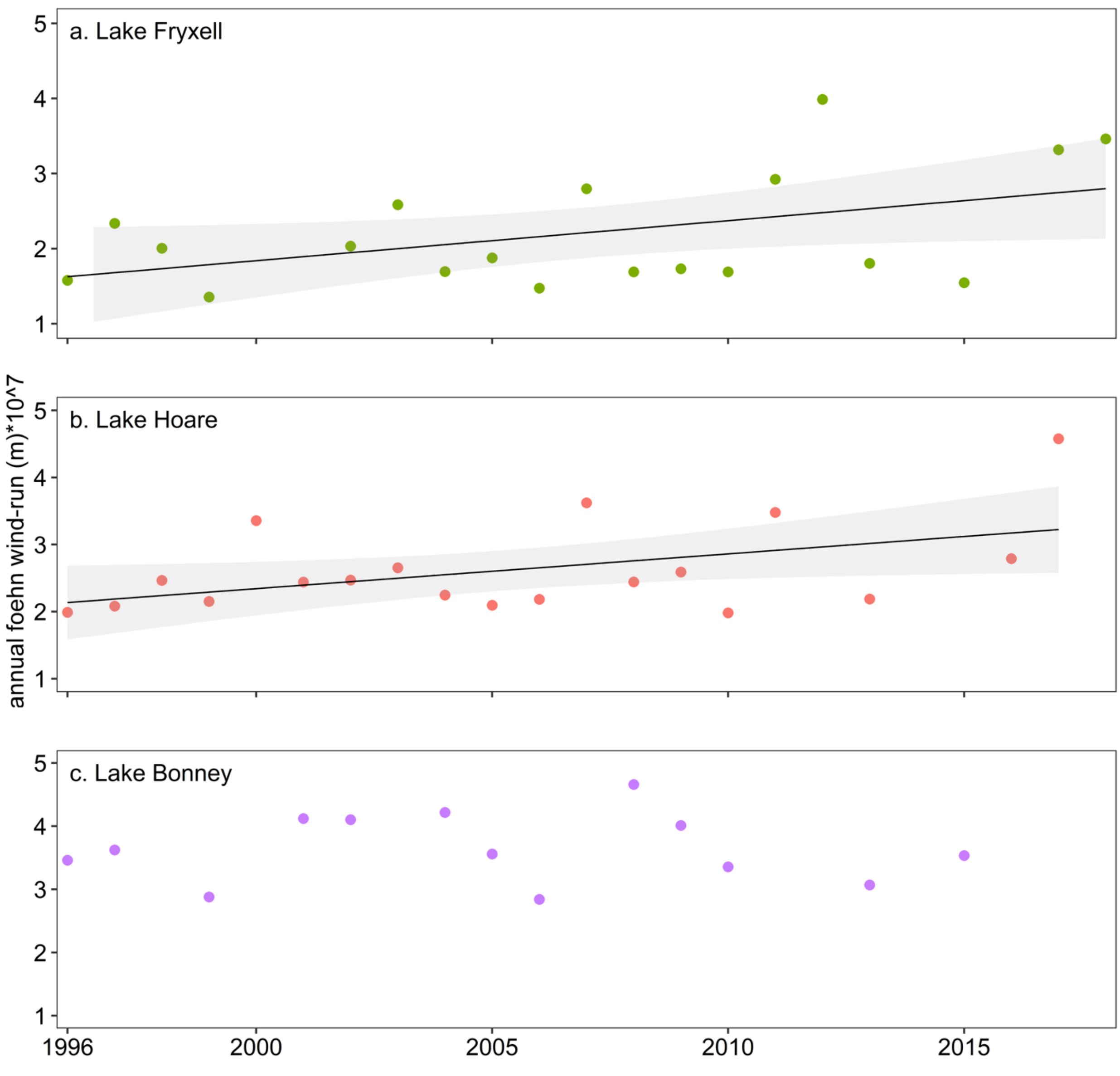

Figure 11: Annual Foehn Wind-run from meteorological stations at a) Lake Fryxell, b) Lake Hoare, and c) Lake Bonney, each lake are plotted with data from years shown in Table 1. This plot suggests a general increase in foehn winds through time, but a significant correlation ($p < 0.05$) was not found at Lake Bonney. (Lake Fryxell: r^2: 0.22, p-value: 0.045; Lake Hoare: r^2: 0.23, p-value: 0.040; Lake Bonney: r^2: 0.03, p-value: 0.563)

3.2. Foehn Identification Metrics

Nylen *et al*. (2004) defined the foehn identification metric for wind direction as an azimuth of 180°-315° for the three considered sites of this thesis. This requirement has been reviewed with recent data as shown in Figure 12. While it appears that upper bounds for wind azimuth could be reduced at some sites, the lack of data in upper regions suggests this change is unnecessary. The metric appears to be applicable to recent data and is supported for future identification of foehn events.

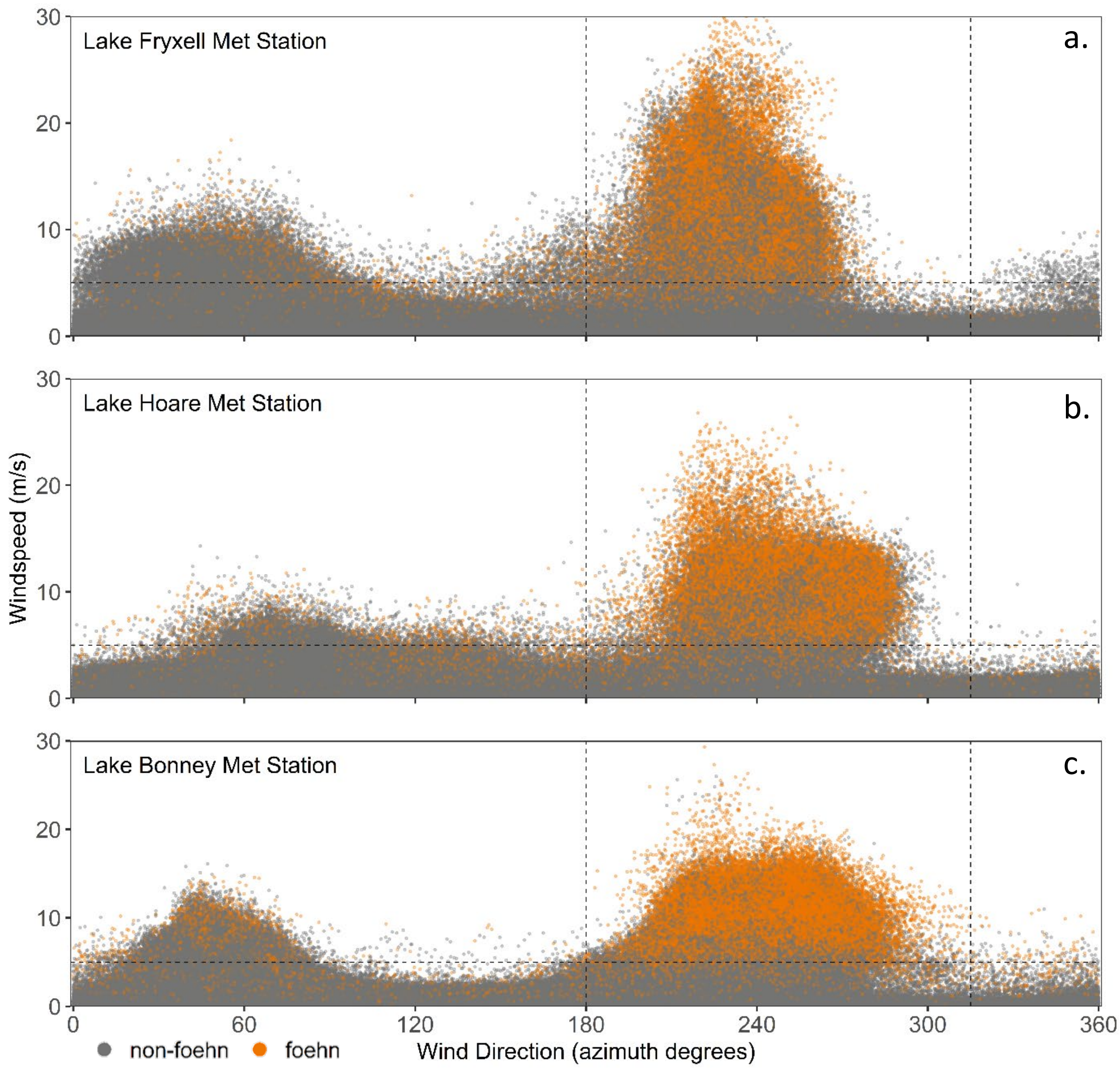

Figure 12: Windspeed vs. wind direction plots for foehn and non-foehn winds at a) Lake Fryxell, b) Lake Hoare, and c) Lake Bonney. Requirement metrics for windspeed and wind direction are shown with dotted lines. Foehn conditions identified outside of the qualifying range of wind direction are parts of tails of foehn events and foehn events interrupted by sea breezes.

As described, three sets of metrics are used to identify foehn events at each location. Because identifying foehn events "manually" requires considering these sets of metrics, it is not possible to compare different methods in terms of statistical accuracy. Each method assumes different definitions for foehn events. However, results from each method are compared in Table 5 and Figure 13. Because the Nylen method does not identify onset or duration, isolated 15-minute points are periodically improperly identified as standalone foehn events (see early/mid-December, Figure 13).

Table 5: Percent of Average Season Identified as Foehn*

Season	Location	Nylen	Speirs	Updated
Summer (Nov 1 – Feb 28)	Fryxell	5.33%	2.83%	3.14%
	Hoare	6.32%	2.42%	2.98%
	Bonney	14.54%	9.86%	10.71%
Non-summer (Mar 1 – Oct 31)	Fryxell	14.09%	8.18%	8.19%
	Hoare	20.39%	13.89%	14.00%
	Bonney	23.21%	18.26%	18.35%

* For specific seasons of data used in these averages, see Table 1.

In Figure 13, a period near January 1st has two foehn events according to the updated method. The Speirs method does not identify the middle of these events, due to strict metrics with strings of foehn events as described. The updated method, utilizing described alternative metrics to onset requirements, provides a potential solution to this problem. Overall, the Nylen method identifies the most points as 'foehn' of the three methods, with the Speirs method typically identifying the least, and the updated method in between them. The increase in number of foehn identified points from the Speirs method to the updated method is less prominent in non-summer months than summer months. This can be attributed to added metrics of the updated method being less relevent when temperatures do not exceed -1.5°C in colder months. Potential improvements to the updated method exist. The updated method is believed to be slightly too strict in identifying onset, as potential foehn events occasionally are seen unidentified (see mid-November and mid-February in Figure 13). Nonetheless, the updated method as described is founded in values from supplemental publications for this thesis and is used in subsequent analyses.

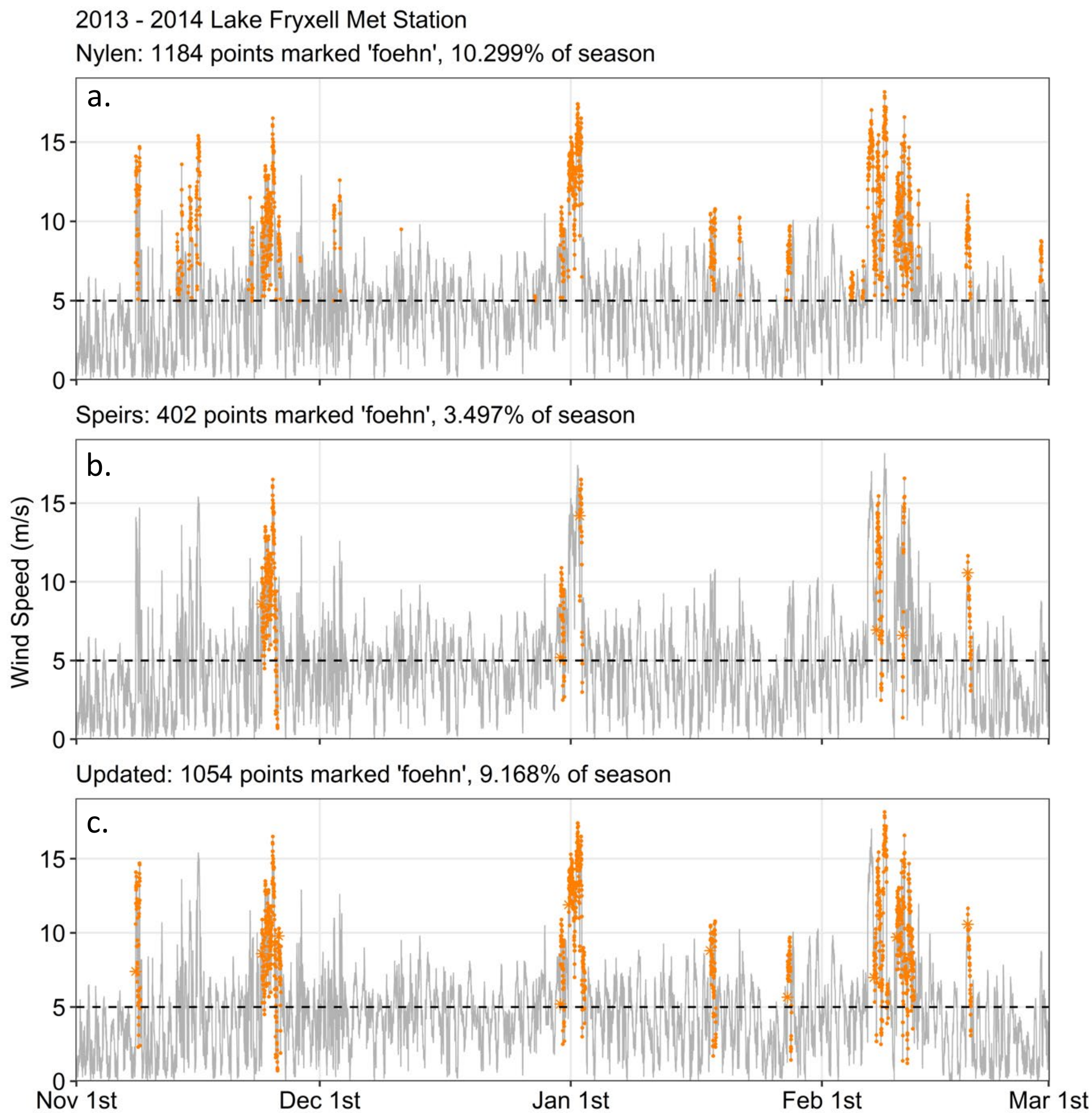

Figure 13: Foehn periods (orange symbols) identified via the a) Nylen, b) Speirs and d) updated methods for the 2013 – 2014 austral summer. Note that the Nylen method never identifies points below 5 m s^{-1} by definition, which is avoided in subsequent methods. The Speirs method fails to properly identify points in mid-February, which the updated method is able to identify appropriately.

3.3. Summer Analysis: Foehn DDAF and Lake Stage

The daily change in lake level for summer periods unaffected by foehn winds is positive for all 3 lakes (Table 6). The average values of the 24, 48, 72 and 96-hr analyses are shown in the last column in Table 6 and as a red line in Figure 14. Daily change for each time window has been averaged due to individual values being graphically indiscernible in Figure 14.

Table 6: Average daily change (cm) in lake stage for periods unaffected by foehn winds.

Location	24-hr	48-hr	72-hr	96-hr	Average
Lake Hoare	0.08	0.17	0.27	0.38	0.23
Lake Fryxell	0.10	0.21	0.32	0.43	0.27
Lake Bonney	0.36	0.69	1.04	1.37	0.87

A correlation between the magnitudes of a foehn event and associated lake level rise was not found (average r^2: 0.11 and p-value: 0.13 across sites and time windows). However, a few distinctions of Figure 13 are to be noted. As expected, lake level rise associated with foehn events having zero or less than zero $DDAF_{-1.5}$ are not found. Above a threshold of zero $DDAF_{-1.5}$, lake level rise increases following foehn events, exceeding the control for foehn-unaffected periods. This suggests that foehn winds do in fact influence lake level, just not in a way that is predictable by $DDAF_{-1.5}$ alone. The magnitude of lake level rise (Figure 14, y-axis) varies substantially between lakes. Lake Bonney appears to be most sensitive, which may relate to the steep hypsometry and topography surrounding the lake. Another consideration is meltwater availability from lake to lake. Lake Fryxell has a higher quantity of connected streams and glaciers than that of Lake Bonney. However, Taylor Glacier (feeding Lake Bonney) is greater in volume than individual smaller glaciers feeding Lake Fryxell.

Non-summer lake ice sublimation in response to foehn winds occurs for at least 4 days after foehn cessation (Figure 14). The 24-hour change in lake stage varies across different time windows. In all cases, the 96-hour window shows the most daily average lake level rise occurring 4 days after foehn events end. This suggests non-linear sublimation occurs in multiple and/or layered phases. Change in lake stage in response to foehn winds may continue beyond 4 days after foehn cessation, which was not studied.

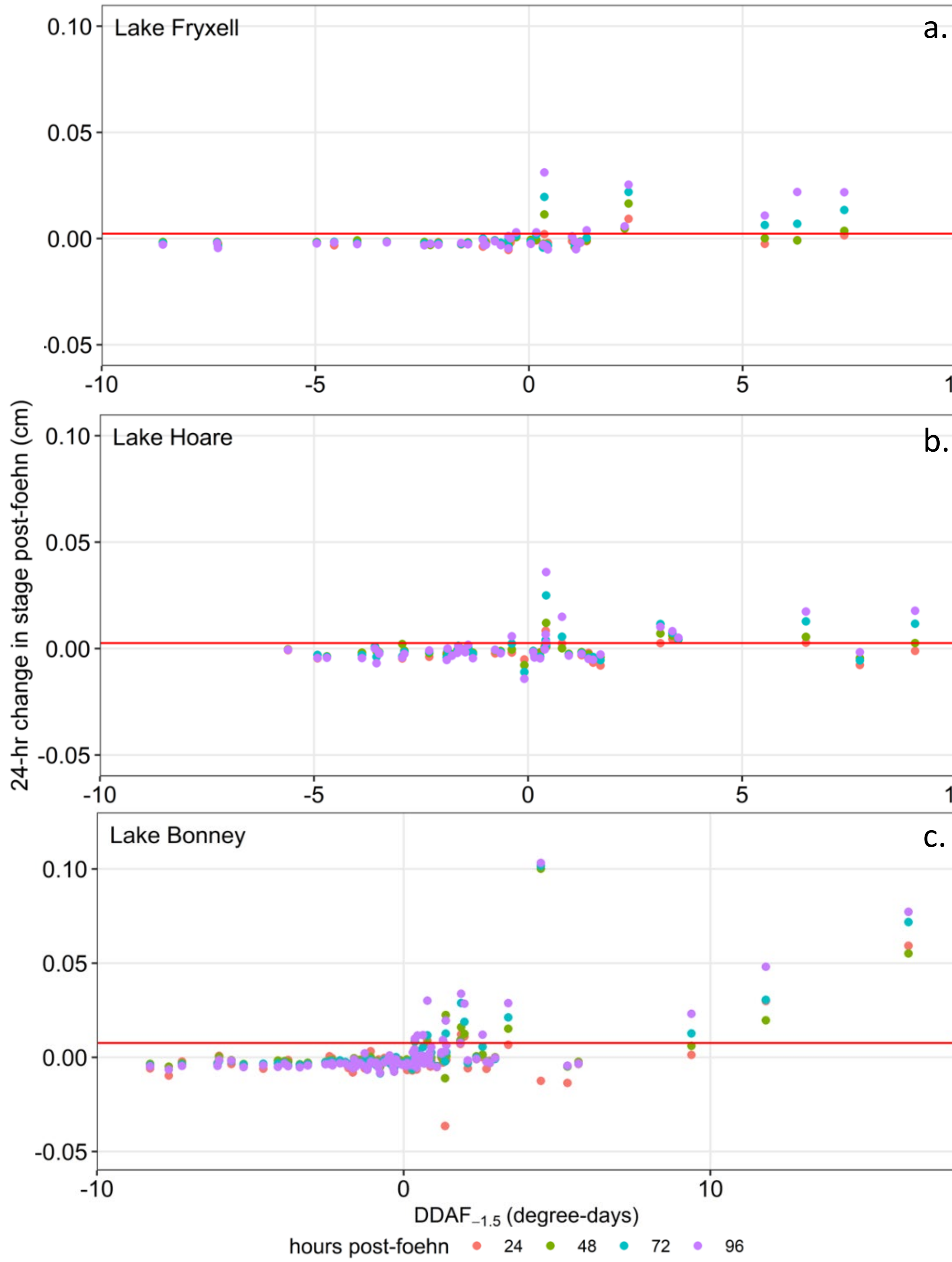

Figure 14: Summer foehn comparison to daily average lake level change for a) Lake Fryxell, b) Lake Hoare, and c) Lake Bonney. A vertical stack of 4 points represents a foehn event in the summer season at a given location. The foehn event-related metric ($DDAF_{-1.5}$) is shown on the x-axis. The y-axis represents lake level change following the given foehn event in a 24-, 48-, 72- or 96-hour window (shown by color). The red line on each plot represents the average daily lake level rise that occurs in times unaffected by foehn events and serves as a control to compare to the average daily lake level rise that occurs in times affected by foehn events.

Further explanation for the lack of direct correlation in Figure 14 may lie within additional factors affecting lake level rise that are not considered. This correlation simplifies the influx of glacial meltwater as lake level rise. Evaporation of stream water, storage of stream flow in the hyporheic zone of streambeds (early in the flow season), lake ice meltwater pools and moat water are all ignored, as well as sublimation of lake ice, which would also affect lake stage. In the future, a more detailed model of the local climate could factor in additional meteorological processes and variables to consider an energy balance and gain a clearer perspective on the relationship between melt and foehn winds. However, certain variables in the energy balance (such as evaporation) are not directly measured and will require modeled data.

Meteorological and climatological factors (such as shortwave radiation, longwave radiation, slope aspect, cloud cover, air temperature, the source air mass of a foehn wind, ice temperature, amongst many others) could affect the impact of foehn winds and ice melt in the MDVs. While this thesis has been carried out and prepared from the perspective of a student in hydrology and water resources, a deeper exploration into meteorological fields could aid in more accurately quantifying foehn wind events in the future. In particular, the explanation that temperature variability of foehn winds are largely prescribed by the source air mass rather than differences in foehn dynamics (Steinhoff *et al*., 2013) may be a crucial consideration. This calls for larger scale models considering the sources for individual foehn winds. Additionally, considering modeled data for glacier mass balances in the MDVs could be connected with streamflow data and the associated lake level rise. Modeling glacial melt and lake ice ablation with and without foehn winds could provide clearer insight for the impact of the winds themselves. It has become clear in this work that the connection is not easily identified and has many variable factors involved, which may require a deeper exploration of climatology and meteorology as well as hydrology to understand.

3.4. Non-summer Analysis: Foehn Influence on Lake Ice Ablation

Outweighing the wind-run of sea breezes, foehn winds can supply over 50% of wind-run in non-summer periods (Figure 15) but occur on average 8-18% of the time (Table 5). Wind-run due to foehn winds is a driver of lake ice ablation, even though foehn winds make up the minority of seasonal time (<24%) (Figure 16). Thus, it appears that the dramatically increased windspeeds (over less time) during foehn events promote more ablation than the lower wind speeds (over more time) of non-foehn periods. This highlights the importance of foehn wind influence on hydrology in the MDVs, particularly if these wind events do increase in frequency, duration and/or magnitude with time as has been hypothesized in previous publications and shown in Figures 10 and 11.

The total duration of foehn events in non-summer months is also a crucial consideration for the change in lake ice ablation (Figure 16). In fact, these plots have more significant correlations that those of Figure 15 as shown with respective r^2 and p-values. As previously stated in Dugan *et al.* (2013), foehn winds are a primary driver of winter ablation at these sites. Figures 15 and 16 supplement this concept with correlations to ablation for foehn-specific metrics. From each of these figures we can glean the importance of considering duration and wind speed in foehn wind magnitude. Both wind speed and duration over a non-summer season are statistically correlated with lake ice ablation.

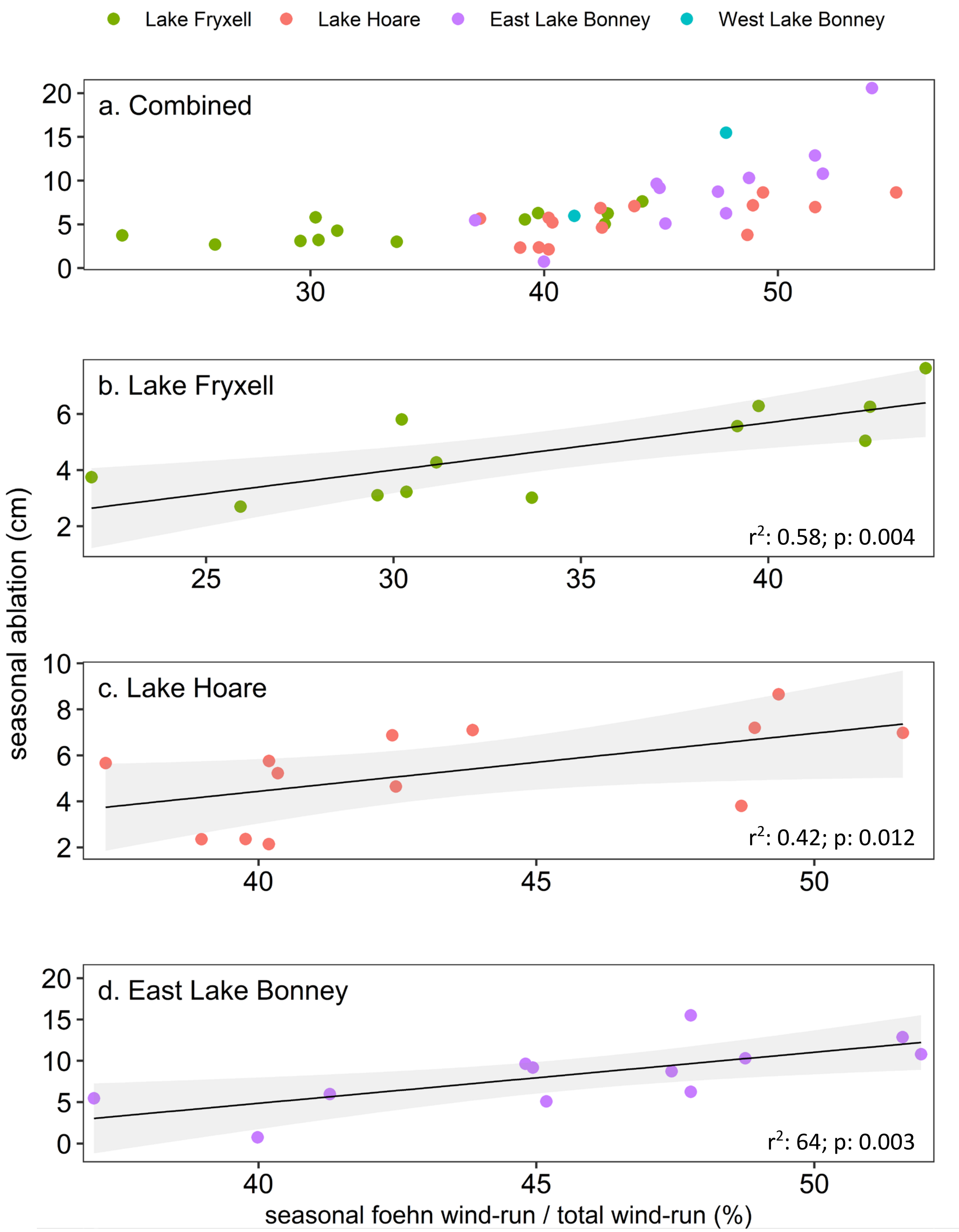

Figure 15: Seasonal lake ice ablation for a) all lakes combined, b) Lake Fryxell, c) Lake Hoare, and d) Lake Bonney, plotted against the seasonal percent of wind-run that is due to foehn events. Figure 15a shows a combined plot for the three locations to provide context for changes in x and y axes. 95% confidence intervals are shown in gray.

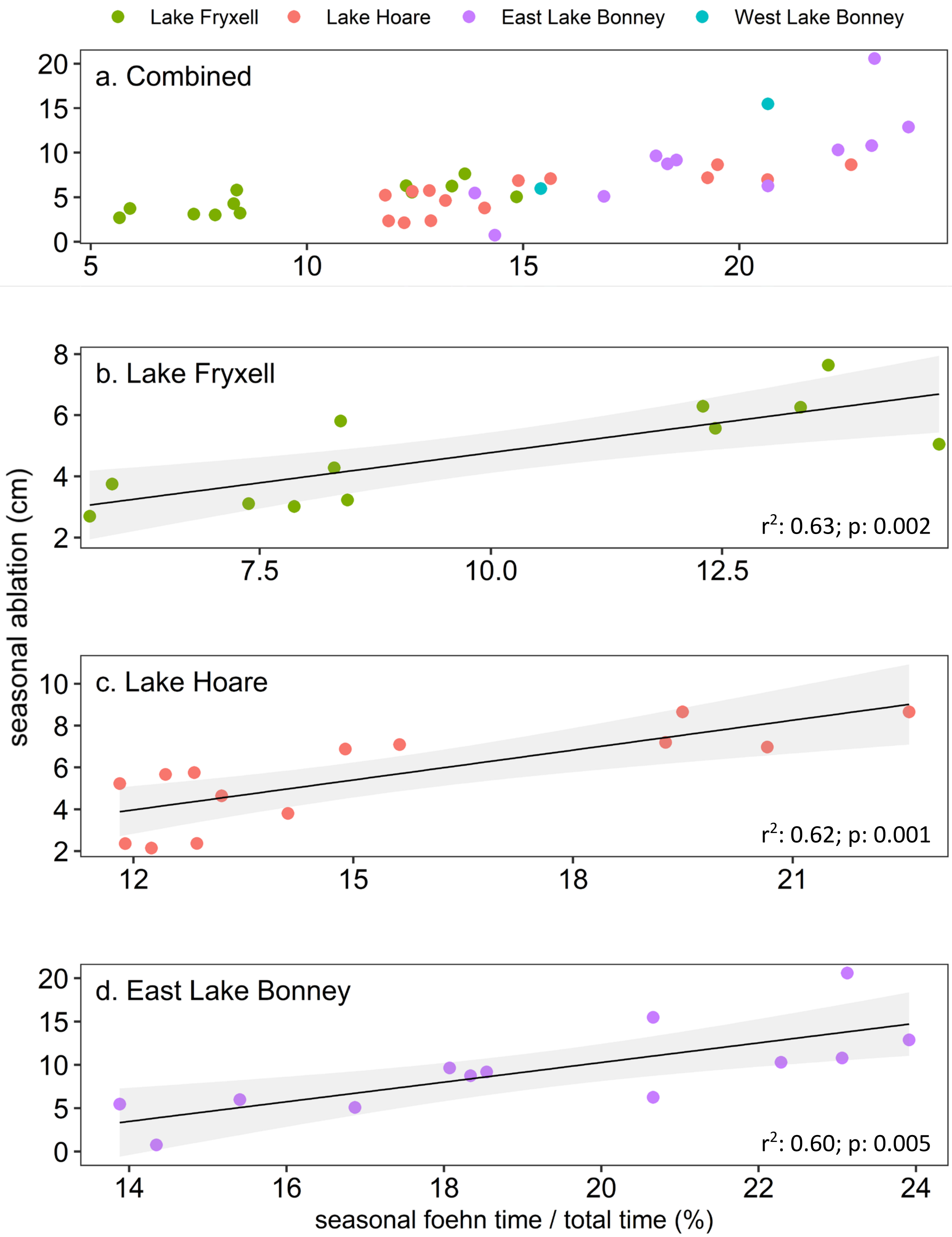

Figure 16: Seasonal lake ice ablation for a) all lakes combined, b) Lake Fryxell, c) Lake Hoare, and d) Lake Bonney plotted against the seasonal percent of time during foehn events. Figure 16a shows a combined plot for the three locations to give context for changes in x and y axes. 95% confidence intervals are shown in gray.

3.5. Future work

Foehn winds have been observed by Antarctic scientists for decades and were documented during early expeditions to the continent (Nylen *et al*., 2004). While this thesis has provided a few steps in better understanding the ecosystem of the McMurdo Dry Valleys, there are many unanswered questions and aspects of the ecosystem to make clear in the future. One curiosity left unsatisfied in this work is the identification and analysis of foehn winds on a valley-wide scale. More specifically, this involves spatially comparing foehn winds at different meteorological sites and considering foehn wind movement through the valleys accordingly (Figure 17). While this thesis looks at foehn events from data at a single location, a larger scale analysis may provide a clearer relationship to hydrology and other parts of the ecosystem. Comprehensive modeling of the climate in the MDVs has been shown in past publications and is expected to continue in future research.

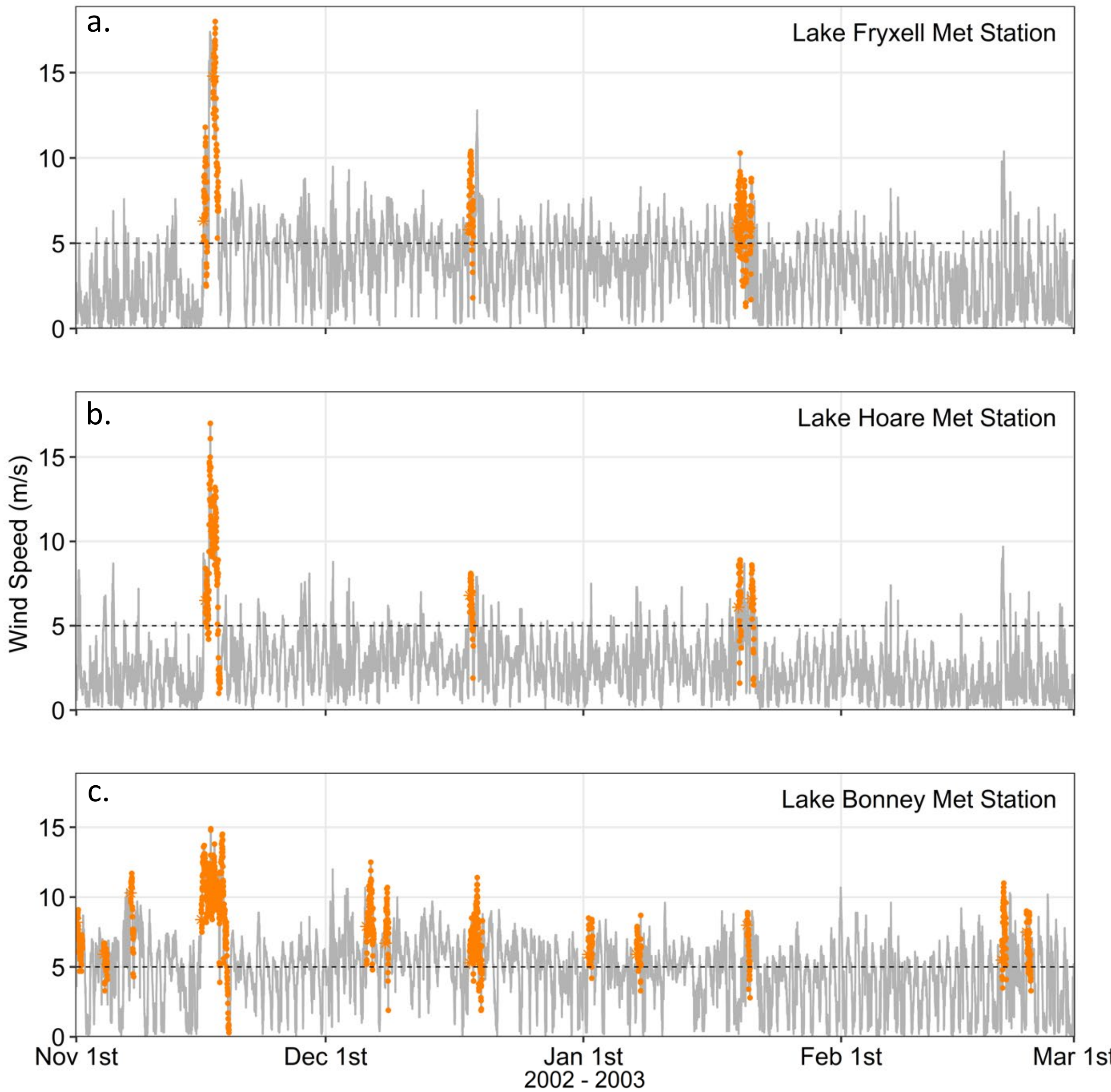

Figure 17: An example of data comparison across Taylor Valley with foehn identified periods shown in orange for a) Lake Fryxell, b) Lake Hoare, and c) Lake Bonney meteorological stations. Each of the three plots shows data from the 2002-2003 summer season. Many additional meteorological sites are available to add to such plots. The three plots shown use the updated method to identify foehn events. Note some events are temporally aligned across the three sites, and others are not. Events vary in magnitude and timing across the three sites.

4. CONCLUSIONS

In the MDVs, foehn winds are a principle vector of landscape connectivity that encourage movement of materials between glaciers, streams, soils, lakes and other parts of the ecosystem. Foehn wind identification metrics in this region have been improved upon by easing requirements for onset and tightening metrics for cessation of an individual event. Tools for identifying foehn wind events from meteorological data are being published to www.MCMLTER.org with the intent that others will not only use them for future scientific efforts, but improve upon existing identification methods.

This research has made scientific contributions to past publications. Doran et. al 2008 provides a correlation between foehn winds and degree-days above freezing. Obryk *et al*. (2017) displays a correlation between DDAF and lake level rise. From these two relationships it can be inferred that there is an indirect connection between foehn winds and lake level rise. While the direct impact of foehn winds on streamflow and lake level rise remains unclear, it is shown that summer lake level rise during foehn events is increased compared to the rise during times unaffected by foehn events when temperatures are sufficiently high. Some unconsidered meteorological data is currently provided by MCMLTER meteorological sites, which may aid in a clearer understanding for this correlation via larger scale climate modeling. Winter lake ice ablation has been shown in previous publications to relate to winter foehn wind magnitude, and this relationship has been further proven with correlations between lake ice ablation, seasonal foehn wind-run and seasonal foehn-wind presence in time. While foehn events occur relatively infrequently, they have significant impacts to large and small parts of the MDVs ecosystem. In order to understand connections between many parts of the ecosystem, it is important to consider these impacts and relationships in a warming climate that will bring more foehn wind events to the valleys in the future.

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APPENDIX

Appendix A: “Map of Antarctica and Southern Ocean” (Geology.com)

Appendix B: “Map 2: Overview – Central Dry Valleys” (Secretariat of the Antarctic Treaty)