An Examination of Lake Breezes in Southern Manitoba

By

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Abstract

Lakes represent a major topographic feature in southern Manitoba, having a direct meteorological influence on a number of communities, including Winnipeg. Therefore, it is crucial that we have an understanding of the characteristics of lake breezes in the region and the influence that they can have on local weather. The Effects of Lake Breezes on Weather in Manitoba (ELBOW-MB) project in 2013 sought to fill in the gaps in our current knowledge of lake breezes in southern Manitoba. The primary research objectives of this thesis are to: (1) provide a radar-based climatology of lake breeze frequency and characteristics and, (2) to characterize the detailed thermodynamic and kinematic properties of lake breezes and lake-breeze fronts. The two results papers presented within this thesis represent the first detailed analysis of lake breezes in southern Manitoba and help to fill important gaps in our knowledge about the occurrence and characteristics of lake-breeze circulations.

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List of Abbreviations Used

AMMOS	Automated Mobile Meteorological Observation System
CYWG	Winnipeg James Richardson International Airport
ELBOW-MB	Effects of Lake Breezes on Weather in Manitoba
HD	High Deformation Circulation
IOP	Intensive Observation Period
IDV	Interactive Data Viewer
JJA	June, July, and August
LBF	Lake Breeze Front
Lidar	LIght Detection And Ranging
LD	Low Deformation Circulation
MAFRI	Manitoba Agriculture, Food, and Rural Initiatives
MARS	Mobile Atmospheric Research System
MD	Moderate Deformation Circulation
Radar	RAdio Detection and Ranging
RAOB	Radiosonde Observation
URP	Unified Radar Processor

Chapter 1 - Introduction

1.0 Introduction

The focus of this thesis is a thorough analysis of lake breezes in southern Manitoba, Canada. Data were collected using remote sensing and *in situ* techniques to better understand the temporal and spatial characteristics of lake breezes.

1.1 Thesis Motivation and Context

A number of investigations have been conducted on sea and lake breezes, particularly in the Great Lakes and Florida regions of North America (see Moroz, 1967; Lyons, 1972; Estoque *et al*., 1976; Sills, 1998; Sills *et al*. 2001, 2011; Laird *et al*., 2001; King *et al*., 2003; Alexander, 2012; Curry, 2012). Lake depth and width can affect local lake breezes differently however. Despite the understanding provided by these studies, fewer investigations have been done in other regions for comparisons. As pointed out by Segal *et al.*, (1997), given the large variety of lakes (in shape, size and orientation), thorough examination of a variety of lake types is required to provide a more detailed understanding of lake breezes.

For example, Lyons' field campaign (1972) focused on the Chicago lake breeze off Lake Michigan between 1966-1968 over the warm season months, with a focus on surface station measurements and development of a lake breeze index for the Chicago lake breeze. Lyons was able to present a detailed lake breeze climatology for the Chicago area, and introduce a revised lake breeze index forecasting lake breezes.

Laird *et al.* (2001) and Sills *et al*. (2001) presented the next major field campaigns focused on lake breezes, with Laird *et al*. focusing on Lake Michigan, and Sills *et al*. focusing on southern Ontario during the ELBOW (Effects of Lake Breezes on Weather) project. Laird *et al*. (2001) conducted a 2 year field study, including surface observations, satellite observations, Doppler radar and further development of the lake breeze index. They were able to demonstrate some of the systematic issues with the lake breeze index, including its tendency to overestimate events and correlate synoptic environments with certain variations of the Lake Michigan lake breeze.

The ELBOW project (Sills *et* al., 2001) consisted of similar measurements, with the addition of aircraft measurements, rawinsonde measurements, wind profilers and mobile-based measurement teams, and included a pilot project in 1997, and a full field campaign in 2001. Data were compared to model performance using a high-resolution numerical weather prediction model. The ELBOW project focused on the additional task of enhancing knowledge about convective development associated with lake breeze events. Much of the research that has been published with regards to ELBOW focused on convective initiation and boundary interactions (e.g. Sills, 1998; Alexander, 2012)

The BAQS-Met project (Sills *et al*., 2011) consisted of a highly detailed analysis of warm season lake breezes in 2007 and an examination of the effects of lake breezes on air quality in southern Ontario and northern United States. The data used were similar to that of the ELBOW field project, providing high temporal and spatial resolution for the dataset. A major outcome of this study was to show that previous criteria for lake breeze occurrences might have been too constricting, as lake breezes were shown to occur on cloudy days and in the presence of synoptic fronts.

For years, weather forecasters have observed radar fine line returns in southern Manitoba that were not associated with synoptic features such as cold/warm fronts, and were not associated with precipitation. In some cases, the boundaries moved and acted in a fashion similar to lake-breeze fronts, but to this date, there have been no studies to determine what caused their existence on radar. Many forecasters consider these boundaries to be lake-breeze fronts and have suggested that a better understanding of these events would be beneficial in improving forecasting for the region. A preliminary examination of lake-breeze front frequency and characteristics was conducted in 2011 (Curry, 2012) using Doppler radar to examine lake-breeze fronts from 2008 to 2011. Finally, in 2013, ELBOW-MB was conducted, providing three weeks of field data directly measuring lake-breeze circulations and lake modified flows; studies from this project are still ongoing.

Southern Manitoba is also at the northern portion of Tornado Alley, a region susceptible to tornadoes throughout the summer months (Cheng *et al*., 2013). Previous studies (Sills, 1998; King *et al*., 2003) have shown that lake breezes in regions such as southern Ontario can play an important role in severe weather, both enhancing and suppressing convection. The lake-breeze front can act as a trigger for convective initiation, and subsidence behind the lake-breeze front can suppress convective development. A lake-breeze boundary was present during the Elie Tornado, Canada's first ever F5 tornado, and while it is unknown whether the boundary played a direct role in the event (Hobson, 2012), evidence from southern Ontario suggests that lake-breeze boundaries found near convective systems can play a significant role in tornadogenesis (King *et al*., 2003). Given that two of Manitoba's largest urban centers, Winnipeg and Portage La Prairie, are within direct influence of the lakes (within 100 km), and at risk for any severe weather associated with the lakes, it is important that we have a better understanding of the behaviour of lake breezes, and the effects on the region's mesoscale environment.

1.2 Thesis Objectives

A field campaign entitled ELBOW-MB (Effects of Lake Breezes on Weather in Manitoba) was organized to address the gaps in our knowledge of Manitoba lake breezes, and to build upon initial work by Curry (2012). There were four primary goals of ELBOW-MB:

1) add to the climatological database of Manitoba lake breezes (after Curry, 2012) by determining variations in lake breeze front (LBF) penetration distances, frequency of occurrence and speeds,
2) characterize LBF and lake breeze air mass thermal and dynamic attributes in high temporal resolution,
3) examine the impacts that the LBF has on convective cloud development in the region in relation to the background synoptic setting (e.g. pre-cloud convective environment), and
4) examine how well the operational 2.5 km GEM-LAM model simulates Manitoba lake breezes and associated convection.

This thesis will address the first two research objectives of the ELBOW-MB field campaign. The campaign was not able to address the third objective directly as minimal convective conditions were present during the intensive observation period (IOP). Kehler *et al*. (2015) addressed the fourth objective. Thus there are two main objectives of this thesis:

1) Provide a radar-based analysis of lake breeze frequency and characteristics,
2) Characterize the thermodynamic and kinematic properties of lake breezes and lake-breeze fronts.

This thesis will represent the most thorough investigation of lake breezes in southern Manitoba to date, aiding in our understanding of the characteristics of lake breezes in the region.

This knowledge provides forecasters significant insight into the mesoscale influences occurring within their forecast region for both severe weather forecasts, and aviation forecasts. Further, the results of Chapter 4 are unique in the lake breeze literature as there have been no published results to date of AMMOS (Automated Mobile Meteorological Observation System) measurements of lake breezes anywhere in the world to our knowledge, and no published results of Doppler wind lidar measurements of lake breezes in Canada. As Segal *et al.* (1997) point out, given the large variety of lakes (in shape, size, and orientation), a thorough examination of a variety of lakes types is required to provide a full understanding of the lake breeze. Thus, the results of this thesis will contribute both locally, as well as to the broader lake breeze and meteorology community.

1.3 Thesis Outline

This thesis is organized into 5 chapters. The second chapter provides a detailed literature review on the current understanding of lake breezes and detection methods. The third chapter is comprised of a paper published in the journal *Atmosphere-Ocean* and addresses the first objective of this thesis. The fourth chapter is comprised of a paper that has been prepared for submission to the journal *Boundary-Layer Meteorology* and addresses the second objective of this thesis. The fifth chapter concludes the thesis and discusses recommendations for future research.

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Chapter 2 - Background

2.0 Background

Sea and lake breezes have been documented throughout history, puzzling such early philosophers as Aristotle, who believed wind to be a dry exhalation (Simpson, 1994). Fishermen as early on as the ancient Greeks would often use daily sea and land breezes as a means to travel to and from port showing a basic understanding of the diurnal nature of the breeze (Atkinson, 1981). The circulation has even been important to military missions, such as during the battle of Salamis in 480BC near to Athens during the second Persian invasion of Greece and during the American Civil War (Simpson, 1994). Even with this basic understanding, it was not until much later that investigations of the sea breeze occurred, and only in the last century that detailed lake and sea breeze investigations were conducted (Sills, 1998; Atkinson, 1981).

One of the first comprehensive studies of lake breezes occurred in the 1880's at Harvard University where a group of over 100 people worked together over a period of 3 months to track over 30 sea-breeze events (Simpson, 1994). Over the past century, hundreds of articles have been written on the nature of sea and lake breezes. Fewer studies have been completed on lake-breeze circulations as compared to sea breezes. As there is a great variety of shoreline configurations and lake depth/size, there are more gaps in our understanding of the characteristics of lake breezes (Segal *et al*., 1997). The advent of numerical models and computers brought the ability to study micro-scale aspects of lake breezes and isolate individual variables, providing a better understanding of lake-breeze circulations. More recent research has been focused primarily outside of Canada (Segal *et al*., 1997; Tsunamatsu *et al*. 2009; Iwai *et al*. 2011), however there is a growing body of research on lake breezes in the North American Great Lakes region (e.g. Lyons, 1972; Laird *et al*., 2001; King *et al*., 2003; Sills *et al.,* 2011; Alexander, 2012). In particular, a number of studies have focused on creating a method to forecast lake breeze events by comparing the buoyant potential (using the lake-land temperature contrast) and the horizontal wind speed to create a lake breeze index (Biggs and Graves, 1962; Lyons, 1972; Laird *et al*, 2001).

2.1 Thermally Induced Mesoscale Circulations

Thermal circulation systems, also sometimes referred to as thermally induced circulations or nonclassical mesoscale circulations (Segal and Arritt, 1992), are driven by the microclimatic differences between two contrasting surfaces. Characteristics such as surface albedo, moisture, surface roughness, thermal, and radiative properties all determine how energy is partitioned at the surface and used for evaporative and heating processes. The resulting difference in temperature and dew point creates horizontal gradients between the surfaces, which are greatest at the boundary between the two surfaces. When synoptic winds are calm, the contrasting conditions can cause pressure differences between the two surfaces resulting in airflow across the boundary to maintain atmospheric balance (Oke, 1987). These circulations can develop as a result of either contrasting surface types (e.g. land and water, crop type differences) or contrasting surface condition (e.g. irrigated and non irrigated crops). An example of this type of circulation will be shown in the next sub-section.

2.1.1 Lake and Land Breezes

In the case where the two surfaces are land and water, as with a lake breeze, land has a greater sensible heat flux (mainly due to land having a much smaller heat capacity) than water resulting in the air over land heating and expanding more rapidly than over water in the morning. Due to thermal heating over the land, pressure tends to fall at the surface as buoyant air rises aloft. This creates a pressure gradient from water toward land at the surface and an onshore flow.

As the terrestrial column of air continues to expand, the air pressure aloft increases relative to the air pressure over the water at the same altitude. Air then flows towards lower pressure over the water in the upper altitudes then descends down to the water surface. The downward flow over the lake and upward flow at the leading edge of the onshore flow over land complete the circulation. Sea/lake breezes are the manifestation of the low level portion of this circulation cell that flows onshore during the daytime (Oke, 1987). Figure 2.1 provides an example of the circulation cell.

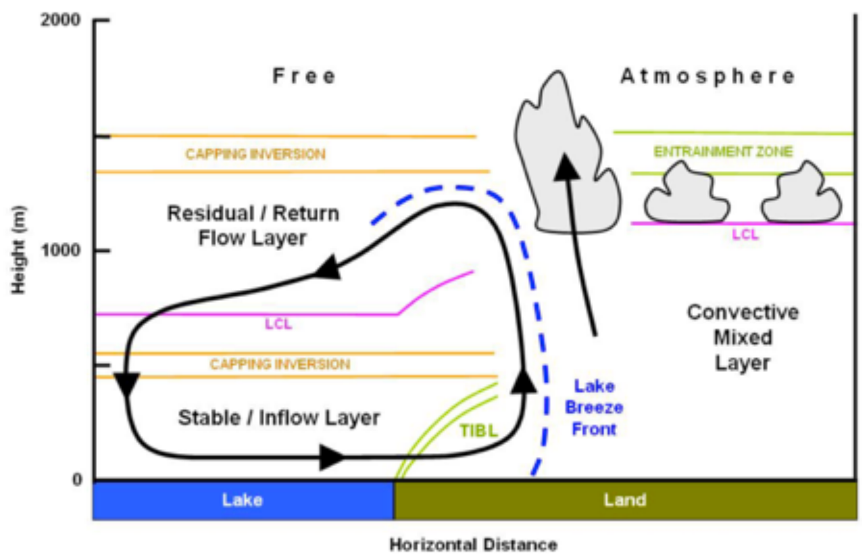

Figure 2.1: Idealized illustration of a lake-breeze circulation. Black streamlines show general wind flow. Note the enhanced uplift along the front of the lake breeze and capping inversion within the lake breeze (Source: Sills et al., 2011; CC license info https://creativecommons.org/licenses/by/3.0/).

Land breezes are identical in process to lake breezes, but occur at night. After sunset, land cools much faster than the water due to land having a smaller heat capacity. As the air over the land cools and contracts, a pressure gradient develops again aloft, this time in favour of air moving towards the lake surface aloft (Oke, 1987). Unlike lake breezes, land breezes are restricted from growing vertically as a result of the stable nocturnal boundary layer (Sills, 1998).

2.1.2 Comparison Between Sea Breezes and Lake Breezes

Sea breezes are forced by the same mechanisms that cause lake breezes, but on a larger scale. There have been a number of studies that have attempted to quantify the differences between lake and sea breezes (e.g. Segal *et al*., 1997; Crosman and Horel, 2012). It is generally accepted that once a lake exceeds a certain diameter, lake breezes will act in a similar manner to sea breezes. Crosman and Horel (2012) found that this threshold occurred between 50 and 100 km, while Segal *et al* (1997) suggest that a lake width of 50 km, with moderate moisture available in the surrounding areas, would result in a lake breeze approximating the sea breeze.

Crosman and Horel (2012) conducted a detailed sensitivity study that not only considered lake diameter, heat flux and stability in terms of the relative forcing of each parameter, but also compared each factor between sea and lake breezes using a large eddy simulation model. They found that as the circulations develop, both sea breezes and lake breezes develop in a similar manner through the mid-morning, however through the afternoon, there are significant differences between the two circulations. They note that by the afternoon, lake breezes in their simulations showed horizontal wind speeds and inland extents that were much less than the sea breezes. Additionally, they point out that while the sea breeze tends to accelerate as it moves inland, this was absent in their lake breeze simulations. When stability and heat flux were considered, they showed that lake breezes were less sensitive to heat flux variations, but were more sensitive to stability as compared to sea-breeze circulations. Crosman and Horel note that one of the reasons for this difference is due to the limited cold air supply over the lake that the circulations off each shore of the lake "compete" for as the circulation moves inland, where a sea breeze, or even an adequately large lake, does not have this same limitation.

2.2 Conditions for Lake Breeze Development

Most studies have cited similar conditions for lake breeze formation, identifying gradient flow less than 5 m s^{-1}, clear to moderately clear skies, a temperature difference between the lake and land, and weak synoptic features (Lyons, 1972; Estoque *et al*., 1976; Laird *et al*., 2001; Crosman and Horel, 2010). Findings from previous studies on the required synoptic conditions are presented in the next subsection.

2.2.1 Synoptic Conditions

One of the main conditions needed for a lake breeze to develop is a horizontal temperature gradient created by differential heating between the land and water. The required temperature difference is proportional to the gradient wind speeds. In order for the lake breeze to form, the temperature gradient must be strong enough to overcome the gradient wind speeds (Sills, 1998). Laird *et al*. (2001) point out that while the local temperature differences help to create the conditions for lake breeze development, increasing the temperature difference doesn't increase the frequency of the development. Crosman and Horel (2010) mention however, that increasing the temperature can act to increase the strength of the breeze. In fact, in a later study, they found that increasing the sensible heat over the land, thus increasing the temperature, results in deeper breezes with stronger shore-perpendicular wind speeds (Crosman and Horel, 2012).

Gradient wind flow is one of the most important factors in determining the strength and frequency of lake breezes. Laird *et al*. (2001) showed that for Lake Michigan, 95% of all lake breezes during their study period occurred with local background wind speeds of less than 5 m s^{-1}. In contrast, Sills (1998; Sills *et al*. 2011) found that lake breezes could form in wind speeds of up to 7.8 m s^{-1}. In their review of numerical model studies of sea and lake breezes, Crosman and Horel (2010) found that most studies cited offshore gradient winds between 6-11 m s^{-1} were likely to keep a sea breeze from forming; however, the exact number was dependent on the strength of the temperature gradient present. Crosman and Horel also point out studies that indicate that this number is slightly lower for small or medium sized lakes.

The direction of the overall gradient wind also plays an important role in the strength of the lake breeze. In a study conducted by Estoque (1962) using a numerical model, six cases were compared to determine the effects of the gradient wind direction on the strength of a sea breeze. Estoque found that in cases where the wind was directed offshore, the temperature gradient increased and the sea breeze strengthened. In contrast, with an onshore gradient flow, the cool air advection acted to weaken the temperature gradient and subsequently weaken the breeze. When the wind is parallel to the shore and the low pressure associated with the gradient flow is over the sea, the difference in friction between the two surfaces causes an increase in the pressure gradient, strengthening the sea breeze. Estoque (1962) also found the reverse to be true, with the gradient wind weakening the breeze when the low was over land instead. Laird *et al.* (2001) noted that over 75% of the cases examined in their study had shore-perpendicular winds less than 2 m s^{-1}.

Clouds can act as a limiting factor, preventing lake breeze formation. Given the dependence on surface heating to a lake breezes formation, having extensive cloud cover can prevent the land surface from substantial heating and prevent a lake breeze from forming. Lyons (1972) found that on days with greater than 40% sun reduction from non-convective cloud, lake breezes failed to form. Following Lyons approach, Laird *et al*. (2001) found that 70-80% of lake breeze days had cloud cover ≤ 5 tenths. Conversely, Sills *et al*. (2011) did not exclude days with cloud cover from their analysis and found that breezes occurred even on days with 3 or more hours of overcast conditions. The differences between the studies may be a result of differences between the study area and annual variability.

2.3 Lake Breeze Detection

Many studies of lake breezes use lake-breeze fronts as a means to identify lake breeze passage. The front marks the division between the warm dry air over the land and the cooler moist air coming off the lake, and as such, is one of the easier features of the lake breeze to detect (Sills *et al*., 2011). The lake-breeze front is characterized by a sharp decrease in temperature, sharp increase in dew point and a rapid shift to onshore winds (Estoque *et al*., 1976; Sills *et al*., 2011). One issue with lake-breeze front detection that Sills *et al*. (2011) point out is that the difference between the lake breeze and surrounding environment becomes subtler as it moves inland and mixes with the surrounding air, making it harder to detect.

Other approaches have been used to detect breezes however. In addition to using the lake-breeze front, Lyons (1972) used 2 other criteria to study lake breezes in the Chicago region to identify a lake breeze occurrence; the presence of a return flow (present as high as 3 km) and that the flow be distinct from synoptic fronts that may be present. Laird *et al*. (2001) used the same criteria as Lyons but included that there might be a sudden or steady increase in the wind speed present with the lake breeze passage.

Regardless of the criteria used to determine if a lake breeze has occurred, there are a number of different data sets that can be employed to help identify and observe a lake-breeze circulation including in-situ observations from meteorological towers and surface observation networks, and remote sensing measurements including ground-based remote sensing, Doppler radar, and satellite measurements. These methods will be discussed further in this subsection.

2.3.1 In Situ Observations

One of the most common measurement platforms used to identify lake breeze events and to track the passage of the lake-breeze front is *in situ* observations in the form of meteorological towers, surface observations, rawinsonde, and aircraft measurements

2.3.1.1 Mesoscale Surface Analysis

A very common technique for tracking the passage of a lake breeze is by analyzing surface observations made from meteorological towers. Surface observations allow for the detection of the main identifying features typically associated with the passage of a lake-breeze front: a reduction in air temperature, an increase in relative humidity/dew point temperature, an increase in wind speeds, and a sharp change in wind direction to on-shore flow. As Sills (1998) points out, with a sequence of station plots, both spatially and temporally, the wind shift associated with the movement of the lake breeze inland becomes readily apparent. A challenge to using this method is that existing networks of stations may be quite sparse, meaning that some details of the lake breeze progression could be lost, or not detectable at all (Alexander, 2012). Many studies have employed this method as one of the main methods of detecting lake breeze movement and occurrence (e.g. Moroz, 1967; Lyons, 1972; Laird *et al.*, 2001; Sills *et al.,* 2011).

A variation on this method is to use mobile weather observations. These can be in the form of a mobile observation team with handheld sensors as was done in the ELBOW project in Ontario (e.g. Alexander, 2012), or as part of a mobile automated weather station on the roof of a vehicle as was done in the UNSTABLE project (e.g. Taylor *et al*., 2010). This method allows for multiple transects across the lake-breeze front. Mobile measurements give the observer the opportunity to fill in data-sparse areas without the limitation of having to have multiple stations. Commonly, temperature, dew point, wind speed and direction, and visual observations such as cloud type and concentration are recorded. This gives higher spatial resolution of measurements over the area of interest, such as multiple transects across a lake-breeze front. Further, this is the only surface based *in-situ* method available to measure the width of the lake-breeze front.

2.3.1.2 Upper Air Soundings

Typically, rawinsonde measurements include vertical profiles of temperature, relative humidity, pressure, wind speed and wind direction, with data recorded every 2 seconds. If launched into the lake breeze air, rawinsonde measurements can be effective in determining if a lake-breeze circulation is present by determining if there is a low-level inversion or a return flow aloft (Alexander, 2012). A drawback of these measurements however is that soundings can be quite expensive and it is not possible to do multiple rawinsonde launches over a short period of time without multiple units. Therefore, the temporal and spatial resolution of the data is somewhat limited. Additionally, as a balloon lifts the rawinsonde it is subject to the environmental winds, which means that the profiles are often not entirely vertical. As the lake breeze occurs in the first 1-3 km of the atmosphere, this issue is somewhat limited.

2.3.1.3 Aircraft Measurements

Similar to using a weather station in conjunction with a vehicle to do surface based measurements of the lake-breeze circulation, aircraft transects of lake-breeze fronts have been conducted in a number of studies (e.g. Lyons and Olsson, 1973; Atkins *et al*., 1995; Hayden *et al*., 2011). Aircraft based measurements provide high-resolution horizontal measurements of temperature, dew point, and wind, with the ability to do transects at multiple heights. Many studies have used aircraft measurements specifically to measure pollutant transport and cycling within the lake-breeze circulation. The limitations of this method include the extremely large cost, inability to do near surface measurements, and need for flight planning in advance of each operational day.

2.3.2 Remote Sensing

In many cases, in-situ measurements can be impractical when measuring processes like meso-scale circulations. In the case of lake breezes, without a dense network of *in situ* measurements many details of the circulation can be missed (Alexander, 2012). Remote sensing provides an effective and accurate way to measure various aspects of a lake breeze with high temporal and spatial resolution. There are a variety of different approaches to remote sensing. The following section will discuss common ground-based remote sensing including Doppler radar, and satellite remote sensing.

2.3.2.1 Ground Based Remote Sensing

There are a variety of different ground based remote sensing systems that can be used to assist in detecting a lake-breeze signature, including Doppler radar, which is covered in the next subsection. Other common systems used in lake breeze studies are wind profilers, and ceilometers.

Wind profilers, radar or lidar based, have been used in a few lake breeze measurement studies (e.g. Asefi-Najafabady, 2010). The greatest advantage of wind profilers is they allow for vertical profiles of the lowest levels of the atmosphere, providing high-resolution data of wind speed and direction. When placed near the shore, the resulting profiles can show evidence of low-level wind shifts, enhanced uplift ahead of the lake-breeze front, as well as the return flow aloft.

Profiling microwave radiometer, or other types of boundary layer thermodynamic profiler (e.g. passive infra-red systems or Raman lidars) are also extremely useful for studying lake breezes. Profilers have the ability to provide high spatial and temporal resolution profiles of temperature, humidity, and liquid water vapour. These systems offer the ability to obtain measurements within the boundary layer with similar accuracy to a rawinsonde and compliment the wind profile measurements providing a complete atmospheric profile. Having vertical measurements of temperature and relative humidity can provide further insight into the thermodynamic structure of lake breezes.

2.3.2.2 Doppler Radar

One of the frequently used detection methods for sea and lake-breeze fronts is Doppler radar. Generally the front appears on radar as clear air fine line (weak reflectivity) returns that form in the shape of the lake edge and move inland.

In most cases, lake and sea-breeze fronts do not produce precipitation as the associated convection is too shallow (Bader *et al.,* 1995). Given the absence of precipitation the cause of the fine line returns has been the subject of much debate. There are two possible causes for the returns often discussed: biological scatterers (birds, insects), and refractive index gradients (or Bragg scattering) (Martin and Shapiro, 2007). It has been argued that in the convective boundary layer over land, these returns are predominantly a result of beam scattering by insects (Geerts and Miao, 2005), however Bragg scattering may also be a contributing factor (e.g. Rinehart, 1997). Martin and Shapiro (2007) showed that in nocturnal returns for example, the returns from beam scattering on insects can range from 10 dBZ to 25 dBZ, comparable to light rain. In areas with strong temperature or humidity gradients, such as in the case of a lake-breeze front, a portion of the radar beam can be refracted back to the antennae resulting in an echo on the radar image (Rinehart, 1997). It has been suggested however, that theses changes would have to occur on a scale that is small compared to the wavelength of the radar beam (Rinehart, 1997). Harrison *et al.* (2009) found that for convective outflow boundaries (which are very similar in appearance and structure in terms of radar analysis), stronger (weaker) outflow boundaries were associated with higher (lower) reflectivity values. It was suggested that this was a result of stronger updrafts, resulting in higher insect concentrations aloft, and an increase in Rayleigh scattering. In contrast, Harrison *et al.* (2009) point out that for weaker outflow boundaries, there was a higher amount of backscatter, indicating Bragg scattering from refractive gradients were playing a more dominant role. In general, there is still much debate as to the exact cause of clear air reflectivity returns and this is certainly an area requiring more research.

One limitation of using radar is that the beam height increases with distance from the radar, and therefore the probability of detecting LBFs decreases with range. At 120 km, the center of the radar beam on a 0.5 degree scan would be approximately 2000 m above the ground, based on a standard vertical thermodynamic atmosphere. Previous research has indicated LBFs generally reach a depth ranging from 100 to 1000 m (Lyons, 1972; Simpson, 1994; Suresh, 2007;Tsunematsu et al., 2009), therefore at 2000 m, the radar beam would often be overshooting the top of the LBF. This limitation is one of the main reasons that there is limited additional utility in using Doppler velocity scans over conventional scans. As you move away from the radar, the wind speed and direction noted on the velocity scans may not be providing an accurate picture of the wind within the lake-breeze circulation if what is being measured it above the circulation.

A recent study by Alexander (2012) showed that using radar analysis alone for boundary detection provided in a hit rate of only 55-65%, and a false alarm rate of up to 13%, resulting in a relatively low probability of detection score. Alexander does point out however, that radar analysis has its strength when the front is within the clear air return area or when there is little to no cumulus development (Alexander, 2012).

2.3.2.3 Satellite Remote Sensing

Satellite images can be a very effective method for tracking lake-breeze fronts. Meteorological satellites generally provide fairly high-resolution visible images (1-2 km in the mid-latitudes) at roughly 15-minute intervals. In cases where fair weather cumulus has developed over the land, the lake-breeze front appears as a line of enhanced cumulus cloud with clearing behind the front and over the lake associated with the stable lake air (Alexander, 2012). If no cumulus cloud development occurs, or if a cloud deck moves in ahead of a synoptic system, this method cannot be used to track a lake breeze. Additionally image offset issues and a shift in the lake-breeze front due to wind shear can result in some error when placing the front (Sills *et al.* 2011, Alexander 2012).

Some work has been done to address the limitations from using visible satellite. Lensky and Dayan (2012) used infrared data from the SEVIRI instrument onboard Meteosat, which is a European geostationary satellite. Lensky and Dayan found that they were able to track the sea-breeze front in Israel over the desert areas where there are little to no observations by tracking the temperature change associated with the front. In this case, the extreme temperature and moisture gradient from the sea air as compared to the dry hot desert air creates a sufficient gradient that is visible even when no clouds are present. Infrared data would be less useful in cases where the temperature and humidity contrast is not as strong.

2.4 Lake and Sea Breeze Characteristics

Numerous studies have been conducted on lake and sea-breeze circulations in a number of different locations, using a variety of the techniques discussed above. Here a brief summary of results on lake and sea breeze characteristics will be provided, including surface measurements, circulation characteristics, front measurements, and return flow characteristics.

Initiation of lake/sea-breeze circulations begins once a temperature gradient forms between the land and water that is sufficiently large to overcome the synoptic winds opposing the flow, if any. Suresh (2007) noted initiation times ranging from 13:00 to 15:00 local time, with the southeast India sea breezes forming as early as 10:00 and as late as 17:00 (LT). Sills *et al.* (2011) found a similar range for southern Ontario lake breezes, from 8:00 to 19:00 LT, but the median start time was considerably earlier, from 10:00 to 11:00 LT. Circulations generally persist until the forcing that caused them is no longer present; when the temperature gradient no longer exists. This means that breezes can often persist until sunset. In some cases, the breezes can continue even after sunset, often in the form as a gravity or density current (Stull, 1988). Sills *et al*. (2011) found a median end time of 20:00 to 21:00 LT, with a range from 15:00 to 22:00 (sunset), but noted in some cases the breezes persisted beyond sunset.

2.4.1 Surface Measurements

As noted previously, the lake-breeze front is one of the defining characteristics of a lake-breeze circulation. Passage of the front is often characterized by a decrease in surface temperature, increase in relative humidity or dew point, a change in wind direction and an increase in wind speeds.

The change in temperature is dependent on the temperature gradient between the land and water surface. Crosman and Horel (2012) noted in their modeling study that the temperature gradient between the land air and the lake-breeze front was as high as 4 K, but weakened as it progressed inland. Sills (1998) points out however, that a temperature drop may not occur if the air mass is sufficiently modified as it moves inland. In addition to temperature decreases, the dew point temperature generally increases as a lake-breeze front passes. Similar to temperature, the increase can be very sharp or may not occur if the lake breeze is modified as it moves inland (Sills, 1998). It's also important to note that when the ambient air temperature and humidity are extremely high, it's possible that the dew point can actually be lower behind the lake-breeze front. While most studies use a temperature and dew point changes as criteria for determining if a lake breeze has occurred, relatively few studies actually note the changes within their results.

Winds can drastically change during a lake-breeze front passage. Lyons (1972) noted that the winds at the Chicago O'Haire airport can switch 180 degrees from offshore to onshore when the front passes and also increase in speed. Stull (1988) points out that surface wind speeds within a sea breeze may be much faster than the speed at which the breeze propagated inland, with onshore wind speeds of 5 to 7 m s^{-1} within the sea-breeze circulation. Suresh (2007) recorded a similar surface wind speed for sea breezes in India, of 7.7 m s^{-1} and Simpson (1994), noting speeds of 6 to 7 m s^{-1} for an Australia sea breeze. Asefi-Najafabady *et al*. (2010) also noted low wind speeds for their study of a small lake in Alabama, finding max winds of only 3 m s^{-1}.

In their modeling study, Crosman and Horel (2012) noted slightly lower wind speeds than those reported by Stull (1988) or Simpson (1994) within the circulation for their sea breeze control simulation, of 4 m s^{-1}. In the higher sensible heat flux simulation in the model, they found a maximum wind speed of 3 to 6 m s^{-1}. In contrast, for the lake breeze portion of the experiment, they only found maximum surface wind speeds of 2 to 4 m s^{-1}. Crosman and Horel (2012) also note that while the area of maximum wind speeds tends to move inland with a sea breeze, it stays relatively close to shore for lake breezes through much of the life of the lake breeze. One reasons they suggest for this is the limited supply of cool "lake" air for a lake breeze as compared to the larger pool of cool air to fuel a sea breeze.

2.4.2 Circulation Characteristics

In addition to measurements at the lake-breeze front, a number of studies have attempted to quantify overall characteristics of lake-breeze circulations such as penetration and depth. The following subsections will discuss the circulation in the context of the front, onshore flow, and the return flow.

2.4.2.1 Front and Onshore Flow

One of the most widely measured metrics of sea or lake-breeze circulations is the penetration distance of the breeze and the speed at which the front moves inland. Stull (1988) notes that sea breezes generally penetrate inland 20 to 50 km, but it if the synoptic flow is in the same direction as the onshore flow, the breeze can penetrate over 100 km. Simpson (1994) noted similar penetration distances, citing some Australian sea breezes to reach 300 km inland. Sills *et al*. (2011) found southern Ontario lake breezes to travel 50 to 70 km inland (as a median) but could travel upwards of 100 to 215 km inland under certain cases. Crosman and Horel (2012) found sea breezes in their modeling study to have penetration lengths between 30 and 60 km while lake-breeze front penetration was considerably shorter, from 20 to 40 km.

Many studies have shown sea and lake breezes to range from 100 m to 1 km in depth (e.g. Lyons, 1972; Simpson, 1994; Suresh, 2007; Tsunematsu *et al.*, 2009). A number of studies have noted that the front is also notably deeper than the trailing onshore circulation. Stull (1988) stated that the nose can be up to twice the size of the training flow, with an range of 100 to 500 m for the onshore circulation. Using lidar measurements, Iwai *et al.* (2011) found the Japan sea-breeze front to reach as high as 2km, while the trailing flow was only 500m.

Model sensitivity studies have shown similar depths reached for both sea and lake breezes (Crosman and Horel, 2012). They also showed that two limiting factors on the depth that the circulation can reach are the sensible heat flux, which provides the energy for the circulation, and the boundary layer stability, which can inhibit vertical motion (Crosman and Horel, 2012). They also found that in a modeled circulation, the onshore flow was 600 m deep, but this increased to more than 900 m at the nose of the circulation.

The lake-breeze front is marked by a narrow, 1 to 2 km wide convergence zone, enhanced upward motion, and enhanced cumulus development along the front (Stull, 1988). Lyons (1972) used the convergence zone as one of the criteria in their study of Lake Michigan lake breezes, and found that the convergence zone is generally associated with updrafts of 1 m s^{-1} on average. Lidar measurements from Japan showed a maximum updraft of 5 m s^{-1} along the sea-breeze front (Iwai *et al.*, 2011), while data from a small lake in the southeast United States showed a maximum of 1.5 m s^{-1} along the front (Asefi-Najafabady *et al.*, 2010). The same study also noted a maximum downdraft speed of 2 m s^{-1} over the lake. Sills *et al.*, (2011) used the area of enhanced uplift as a marker for lake breezes in southern Ontario when using the GEM-LAM model output, with a minimum criterion of 0.1 m s^{-1} uplift, quasi-parallel to the shore.

2.4.2.2 Return Flow

The return flow is one of the hardest aspects of a sea or lake breeze to measure. Most studies have used remote sensing techniques or models, however in some cases rawinsondes have been used as well as smoke plume observations. The return flow is often masked or embedded within the offshore synoptic flow, making it particularly hard to study. Lyons (1972) found that the return flow layer for a lake breeze was twice the depth of the on-shore circulation; 1 to 2 km deep in most cases. Lyons also notes that the wind speed within the return flow is about half the speed of the inflow layer. Tsunematsu *et al*. (2009) found offshore flow above 1 km in their study of a sea breeze in Japan using lidar measurements. They found that wind speeds were much slower between the inflow and outflow layers. Stull (1988) noted return speeds of only 1 to 2 m s^{-1}, which is slightly less than half the speed noted for the onshore flow, and more in agreement with Lyons (1972) assessment. Crosman and Horel (2012) found the inflow layer within a modeled sea breeze to be between 1 and 2 km. While return flow speeds weren't explicitly stated, figures provided show return flow speeds roughly equivalent to the inflow speeds for both the sea and lake breeze models. This difference could be attributed to differences in synoptic flow aloft between the real measurements and modeled estimates, or could be a potential weakness in the model data.

2.5 Meteorological Implications of the Lake Breeze

Sea and lake breezes, and other water-modified flows, play an important role in regulating the climate of near shore communities and can act as triggers for convective storm systems (Sills, 1998; Alexander, 2012; King *et al*. 2003). Detailed discussions of these are provided in the following sub-sections.

2.5.1 Climatological Impacts for Costal Communities

Sea and lake breezes have been known to significantly modify coastal climates for near shore communities in a number of different ways. Air associated with lake breezes is notably cooler, and more moist than the ambient air over land. As the lake breeze progresses inland, communities along the shore, and up to 10's of kilometers inland can experience daily maximum temperatures a few degrees cooler than stations further inland. The relative humidity is also generally higher on average for these communities. (Lyons, 1972; Laird *et al.*, 2001) An example of this is most prevalent during early season lake breezes. During late spring and early summer, there can still be ice cover over the lakes in mid latitudes, while temperatures over the land may reach into the mid-teens for the daily maximum temperature. In these circumstances, lake breezes have been known to develop, with communities within the influence of the lake breeze having daytime highs barely above freezing.

Wind direction shifts generally associated with lake breezes are also of special significance for airports along coasts. Lyons (1972) notes that the wind direction within the Chicago lake breeze is often opposite to the ambient wind direction at the O'Hare airport, significantly influencing aviation forecasts for that airport. Convective cloud along the lake-breeze front can also present challenges for aviation forecasts if the lake breeze is not being resolved in the model when forecasting cloud.

The lake breeze can also impact air quality. Lake breezes contain cooler, more stable air as compared to the ambient terrestrial flow and are associated with subsidence. As Sills (1998) points out, this can result in a fumigating effect when air pollution is released within the lake breeze. The breeze can also drag the pollution inland. Lake breezes require similar conditions for development as ground-level ozone. The circulation can subsequently trap the ozone within the lake-breeze (Brook *et al.,* 2013).

2.5.2 Influence of Lake Breezes on Convection

There has been a considerable body of research looking into the influence of lake-breeze circulations on convection. Sills (1998) points out that lake-breeze circulations can act to both hinder convection due to subsidence associated with the air within the lake breeze, and to enhance or trigger convective development due to lift along the lake-breeze front. Alexander (2012) was able to show that 70% of the thunderstorm development (with 40dbz or higher radar returns) during their study period developed within 20 km of a pre-existing boundary, mostly lake-breeze fronts. Additionally, in their study they found that the cells generally developed ahead of the lake-breeze front.

King *et al*. (2003) presented data linking lake-breeze front occurrence to tornado locations in Southern Ontario, suggesting that lake-breeze fronts may provide more favorable environments for supercell and landspout tornado development. There are two mechanisms that can enhance tornadogensis near lake-breeze fronts. For supercell tornadoes, horizontal vorticity created by baroclinicity at the lake-breeze front can be tilted and stretched creating a low-level mesocyclone, which can be ingested and enhanced by a supercell thunderstorm. (Wakimoto and Wilson, 1989). The second mechanism is caused by shearing instability along the lake-breeze front. This creates pockets of vertical vorticity, which can merge and help to initiate or to enhance convection and result in landspout type tornadoes (Sills, 1998).

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Chapter 3 - A Radar Based Investigation of Lake Breezes in Southern Manitoba, Canada

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Chapter 3 is the first of two major results chapters and was conceived, analyzed, and reported by me as the senior author. This chapter addresses the first objective of my thesis, namely to provide a radar-based analysis of lake breeze frequency and characteristics in southern, Manitoba. This paper has been published in the journal *Atmosphere-Ocean* and has undergone peer review. It is reproduced here with minor edits with permission from *Atmosphere-Ocean*.

Abstract

Lake breezes are thermally direct circulations that form as a result of the differential heating of land and water and are important in modifying local climate and triggering convection; they have also been linked to tornadogenesis. Although lake breezes are generally well understood, studies of smaller lakes have been relatively scarce, and none have examined lake-breeze circulations in southern Manitoba even though they are seemingly apparent on weather radar. The objectives of this paper are to provide a radar-based analysis of lake-breeze frequency and characteristics in southern Manitoba, determine the detectability of lake-breeze fronts using the radar analysis with data collected in 2013, assess the types of lake-breeze circulations that occur, and examine the meteorological conditions in which they occur. Between 2008 and 2013, lake-breeze fronts were noted on 205 days using radar over the summer months, accounting for 37% of study days, with an average of 11–12 days with lake-breeze fronts each month. These findings agree fairly well with, and are only slightly less than, frequencies reported for Lake Michigan but are lower than the most recent findings for southern Ontario. In an effort to validate the results, a broad comparison between the radar analysis and a more complete analysis using satellite and surface stations is provided for 2013 demonstrating that radar is more useful for detecting lake breezes around Lake Manitoba than around Lake Winnipeg. Lake-breeze circulations originating on Lake Manitoba and the Shoal lakes were classified into three types. The distribution of types for the Shoal lakes was similar to previous findings by other authors with "moderate deformation" circulations being the most frequent. Finally, a brief meteorological analysis was completed for each month of this study. The results of the analysis were inconclusive with no single meteorological factor being consistently well correlated to higher or lower lake-breeze frequency.

3.1 Introduction

Sea and lake breezes play an important role in regulating the climate of nearshore communities and can act as triggers for convective storm systems (Sills, 1998; King *et al*. 2003; Alexander, 2012). Evidence from southern Ontario suggests that lake-breeze boundaries can play a significant role in tornadogenesis (King *et al*., 2003). A number of investigations have been conducted on sea and lake breezes particularly in the Great Lakes and Florida regions of North America (e.g., Lyons, 1972; Estoque *et al*., 1976; Sills, 1998; Laird *et al*., 2001; King *et al*., 2003; Sills *et al*., 2011). Despite the knowledge gained from these studies, few investigations have been carried out in other regions for comparison. As pointed out by Segal *et al.* (1997), given the large variety of lakes (in shape, size, and orientation), a thorough examination of a variety of lake types is required to provide a full understanding of lake breezes.

Lake breezes are a type of thermally induced mesoscale circulation, or nonclassical mesoscale circulation, driven by the microclimatic differences between the terrestrial surface and water (e.g., Pearce, 1955; Oke, 1978). Sensible heat flux is typically greater over land than water (mainly because land has a much smaller heat capacity), which results in the air over land heating and expanding more rapidly than over water during daylight hours. Because of this thermal heating over the land, pressure tends to fall at the surface as buoyant air rises aloft. As the terrestrial column of air expands, the air pressure aloft increases relative to the air pressure over the water at the same altitude. Air then flows towards lower pressure over the water in the upper altitudes then descends to the water surface, in turn creating higher pressure at the surface. This creates a pressure gradient from water towards land at the surface that completes the circulation cell. Sea and lake breezes are the manifestations of the low-level portion of this circulation cell that flows onshore during the daytime (Oke, 1978).

A number of studies use the lake-breeze front (LBF) as a means of identifying the passage of a lake breeze, which moves inland with time. The front marks the division between the warm and typically drier air over the land and the cooler moist air coming off the lake and is one of the easier features of a lake breeze to detect (Sills *et al*., 2011). The LBF passage is characterized by a sharp decrease in temperature, a sharp increase in dew point, and a rapid shift to onshore winds (Estoque *et al*., 1976; Sills *et al*., 2011). Klemp and Rotunno (1982) have shown that similar thermal gradients can enhance horizontal vorticity through baroclinic vorticity generation and are, therefore, important for convective initiation and enhancement. One issue with LBF detection is that as the front moves inland and mixes with the surrounding air mass, the difference between the lake breeze and the surrounding environment becomes more subtle making the front harder to detect (Lyons, 1972; Sills *et al*., 2011).

The extent to which the LBF penetrates inland depends on various factors including the temperature gradient between the land and water, the background (synoptic-scale) boundary layer flow, the shape of the shoreline, and the land-surface characteristics such as land use and vegetation cover (e.g., Crosman and Horel, 2010; Hill *et al*., 2010). Lake breezes have been known to penetrate quite far inland, from a few kilometres to hundreds of kilometres, depending on the prevailing synoptic conditions and the strength of the temperature difference between water and land (e.g., Simpson, 1994; Sills, 1998; Sills *et al*., 2011). Frequency of lake-breeze occurrence varies depending on the detection criteria; however, Sills *et al.* (2011) showed that lake breezes occurred about 90% of the time during the BAQS-Met 2007 field study in southern Ontario, which is considerably higher than previous studies that reported frequencies of 30–50% for June, July, and August (JJA; Lyons, 1972; Laird *et al.,* 2001).

With the majority of Manitoba's population situated within the influence of Lake

Manitoba and Lake Winnipeg, LBFs are an important focus of research on convective initiation and interactions with existing storms. Having a better understanding of the frequency and characteristics of LBFs will provide meteorologists with more information to better forecast both general weather and severe weather events in southern Manitoba. Curry (2012) conducted the first detailed study documenting lake breezes in Manitoba by using weather radar, satellite imagery, and available surface meteorological data during the warm season (JJA) between 2008 and 2011. This paper aims to expand on the results presented by Curry (2012) by adding two additional years to the radar analysis of lake-breeze frequency, and summarizing the findings presented in the initial study because it was not formally published.

Thus, the objectives of this paper are (i) to provide a radar-based analysis of lake-breeze frequency and characteristics in southern Manitoba, (ii) determine the performance or detectability of LBFs by radar analysis using data collected in 2013 relative to other datasets for LBF detection, (iii) assess the types of lake-breeze circulations that occur (e.g., Sills *et al*., 2011), and (iv) examine the meteorological conditions in which they occur. The paper begins by highlighting the study area and data used in Section 2; then presents the results for each objective in Section 3, followed by a discussion and summary (Section 4).

3.2 Data and Methods

3.2.1 Study Area

The study region within southern Manitoba, shown in Figure 3.1, was defined to include the Environment Canada radar at Woodlands and any breezes that could be captured using this method of detection. The southern basins of Lake Winnipeg and Lake Manitoba and all the Shoal lakes were considered within the study region. Note, there are three shoal lakes in Manitoba; Shoal Lakes in this study refers to the group of East, West, and North Shoal Lakes. Specifically, only the shores that are visible on the Woodlands Doppler radar, including the east, south, and west shores of Lake Manitoba, all shores of the Shoal lakes, and the west and south shores of Lake Winnipeg, were considered. Figure 3.1 includes range rings from the Woodlands radar site up to 120 km. The maximum detection range for the Woodlands radar in Doppler mode is 120 km; however, the beam height increases with distance from the radar, so the probability of detecting lake breezes is expected to decrease with range. At 100 km, the centre of the radar beam is approximately 2000 m above the ground, based on a standard vertical thermodynamic atmosphere.

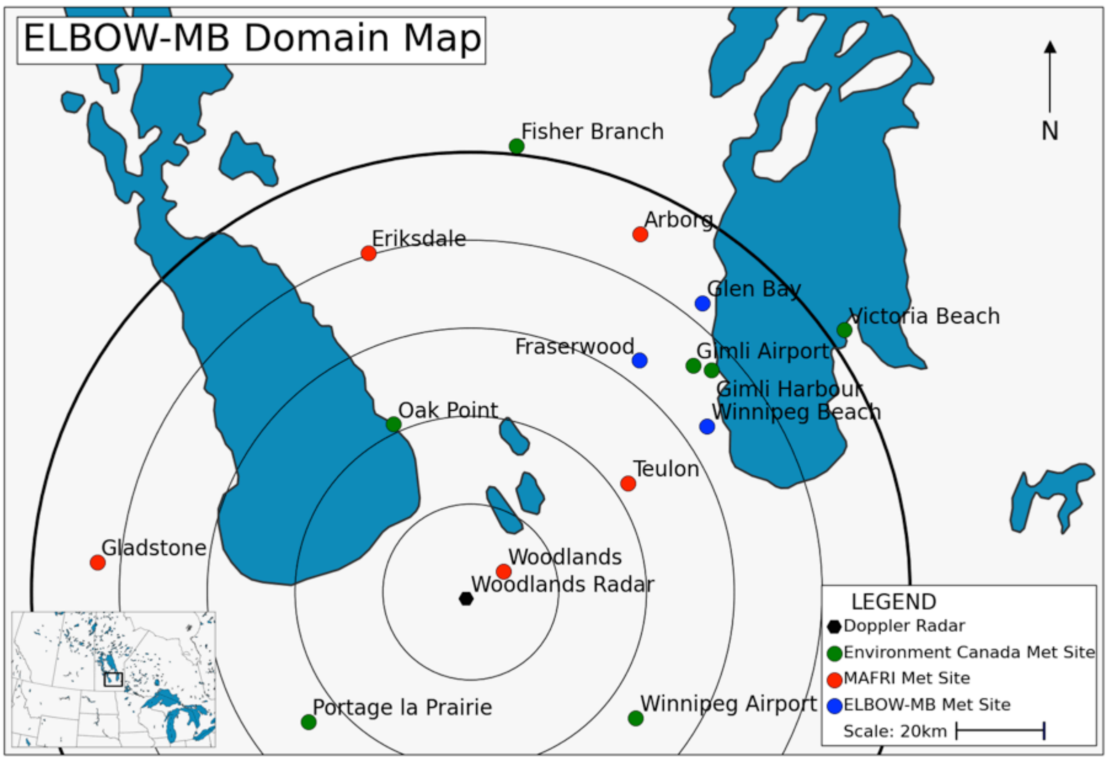

Figure 3.1: Map of study area. The Environment Canada stations are indicated in green, the University of Manitoba stations are indicated in blue, and the MAFRI stations are indicated in red. The Environment Canada Doppler radar site at Woodlands (XWL) is indicated with a black dot, and rings indicate the distance from the radar in 20 km intervals with the outer ring indicating 100km, the outer range of detection.

Two of the largest freshwater lakes in the world are located in southern Manitoba: Lake Winnipeg (11th largest) and Lake Manitoba (33rd largest). Combined, these lakes have an area of 29,318 km^2 and 2773 km of shoreline. The lakes lie in the basin of Lake Agassiz, a glacial lake, with flat plains in the surrounding regions and minimal elevation changes. The waters are generally shallow, between 7 and 12 m deep. Lake Winnipeg has a narrow southern basin with an irregular shoreline, and Lake Manitoba has a wide southern basin with a rounded shoreline. The Shoal lakes are considerably smaller and consist of three small lakes ranging in diameter from 3 to 6 km. In recent years, flooding in the area has resulted in the Shoal lakes flooding overland and merging, resulting in one lake approximately 12 km in diameter. This is in stark contrast to the Great Lakes bordering southern Ontario, which are considerably deeper and colder, cover more surface area, and have a longer shorelines. Water temperatures are available for Lake Winnipeg through an Environment Canada buoy; these range from 14°C in early June to 22°–26°C by July and August at the peak of summer heating. The average lake temperature for JJA is 19°C.

3.2.2 Radar Data

Because of the number of years being analyzed, data availability, and spatial resolution of other datasets, the analysis presented primarily uses radar images to determine whether a lake breeze occurred by examining each image for the presence of an LBF. Further, given the limited data coverage for southern Manitoba, it is valuable to understand the effectiveness of Doppler radar when analyzing lake breezes in this region.

The LBFs appear on radar as clear air, fine line (weak reflectivity) returns, which form in the shape of the lake edge and move inland. In many cases, LBFs and sea-breeze fronts do not produce precipitation because the associated convection is too shallow (Bader et al., 1995).

Given the absence of precipitation in the majority of cases in which these returns are seen, the cause of the fine line returns has been the subject of much debate and requires further research. There are two possible reasons that are often discussed as the cause for these returns: biological scatterers (birds and insects) and refractive index gradients (or Bragg scattering) (Martin and Shapiro, 2007). Clear-air returns occurred on almost all days examined, except when significant widespread precipitation was occurring within the region. In addition to any lake breezes that may have occurred, common other clear-air returns were horizontal convective rolls and outflow boundaries from thunderstorms.

A radar archive for 2008–2013 in 10-minute intervals was examined for each day during the study period of JJA. For earlier years, it was not feasible to access the radar data during the initial scope of this project. All radar images were processed using the Unified Radar Processor (URP) software, which is the software package used by Environment Canada for radar analysis (Patrick and McCarthy, 2008). Each image was examined to first determine whether fine lines were present and second whether the source of the fine lines was a result of a lake breeze or other mesoscale processes, such as a convective outflow. In those cases in which it was determined that the source of the radar returns was not other forcing mechanisms (such as convective outflow), an assumption was made based on the radar analysis that the fine line returns were either a result of a lake breeze or a representation of the associated LBF. On days when an LBF was believed to be present, URP was used to obtain (i) the value of the highest reflectivity value along the LBF, (ii) the maximum speed at which the LBF moved, and (iii) the furthest detected point travelled from the lakeshore. Each measurement was calculated individually for each shore and lake (e.g., the reflectivity, speed, and penetration distance of an LBF from the east, south, and west shores of Lake Manitoba, and the west and south shores of

Lake Winnipeg). The measurements taken for each shore of the Shoal lakes, Lake Manitoba, and Lake Winnipeg were compared, and statistical tests were performed to determine if the values for the various shores were statistically similar. The analysis showed no statistically significant differences in the measurements between the shores of Lake Winnipeg and the Shoal lakes. Therefore, the results for those lakes are presented as the maximum value recorded for that particular lake. Lake Manitoba did exhibit significant differences in measurements between the three shores; therefore, each shore is presented separately. One potential reason for the significant differences in measurements among the three shores is that the western shore of Lake Manitoba is over 50 km from the radar (similar to the eastern shore of Lake Winnipeg) and, as a result, some LBFs may not appear on radar because they would not reach the beam height. Further, any LBFs that do originate from Lake Manitoba and penetrate westward would soon move out of Doppler radar range, influencing the results.

3.2.3 Data analysis for 2013

As part of the Effects of Lake Breezes on Weather in Manitoba (ELBOW-MB) 2013 field project (Hanesiak, 2013), data were collected for JJA from Environment Canada weather stations within the study area (shown in Figure 3.1), from three meteorological towers deployed for the field project, from Manitoba Agriculture, Food and Rural Initiatives (MAFRI) weather stations, and from satellite-based visible imagery. Because there were issues archiving the data initially, data were only available from 6 June to 31 August 2013, a total of 87 days.

Visible images from the GOES-13 satellite with coverage over southern Manitoba were archived for all days between 6 June and 31 August 2013. The spatial resolution of the images is 1.5 km, and they are available at 15-minute intervals. Because satellite-based visible images were used, this dataset only provides information during daylight hours, which is sufficient for lake-breeze occurrence because it is a daytime phenomenon.

Data were collected from a mesoscale network (mesonet) of surface weather stations within the study region and archived each hour for JJA 2013. In addition to the seven surface stations operated by Environment Canada within the study area, there are five surface stations operated by MAFRI. To supplement these data, the University of Manitoba deployed three meteorological towers near the west shore of Lake Winnipeg at Glenbay, Fraserwood, and Winnipeg Beach (Figure 3.1). Measurement heights for each variable were not uniform across all stations. The Environment Canada and University of Manitoba stations recorded temperature, dew point, and wind speed and direction at the standard heights specified by the World Meteorological Organization, between 1.25 and 2 m for temperature and dew point, and 10 m for wind measurements. Many of the MAFRI stations collect temperature and dew point measurements at 1 m and winds at 3 m because these stations are used for agricultural applications. Because the wind measurements were not used in a quantitative analysis for this paper, it was not necessary to adjust for height discrepancies between stations. Note the hourly values from Environment Canada are reported as the current temperature, dew point, and wind direction for that hour, but the wind speed is reported as the 2-minute average prior to the hour of reporting. The University of Manitoba and MAFRI data were reported as hourly averages for each value. The MAFRI averages are based on 5-second averages for the previous hour, whereas the University of Manitoba data were based on the 1-minute averages for the previous hour. Because the data were not being used in a quantitative manner, no effort was made to adjust for these discrepancies.

Hourly values for temperature, dew point, wind speed, and wind direction were plotted using an Interactive Data Viewer (IDV). This allowed data to be viewed as a plot of surface stations, similar to the view available to meteorologists forecasting for the area. It is important to note, however, that at any given time, the mesonet stations available to meteorologists for analysis is generally limited to the Environment Canada stations; thus our analysis here may contain more detail than seen in an operational capacity.

To compare lake-breeze detection performance using multiple data sources rather than individual datasets, the LBF frequency analysis was done in two ways. First, each of the three datasets were analyzed independently to determine if an LBF was present on any given day for each lake. It was only possible to conduct this analysis for Lake Manitoba and Lake Winnipeg, because the Shoal lakes are not well resolved on satellite images. Second, once the dataset was compiled for 2013 for each data source, the results from each dataset were combined to determine the likelihood of an LBF being present on any given day on each lake. It was not possible for this study to perform an "integrated analysis" with all three datasets being overlaid because the data were collected at different intervals and were collected as images rather than raw data values, making overlaying the data impossible. Therefore, the combined approach taken was to examine the notes for each day during the study period for each dataset and determine whether it was likely that an LBF was present. For example, if the analysis notes suggested that the mesonet indicated a wind shift and dew point increase that would be expected with an LBF passage, but radar indicated significant widespread precipitation, and satellite imagery indicated widespread cloud cover, the assumption would be made that no LBF was present. However, if, for example, the notes in the radar analysis indicated that fine line returns were present in the form expected of an LBF, while satellite images showed no cloud cover, and the mesonet analysis was inconclusive, the assumption would be made that an LBF was present. This analysis is similar to that presented by Sills *et al*. (2011). We were then able to compare individual datasets and use the combined approach to determine the effectiveness of each dataset for LBF detection and any potential differences or biases.

3.2.4 Meteorological and climatological data

The Environment Canada weather station at the Winnipeg James Richardson International Airport (CYWG) was selected as a representative general climatological station for the region, generally free from the influence of lake breezes, except under extreme circumstances. To provide context to the radar climatology, temperature, relative humidity, wind speed, and wind direction averages for each month and year were compared with the Environment Canada 30-year climatology to determine whether the year had abnormal conditions that may have influenced lake-breeze frequency or intensity for that year. Daily maximum temperatures were calculated first, and then averaged for each month of the study period; all other values were hourly values averaged for the entire month. Additionally, data were collected from the Lake Winnipeg south basin buoy for lake surface temperature and lake air temperature. Again, daily maximum temperatures were calculated first for each variable then averaged for the study month. Because no climatological data for the buoy are readily available, the average given for comparison was calculated for each month over the six years of the study period.

3.3 Results

The following sub-sections provide the results for the frequency and characteristics of lake breezes in southern Manitoba, the performance of the radar analysis, the lake-breeze typing analysis, and the meteorological analysis for the study period.

3.3.1 Radar analysis of lake breezes

The main objective of the initial study presented by Curry (2012) was to provide a radar analysis of lake-breeze frequency using radar images for 2008–2011. The initial analysis has since been updated and revised, with cases and statistics added for 2012 and 2013.

A total of 522 days were analysed using URP for JJA from 2008 to 2013. An LBF was recorded somewhere within the study region on 205 study days. Table 3.1 provides a summary of the frequencies of LBFs by lake, month, and year. The lowest number of LBFs was recorded for Lake Winnipeg, with 89 LBFs occurring between 2008 and 2013. There were 176 LBFs for Lake Manitoba and 102 LBFs for the Shoal lakes. The median number of days with LBFs present within the region in a year was 35, accounting for 37% of days in JJA. The lowest median frequency of days with LBFs was recorded in June with 11 days, while July and August both showed median values of 12 days. The median number of days with LBFs present for Lake Manitoba was 10 per month, while the Shoal lakes and Lake Winnipeg had a slightly lower median of 5 days. The median number of days when LBFs were noted on all lakes on a given day was just below 3 days. The highest frequency of days with an LBF present occurred in 2013, when LBFs were recorded on 48 days.

The frequency of LBFs presented here was generally lower than in other studies, such as those of Lyons (1972), Laird *et al.* (2001), and Sills *et al.* (2011). The results of Lyons (1972) and Laird *et al*. (2001) were presented by lakeshore for Lake Michigan, with values reported for the east shore, west shore, and both shores, allowing for reasonable comparisons between Lake Michigan and Lake Manitoba. Lyons' results are reported for 1966 to 1968 while Laird *et al*. presented results for 1996 to 1997. The comparison is summarized in Table 3.2. In contrast, Sills *et al*. (2011) presented frequencies for each lake in their study region individually, for any lake, and for all lakes for JJA of 2007.

Table 3.1: Number of days with LBFs for 2008-2013 (JJA), and frequency of days per month (number of days with LBFs divided by total days in the month). Frequency is displayed individually for each lake (and shore in the case of Lake Manitoba). Also listed is the regional frequency for days where a LBF occurred on any lake, or on all lakes.

		Lake Manitoba								Shoal Lakes		Lake Winnipeg		Any		All	
		West Shore		South Shore		East Shore		Any Shore									
		Days	%	Days	%	Days	%	Days	%	Days	%	Days	%	Days	%	Days	%
2008	June	9	30%	6	20%	13	43%	15	50%	5	17%	7	23%	16	53%	0	0%
	July	8	26%	4	13%	9	29%	11	35%	4	13%	4	13%	12	39%	3	10%
	August	4	13%	6	19%	4	13%	8	26%	4	13%	6	19%	10	32%	2	6%
2009	June	5	17%	3	10%	7	23%	8	27%	4	13%	4	13%	10	33%	2	7%
	July	7	23%	3	10%	11	35%	11	35%	2	6%	6	19%	11	35%	2	6%
	August	7	23%	3	10%	8	26%	11	35%	5	16%	7	23%	13	42%	3	10%
2010	June	2	7%	4	13%	3	10%	6	20%	4	13%	3	10%	9	30%	1	3%
	July	4	13%	1	3%	5	16%	6	19%	5	16%	1	3%	8	26%	0	0%
	August	2	6%	2	6%	1	3%	4	13%	2	6%	1	3%	5	16%	0	0%
2011	June	2	7%	3	10%	6	20%	6	20%	6	20%	3	10%	8	27%	1	3%
	July	4	13%	3	10%	4	13%	7	23%	4	13%	3	10%	9	29%	0	0%
	August	7	23%	4	13%	5	16%	9	29%	5	16%	6	19%	11	35%	3	10%
2012	June	6	20%	6	20%	4	13%	8	27%	5	17%	3	10%	8	27%	3	10%
	July	6	19%	5	16%	4	13%	10	32%	10	32%	6	19%	14	45%	4	13%
	August	8	26%	2	6%	11	35%	13	42%	6	19%	4	13%	13	42%	3	10%
2013	June	4	13%	11	37%	11	37%	15	50%	10	33%	9	30%	16	53%	5	17%
	July	8	26%	6	19%	7	23%	12	39%	11	35%	8	26%	15	48%	7	23%
	August	7	23%	7	23%	15	48%	16	52%	10	32%	8	26%	17	55%	4	13%
Average	June	5	16%	6	18%	7	24%	10	32%	6	19%	5	16%	11	37%	2	7%
	July	6	20%	4	12%	7	22%	10	31%	6	19%	5	15%	12	37%	3	9%
	August	6	19%	4	13%	7	24%	10	33%	5	17%	5	17%	12	37%	3	8%

Table 3.2: Median frequency of days with LBFs for Lake Michigan and Lake Manitoba reported here by Curry *et al*, Lyons (1972), and Laird *et al.* (2001) for Lake Manitoba and Lake Michigan respectively, for June, July, and August.

		June	July	August
Curry *et al*	East Lake Manitoba	7	7	7
	West Lake Manitoba	5	6	6
Lyons (1972)	East Lake Michigan	8	8	5
	West Lake Michigan	11	14	11
Laird *et al*. (2001)	East Lake Michigan	14	10	13
	West Lake Michigan	7	7	10

The frequencies in Lyons (1972) study, which was one of the pioneering studies of lake breezes in the Great Lakes, showed the closest agreement with the frequencies reported here. The frequency of days with LBFs for JJA for the east shore of Lake Michigan was almost identical to the values for the east shore of Lake Manitoba, while the frequency for the west shore of Lake Michigan was much higher than for the west shore of Lake Manitoba. In contrast, Lyons' analysis showed much higher frequencies for the *east* shore of Lake Michigan compared with Lake Winnipeg and more comparable frequencies for the west shore of each lake, respectively. Interestingly, the frequency of lake-breeze days for Lake Manitoba was more uniform for either side of the lake, while both Lyons and Laird *et al.* showed that lake breezes occurred on more days on the west and east sides respectively (Table 3.2). This may be a result of a difference in synoptic wind patterns between study years and study regions, as well as detection method limitations in each study.

Sills *et al*. (2011) found much higher frequencies of days with lake breezes in southern Ontario than was recorded for southern Manitoba. The lowest frequency of lake breezes found in their study for any of the lakes examined (Lake Huron, Lake Erie, and Lake St. Clair) was 19 days for Lake Huron in August. In comparison, the highest number of lake-breeze days in one month for southern Manitoba for one lake was 15 days for Lake Manitoba (June 2008 and June

2013). When considering days when an LBF was present on any lake, the difference becomes even greater. Sills *et al*. (2011) found lake breezes occurring somewhere in the region on 29 days of June, 30 days of July, and 22 days of August; in southern Manitoba, the median was 11, 12, and 12 days, respectively. The year with the highest frequency for southern Manitoba was 2013 with 16, 15, and 17 lake-breeze days for JJA, respectively. Sills *et al*. (2011) also reported that lake breezes developed on all lakes for 26 days in June and July and 16 days in August. The maximum found for Manitoba was considerably less at 5, 7, and 4 days, respectively. The median for Manitoba was even lower, with only 2 days with LBFs developing on all lakes for June and 3 days for July and August. One reason the results are significantly different could be the difference in detection ability (e.g., southern Ontario having better radar coverage and more surface stations). Sills *et al*. (2011) considered a variety of data sources for detecting lake breezes including radar, satellite-based visible imagery, and surface stations. In their discussion, they point out that the year studied was not significantly different meteorologically from the climatology for the region so their results are likely different because of detection ability.

3.3.1.1 Lake-breeze front characteristics

For each LBF that was identified, penetration distance and speed, as well as the highest reflectivity along the boundary were recorded. As noted earlier, there were significant differences between the measurements for LBFs off each shore of Lake Manitoba, whereas those differences did not exist for Lake Winnipeg or the Shoal lakes. As a result, for Lake Winnipeg and the Shoal lakes the maximum values are presented for each lake as a whole, but the Lake Manitoba results are presented by shore.

The furthest distance recorded for an LBF moving inland was for Lake Manitoba, with one front moving 112 km inland from the south shore. Lake Winnipeg also had high penetration distances, with a maximum of 109 km recorded. The median for LBFs from each lake, as shown in Figure 3.2a, ranged from 8 km for the Shoal lakes to 35 km for Lake Winnipeg. The median LBF penetration distances for all shores of Lake Manitoba ranged from 16 to 19 km.

The penetration speed, shown in Figure 3.2b, was quite consistent across all lakes, with median speeds ranging from 0 to 2 m s^{-1}. The Shoal lakes were a notable exception, with the median speed of LBF penetration being only 0.3 m s^{-1}. The fastest speed measured (11.7 m s^{-1}) for a front was from south Lake Manitoba. The median and maximum reflectivities also showed similar ranges across all lakes, as shown in Figure 3.2c. The median reflectivity recorded ranged from 15 dBZ (east Lake Manitoba), to 20 dBZ (west Lake Manitoba). The maximum reflectivity recorded for a front along each shore ranged from 30 to 37.5 dBZ.

Further analysis was done to quantify the relationship between reflectivity and penetration speed and distance values for each case. The correlation between reflectivity and penetration speed for an LBF and between reflectivity and penetration distance for an LBF were calculated and plotted (Figure 3.3a and 3.3b). The results indicated that there was a small, but significant (p value < 0.05) correlation between reflectivity and both speed and penetration, respectively; namely, LBFs with higher reflectivity values tended to have higher penetration speeds and distances. The relationship appears to be mainly limited by cases in which the speed and penetration distance of an LBF is hindered by a strong synoptic wind opposing the motion of the boundary. In these cases, the reflectivity may have been enhanced due to greater convergence and vertical motion at the LBF. Note that there are very few points on either Figure 3.3 a or b where high speed and penetration values are seen in conjunction with a low reflectivity value. This remains an area in which more research is required in order to understand more of the specifics of the relationships between reflectivity and speed and reflectivity and penetration.

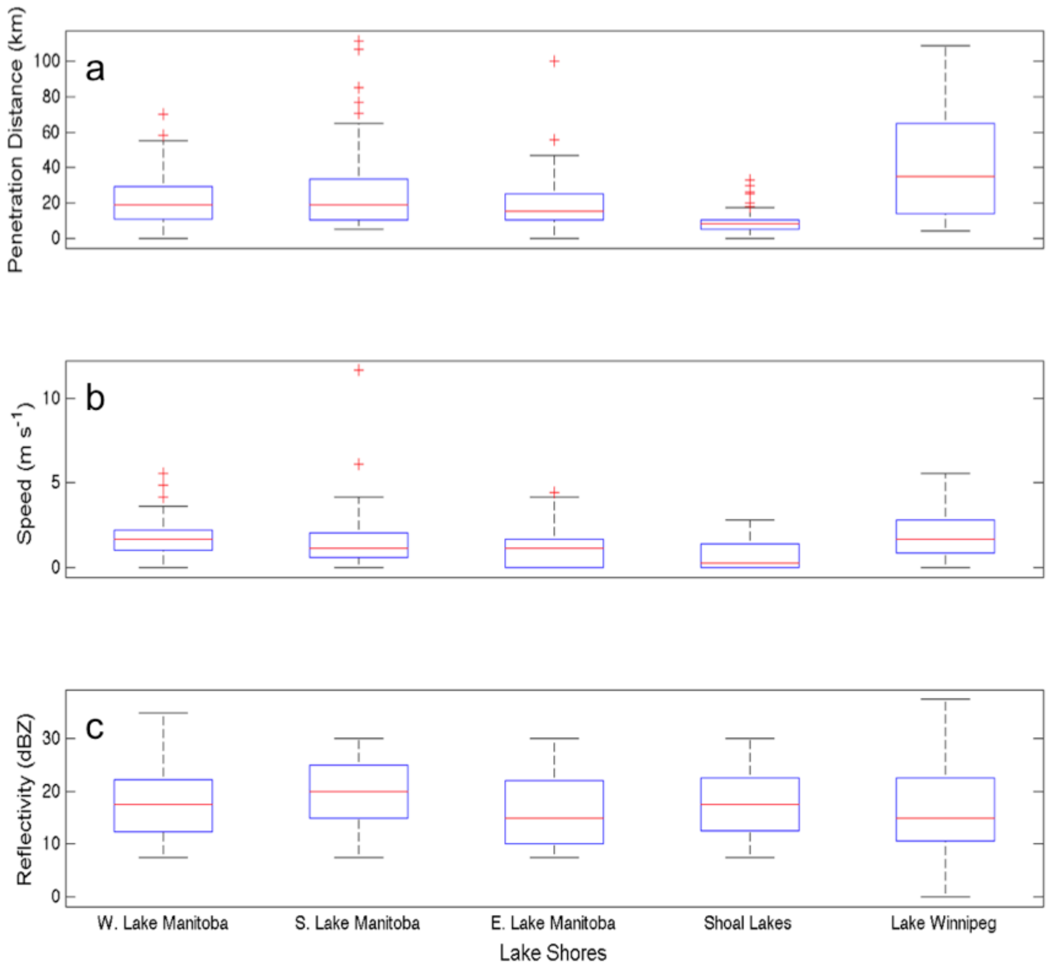

Figure 3.2: Box and whisker plot providing the a) distance (km) LBFs travelled, b) speed of travel (m s^{-1}) and c) highest reflectivity (dBZ), grouped by lake shore. The whiskers represent the most extreme data not considered outliers, the box the 25-75th percentile, and the red line the median for each distribution. The crosses are the outlying values of the dataset. A point is considered an outlier if the value is greater or less than 1.5 times the interquartile range.

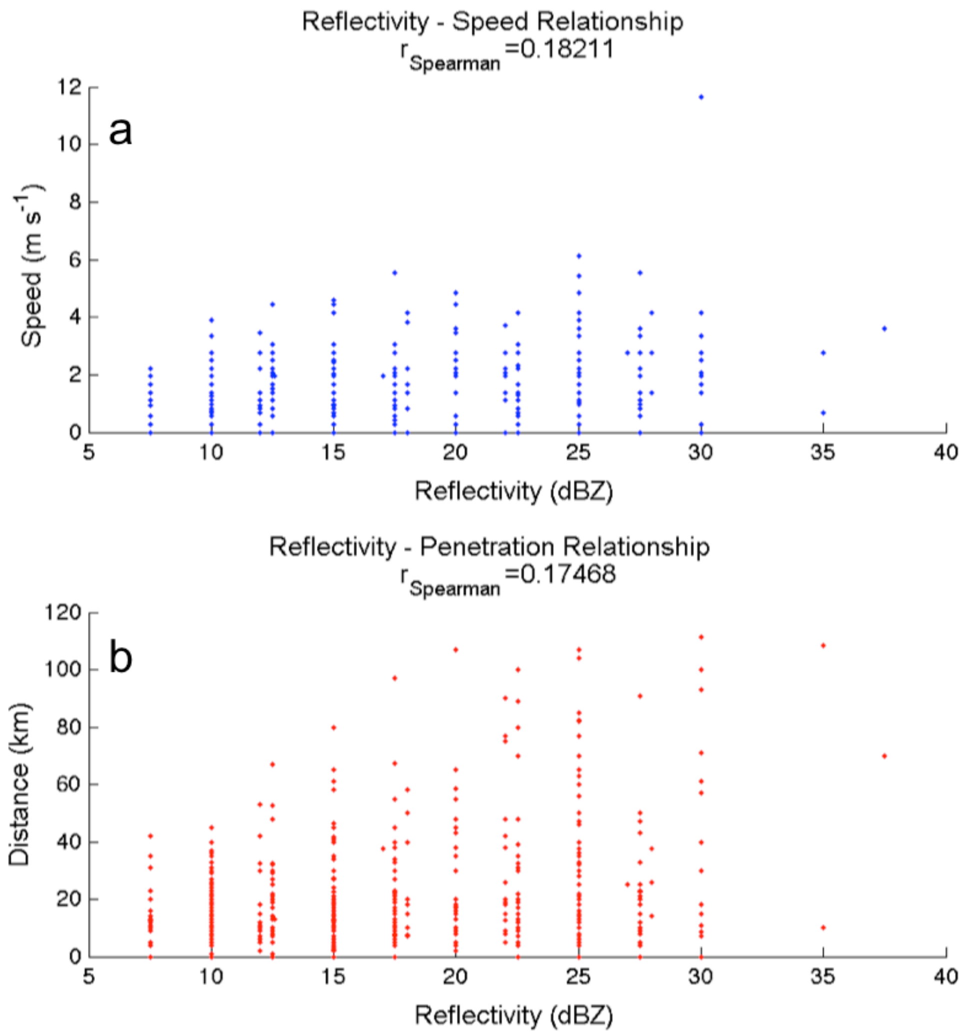

Figure 3.3: Scatter plots showing the correlation between a) radar reflectivity (dBZ) and LBF penetration speed (m s^{-1}) and b) radar reflectivity (dBZ) and penetration distance (km). The Spearman correlation coefficient is listed for both plots, and is considered significant with a p value less than 0.05.

Interestingly, previous work did not appear to examine the range of radar returns for LBFs nor did they examine the speed at which the breeze propagated from the lake. Therefore, it is not possible to compare the results of these findings to work done in the past. Harrison *et al.* (2009) reported findings on convective outflow boundaries, which are very similar in appearance and structure in terms of radar analysis, and found that stronger (weaker) outflow boundaries were associated with higher (lower) reflectivity values. It was suggested that this was a result of stronger updrafts at the outflow's leading edge, resulting in higher insect concentrations aloft and an increase in Rayleigh scattering. The values presented for LBF penetration distance are comparable to results presented in previous work. While early studies surrounding the Great Lakes described penetration distances as fairly small, between 15 and 45 km on average (Moroz, 1967; Lyons, 1972), later studies in the region found median distances ranging from 45 to 75 km (Sills *et al*., 2011). Maximum distances were even higher, between 100 km and 215 km (Sills, 1998; Sills *et al*., 2011). In other regions of the world, sea-breeze studies have shown maximum penetration distances between 100 and 300 km (Simpson, 1994). The distance a breeze moves inland can be influenced by topography, synoptic-scale winds, and the strength of the circulation itself. Therefore, it is unsurprising that the results have varied so widely among studies. The fact that the values from this study were at the lower end of values from previous studies is to be expected, because the Manitoba lakes are generally warmer, smaller, and shallower than the Great Lakes and ocean basins.

3.3.2 Radar analysis detectability

A recent study by Alexander (2012) examined the accuracy of various datasets for detecting LBFs in southern Ontario, including radar, mesonet stations, satellite images, and a combination approach. They examined LBFs from Lake Huron and Lake Erie separately and compared various datasets and approaches to a "truth" dataset, or a set that was considered the most accurate representation of the LBF frequency for each lake. A similar approach was taken here to determine how well radar analysis detected LBFs in southern Manitoba. It was not possible for this study to create a truth set as detailed or accurate as Alexander's; therefore, our reference set is considered to be a combination approach of using all three data sources, as outlined in Section 2c.

Of the 87 days analyzed for JJA 2013 using Doppler radar, LBFs were noted around Lake Manitoba on 39 days and around Lake Winnipeg on 21 days, for a frequency of 45% and 24% of study days, respectively. These numbers are slightly lower than those shown in Table 3.1 because, as mentioned previously, the first five days of June were dropped for this analysis. In comparison, using satellite images, LBFs were noted to have occurred around Lake Manitoba on 42 days and on 37 days around Lake Winnipeg (48% and 43% frequency, respectively). Using the mesonet station data, a total of 36 days showed evidence for LBFs around Lake Manitoba and 39 days for Lake Winnipeg (41% and 45% frequency, respectively). The combined analysis dataset indicated LBFs on 48 days around Lake Manitoba and on 42 days around Lake Winnipeg, resulting in a frequency of 55% and 48%, respectively. Note that for all datasets, it is possible that LBFs may have been missed; thus this number may still be an underestimate of the frequency of LBFs for southern Manitoba. As would be expected, using a combination approach yielded the highest frequency of days with LBFs for both lakes.

A number of additional parameters were calculated for this analysis to determine the performance of the radar dataset compared with the performance of the combined dataset. A contingency table approach, similar to that used by Alexander (2012), was used to determine how well the radar dataset agreed with the combined dataset. The first metric calculated was the probability of detection (POD) defined as

$$\mathrm{POD} = a/(a+c),$$

where a is the number of times both the individual dataset and the combined analysis indicated that an LBF was present, and c is the number of times when the combined analysis indicated that an LBF was present but the individual dataset did not. A perfect score would be 1 indicating that the radar analysis detected all cases of LBFs detected by the combined approach. The POD for the radar analysis for Lake Manitoba was 0.77 but only 0.50 for Lake Winnipeg. A second similar metric is the bias of the dataset, defined as

$$\text{Bias} = (a+b)/(a+c)\ ,$$

where a and c are defined as before, and b is the number of cases when the combined dataset indicated no LBF was present but the individual dataset indicated an LBF was present. If the number is greater than 1, this indicates that the radar detected more LBFs than the combined approach, while a number less than 1 indicates the radar analysis yielded fewer cases. The bias was 0.81 for Lake Manitoba and 0.50 for Lake Winnipeg. This indicates that the radar analysis is better suited to capturing LBFs occurring around Lake Manitoba than those occurring around Lake Winnipeg but will potentially miss cases for both lakes. The false alarm ratio (FAR) was also calculated, defined as

$$\text{FAR} = b/(a+b)\ ,$$

where a and b are defined as before, representing the number of cases when the radar analysis suggested the presence of an LBF but the combined analysis did not. The FAR for the radar analysis was very low for both lakes, zero for Lake Winnipeg, and 0.05 for Lake Manitoba. Thus, although radar analysis may miss a number of LBFs, particularly around Lake Winnipeg, the majority of cases are likely true LBFs as opposed to other sources of fine line returns.

In comparison, Alexander's (2012) analysis yielded a POD score for radar between 0.20 and 0.46 for Lake Huron and between 0.20 and 0.37 for Lake Erie depending on the time of day being analyzed. Similarly, the bias for the Lake Huron radar analysis was 0.30 to 0.47 and 0.19 to 0.37 for Lake Erie, which is again much lower than the values reported here for southern Manitoba lakes. This may be a result of a more accurate truth set being used in Alexander's study, as well as the location of the Doppler radar site in relation to the lake shores being studied. The FAR agreed with those presented here; however, the Lake Huron radar analysis showed a false alarm ratio of 0.03 to 0.13 and zero for Lake Erie.

As a reference, similar statistics were calculated for the satellite dataset and the mesonet dataset. The satellite dataset had the highest POD rate for Lake Manitoba (0.83) while the mesonet had the highest for Lake Winnipeg (0.86). The satellite dataset appears to be the closest measure to the combined approach, with a bias of 0.88 for both Lake Winnipeg and Lake Manitoba. The mesonet dataset performed best when considering Lake Winnipeg, with a bias of 0.93, which is the best performance of any dataset. The highest FAR recorded was for the mesonet analysis, with a rate of 0.14 for Lake Manitoba.

These results suggest that although radar is an effective tool for detecting LBFs around Lake Manitoba, it is quite ineffective for detecting LBFs around Lake Winnipeg. In contrast, using mesonet stations in southern Manitoba is most effective around Lake Winnipeg, but around Lake Manitoba it may overestimate the number of LBFs present. Satellite images are generally best overall at detecting the presence of LBFs in southern Manitoba. These results are close to those expected given the locations of the data collected for each dataset. Although it is possible to view the entire study region on satellite, radar coverage does not extend over the entirety of the lakes and is more effective within a limited range. The mesonet station network in southern Manitoba is relatively sparse, with more stations located on either side of Lake Winnipeg and more near the lake shore making LBFs easier to detect, particularly if they do not track far inland. Around Lake Manitoba, there is only one shore station, located on the east shore of the lake. This can make it more difficult to determine when a true lake-breeze circulation is developing around Lake Manitoba as opposed to synoptic flow influence, particularly when the wind is from the west.

With this information, we can then extend these results to the broader dataset collected for this study to provide an estimate of how many LBFs could be occurring. For example, referring to the values in Table 3.1, the radar analysis yielded an average LBF frequency for Lake Manitoba of 30 days per season (JJA). If we apply the POD score for radar (0.77), we could expect approximately 1.23 times more days with LBFs, or 37 days on average. For Lake Winnipeg, with a radar POD score of only 0.5, we could potentially expect double the number of days with LBFs to occur, from 15 days per season to 30. Looking at individual years, this could mean some years may have seen as many as 53 days with LBFs on Lake Manitoba (2013, if the first five days of June are included) and as high as 50 days for Lake Winnipeg (2012 and 2013). This is of course a generalization, subject to error, but does provide an estimate of the potential LBF frequency in Manitoba.

This analysis provides a general sense of the degree to which radar analysis may have underestimated LBF frequency. This has important implications for the forecasting community in southern Manitoba and reinforces the need to approach nowcasting from a variety of data sources and to avoid relying too heavily on one data source, such as radar or mesonet stations. Additionally, an integrative approach to the datasets, which allows the user to examine all the data available (radar reflectivity, cloud cover, and surface observations), would yield the most accurate analysis. For cases in which not all data are available, radar would be an appropriate means for detecting boundaries around Lake Manitoba but would potentially miss an LBF present around Lake Winnipeg. An example of such a scenario for which this may be a consideration would be a day when meteorological conditions are such that significant high cloud is present on satellite imagery obscuring the lake, or no cloud is present, thus limiting the utility of satellite imagery for detecting an LBF.

3.3.3 Lake-breeze circulation typing

Further to the results presented by Curry (2012), the lake breezes in southern Manitoba were reanalyzed and classified by circulation type. The typing was only completed for Lake Manitoba and the Shoal lakes. It was not possible to classify the lake-breeze circulations on Lake Winnipeg because only the west and south shorelines were within reasonable radar detection range.

Sills *et al*. (2011) present three types of lake-breeze circulations in their study: low deformation (LD), moderate deformation (MD), and high deformation (HD) circulations. Criteria similar to those used by Sills *et al.* (2011) were used and adjusted to reflect the constraints of the study region and radar detection network. It is important to note that in the analysis completed by Sills *et al*. (2011) a greater variety of data sources were used, including the 850 hPa winds and surface station data, allowing for a more accurate and complete analysis. For the purposes of this study, winds were estimated using Doppler radial velocity scans. For a complete description of the circulations, as well as a conceptual model, the authors would encourage the reader to refer to Sills *et al.* (2011).

A lake breeze was categorized as LD circulation if an LBF was present on all possible sides of a lake parallel to the shore (as in the case of the Shoal lakes), or if a boundary was present on the downwind side of the lake when not all lake edges were in the radar detection zone (as in the case of Lake Manitoba) or visible (Figure 3.4a and d). This is most like a "classical" or typical lake-breeze event and requires light background winds (Lyons, 1972; Sills *et al*., 2011). A case was classified as an MD circulation if LBFs were visible on the upwind side of the lake, but *not* on the downwind side of the lake (Figure 3.4b and e). If fronts were visible

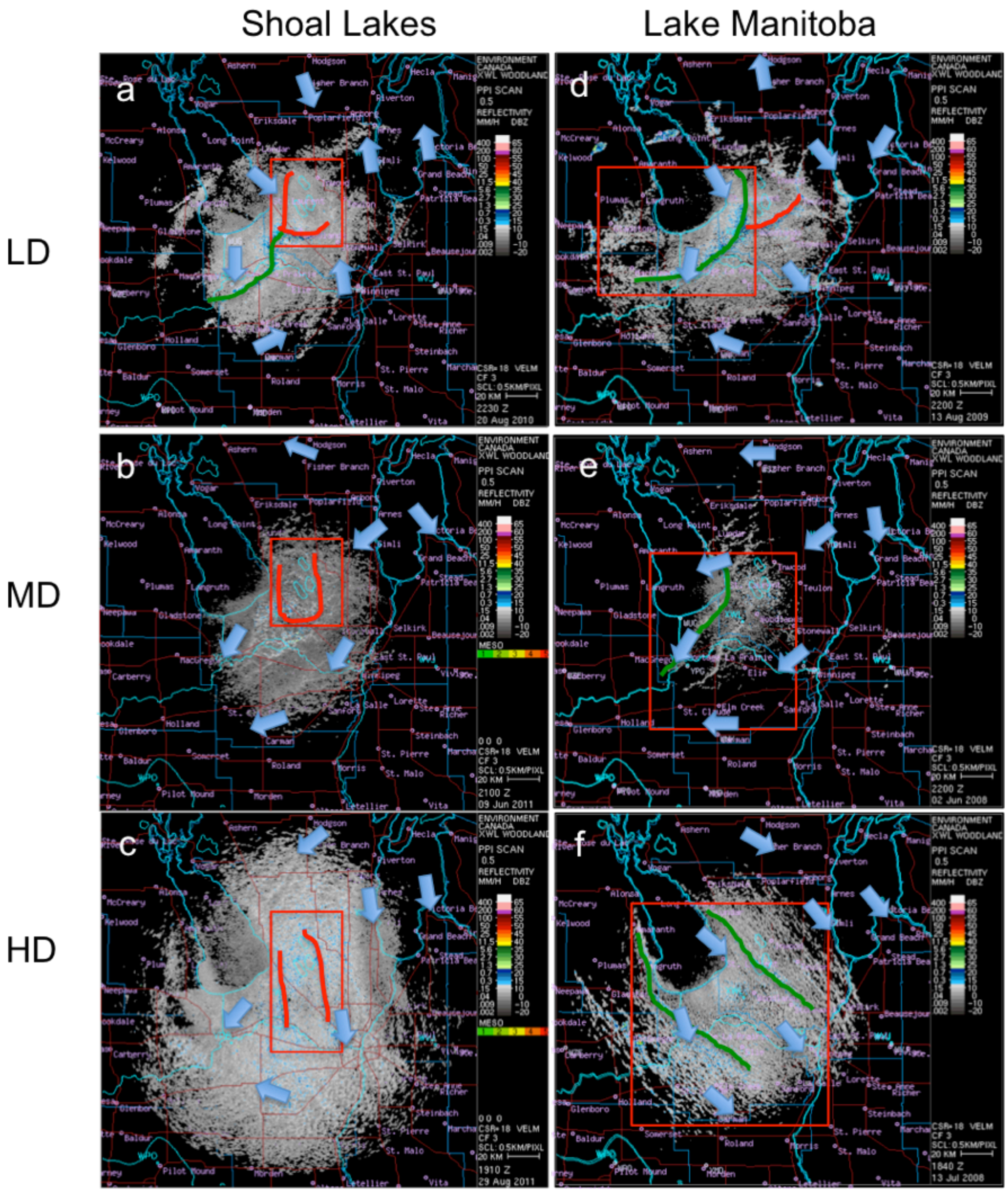

Figure 3.4: Doppler radar images (courtesy of Environment Canada), showing LD lake-breeze circulation (a), MD circulation (b) and HD circulation (c) for the Shoal Lakes, and for Lake Manitoba (d, e, f as in a, b, c). The red box highlights the area of focus, with LBFs from Lake Manitoba highlighted by a green line, and LBFs from Shoal Lakes highlighted in red. Arrows indicate wind direction at the nearest hour at various Environment Canada stations in the area.

parallel to the wind direction and lakeshore but not present on the shore perpendicular to the wind direction, then the case was classified as an HD circulation (Figure 3.4c and f). Examples of each type are provided in Figure 3.4 for both Lake Manitoba and the Shoal lakes. This analysis is considered most accurate for the Shoal lakes because all boundaries of the lakes can be viewed using the Woodlands radar. For Lake Manitoba, the margin of error and potential overlap between case types is significantly higher because the northern shore of the lake is not within Doppler radar range.

All three types of lake-breeze circulations were detected in southern Manitoba. Interestingly, the distribution of types varied significantly between Lake Manitoba and the Shoal lakes, shown in Figure 3.5. The most frequently occurring lake-breeze circulations for Lake Manitoba were HD, while this was the lowest frequency of occurrence for the Shoal lakes. The least frequent type for Lake Manitoba was the LD circulation or more classic breeze type, and the lowest for the Shoal lakes were the HD circulations. The Shoal lakes had the highest frequencies for MD types.

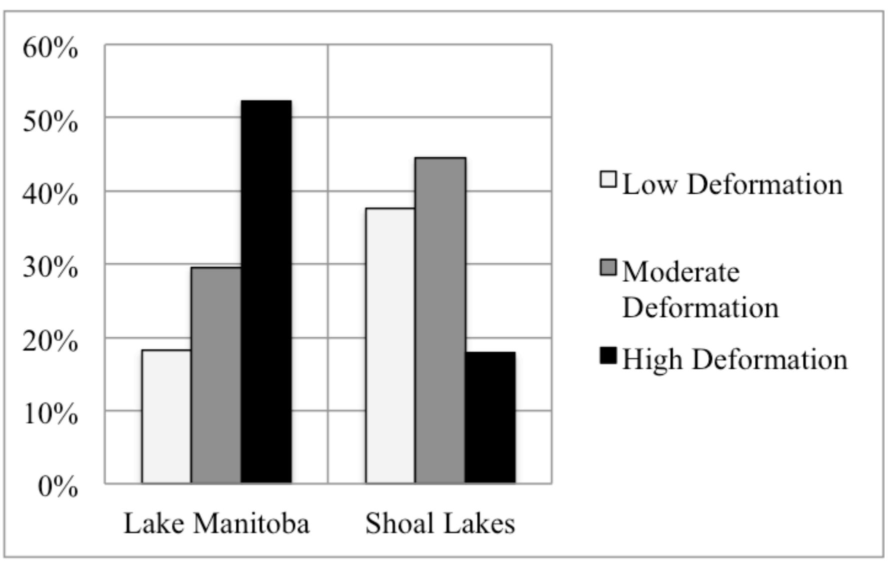

Figure 3.5: Histogram showing the distribution of lake-breeze circulation types by lake, for LD, MD, and HD circulation types.

Comparing these results with the analysis by Sills *et al*. (2011), the frequency distribution for the Shoal lakes agrees quite well with the frequency distribution in their study. In the case of their study, LD circulations accounted for 24% of breezes, MD circulations for 57% of breezes, and HD circulations for 19%. This compares reasonably well with the 38%, 45%, and 18% frequencies reported here for the Shoal lakes. One reason that the distribution is skewed for Lake Manitoba could be the orientation of the lake with regard to the radar, and the lack of coverage towards the north end of the lake. For example, in a north wind, the LBFs may in fact be due to an MD lake-breeze circulation; however, the front at the north end of the circulation is not observed because of the radar range; thus the boundary would be misclassified as an HD lake-breeze circulation. Additionally, it is important to note that the primary factor in whether or not a circulation will be classified as LD, MD, or HD is the wind direction and speed relative to the thermal gradient. Therefore, any significant regional differences in wind regimes will influence the frequency of each circulation type within a region. As mentioned previously, the results were presented here for Lake Manitoba for no other reason than comparison and should not be considered as truly "accurate" due to the limitations mentioned.

3.3.4 Meteorological and climatological conditions

To help provide context for the results presented, a meteorological analysis for the conditions for JJA from 2008 to 2013 was conducted and compared with the climatology for the region. The CYWG station was selected as representative of the region, partly for its location and distance from the lakes, as well as the quality and length of the climatological record for that station. A variety of variables was used, including mean and maximum temperature, days with rainfall, relative humidity (at 2000 UTC), modal wind direction, average wind speed, maximum daily lake surface temperature, and maximum daily lake air temperature (Table 3.3). For the temperature, humidity, and wind values, daily averages (or maxima) were calculated first then averaged for the month in question.

Table 3.3: Winnipeg James Richardson International Airport climatology and yearly meteorological data for 2008-2013. Lake surface and lake air temperature data are measured from the Lake Winnipeg South Basin Buoy. Mean temperatures were calculated by averaging all temperatures in the given month. Maximum temperatures were calculated by averaging the daily maximum temperatures for each month. LBF frequency is also provided for reference for each year, as well as the average, and is listed as the total number of days in a given month/year with a LBF present somewhere in the study area.

		2008	2009	2010	2011	2012	2013	Normal
June	Mean Temp (°C)	16.1	15.8	20.3	17.3	18.2	17.9	**17**
	Max Temp (°C)	21.8	21.4	25.7	22.3	23.8	23.5	**23.3**
	Days with Rainfall	14	16	19	18	18	11	**13**
	Relative Humidity - 1500 LST (%)	52	53	63	55	58	49	**52**
	Modal Wind Direction	NW	S	S	S	W	N	**S**
	Average Wind Speed	4.5	4.6	3.9	4.7	4.2	4.6	**4.6**
	Max Lake Surface Temperature (°C)	15.9	15.6	18.9	19.2	18.6	18.9	**17.8**
	Max Temp - Lake Surface Difference	5.9	5.8	6.8	3.1	5.2	4.6	**5.2**
	Max Lake Air Temperature (°C)	17.6	17.1	19.1	19.6	19.7	19.2	**18.7**
	Max Temp - Lake Air Temp Difference	4.2	4.3	6.6	2.7	4.1	4.3	**4.4**
	LBF Frequency	16	10	9	8	8	16	**11**
July	Mean Temp (°C)	18.8	16.9	19.1	21.3	22.7	19.3	**19.5**
	Max Temp (°C)	23.9	22.3	24.5	27.7	28.8	24.7	**25.8**
	Days with Rainfall	15	15	15	14	14	15	**11**
	Relative Humidity - 1500 LST (%)	60	61	59	45	51	52	**54**
	Modal Wind Direction	W	NW	W	W	W	S	**S**
	Average Wind Speed	4.6	4.4	4.1	4.3	3.6	4	**4.1**
	Max Lake Surface Temperature (°C)	20.8	20	21.6	23.2	25.1	22.6	**22.2**
	Max Temp - Lake Surface Difference	3.1	2.3	2.9	4.5	3.7	2.1	**3.1**
	Max Lake Air Temperature (°C)	21.6	20	22.7	24.1	25.4	22.6	**22.7**
	Max Temp - Lake Air Temp Difference	2.3	2.3	1.8	3.6	3.4	2.1	**2.6**
	LBF Frequency	12	11	8	9	14	15	**12**
August	Mean Temp (°C)	19.9	17.4	19.1	20.5	19.5	19.3	**18.5**
	Max Temp (°C)	25.7	22.3	24.5	27.2	26.4	25.8	**25**
	Days with Rainfall	15	17	19	12	14	16	**10**
	Relative Humidity - 1500 LST (%)	52	63	63	41	47	48	**52**
	Modal Wind Direction	S	S	W	S	S	S	**S**
	Average Wind Speed	4.8	4	4.6	4.3	4.2	3.7	**4.1**
	Max Lake Surface Temperature (°C)	22.2	20	22	23.2	22.9	21.7	**22**
	Max Temp - Lake Surface Difference	3.5	2.3	2.5	4	3.5	4.1	**3.3**
	Max Lake Air Temperature (°C)	23.1	20.1	22.3	23.9	22.8	22.1	**22.4**
	Max Temp - Lake Air Temp Difference	2.6	2.2	2.2	3.3	3.6	3.7	**2.9**
	LBF Frequency	10	13	5	11	13	17	**12**

In general, months with higher than average rainfall days had lower than average LBF frequencies, but this was not always the case. For example, while had the lowest LBF frequency of 5 days and 19 days of rainfall occurred in August 2010, the highest LBF frequency of any month occurred in August 2013 in which the number of days with precipitation was above normal. Interestingly, we would expect that years with higher than normal differences in maximum daily temperatures between CWYG and the Lake Winnipeg buoy would result in higher than average LBF frequency, but again this was not always the case. For example, July 2010 and July 2013 had comparable average wind speeds, comparable number of days with precipitation, and comparable maximum differences between daily temperature and lake air temperature; however, July 2013 had almost double the LBF frequency. It was not possible to confidently isolate one variable that seemed to influence the LBF frequency in a given month or year. This remains an area of research requiring further study in order to determine the key determining meteorological factors for lake-breeze development in southern Manitoba.

3.4 Summary and Future Research

For the first time, findings from a preliminary study of lake breezes in southern Manitoba have been presented, providing a basis for future research in this region. With the majority of Manitoba's population situated within the influence of Lake Manitoba and Lake Winnipeg, lake breezes are an important area for convection initiation and interactions with pre-existing storms. Having a better understanding of the frequency and characteristics of lake breezes and associated LBFs will provide meteorologists with more information to better forecast both general weather and severe weather events in southern Manitoba. The main objectives of this study were to (i) provide a radar-based analysis of LBF frequency and characteristics in southern Manitoba, (ii) determine the detectability of LBFs by radar using data collected in 2013 relative to other datasets for LBF detection, (iii) assess the types of lake-breeze circulations that occur, and (iv) examine the meteorological conditions in which they occur.

A radar-based analysis of LBF frequency using data from the Environment Canada Doppler radar at Woodlands was presented; LBFs were recorded on 37% of the days studied between 2008 and 2013, during JJA. The median frequencies of LBFs were 11 in June, 12 in July, and 12 in August, which was shown to be significantly lower than results reported for other regions (e.g., Sills *et al.*, 2011). The frequency of events for Lake Manitoba compared favourably with frequencies reported for Lake Michigan by Lyons (1972) for the west shore and Laird *et al.* (2001) for the east shore, though Lake Manitoba LBF frequencies were slightly lower.

Each event was studied in detail using the URP software to determine the penetration speed and distance and maximum reflectivity for each LBF. The median penetration distances ranged from 8 km (the Shoal lakes) to 35 km (Lake Winnipeg), with maximum distances of 112 km for the south shore of Lake Manitoba and 109 km for Lake Winnipeg. The median speed ranged from 0 to 2 m s^{-1}, with a maximum speed of 11.7 m s^{-1}. These values agree well with previous studies. The maximum radar reflectivity was also recorded for each boundary, and median values ranged from 15 to 17.5 dBZ for each lake. The maximum reflectivity recorded was 37.5 dBZ.

Using other data sources collected during the 2013 ELBOW-MB field project (Hanesiak, 2013), including satellite imagery and surface station data, we were able to create a combination dataset to assess the utility of the radar dataset for detecting LBFs. The radar analysis was most useful for detecting LBFs around Lake Manitoba when compared with a combination approach with a bias of 0.81, but was quite poor at detecting LBFs around Lake Winnipeg. Although only about 23% of days with LBFs were missed for Lake Manitoba, potentially 50% of days were missed for Lake Winnipeg. Further, a comparison of radar, satellite, and the mesonet surface data indicates that radar is an effective data source when looking for LBFs around Lake Manitoba, but using existing surface stations is more effective for determining whether an LBF is present around Lake Winnipeg. Satellite images are also an effective data source when examining LBF occurrence when boundary layer cloud is present, with a bias of 0.88. This has important implications for the forecasting community in southern Manitoba and reinforces the need to use a variety of data sources when nowcasting to avoid relying too heavily on one data source, such as radar or the surface network.

Lake breezes originating from Lake Manitoba and the Shoal lakes were classified into three circulation types, according to the types developed by Sills *et al*. (2011): LD, MD, and HD circulations. The distribution of types for the Shoal lakes was found to be similar to the reported distribution by Sills *et al*. (2011) with 45% of cases being classified as MD, 38% as LD, and 18% as HD circulations. In contrast, only 30% of Lake Manitoba cases were classified as MD circulations, with 18% being LD, and 52% being HD circulations. The overabundance of HD circulations is likely a result of the orientation of the lake to the radar and the limited data for the north shore of the lake.

A brief meteorological analysis was conducted using data from the CYWG meteorological station and Lake Winnipeg buoy data. The results of the analysis were inconclusive. It was not possible to isolate single variables in connection with higher or lower LBF frequency, with different variables seeming to be more influential some years than others. This remains an area of research requiring further study in order to better understand the key determining meteorological factors for lake-breeze development in southern Manitoba.

There are still areas that require further research and study to better understand lake breezes in southern Manitoba as well as globally. There have been few studies of lake breezes resulting from smaller sized lakes (< 50 km). Further research on a variety of lake sizes and shapes will enable a better understanding of the different driving forces behind lake-breeze circulations and help validate modelling studies such as those of Crosman and Horel (2012). Further, Asefi-Najababy *et al*. (2012) point out that studies examining small lakes have done so using numerical models or point measurements. Studies, such as the one presented here, act to further validate the measurements already provided by previous studies and those from modelling studies. Further research focused on modelling lake-breeze behaviour in the region would provide a more detailed understanding of the limiting factors for lake-breeze development and a better understanding of the skill of models in predicting lake-breeze development, particularly with high-resolution models (< 1 km grid spacing). Crosman and Horel (2012) suggest further simulations looking at the sensitivity of lake breezes to time of day and seasons, as well as looking further into vertical wind measurements at the LBF and return flow depth and speed.

The ELBOW-MB field project was conducted in July 2013 (Hanesiak, 2013). The project gathered a variety of data including Doppler radar, targeted rawinsonde launches, mobile weather observations, multiple meteorological tower measurements, and lidar wind profiles to better understand lake-breeze characteristics. Results from this study will help to build upon the results presented here and provide a more detailed understanding of the influence and structure of lake breezes in southern Manitoba.

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Chapter 4 - Ground based observations of the thermodynamic and kinematic properties of lake-breeze fronts in southern Manitoba, Canada

Curry, M.E., Hanesiak, J., Kehler, S., Sills, D.M., and Taylor, N. (In preparation) Ground-based observations of the thermodynamic and kinematic properties of lake-breezes in southern Manitoba, Canada, *Boundary-Layer Meteorology.*

Chapter 4 is the second major results chapter of my thesis and was conceived, analyzed, and reported by me as the senior author. This chapter addresses the second main objective of this thesis, to characterize the thermodynamic and kinematic properties of lake breezes in southern Manitoba. This paper has been prepared to submit to the journal *Boundary-Layer Meteorology.*

Abstract

Lake breezes are thermally direct circulations that form as a result of the differential heating of land and water and are important for modifying the local climate and in some cases triggering convection. The Effects of Lake Breezes on Weather in Manitoba (ELBOW-MB) project was conducted 6-24 July, 2013 to examine the effect of lake breezes on southern Manitoba's weather. Data were collected using a variety of platforms including Doppler lidar, rawinsondes, Doppler radar, surface stations, and a mobile weather station. The spatial and temporal variability of the thermodynamic and kinematic characteristics of lake-breeze fronts are presented for three cases. Lake breeze frontal passage was characterized by an average increase in dew point of 2.5 °C and decrease in temperature of 0.5 °C. The lake-breeze front width varied significantly over subsequent measurements and cases, ranging between 50 and 690 m. The depth of the lake-breeze circulation varied between 120 and 680 m. Rawinsonde profiles taken within the lake breeze showed a greater depth of marine influence on the temperature and dew point than wind direction. Enhanced vertical velocities were measured at the lake-breeze front using a mobile lidar, with upward velocities of 2 to 3 m s^{-1} and weak downward velocities of 0.5 m s^{-1} behind the front. These unique observations of lake-breeze fronts in southern Manitoba contribute both to the local understanding of lake breezes and to the broader understanding of inland shallow water body lake breezes.

4.1 Introduction

The sea/lake breeze, a type of thermally induced mesoscale circulation, plays an important role in regulating the climate of near-shore communities (e.g., Pearce, 1955; Oke, 1987; Simpson, 1994) and can influence the location, timing, and intensity of convective storm systems (Sills, 1998; King *et al*. 2003; Alexander, 2012). Evidence from southern Ontario suggests that lake-breeze circulations have a large influence on the tornado climatology, with both suppression and enhancement occuring (King *et al*., 2003). A number of investigations have been conducted on sea and lake breezes, particularly in the Great Lakes and Florida regions of North America (e.g., Lyons, 1972; Estoque *et al*., 1976; Sills, 1998; Laird *et al*., 2001; King *et al*., 2003; Sills *et al*., 2011). Despite the understanding provided by these studies, fewer investigations have been done in other regions for comparison. As pointed out by Segal *et al.* (1997), given the large variety of lakes (in shape, size, and orientation), a thorough examination of a variety of lake types is required to provide a full understanding of lake breezes.

Lake breezes are driven by the microclimatic differences, namely the pressure gradient that results from a difference in air temperature between the terrestrial surface and water (e.g., Pearce, 1955; Oke, 1987). Sensible heat flux is typically greater over land than water (mainly due to land having a much smaller heat capacity), which results in the air over land heating and expanding more rapidly than over water during daylight hours. As the terrestrial air column expands and rises, an area of lower pressure at the surface and an area of higher pressure aloft are created, relative to the same heights over the lake surface. Low-level air from the lake moves onshore toward the area of lower pressure creating convergence and subsequent ascent. A return circulation forms aloft to complete the lake-breeze circulation. The sea/lake breezes experienced near the surface are the manifestation of the low-level portion of this circulation cell that flows onshore during the daytime (Oke, 1987). As the circulation continues to develop, the onshore flow at the surface propagates further inland. The lake-breeze front (LBF) is the maximum inland extent of this flow and is usually characterized by a sharp change in wind direction, decrease in temperature, increase in dew point, and enhanced lift due to the circulation and convergence of the onshore flow with the larger scale flow (Lyons, 1972; Sills *et al*. 2011).

Lake breezes have long been recognized by local forecasters to occur in Manitoba and initiate or enhance convection in unstable environments. As the majority of Manitoba's population is situated within the influence of Lake Manitoba and Lake Winnipeg, having a better understanding of the characteristics of LBFs will provide meteorologists with more information to better forecast both general and severe weather near the lakes. The first attempt to characterize Manitoba LBFs was made by Curry *et al*. (2015) using a radar-based analysis approach. Their results showed that LBFs occur on roughly 40% of days in the warm season months. However, there was large variability from month to month, and year to year. Their analysis also showed that while radar is fairly useful for detecting LBFs forming around Lake Manitoba, up to half of LBFs from Lake Winnipeg could be missed due to the distance from the lake to the Woodlands radar.

The Effects of Lake Breezes on Weather in Manitoba (ELBOW-MB) field project was developed to better understand the lake breezes in southern Manitoba. A three-week intensive observation period (IOP) was conducted between 6 and 24 July, 2013 to collect high-resolution spatial and temporal data for a number of LBF cases. Previous field campaigns have been conducted in southern Ontario [ELBOW 1997: (Sills, 1998); ELBOW 2001: (Sills *et al.*, 2002); Border Air Quality and Meteorology Study (BAQS-Met): (Sills *et al.*, 2011)]. The primary goal of ELBOW-MB is to gain a better understanding of the properties of LBFs and their influence on weather in southern Manitoba.

The overall research goal of this paper is to examine the spatial and temporal variability of the thermodynamic and kinematic characteristics of LBFs in southern Manitoba. We will present three cases from the IOP: two for LBFs that formed near the west shore of Lake Winnipeg, and one for a LBF near the south-east shore of Lake Manitoba. The study area characteristics and data collected are discussed in Section 2. The synoptic-scale environment and characteristics of the resulting LBFs will be examined individually in Section 3, and then summarized and discussed in a broader context in sections 4 and 5.

4.2 Data and Methods

4.2.1 Study Area

Two of the largest fresh water lakes in the world are in southern Manitoba, Lake Winnipeg (11th largest) and Lake Manitoba (33rd largest). Combined, the lakes represent an area of 29 318 km^2 and 2 773 km of shoreline. The lakes are in the basin of the former glacial Lake Agassiz with flat plains in the surrounding regions and minimal elevation changes. The waters are generally shallow, between 7 and 12 m deep. While Lake Winnipeg has a narrow southern basin, with an irregular coastline, Lake Manitoba has a wide southern basin with a rounded coastline. There is also a group of three small lakes; East, West, and North Shoal Lake (referred to hereafter as the Shoal Lakes) ranging in diameter from 3 to 6 km. In the years prior to this study, flooding in the area resulted in the Shoal lakes merging, resulting in one shallow lake approximately 12 km in diameter at the time of the field project. Water temperatures available for Lake Winnipeg through an Environment Canada buoy range from 14 °C in early June to between 22 and 26 °C at the peak of summer heating by July and August, with an average temperature of 19 °C in 2013. This is in contrast to the Great Lakes bordering Ontario and Michigan, which are generally deeper and colder (15 °C for Lake Superior to 24 °C for Lake Erie; NOAA, 2015) and cover more surface area.

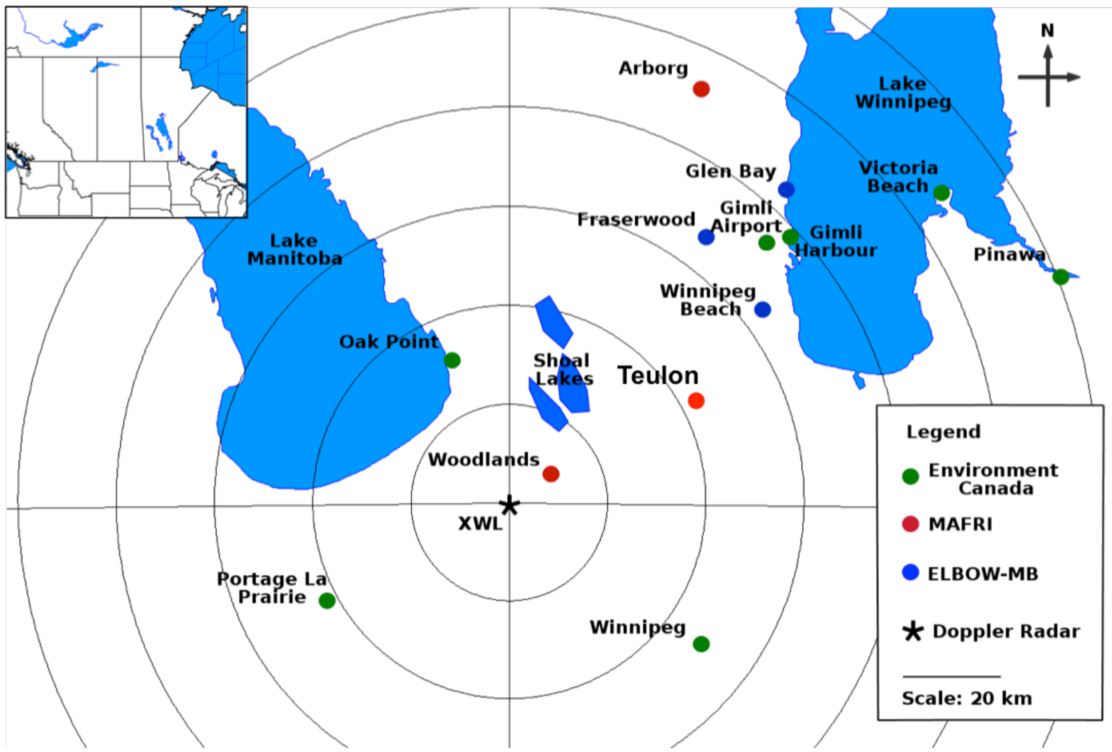

Figure 4.1: The ELBOW-MB domain highlighting surface meteorological stations (filled circles) and the location of the Woodlands radar (star). The concentric circles are radar range rings at 20 km intervals.

Figure 4.1 shows the study region and location of important data collection locations such as the XWL Radar and includes range rings from XWL to 120 km (near maximum detection range for XWL in Doppler mode). However, the beam height increases with distance from the radar, and therefore the probability of detecting LBFs decreases with range. At 120 km, the center of the radar beam on a 0.5 degree scan would be approximately 2000 m above the ground, based on a standard vertical thermodynamic atmosphere. Previous research has indicated LBFs generally reach a depth ranging from 100 to 1000 m (Lyons, 1972; Simpson, 1994; Suresh, 2007;

Tsunematsu *et al.*, 2009), therefore at 2000 m, the radar beam would often be overshooting the top of the LBF.

4.2.2 Data

Data were collected from a variety of platforms including meteorological towers, an Automated Mobile Meteorological Observation System (AMMOS), a mobile rawinsonde unit and a Windcube 70S Leosphere Doppler LiDAR (Light Detecting and Ranging, referred to hereafter as lidar). The mobile rawinsonde unit and lidar were run together as a Mobile Atmospheric Research Station (MARS). These data were supplemented by archived data from a variety of online sources including satellite images, upper air analyses, Doppler radar, Environment Canada weather stations, and Manitoba Agriculture, Food, and Rural Initiatives (MAFRI) weather stations (locations shown in Figure 4.1).

4.2.2.1 Regional Data

The environmental conditions for each case are characterized using meteorological data from weather stations from various networks within the study area and the Environment Canada buoy in the south basin of Lake Winnipeg. Winds were categorized for each case in a similar fashion to Sills *et al*. (2011); light (<5 m s^{-1}), moderate (5–10 m s^{-1}), or strong (>10 m s^{-1}). Radar and satellite images were used to illustrate the evolution of LBFs for each case. The XWL (Woodlands) radar is a 5-cm (C-Band) Doppler radar with a 10-minute scan interval. Images from the lowest-level (0.5 degree) Doppler reflectivity scan were found to best capture clear air returns and boundary-associated fine lines. Start and end times (first and last image where a fine line was visible in the clear air returns, respectively), penetration distance, speed, and maximum reflectivity values along the LBF were analyzed with URP (Unified Radar Processor). Visible satellite images were archived for each case from the GOES-13 satellite (~ 4 km resolution).

Following the criteria outlined by Sills *et al.* (2011) these data were analyzed to determine if it was likely that a lake breeze had occurred. Criteria include, for example, the presence of a fine line on radar forming near the lake and moving inland, enhanced cumulus clouds at the edge of the LBF zone, and a switch to onshore winds at surface stations within the lake breeze. For a detailed description of the criteria used refer to Sills *et al.* (2011).

4.2.2.2 MARS

The MARS was equipped with a Leosphere Windcube 70S Doppler LiDAR and a mobile rawinsonde unit. The lidar uses a 1.54 micron laser, with a 0.1 Hz scan frequency. The maximum height of detection ranges from 100 m to 2000 m AGL (depending on the number of aerosols in the lower troposphere), with a wind speed (both horizontal and vertical) accuracy of 0.3 m s^{-1} (between 0 and 100 m s^{-1}), and direction accuracy of 1.5 degrees. The lidar was deployed in a strategic location, such as near the shore, or in some cases downstream of the lake, and left stationary to measure changes in wind direction, wind speed, and vertical velocity over time. Visual inspection of areas of stronger vertical velocity and depths of different mean airflow layers were noted for each profile along with how these values evolved over the time of investigation.

The rawinsonde unit was mobile during the IOP with launches generally done prior to lake breeze development to sample the planetary boundary layer (PBL) and terrestrial air mass, and then after a LBF passage to sample the lake breeze modified air mass. Additional launches were done where possible in both air masses to capture changes over time. Each profile was plotted with data limited to the surface to 700-hPa layer to better display the PBL. The depth of each lake breeze was estimated from lake-modified air mass soundings by noting maximum depth of the shoreward winds and the maximum depth of the thermodynamic influence of the lake-modified air mass. The depth measurement is rounded to the nearest 50 m to reflect uncertainties in the measurements. All cases included for this study had a background flow directed offshore in the low levels. Had the background flow been onshore at the low levels, this method would be less effective for determining the depth of the circulation.

4.2.2.3 AMMOS

Transects across the LBF were collected using the AMMOS. The AMMOS was equipped with a Campbell Scientific fast-response YSI 44212 temperature sensor and a Campbell scientific HMP45 temperature and relative humidity sensor. Both were encased in a ventilated tube to regulate airflow and to prevent rain and road wash from reaching the humidity sensor. Other sensors included an R. M. Young anemometer, barometer and GPS. All instruments were mounted on top of a Toyota Prius (Figure 4.2). The data were sent to a computer within the vehicle to assist in the real-time detection of the LBF. Wind measurements were automatically corrected for the movements of the vehicle using GPS to provide real-time true wind speed and direction. Data were collected for a minimum of 1 minute at the start and end of each transect to ensure that the sensors had stabilized in the given air mass before proceeding.

For each transect across a LBF, the AMMOS vehicle would first be stopped for a minimum of 1 minute prior to crossing the breeze to indicate the start of a transect. Then the AMMOS would be driven through the breeze at a consistent speed, varying between transects depending on the intensity of LBF measured on the first transect. After the vehicle was well past the front, another stop would be made to signify the end of each transect for a minimum of 1 minute, or until observations stabilized to account for any lag in the sensors. In some cases, for a particularly strong or sharp LBF, or a fast moving LBF, the AMMOS would be kept stationary letting the LBF pass over the vehicle.

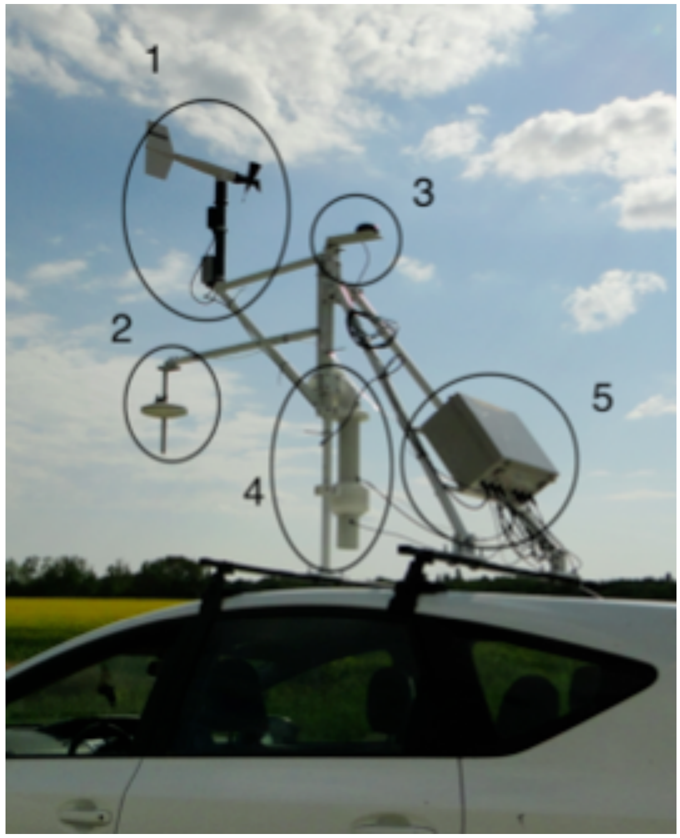

Figure 4.2: Automated Mobile Meteorological Observation System (AMMOS) including: (1) Anemometer, (2) pressure intake port, (3) GPS used in wind calculations, (4) aspirated PVC tubing containing a HMP45 temperature and relative humidity probe and a YSI 44212 fast response temperature probe, (5) datalogger unit containing barometer.

The start of the LBF was considered the first data point where large and sustained changes in dew point occurred combined with a wind shift to onshore flow. The end of the LBF was considered the final data point where wind shift or dew point changes occurred and the data began to stabilize. The latitude and longitude of the AMMOS at the start and end of the LBF was then used to determine the width of the front. It is important to note that given the relative speed of the AMMOS vehicle and speed of the LBF, our calculations were done assuming the LBF was stationary at the time of the measurements. This introduces larger error in the width calculations when considering transects made moving opposite to the motion of the LBF progression, or fast moving LBFs. Width measurements are rounded to the nearest 50 m to reflect uncertainties in measurements. Temperature, dew point, and wind speed values were averaged from the start of the transect to the beginning of the LBF, and from the end of the LBF to the end of the transect to calculate average air mass characteristics on either side of the front.

4.3 Results

4.3.1 July 13, 2013 – Lake Manitoba

IOP data collection on July 13 was focused on Lake Manitoba, with Figure 4.3a showing the progression of the LBFs over the course of the day. An area of high pressure (1019 hPa) centered over the Alberta-Saskatchewan border resulted in surface winds in the northern extent of the study area being generally northeasterly. Further south, winds near the southern basins of the lakes generally had a more easterly component by the afternoon in response to a surface warm front pushing north from North Dakota. Wind speeds over the course of the day within the study area were light, ranging from calm to 5 m s^{-1}. Figure 4.3b shows surface winds at noon LT, prior to significant lake breeze development. Daytime temperatures at Woodlands, a representative land temperature station, reached a maximum of 28 °C while the Lake Winnipeg Buoy reached a daytime high of 26 °C for lake surface temperature, and 25 °C for air temperature above the water. We do not have direct observations for the temperature of Lake Manitoba, however, we can infer a similar temperature due to similar lake characteristics. Therefore, a temperature gradient between the lake and land was likely in place to support lake-breeze development.

Visible satellite images (Figure 4.3c) showed no cloud development in response to daytime heating. Soundings during IOP operations indicated subsidence in the mid levels (Figure 4.4), likely associated with the high-pressure center moving in, inhibiting cumulus development. An area of mid-high level cloud began to impact the study area by 20:00 LT (0100 UTC; all times reported hereafter are in LT, which is CDT) associated with thunderstorms in southwestern Manitoba.

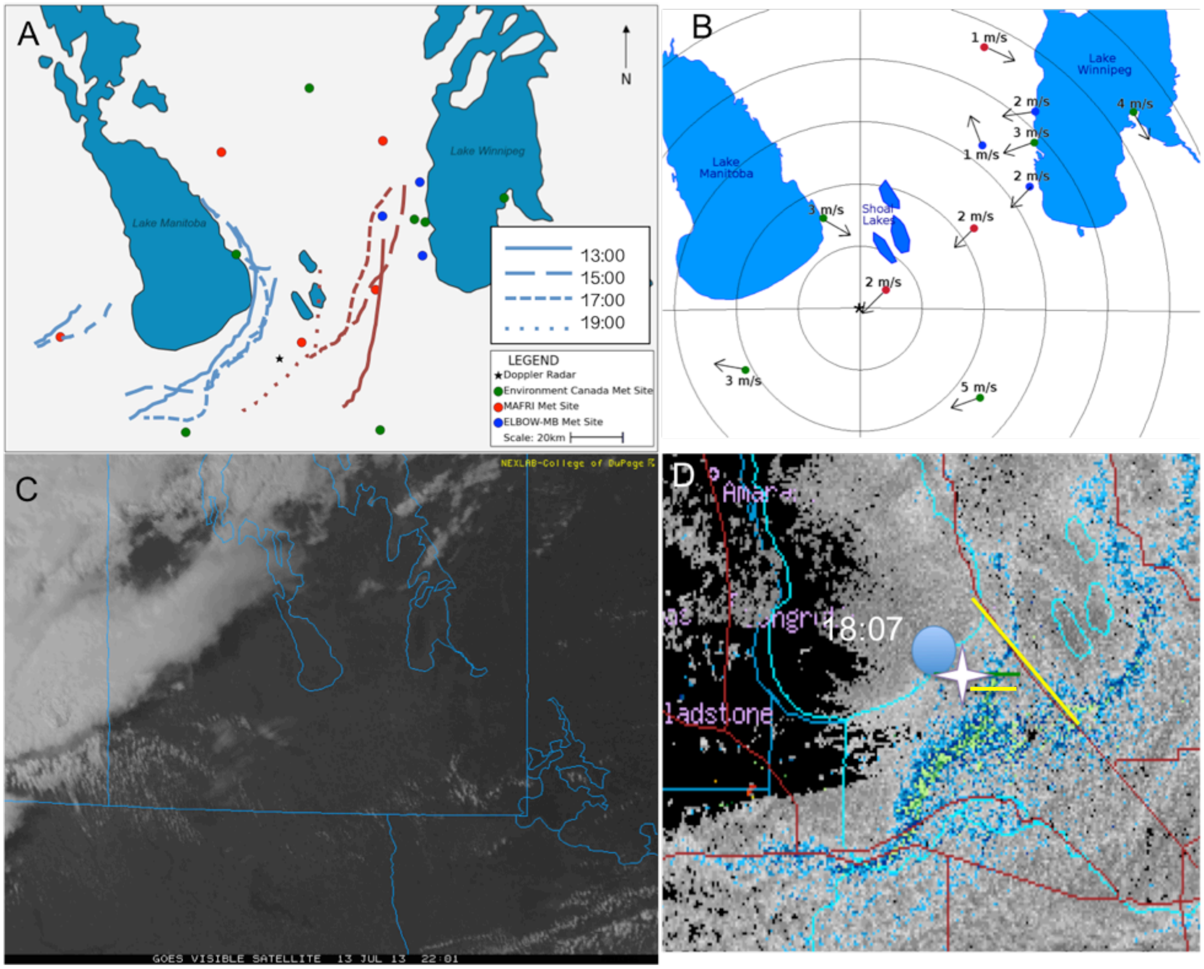

Figure 4.3: Observations for July 13, 2013: A) shows the locations of the LBF every 2 hours for Lake Manitoba (blue) and Lake Winnipeg (red) with times indicated (LT), B) surface wind observations for 12:00 LT, C) visible satellite image for 17:00 LT, and D) Doppler radar image at 17:00 LT showing the sounding launch location (blue dot), lidar location (white star), and AMMOS transects (yellow lines).

A fine line first appeared on Doppler radar at 11:00 LT near Lake Manitoba. Boundaries persisted on radar until 20:20 LT. The penetration distance recorded for Lake Manitoba varied from 10 km on the east shore, to 15 km on the south shore. Figure 4.3d provides an example radar image valid for 17:00 LT with locations of main IOP operations for the day as indicated in the figure.

4.3.1.1 Rawinsonde Data

One rawinsonde was released on the southern shore of Lake Manitoba at 17:40 LT within the lake breeze (location shown in Figure 4.3d). As the southern shore of Lake Manitoba is oriented southwest-northeast, the wind velocity components were transformed such that V' represents northwest-southeast flow perpendicular to the shoreline. A negative V' value indicates onshore flow. The profile, shown in Figure 4.4, shows a marine influence (reduction in temperature, increase in dew point, onshore flow) to 250 m (all heights reported in AGL unless otherwise noted). While the strongest thermodynamic changes occurred within the lowest 100 m, there was evidence of a reduce temperature and increased dew point to approximately 1000 m,

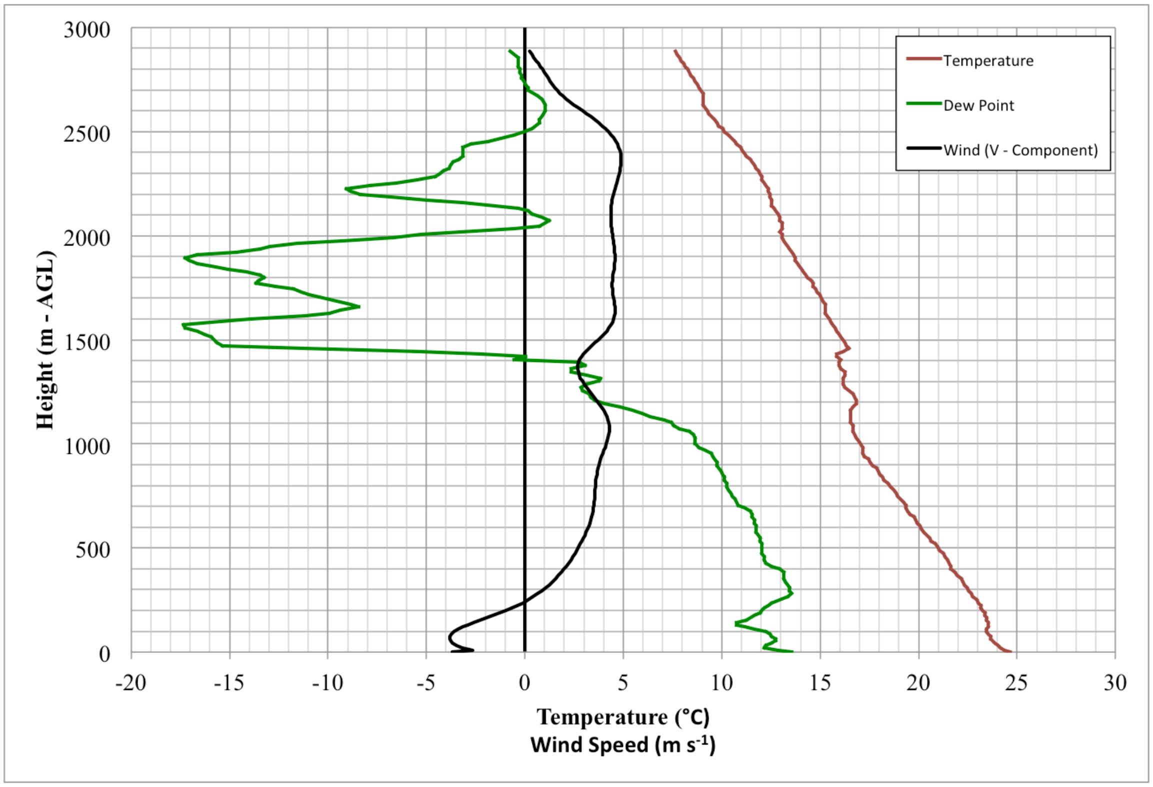

Figure 4.4: Plot of sounding data for 18:07 LT 13 July. Wind components were transformed to account for the SW-NE orientation of the Lake Manitoba shore, and the V' wind component (NW-SE wind directions), temperature, and dew point plotted. A negative V' value corresponds to a NW wind, which is an onshore flow.

which is higher than the onshore flow extends. This may be attributed to subsidence in the mid-levels of the atmosphere from an area of high-pressure which would also result in a simultaneous warming and drying of the air mass that we see between 1000 and 3000 m on Figure 4.4. The general background flow at 1.5 km is from the south (offshore), therefore the return flow in this case may be embedded within the background flow and would be difficult to identify.

4.3.1.2 Lidar

The lidar was deployed south of Lake Manitoba, after the LBF had passed (location noted in Figure 4.3d). Data were collected between 17:55 and 19:00 LT for the depth of the lake-breeze circulation behind the front (Figure 4.5). No areas of strong upward vertical over the study area were identified. Generally, negative velocities of 0.5 m s^{-1} were recorded, with occasional values

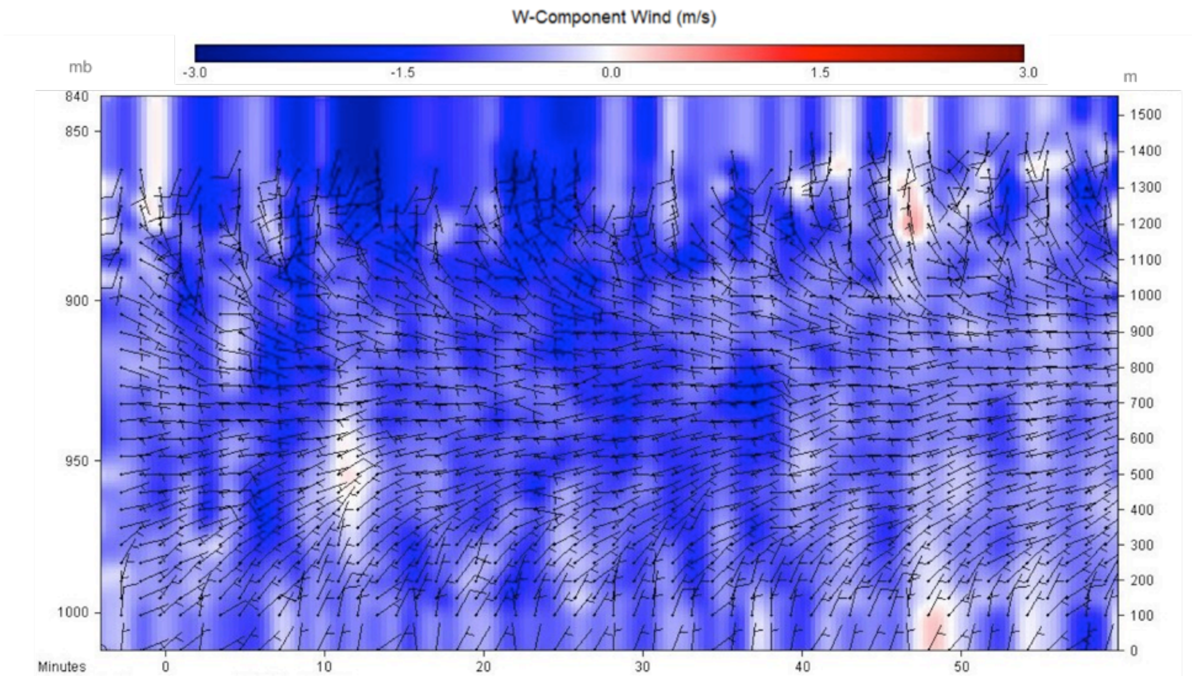

Figure 4.5: Lidar wind observations for 17:55-19:00 LT on 13 July. Time is in minutes on the horizontal axis (0 indicates 18:00 LT). Wind barbs are horizontal wind speed (half barb = 2.5 m s^{-1}, full barb = 5.0 ms^{-1}). Vertical velocity is shaded with blue (red) indicating descent (ascent). Note that data above 860 hPa and below 1000 hPa is interpolated by the lidar.

as high as 2.0 m s^{-1}. This follows the conceptual model for a lake breeze, as the circulation behind the LBF is associated with downward motion and an inversion at the interface between the onshore lake breeze air and residual layer/return flow aloft. The depth of the onshore flow oscillated between 300 to 400 m over a short time period (5 to 10 minutes) during the observations. These depth measurements are comparable with those from our rawinsonde profile. Also notable was that wind speeds at the transitional layer between the onshore flow and the south flow aloft appear to briefly decrease, possibly as a result of mixing between these layers.

4.3.1.3 AMMOS Data

Three complete transects were obtained of the LBF from Lake Manitoba using the AMMOS (see Table 4.1). The first two transects were taken in a line northwest to southeast from the southeast corner of the lake, as shown on Figure 4.3d, between 16:16 and 16:35 LT, and 16:49 and 16:59 LT, respectively. The third transect was taken south of the lake, moving west across the LBF between 17:09 and 17:28 LT. The location of the LBF found using AMMOS transects agreed well with the location of the fine line returns noted on Doppler radar. Figure 4.6 shows a transect of the LBF at 17:20 LT, marked by a sharp increase in dew point, shift to northerly winds (as opposed to easterly), and a gradual reduction in temperature.

Table 4.1: AMMOS transects completed on July 13, 2015. Gradients are calculated as the land to marine transition.

Time Start (LT)	Time Finish (LT)	Direction Travelled	Width of LBF (m)	Temperature Gradient (°C km^{-1})	DP Gradient (°C km^{-1})	Wind Speed Gradient (m s^{-1} km^{-1})	Temperature Difference (°C)	Dew Point Difference (°C)	Wind Speed Difference (m s^{-1})
16:16	16:35	NW	650	-1.0	3.6	0.9	-0.6	2.4	0.6
16:49	16:59	SE	500	-0.6	4.9	1.6	-0.3	2.6	0.8
17:09	17:28	W	700	-0.6	3.7	2.0	-0.4	2.6	1.3
Mean			**650**	**-0.7**	**4.1**	**1.5**	**-0.5**	**2.5**	**0.9**

The thermodynamic characteristics of the land and lake-modified air masses, respectively, were fairly similar between the three transects, shown in Table 4.1. The wind direction within the lake-modified air mass was generally northerly (onshore) while the direction within the land air mass was more easterly creating a zone of convergence at the LBF. The average width of the LBF over the three transects was 650 m resulting in gradients of temperature of 0.7 °C km^{-1}, dew point of 4.1 °C km^{-1}, and wind speed of 1.5 m s^{-1} km^{-1}.

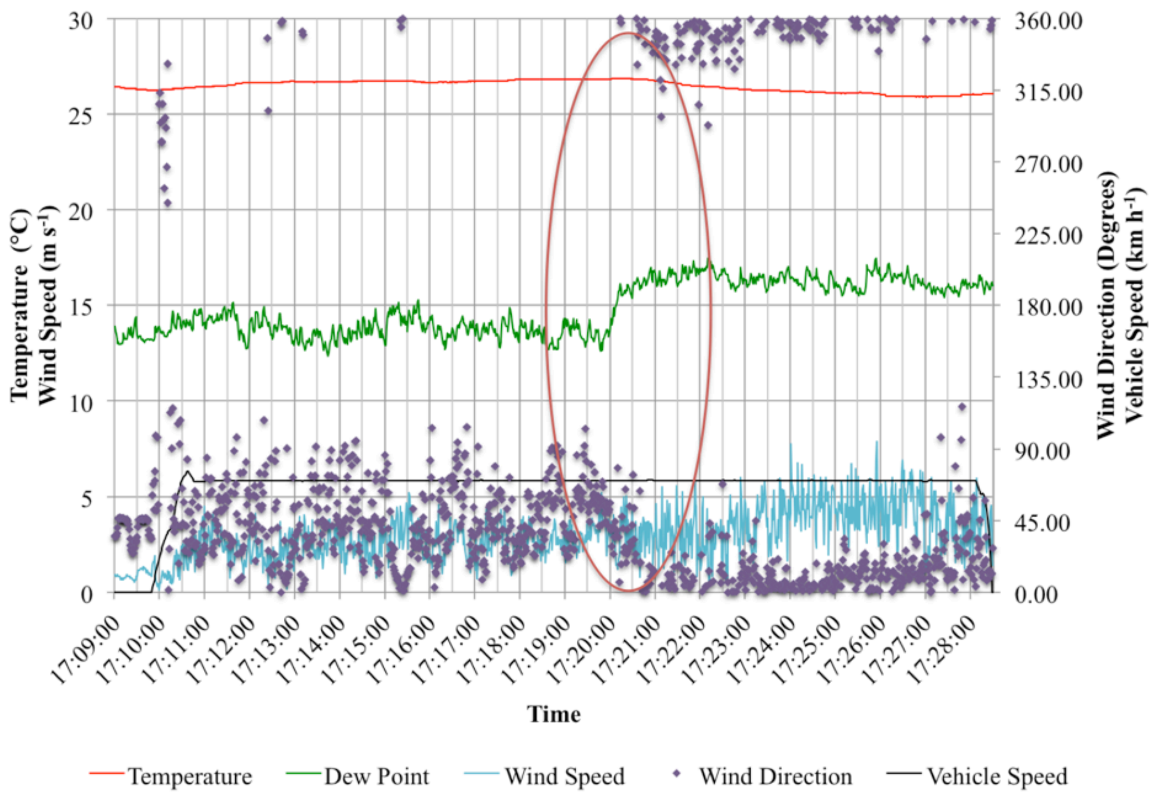

Figure 4.6: AMMOS transect for 17:09-17:28 LT July 13. Sampling of the LBF is highlighted with a red oval. Observations and units are as indicated in the figure.

4.3.2 July 14, 2013 – Lake Winnipeg

Data collection on July 14 was focused on the LBF occurring near Lake Winnipeg. Figure 4.7a shows the progression of the LBFs from both Lake Winnipeg and Lake Manitoba. Surface stations in the study area recorded an average wind speed of 4 m s^{-1} through daylight hours, with winds veering from a north/northwest flow to a north/northeast flow by the evening. Figure 4.7b shows surface winds at noon LT, prior to significant lake breeze development. Temperatures at inland stations reached highs of approximately 24 - 26 °C. The Lake Winnipeg buoy reached a maximum lake surface temperature of 21 °C, with a maximum air temperature of 21 °C. Therefore a temperature gradient was present to support lake breeze development.

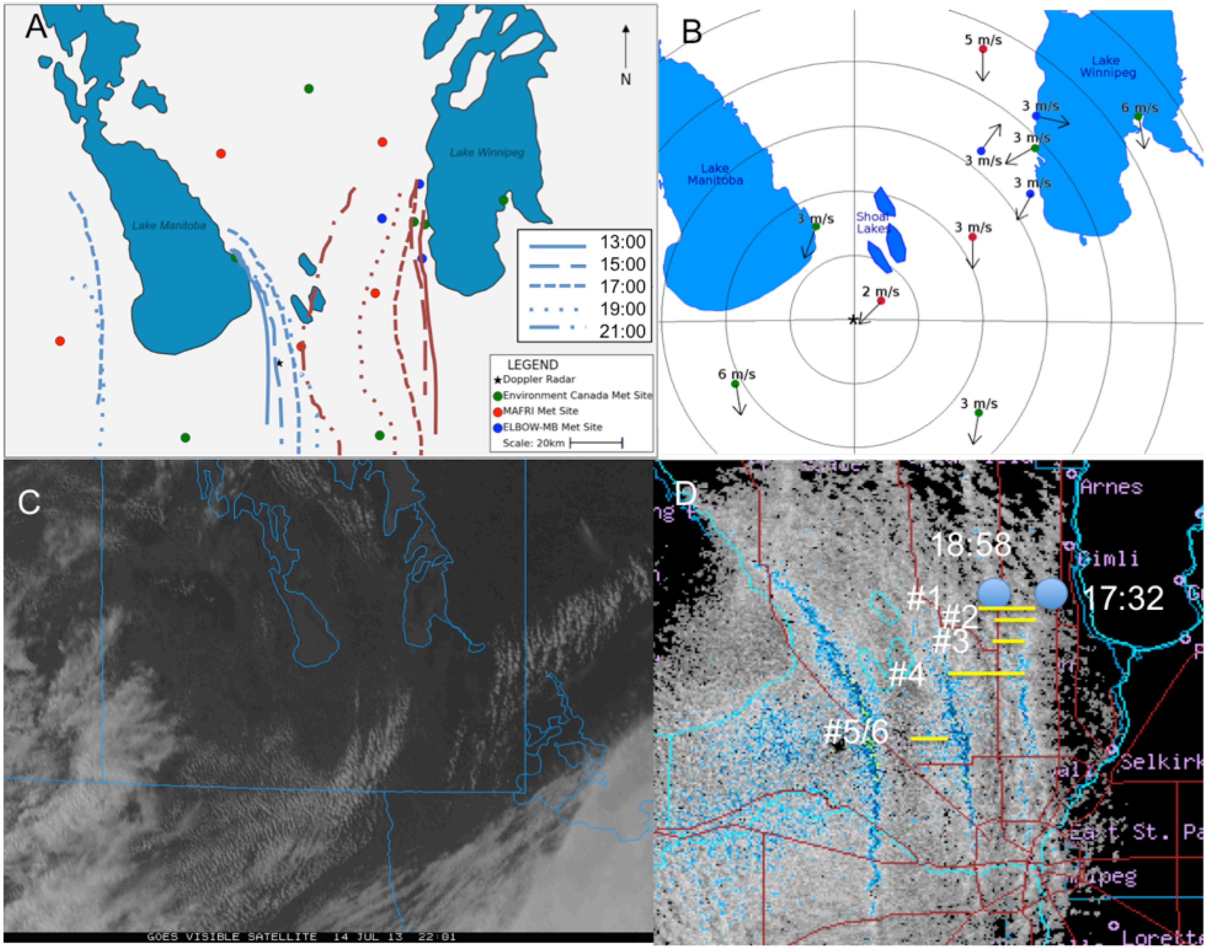

Figure 4.7: Observations for July 14, 2013: A) shows the locations of the LBF every 2 hours for Lake Manitoba (blue) and Lake Winnipeg (red) with times indicated (LT), B) surface wind observations for 12:00 LT, C) visible satellite image for 17:00 LT, and D) Doppler radar image at 17:00 LT showing the sounding launch locations (blue dots), and AMMOS transects (yellow lines).

Visible satellite imagery showed patchy cumulus fields developing through the early afternoon in response to daytime heating (Figure 4.7c), but cumulus development was absent over the lakes as a result of a lack of convection in the marine environment. Lines of enhanced cumulus development were noted in the afternoon at the leading edge of the lake-modified air mass suggesting a LBF was present. Fine line returns were first noted on radar (Figure 4.7d) at 11:00 am LT, and persisted until 9:40pm LT, and were collocated with the enhanced cumulus development noted on visible satellite imagery (Figure 4.7c). The LBF penetrated 110 km from the western shore of Lake Winnipeg, moving as far west as the Shoal Lakes. Note that by 18:30 LT, the Lake Winnipeg LBF had penetrated as far west as the Shoal Lakes LBF, and by 20:30 LT had penetrated as far west as the Lake Manitoba LBF. The Lake Winnipeg LBF overtook both the Shoal Lakes and Lake Manitoba LBF's.

4.3.2.1 Rawinsonde

Two sondes were launched into the lake-modified air mass, 17:32 LT from Winnipeg Beach and 18:58 LT 15 km to the west (Figure 4.7d and Figure 4.8). The first profile showed onshore winds (negative U component or east wind) to a depth of 410 m, with a corresponding decrease in temperature to the same depth. Dew point increase was confined to the lowest 100 m. The second profile showed an increased depth of onshore flow to 600 m, with thermodynamic changes occurring to roughly the same depth (within 100 m).

The first sounding recorded slightly stronger off-shore winds (8 m s^{-1} on average) between 1000 and 1500 m compared to the second sounding (6 m s^{-1}). As this sounding was taken directly near the lake-shore, it is possible that this increase in winds is a result of the return flow of the lake-breeze circulation. The second sounding also shows a localized increase in wind speeds at the same height, but not as strong. The wind speed decreases to less than 2 m s^{-1} on both soundings directly above this height as well, further suggesting the presence of a return flow aloft on the soundings.

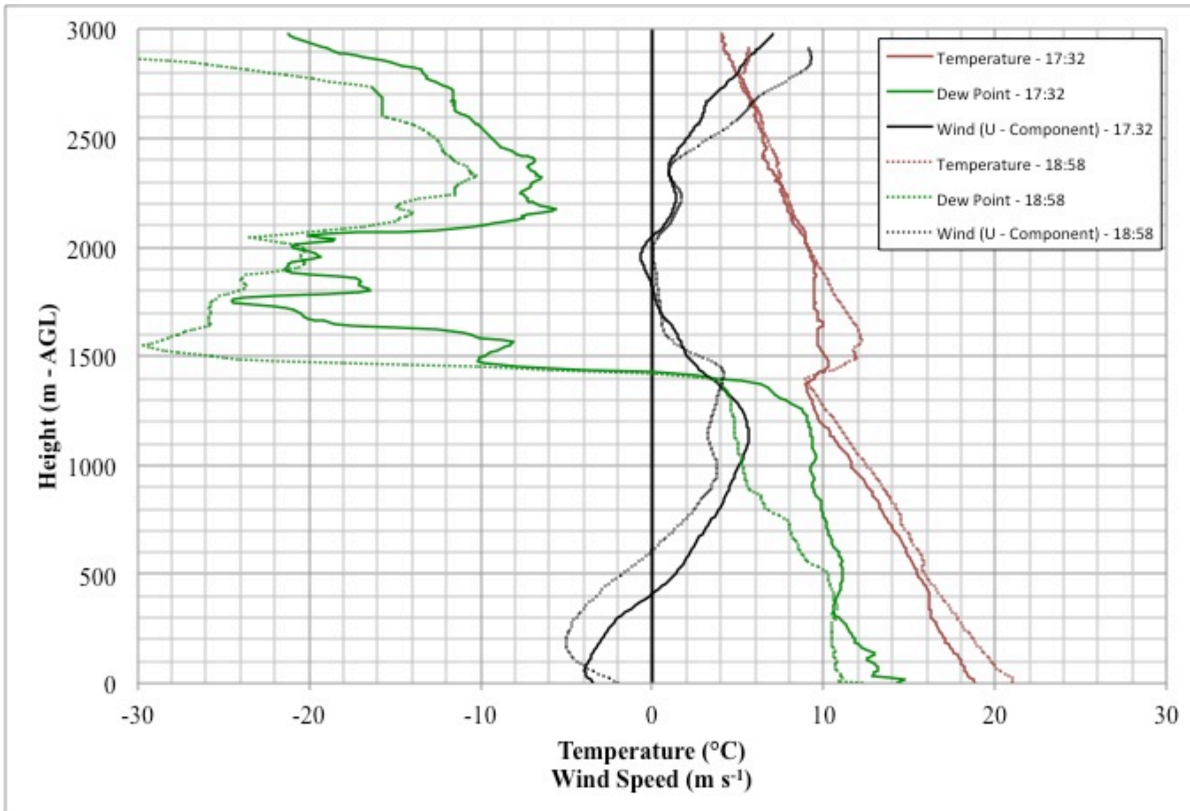

Figure 4.8: Plot of the sounding data for 17:32 and 18:58 LT 14 July. U wind component (E-W wind directions), temperature, and dew point plotted. A negative U value corresponds to an east wind, which is an onshore flow.

4.3.2.2 AMMOS

There were four transects using the AMMOS across the Lake Winnipeg LBF selected to represent this case. Three additional transects were taken before and after a collision of the Shoal Lake LBF and Lake Winnipeg LBF. After the collision, only the Lake Winnipeg LBF was visible on radar, with the timing and location corresponding to when the collision was noted in the AMMOS. Table 4.2 provides a list of transects of the LBF. The average LBF width over the first four transects was 350 m. The differences between the air masses were similar to the first case, with a temperature difference of 0.6 °C, a dew point difference of 2.3 °C, and a 0.8 m s^{-1} wind speed difference. As the LBF was calculated to be 300 m narrower than the first case, this lead to a much sharper thermodynamic gradient at the LBF (-1.8 °C km^{-1} temperature gradient and 7.1 °C km^{-1} dew point gradient).

Table 4.2: AMMOS LBF transects completed on July 14, 2015. Final three transects were taken directly before and after a collision between the Lake Winnipeg LBF and the Shoal Lakes LBF. Gradients are calculated as the land to marine transition. Note that no gradients were calculated for the 19:00-19:10 transect as the AMMOS was stationary and no width was caculated.

Time Start (LT)	Time Finish (LT)	Direction Travelled	Width of LBF (m)	Temperature Gradient (°C km^{-1})	DP Gradient (°C km^{-1})	Wind Speed Gradient (m s^{-1} km^{-1})	Temperature Difference (°C)	Dew Point Difference (°C)	Wind Speed Difference (m s^{-1})
15:44	15:56	E	250	-2.0	7.8	1.3	-0.5	2.0	0.3
15:59	16:10	W	350	-1.6	6.1	2.3	-0.6	2.1	0.8
16:42	16:50	E	350	-1.0	6.9	1.6	-0.3	2.3	0.6
17:06	17:26	W	400	-1.9	7.5	3.1	-0.7	2.9	1.2
Mean			**350**	**-1.8**	**7.1**	**2.2**	**-0.6**	**2.3**	**0.8**
19:00	19:10						-0.7	3.2	0.3
19:12	19:22	W	600	0.0	0.0	0.0	0.1	0.6	1.2
19:24	19:30	E	200	0.0	0.1	0.01	0.2	0.1	1.4

The final three transects shown in Table 4.2 are unique in that they were completed just before and just after the Lake Winnipeg LBF and Shoal Lakes LBF interacted between 19:00 and 19:30 LT (Figure 4.9). Pre-collision measurements were taken while leaving the AMMOS stationary, and letting the LBF pass over the vehicle (19:08 LT, outlined in red on Figure 4.9). No width measurement is provided for this transect as it is not possible to calculate the width without knowing the speed of the LBF when the AMMOS is stationary. Between 19:10 and 19:20 LT, Doppler radar showed that the Lake Winnipeg LBF collided with the Shoal Lakes LBF, and a transect was taken westward to measure the difference between air masses post LBF collision (outlined in green in Figure 4.9), in this case the Lake Winnipeg air mass and the Shoal Lakes air mass. Operators of the AMMOS noted at 19:30 LT that the cumulus clouds along the LBF were more vertically developed after the collision took place. The final transect was taken eastward back across the remnant front, into the lake air mass associated with Lake Winnipeg.

After the collision occurred, the width of the LBF was slightly wider than earlier in the day, at 600 m, and there was almost no change in moisture or temperature across the LBF as both air masses sampled were modified by lake-breeze circulations. The wind speed was the only significant difference, with winds on the Lake Winnipeg side of the LBF being 1.4 m s^{-1} stronger than those on the Shoal Lakes side. Winds also briefly switched to a more north-northwest direction briefly before they switch back to east, as seen in Figure 4.9, as the AMMOS was driven back east across the LBF.

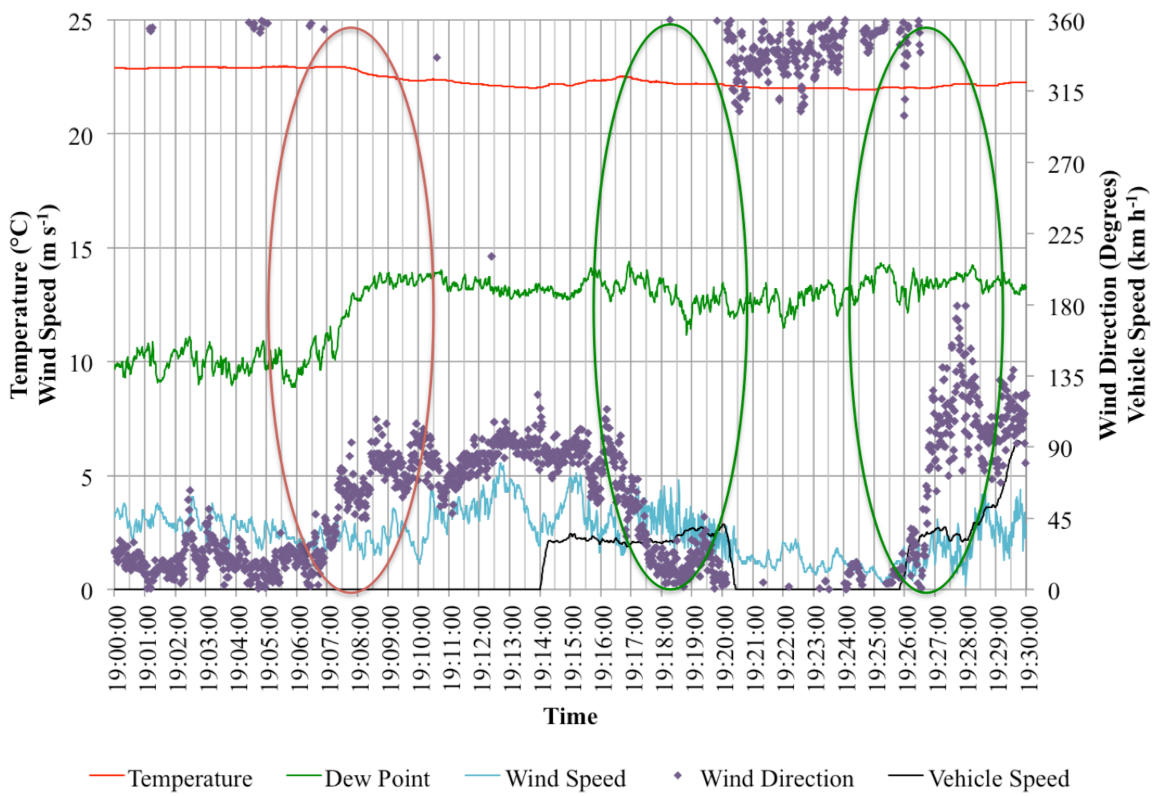

Figure 4.9: AMMOS transect for 19:00-19:30 LT on July 14. Sampling of the LBFs is highlighted with ovals; Lake Winnipeg (red) and Lake Winnipeg-Shoal Lakes LBF collision (green). Observations and units are as indicated in the figure.

4.3.3 July 17, 2013 – Lake Winnipeg

The focus of the IOP data collection on July 17 was on Lake Winnipeg. Figure 4.10a shows the progression of the LBFs from both Lake Winnipeg and Lake Manitoba. Surface winds were light (1-2 m s^{-1} from the west to northwest) in response to a high-pressure center (1024 hPa) over the Manitoba-Saskatchewan border. Figure 4.10b shows surface winds at noon LT, prior to significant lake breeze development. The maximum temperature for the day at Gimli reached 25 °C, while Victoria Beach reached 30 °C. The lake water surface temperature reached 25 °C and air temperature over the lake reached 24 °C. This created a temperature gradient of up to 7 °C around portions of the southern basin to support lake breeze development.

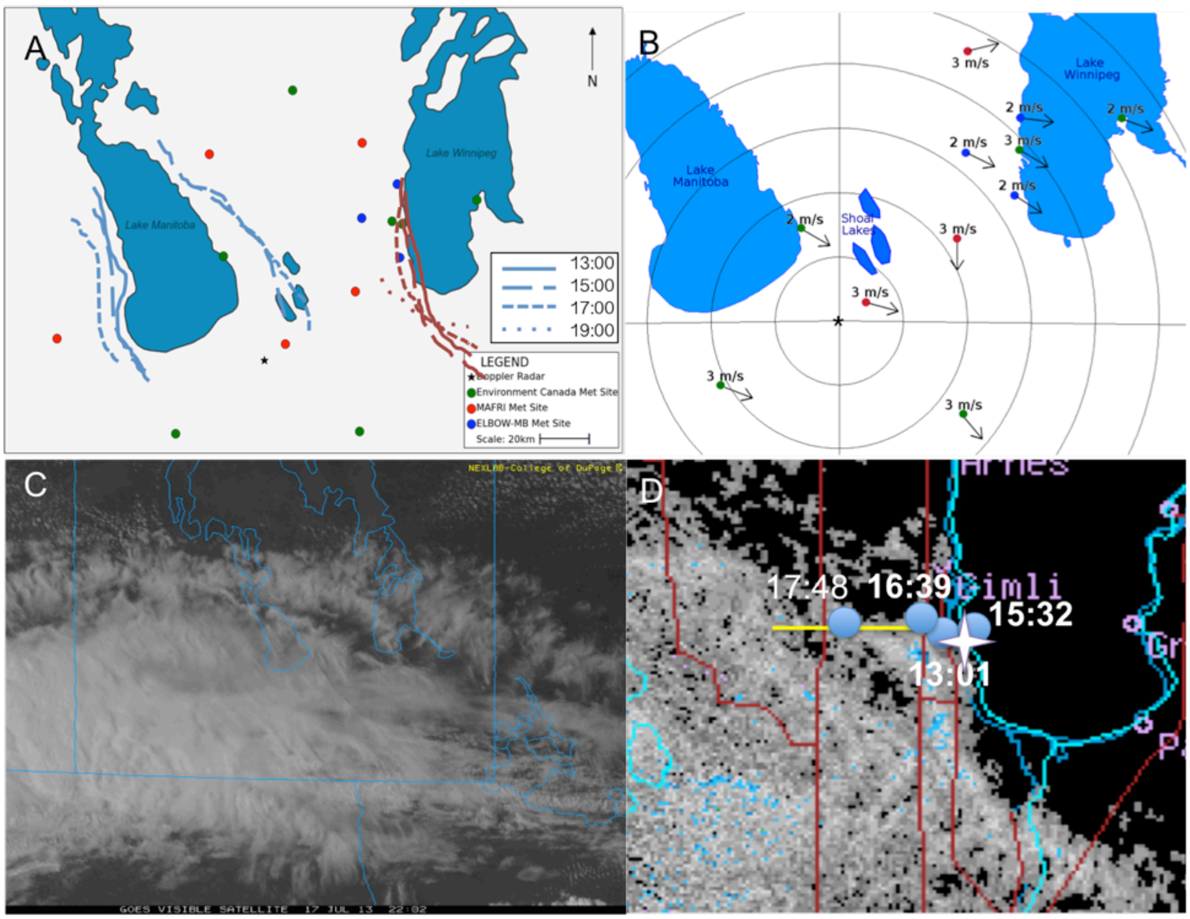

Figure 4.10: Observations for July 17, 2013: A) shows the locations of the LBF every 2 hours for Lake Manitoba (blue) and Lake Winnipeg (red) with times indicated (LT), B) surface wind observations for 12:00 LT, C) visible satellite image for 17:00 LT, and D) Doppler radar image at 17:00 LT showing the sounding launch locations (blue dots), lidar location (white star), and AMMOS transects (along the yellow line).

Visible satellite imagery showed limited development of cumulus clouds over the study area. Patchy areas developed over the extreme eastern and northern portions of the study area (Figure 4.10c). An area of high cirrus cloud started moving into the study area at 14:00 LT, with thicker cirrus moving in after 17:00 LT, which reduced insolation. Figure 4.10d provides an example of the LBF at 17:00 LT on Doppler radar with locations of IOP operations also noted. The first indication of a LBF on radar occurred fairly late (on the 12:50 LT radar scan), and persisted until 6:20 LT at which point the thicker cloud cover moved over the study area and the LBF dissipated. The Lake Winnipeg LBF reached 20 km inland.

4.3.3.1 Rawinsonde Data

Table 4.3 provides the locations (also Figure 4.10d), times, and target air mass of 4 rawinsondes released. The first was released at 13:01 LT, and was taken from UWPG prior to lake breeze initiation (see Figure 4.11). Winds were light (3 m s^{-1}) from the west (positive U component) through the PBL. The profile shows dry adiabatic lapse-rates, indicating the PBL was well-mixed to 1500 m. The second profile was taken at the Winnipeg Beach Marina at 15:32 LT, after the LBF had moved inland (Figure 4.11). Winds below 400 m shifted from light offshore (westerly, positive U component) to light onshore (easterly, negative U component). The sharpest changes in dew point and temperature occurred within the same depth as the kinematic influence, however, changes are noticeable to 600 m, 150 m higher than the height of the wind shift.

The third rawinsonde, also in the lake-modified air mass approximately 1 km inland at 16:39 LT (Figure 4.12), showed that the surface meteorological variables stayed relatively constant between the second and third profile. However, the depth of the lake breeze increased with onshore flow reaching a depth to 700 m. Similar to the second launch, the thermodynamic influence of the lake air reaches higher than the onshore flow, up to 850 m and we see a similar regime change to the warmer air mass.

Table 4.3: Time, and sample air mass for each of the rawinsondes launched on July 17, 2013. The locations relative to the lake of each sounding are shown in Figure 4.10d.

Sonde Release	Launch Time (LT)	Air Sampled
1	13:01	Land
2	15:32	Lake
3	16:39	Lake
4	17:48	Land

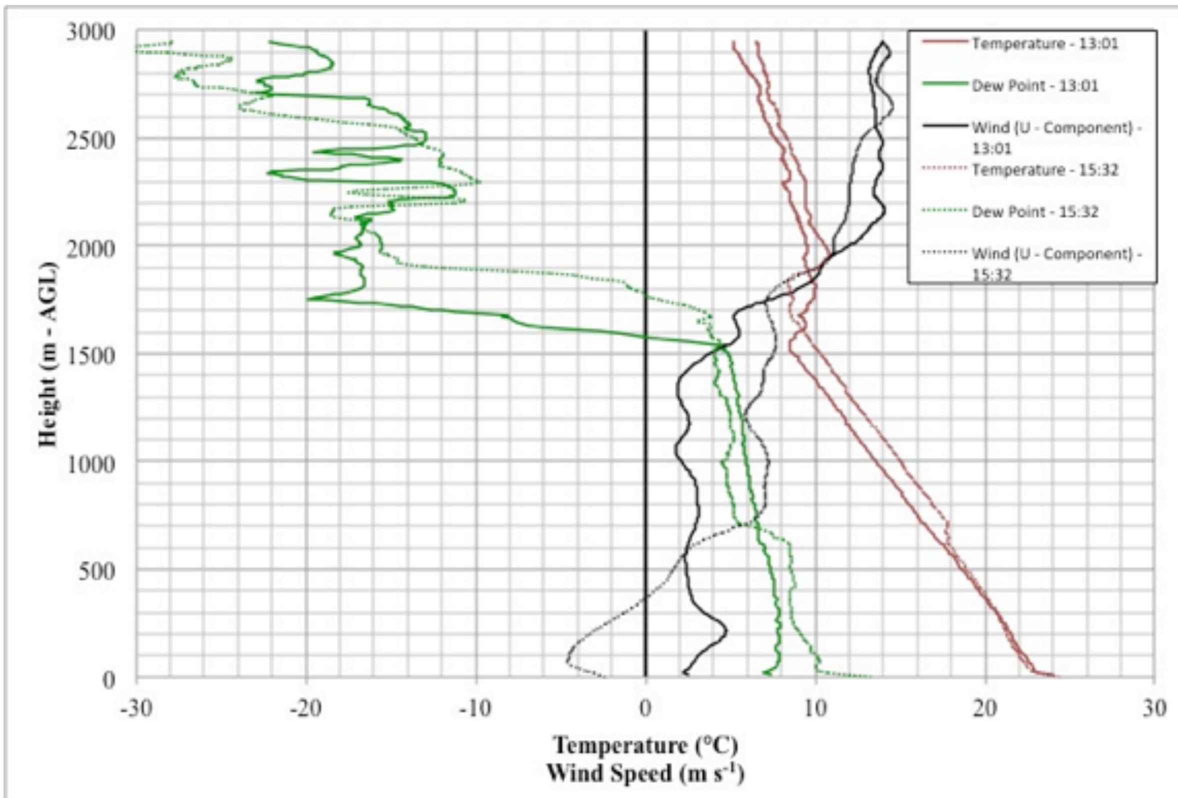

Figure 4.11: Plot of the sounding data for 13:01 and 15:32 LT 17 July. U wind component (E-W wind directions), temperature, and dew point plotted. A negative U value corresponds to an east wind, which is an onshore flow.

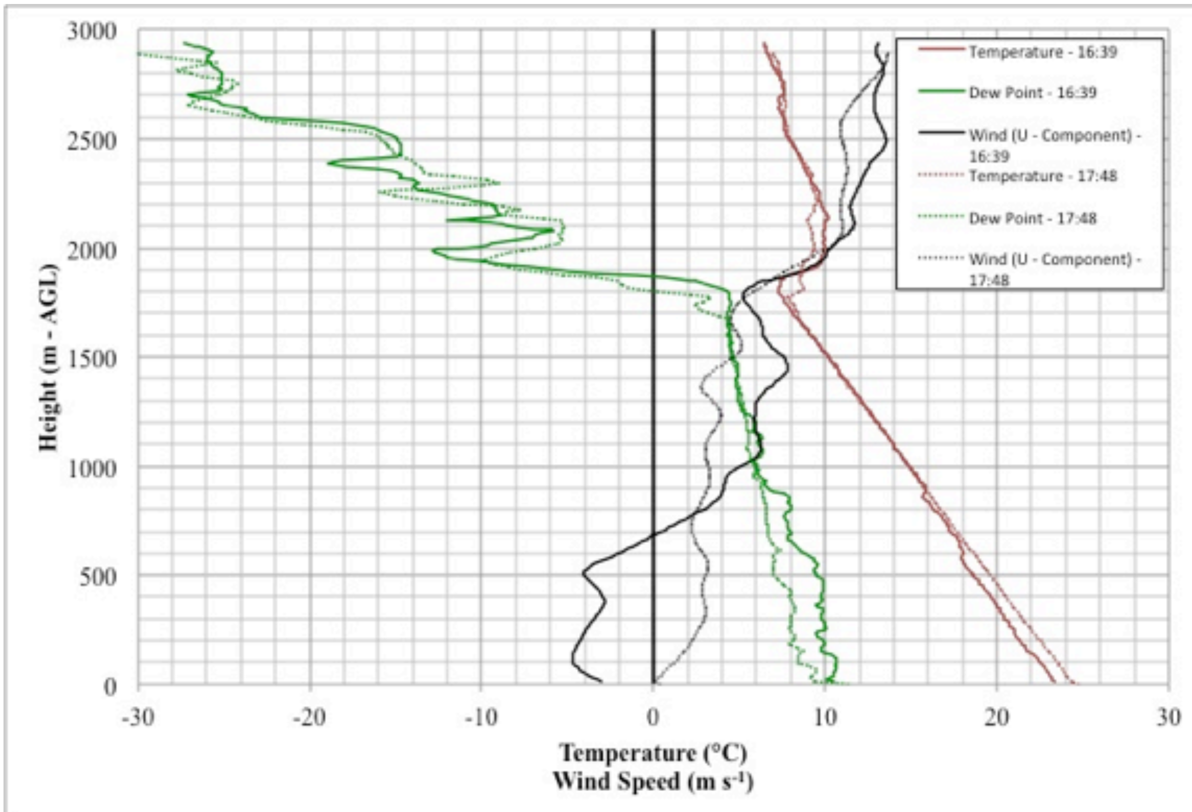

Figure 4.12: Plot of the sounding data for 16:39 and 17:48 LT 17 July. U wind component (E-W wind directions), temperature, and dew point plotted. A negative U value corresponds to an east wind, which is an onshore flow.

In our third sounding (16:39 LT), there was a slight increase in wind speed (from 6 m s^{-1} to 8 m s^{-1}) at 1450 m, with slower wind speeds below and above. There was no localized increase in wind in the first lake-modified sounding. There was however, a reduction in wind speed directly above the onshore flow then a gradual increase in wind speed with height. The final rawinsonde for the day (Figure 4.12) was launched just to the west of the LBF into the land air mass at 17:48 LT. At this point in the afternoon, the PBL remained well mixed extending to 1800 m.

4.3.3.2 Lidar

The lidar was located in Winnipeg Beach, less than 1 km from the lakeshore throughout the day on July 17. Figure 4.13 illustrates the lidar profile taken between 14:20 and 14:50 LT. The LBF passed the lidar at 14:31 LT, with the circulation persisting until about 17:30 LT. Prior to the passage of the LBF, vertical velocity ranged from +0.5 m s^{-1} (upward) to -1.0 m s^{-1} (downward) (not shown). These initial broad areas of positive and negative vertical velocities are attributed to convective PBL mixing. Winds were consistently from the west-northwest at 4.0 m s^{-1}. Just prior to the LBF passing, at 14:20 LT, there was an increase in positive vertical velocity aloft, with speeds reaching 2.0–3.0 m s^{-1} through the depth of the scan. There were also wind gusts up to 10.0 m s^{-1} in the lowest levels of the profile. This was attributed to thermal updrafts within the PBL.

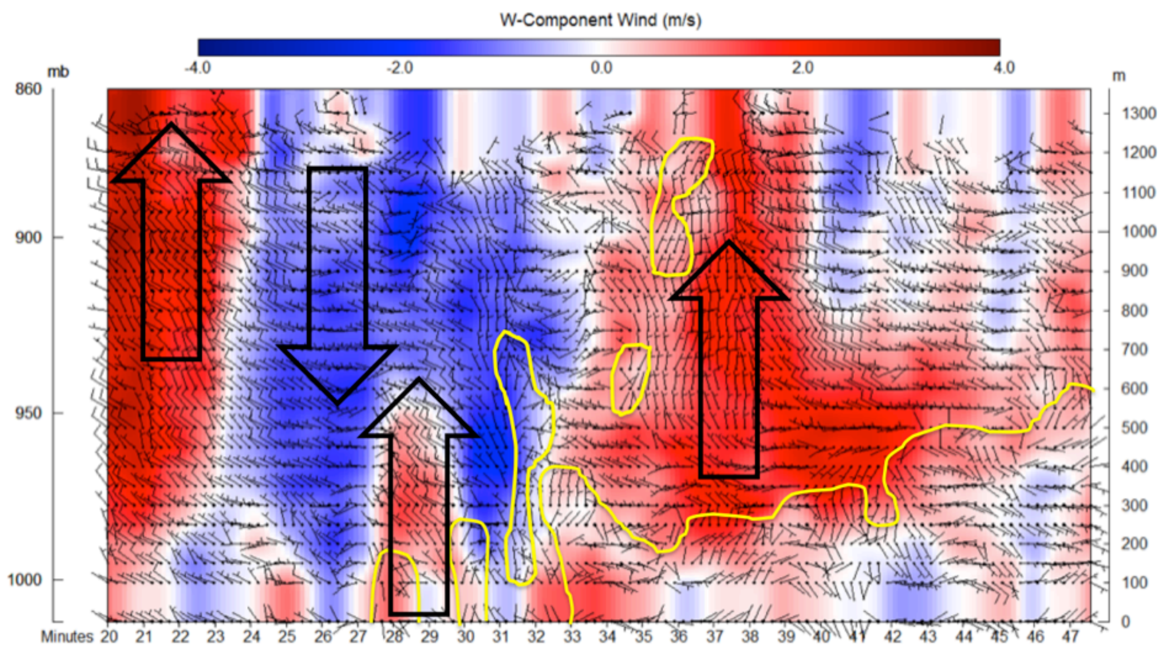

Figure 4.13: Lidar wind observations for 14:20-14:50 LT 17 July. Time is in minutes on the horizontal axis. Wind barbs are horizontal wind speed (half barb = 2.5 m s^{-1}, full barb = 5.0 ms^{-1}). Vertical velocity is shaded with blue (red) indicating descent (ascent), with large areas of ascent and decent marked by arrows. Yellow line delineates separation of onshore and offshore flow (zero value U-Component). Values above 850 mb and below 1000 mb are interpolated.

Easterly flow from the LBF started at 14:27 LT, with a brief increase in vertical velocities, before winds switched back to offshore. This pulsing nature was noted on a number of days during the IOP, with the LBF moving onshore only a few hundred meters before retreating offshore again. This appears to have happened twice before continuous onshore flow began between 14:29 and 14:31 LT. Onshore flow was first noted 150–250 m above the surface, increasing to a depth of 600 m by 14:32 LT. During this time, positive vertical velocity at the surface only extended to 200 m, with winds still from the west through the lowest 200 m. More consistent positive vertical velocities were recorded from 14:31 to 14:34 LT as the LBF passed with values ranging from 1.0-1.5 m s^{-1} and the depth of the ascent increased from 550-1000 m; higher than the depth noted for the onshore flow. The 0 m s^{-1} contour for the U component wind velocities was included on Figure 4.13 to better delineate the onshore flow. While there is an initial lobe of onshore flow, the general shape of the flow is more of a wedge shape, with the depth of the lake-breeze circulation increased with time over the course of the observations. This corresponded to a rather broad area of positive vertical velocities near the front edge of the lake breeze. The most likely cause of this is that the LBF forced a thermal updraft aloft as the front progressed inland.

Similar to the first case, the depth of the onshore flow did not remain consistent over the life of the lake breeze, ranging from 300 to 600 m, in agreement with the values from the rawinsonde profiles. Once the LBF passage occurred, large areas of positive vertical velocity were no longer present (not shown); likely a result of subsidence in the cooler marine air behind the LBF.

4.3.3.3 AMMOS

A number of transects of the LBF were completed, with 5 examples presented here (Table 4.4). The majority of transects were oriented east to west, perpendicular to the lakeshore. The first transect was taken between 14:45 and 14:50 LT, and the final transect was taken just before the LBF dissipated, between 17:22 and 17:30 LT. Doppler radar fine line returns were quite faint on this day (see Figure 4.10d), however the locations where it was possible to discern a faint fine line return corresponded with where LBF locations were noted using AMMOS data. The width of the LBF over this time period ranged from 50 m to 400 m.

Table 4.4: List of AMMOS transects For July 17. Gradients are calculated as the land to marine transition.

Time Start (LT)	Time Finish (LT)	Direction Travelled	Width of LBF (m)	Temperature Gradient (°C km^{-1})	DP Gradient (°C km^{-1})	Wind Speed Gradient (m s^{-1} km^{-1})	Temperature Difference (°C)	Dew Point Difference (°C)	Wind Speed Difference (m s^{-1})
14:45	14:51	W	200	-4.0	21.1	-2.9	-0.9	4.6	-0.6
16:08	16:16	E	50	-15.9	76.0	30.7	-0.8	3.8	1.5
16:17	16:26	W	100	-9.0	28.3	5.5	-0.9	3.0	-0.6
16:44	16:51	W	300	-0.8	3.6	3.4	-0.3	1.1	1.1
18:22	18:30	E	400	0.5	-0.8	-0.3	0.2	0.4	-0.1
Average			**200**	**-5.8**	**25.6**	**7.3**	**-0.5**	**2.4**	**0.5**

The difference in wind between the lake-modified air mass and land air mass was strongest during the second transect when the LBF width was measured at 50 m. Figure 4.14 shows the data from the AMMOS during this cross section, with the LBF transect at 16:14 LT. Between 16:14 and 16:15 LT, winds shift to an onshore flow, with the dew point increasing 4 °C, and temperature decreasing 1 °C. The wind within the land air mass was from the west, at an average speed of 0.8 m s^{-1}. In contrast, in the lake-modified air mass, the wind was from the southeast at 2.4 m s^{-1}, creating an area of convergence, aiding the strong gradient across the front. On average, the temperature was 0.5 °C cooler in the lake-modified air mass, and the dew point was 2.4 °C higher. The average wind speed difference was 0.5 m s^{-1}.

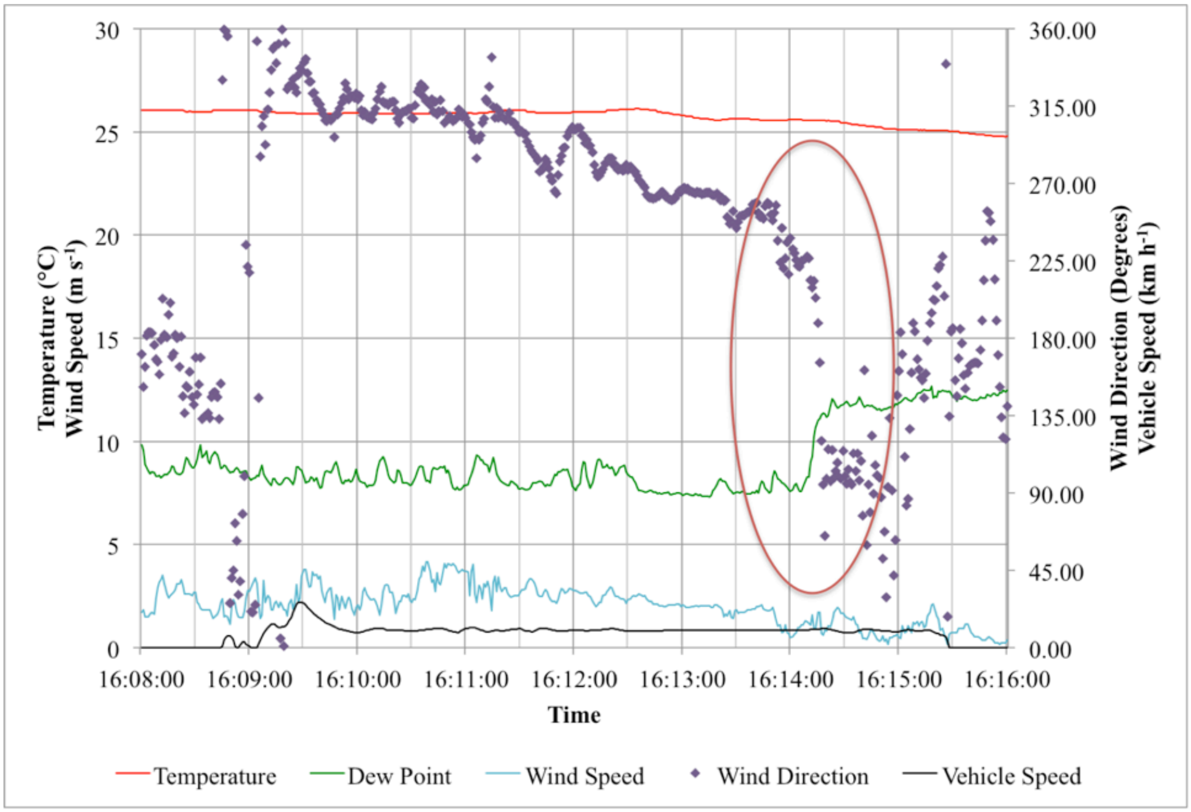

Figure 4.14: AMMOS transect for 16:08-16:16 LT July 17. Sampling of the LBF is highlighted with a red oval. Observations and units are as indicated in the figure.

The LBF was the both the most narrow, and had the strongest gradients of any case (Table 4.4). The absolute changes in temperature, dew point, and wind speed were comparable to the other two cases. The initial transects showed a stronger gradient, with a tighter LBF. As the afternoon progressed and the LBF moved inland, subsequent transects showed a wider LBF, with less noticeable changes in the temperature, moisture, and wind, and generally weaker gradients across the LBF. This follows past studies of LBF (e.g., Lyons, 1972), which showed that the lake air mass becomes modified by the land surface as the LBF moves inland, reducing the difference between the lake and land air masses.

4.4 Discussion

A number of recent studies have incorporated radar measurements and lidar wind measurements of sea and lake breezes to calculate variables such as LBF (or sea-breeze front) depth, circulation depth behind the LBF, vertical velocities at the LBF, and kinematic characteristics within the lake-breeze circulation (e.g., Tsunematsu *et al*. 2009; Asefi-Najafabady *et al*. 2010; Iwai *et al*. 2011; Sills *et al*. 2011). The results presented incorporated data from rawionsondes, Doppler wind lidar, and AMMOS measurements to calculate similar lake-breeze characteristics. A summary of our results in relation to previous studies is provided in Table 4.5.

Table 4.5: Summary of the results from this study (Curry et al.) to other studies. Note that lake breeze depths are provided for both the circulation depth and the LBF depth. *The results of Crosman and Horel (2012) represent a modeling study.

Study Author	Wind Speed Change (m s^{-1})	Lake Breeze Depth (m)	Vertical Velocity (m s^{-1})	LBF width (m)
Curry *et al*.	1.0	100-600	2-3	350-650
Asefi-Najafabady *et al*. (2010)	2-3	1500	1.5	
Iwai *et al*. (2011)	1.5	2000 (LBF) 500	5	500
Lyons (1972)		100-1000	1	1000-2000
Stull (1988)		2x circulation depth at LBF 100-500	0.5-2.5	1000-2000
Tsunematsu *et al*. (2009)		100-1000		
*Crosman and Horel (2012)		900 (LBF) 600		

A key component of this study was to examine the thermodynamic characteristics of the lake breezes in southern Manitoba. Using AMMOS measurements, all three cases showed a reduction in temperature after LBF passage of 0.5 °C on average, and a corresponding increase in dew point of 2.5 °C. Successive transects of the LBF indicate differences can vary significantly spatially, as well as temporally over the life of the lake-breeze circulation, with dew point differences ranging from 0.5 °C to 4.6 °C between successive transects, for example.

Rawinsonde data indicated that the depth of these thermodynamic changes can reach vertically higher than the depth of the onshore flow, by up to 100 m or more, though the strongest thermodynamic differences occur in the same depth as the onshore flow.

Kinematic characteristics within the lake-breeze circulation were examined for each case. Using AMMOS measurements across the LBF in each case, wind speeds were found to be 1.0 m s^{-1} faster on average within the lake breeze. Asefi-Najafabady *et al.* (2010) found mean wind speed perturbations within the lake-breeze circulation of 2 to 3 m s^{-1} in their study, and Iwai *et al.* (2011) reported a wind speed increase of 1.5 m s^{-1} in their sea breeze study. In contrast, the highest noted in our observations was 1.4 m s^{-1}.

Tsunematsu *et al.* (2009) studied the mean wind speed within the Tokyo sea-breeze circulation vertically, and found that wind speeds were enhanced within both the onshore flow and within the return flow aloft, but noted an area of slower winds between the two layers. This was consistent with observations in both lidar measurements and rawinsonde profiles for this study, but not in all of our cases.

Lake-breeze depth varied considerably between cases with measurements ranging from 100 m to 600 m. In both cases it was noted in the lidar data that the depth of the onshore flow behind the LBF varied by hundreds of meters, not remaining consistent for any significant length of time. This was mirrored in our rawinsonde observations, which showed variation in depth only an hour or two apart. Stull (1988) observed that the leading edge of a sea-breeze circulation at the front can be up to twice the height of the inflow layer behind, with average onshore flow depths of 100 to 500 m. Tsunematsu *et al*. (2009) observed a sea breeze depth varying from 100 to 1000 m in their study, with a return flow aloft reaching above 1000 m, and Iwai *et al* (2011) identified a depth of 2000 m at the sea-breeze front in their study, with an onshore flow behind the front of only 500 m. Crosman and Horel (2012) conducted a modeling study of lake-breeze circulations and found similar findings in their model, with onshore flow reaching a depth of 900 m at the LBF, and 600 m behind the front. Lidar measurements for the July 17 case show a similar finding, with a greater depth at the LBF, and lower depths behind in the onshore flow. Our findings fall within the lower end of other studies but are comparable to past findings.

Lidar observations of the passage of a LBF showed positive vertical velocities as high 3.0 m s^{-1} ahead of the LBF in thermal updrafts, and up to 2.0 m s^{-1} in the updrafts associated with the LBF passage. A number of studies have sought to quantify vertical velocities at the LBF (or sea breeze front). Lyons (1972) noted upward vertical velocities of 1 m s^{-1} in their study, while Stull (1988) provided a range of 0.5 to 2.5 m s^{-1} for vertical velocities ahead of the LBF. Asefi-najafabady *et al*. (2010) noted upward vertical velocities of 1.5 m s^{-1} at the LBF in their study. Iwai *et al.* (2011) reported vertical velocities of up to 5 m s^{-1}, however, they speculate that thermal updrafts ahead of the sea breeze front contributed to the high velocities, which may have also happened in our case as well. While the measurements in our study are consistent with past results, further measurements using lidar would be beneficial to better generalize vertical motions and understand the mesoscale impact of lake-breeze circulations on local winds.

Fewer studies have noted measurements of the width of the LBF. The AMMOS measurements showed a narrow LBF, with the average width for each case ranging from 350 m to 650 m, and as narrow as 50 m, resulting in significant changes in temperature, moisture, and wind speed and direction over short distances. This information is particularly important for forecasting and modeling studies. Stull (1988) and Lyons (1972) suggested that the LBF is marked by a narrow convergence zone of 1-2 km, while Simpson (1994) noted the thermodynamic change to occur over 100 m.

4.5 Conclusions

The overall research goal of this paper is to examine the spatial and temporal variability of the thermodynamic and kinematic characteristics of lake-breeze fronts in southern Manitoba. Using a variety of data including surface observation charts, visible satellite images, Doppler radar, and in-situ measurements including rawinsonde, AMMOS, and lidar wind profiles for three cases, information on the fine-scale structure of lake breezes in this region has been provided. Some of the key findings of this research include:

- Thermodynamic changes were strong across the LBF, with dew points increasing by 2.5 °C and temperatures falling by 0.5 °C over distances ranging from 50 m to 700 m. This creates a sharp thermodynamic gradient in the vicinity of the LBF.
- Each LBF was marked by a narrow area of convergence, with winds generally 1.0 m s^{-1} faster within the lake-breeze onshore flow.
- Lake-breeze circulations vary in depth both spatially and temporally. Lake-breeze depths were noted to range from 100 m to 650 m on both lidar and rawinsonde measurements, with significant variability between cases and over the life-cycle of the lake breeze.
- Thermodynamic changes in some cases extended higher vertically than the depth of the onshore flow by 100 m.
- Localized increases in wind speed above the onshore flow, which may indicate the presence of the return flow aloft, were noted on some soundings, but not all. However, a weakening of the winds above the onshore flow was noted for all cases.
- Vertical velocities within the nose of the LBF ranged between 1.0 - 2.0 m s^{-1} based on lidar measurements, velocities in thermal updrafts ahead of the LBF ranged from 2.0 – 3.0 m s^{-1}, and generally downward vertical velocities were recorded behind the LBF.

– Radar fine lines were found to correspond with the LBF locations during AMMOS transects.

The results from ELBOW-MB demonstrate that both the thermodynamic and kinematic properties of the LBF and lake-breeze circulation can vary considerably both spatially and temporally as the lake breeze develops and continues to move onshore. While only three cases are represented here, the results further reinforce that lake breezes are a complex and dynamic mesoscale phenomena. Our results fall within the spectrum of previous studies, however, our findings indicate a much narrower zone of convergence, and also a more shallow lake-breeze circulation. Measurements of the lake breeze depth and LBF width, and of both vertical and horizontal velocities, showed large variability within our study and in previous studies. These differences may have resulted from the high-resolution data that was used for this study compared to past studies, and also differences in the size of the lake in question. As well, the measurements only represent lake breezes in July 2013; the same measurements taken in other months or years may show even more variability. Further investigations into the temporal and spatial evolution of the thermodynamic and kinematic characteristics of the LBF and lake-breeze circulations with high-resolution measurements from ground-based remote sensors (e.g., radiometers and lidars) will aid in furthering our understanding of the behavior of lake breezes and better understanding the variability.

The results presented here suggest model resolutions of potentially less than 1 km may be needed to properly resolve the detail of lake-breeze circulations in regions with shallow, warmer lakes, such as Manitoba. Kehler *et al*. (2015) found that a high-resolution deterministic model with a grid spacing of 2.5 km was able to simulate many of the key features of Manitoba lake breezes, however, some aspects (e.g. timing, depth, inland penetration) would potentially benefit from higher resolutions. High-resolution observational studies can then be used in conjunction with high-resolution models to better understand the development and behavior of lake breezes in southern Manitoba.

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Chapter 5 - Conclusions and Recommendations

5.1 Summary

The overall objective of this research was to fill some of the knowledge gaps in our understanding of lake breezes associated with more shallow and warmer lakes, such as those in southern Manitoba. Lakes represent a major topographic feature in southern Manitoba, having a direct meteorological influence on a number of communities, including Winnipeg, Manitoba's largest population center. Therefore, it is crucial that we have a better understanding of the characteristics of the lake breezes in the region and the influence that they can have on local weather. To that end, the specific objectives of this thesis as outlined in Chapter 1 were two fold:

1) Provide a radar-based analysis of lake breeze frequency and characteristics,
2) Characterize the thermodynamic and kinematic properties of lake breezes and lake-breeze fronts.

These objectives contribute to the overarching research objectives of the ELBOW-MB (Effects of Lake Breezes On Weather in Manitoba) project. Chapter 3 addresses the first objective of this thesis in the form of a paper published in the journal *Atmosphere-Ocean*. There were 4 research objectives addressed within this paper, contributing to the first thesis objective:

1) Provide a radar-based analysis of lake breeze frequency and characteristics in southern Manitoba,
2) Determine the performance or detectability of the radar analysis using data collected in 2013 relative to other datasets for lake-breeze front (LBF) detection,
3) Asses the types of lake-breeze circulations that occur (e.g. Sills *et al*., 2011), and

4) Examine the meteorological conditions in which lake breezes occurred.

The results of Chapter 3 focus on a summer (JJA) six-year radar climatology (2008-2013) for the region as well as using standard surface meteorological data. We found that lake breezes occur with an average yearly frequency of 37% for the warm season months (JJA), with 11-12 days having a lake breeze present somewhere in the region each month. Our results are consistent with older findings of lake breeze frequency by Lyons (1972) and Laird *et al*. (2001), however, are lower than the most recent frequencies reported by Sills *et al*. (2011) in southern Ontario. The penetration distance of the LBFs from each lake (Lake Winnipeg, Lake Manitoba, and Shoal Lakes) ranged from 8 to 35 km, with a maximum penetration distance recorded of 112 km (Lake Manitoba). The penetration speed of the LBFs ranged from 0 to 2 m s^{-1}, agreeing with previous findings reviewed in Chapter 2. The maximum reflectivity values ranged from 15-17.5 dBZ on average. A correlation analysis was completed to compare the reflectivity values for each LBF, and the corresponding penetration distance and speed. Both penetration distance and speed had a small, but significant correlation to reflectivity values. Generally, higher reflectivity values corresponded to faster, further penetrating LBFs. However, in some cases, the penetration distance and speed were reduced due to synoptic wind opposing the movement of the LBF, resulting in increased convergence and reflectivity, but lowered penetration speed and distance.

To determine performance or detectability of lake breezes using weather radar, a comparison was done with a more complete analysis using visible satellite and surface observation stations for 2013. This comparison demonstrated that the radar was able to detect LBFs 77% of the time for the south and south-east shores of Lake Manitoba as the radar is located quite close to the southern edge of Lake Manitoba. Significant errors were found for the detection of Lake Winnipeg LBFs however, with the radar analysis yielding only half the lake breezes that a combined analysis using radar, satellite, and surface observations yielded. We concluded this might be a result of the distance that the western shore of Lake Winnipeg is from the radar, with the radar beam being approximately 2 km above the surface.

Further analysis was done to group LBFs occurring from Lake Manitoba and Shoal Lakes to classify them by circulation type as done by Sills *et al*. (2011). As radar range were different for the west, south, and eastern shores of Lake Manitoba, it was not possible to provide a complete analysis. The types were estimated based on available data and provided as an approximate comparison to the results from the Shoal Lakes. The distribution determined for the Shoal Lakes was similar to the distribution of types in southern Ontario reported by Sills *et al*. (2011), with the majority of cases reported as moderate deformation circulations. In contrast, the highest occurring type for Lake Manitoba was the high deformation circulation, which accounted for half of all cases.

Finally, a meteorological analysis was conducted to better understand the conditions in which lake breezes occur. Data were compared from the CYWG surface station and the Lake Winnipeg surface buoy. The results however were inconclusive. There was no consistent and apparent connection between the meteorological variables calculated and the frequency of lake breezes in a given month, or given year. While temperature difference between the lake surface and land surface, and precipitation days per month appeared to be related to the frequency of LBFs, the relationship was not consistent.

Chapter 4 addresses the second research objective of this thesis, to characterize the thermodynamic and kinematic properties of lake breezes in southern Manitoba. This paper has been prepared for submission to the journal *Boundary Layer Meteorology* for publication. The data used within this chapter was obtained during the ELBOW-MB field project in 2013. Three cases with the most data available were selected and presented as case studies, followed by a discussion of the findings. A synoptic summary, as well as evidence of the lake breeze on synoptic scale datasets and radar was provided first, with more detailed analysis of the LBF following.

Data from rawinsonde profiles within and outside of the lake breeze air mass as well as AMMOS measurements were used to assess the thermodynamic properties of LBFs. The results showed that while the temperature gradient between the lake and a land was between 2 and 3 °C, the gradient across the LBF was much smaller, only 0.5 °C on average, and decreased over the life of the lake breeze as the LBF continued to move inland. The dew point temperature gradient across the LBF was 2.5 °C on average, and also decreased over time. These changes occurred over a distance of 50 to 690 m. These results agree with findings from Kehler *et al*. (2015) and predicted differences in a high-resolution deterministic model. The increase in moisture, and reduction in temperature, was evident in sounding comparisons between the land and lake air mass soundings.

The kinematic properties of the lake breeze were examined using data from rawinsonde profiles, AMMOS transects, and lidar wind profile measurements. This provided a quasi three-dimensional analysis of the lake breeze and LBF as measurements were taken in both the horizontal and vertical, over multiple planes of the LBF and over time. The lidar profiles showed that the height of the wind shift to onshore flow varied in height over time. Repeated transects across the LBF in the AMMOS showed a high amount of variability in the wind speeds on either side of the front. The depth of the three lake breeze cases ranged from 100 m to 700 m, with thermodynamic changes extending slightly higher in some cases than the onshore flow. Vertical velocities ahead of the LBF were 2.0 to 3.0 m s^{-1} in thermal updrafts, and 1 to 1.5 m s^{-1} at the

LBF. However, it was noted that in the one case, the vertical motion may have been enhanced by a thermal updraft. It is important to note that the kinematic and thermodynamic properties measured are representative of the conditions in July 2013, and may vary seasonally or annually.

The findings from these two papers provide the first in depth analysis of lake breezes conducted in southern Manitoba. In addition to compiling a dataset of lake-breeze events for the region, we were able to provide a short term assessment of the frequency and variability of lake breeze events. Further, we were able to provide high-resolution measurements of lake breeze cases to help enhance the conceptual model of the structure of the LBFs and lake-breeze circulations. The combination of these data sets is important for forecasters to be able to better adapt their forecasts based on the presence of lake breezes. The results of both papers also helped to reinforce other (limited) high-resolution observational studies presented in recent years (e.g., Tsunematsu *et al*. 2009; Asefi-Najafabady *et al*. 2010; Iwai *et al*. 2011; Sills *et al*. 2011 Additionally, since the Manitoba lakes are considered to be small lakes for their southern basins as they are less than 50 km wide, these results will help to fill a knowledge gap on lake breezes that form from smaller, more shallow and warmer lakes.

5.2 Recommendations for future research

The ELBOW-MB field campaign was successful in helping to fill a large gap in our knowledge of Manitoba lake breezes. Despite this, there are a number of questions that remain unanswered and require further research.

One of the research objectives of ELBOW-MB was to study the effect of the Manitoba lake breeze on convection. Unfortunately, the weather pattern over the course of the project was not conducive to moist deep convection and we were unable to address this research question. A second ELBOW-MB field campaign with a primary focus on convection is still needed to better understand the role that the LBF has in convective initiation in Manitoba. Based on the challenges faced during ELBOW-MB in 2013, an ideal plan for a follow up campaign would allow the IOP dates to be more flexible and allow for an “on-call” style field campaign. This could reduce costs significantly as the research base could remain in Winnipeg, and the focus can be on days with a high likelihood of lake-breeze initiated convection.

Further research is also necessary to better understand the forcing and limiting factors for lake breeze development around the Manitoba Lakes. Studies such as those by Crosman and Horel (2012) that use a high-resolution model to simulate the lake breeze under a variety of conditions would help forecasters and researchers alike to better predict days where lake breeze development is more likely to occur. Results could then be compared to a climatology similar to that presented in Chapter 3, allowing us to improve the predictability of the lake breeze.

These recommendations, if successful, would provide a much stronger basis of information for meteorologists to incorporate the influence of the lake breeze when making forecast decisions. In particular, having a better understanding of when lake breeze development is expected can help forecasters to better identify the most likely area of moist deep convection during the summer months.

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Appendix A – Contributions of Other Authors to Thesis

Radar data used in Chapter 3 was collected with the assistance of personnel at Environment Canada including Dave Patrick and Jason Knight. Field data used in Chapter 3 and 4 was collected as part of the ELBOW-MB Field project with participation from students, principal investigators, and personnel from Environment Canada. I was involved in the collection of the majority of the data, in particular the AMMOS data collection that was used as part of this thesis. Each chapter was conceived, analyzed, and reported by me as the primary author. Specific contributions of coauthors are listed below.

Chapter 3

Dr. John Hanesiak and Dr. David Sills provided expertise and discussion with regards to the best way to present the data, and commentary if any additional analysis or description was needed. They also provided comments and assistance with revisions on manuscript drafts.

Chapter 4

Dr. John Hanesiak provided expertise and direction on the most effective way to present the case studies, as well as helpful advice and correction to the manuscript draft. Dr. Hanesiak also provided financial support of the field project, and assistance in collection of the data. Scott Kehler provided assistance for data collection during ELBOW-MB as well as helpful revisions on the manuscript draft. Kehler further provided helpful insight during the initial planning phases for this chapter as well as co-producing some graphics. Dr. David Sills and Neil Taylor assisted in data collection during ELBOW-MB, as well as help with revisions on the manuscript draft. They also provided useful advice and discussion for data interpretation and processing, including providing programs to assist in quality control processing of the data sets.