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A Climatology of Lake-Effect Snowfall and Evaluation of the Cobb Method for the Great Lakes Region

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A CLIMATOLOGY OF LAKE-EFFECT SNOWFALL AND EVALUATION OF THE COBB METHOD FOR THE GREAT LAKES REGION

by

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Accuracy in snowfall prediction has lagged behind other short-term weather forecasting areas. Errors in quantitative precipitation forecasts ensure that any snow ratio applied to snow may result in inaccurate snowfall amounts, and snowfall observations are not consistent or fully reliable. In this study, the Cobb Method is tested on lake-effect snowfalls to determine if the top-down ice crystal growth modeled in the algorithm can be applied to convective snowfalls. To establish the spatiotemporal and physical characteristics of lake-effect snowfalls at selected study locations near the Great Lakes, snowfall and snow ratio climatologies are produced that separate events by lake-effect and non-lake-effect snowfall type. Lake-effect snowfalls occur most frequently at all locations in December and January, and progressing from November to March there is a decreasing proportion of lake-effect to all snowfalls from around 0.6 to near 0.1. With respect to non-lake-effect snowfalls, snow ratios of lake-effect snowfalls are higher and more variable. For snowfalls calculated by the Cobb Method, lake-effect and non-lake-effect snowfalls are 60.6% and 63.7% accurate compared to observations, respectively. Adding an empirical compaction factor improves the non-lake-effect events by 4.0% and worsens lake-effect snowfalls by 8.4%, which reflects a bias towards underforecasted snowfalls for lake-effect snow of all snow amounts. Snow ratios of lake-effect snowfalls also have higher mean and variance than non-lake-effect snowfalls; however, snow ratios

are lower in magnitude than for observations. The results of this study show that the Cobb Method may be applied to lake-effect snow forecasting with the knowledge that the snow ratios produced on average will be lower than what is observed, therefore snowfalls will be greater. Events that are depicted well by a numerical prediction model with the knowledge that snow ratios are too low and used by the forecaster will be associated with more accurate snowfalls. Use of a high-resolution model that resolves mesoscale processes is also an important consideration, since lake-effect snowfall is a mesoscale process.

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CHAPTER 1: Introduction

Snowfall forecasting is challenging, especially due to the cumulative error associated with three variables: snow duration, precipitation amounts, and snow density. Small changes in any of these three variables can drastically change the societal impacts, such as the effects of snow cover on agriculture or transportation. While the forecasted amount of precipitation and density of snow are critical for interests in water resources and avalanches, respectively, the primary concern for the general public is snowfall. Since snow removal practices are reliant on accurate snowfall amounts, improved short-term forecasts of snowfall could greatly improve road transportation during an event. The end result could be a reduction in traffic incidents and economic losses from missed work, especially for events that are not as severe as forecast. After a snowfall event, taking a measurement of the fresh snowfall is fraught with difficulty, and the subjectivity associated with these observations could cause observed snowfall and its characteristics to be misinterpreted. Areas that receive snowfall from locally enhanced synoptic weather systems, such as in mountainous terrain and near large lakes, have an increased level of challenge. In this paper, we will focus on snowfalls occurring in the Great Lakes region of the United States, with particular interest in lake-effect snow, defined as snow being generated purely by the thermodynamic mechanism of having cold dry air flow across a warm lake.

The Cobb Method snowfall forecasting algorithm, discussed in detail in Cobb and Waldstreicher (2005), has not been well tested in cases of lake-effect snowfalls. Knowing the mean and variability of snow density or snow ratio (the inverse of snow density) will

aid in snow forecasting and can be applied to the Cobb Method to improve the algorithm. Literature regarding the climatological snow density of lake-effect snowfalls, independent of non-lake-effect, in the Great Lakes is limited. A recent study by Dutter (2012) classified snowfalls in Marquette, MI and found very high snow ratios during lake-effect snowfalls (with a mean of at 30:1) compared to non-lake-effect snowfalls (mean of 12:1). The work presented here aims to produce snowfall and snow ratio climatologies for six selected stations in typical lake-effect locations and compare the results with Dutter (2012). Another important goal is to find how much pure lake-effect snowfall is received each year for areas downwind of the Great Lakes. This study will therefore provide a baseline value to how much added snowfall the lakes provide.

Lake-effect snow circulations have a horizontal scale from around 2 km to 20 km, suggesting high-resolution 4 km or smaller grid size computer models are needed to fully depict lake-effect snow. However, coarser models do produce reasonable snow bands (Ballentine et al. 1998). Since lake-effect convection is only up to about 2 km deep, the aspect ratio ranges from 5 to 20 (Sousounis 2001). This ratio falls near the edge of where the hydrostatic assumption breaks down in a weather model. Given the available numerical weather prediction (NWP) models used operationally by the National Weather Service (NWS), the Rapid Update Cycle 13 km model (RUC13) was used for this study to hindcast snowfalls. Since the RUC13 is a hydrostatic model, it can only infer weather phenomena resulting from vertical motion. In using the Cobb Method (Cobb and Waldstreicher 2005), it is assumed that the upper air data from the NWP is accurate, so it is important to establish if the convective parameterization of the RUC13 generates

accurate quantitative precipitation forecasts (QPF) associated with lake-effect events. Our goal is to determine how closely Cobb Method-derived lake-effect snowfalls match observations and the snowfall results from our climatology study. In addition, we want to assess if the Cobb Method produces reasonable lake-effect snow ratios based on the Baxter et al. (2005) snow-to-liquid ratio climatology, which suggests that snow ratios for all snow types (lake and non lake-effect) should be in the average range of 14: 1 to 16:1 for most snow belts associated with lake-effect snow regimes.

CHAPTER 2: BACKGROUND

2.1. Lake-effect Snowfall

Snowfalls in the lee of the Great Lakes are anomalously heavy and frequent compared to snowfalls upwind of the lakes. Chagnon (2006) found that the frequency of heavy [greater than or equal to 15.24 cm (6 in)] snowfalls is enhanced around the Great Lakes. Braham and Dungey (1984) analyzed snowfall data on decade-long timescales downwind of Lake Superior and Lake Michigan and found that lake-effect snows cause up to 50% of seasonal snowfall. Norton and Bolsega (1993) show a sharp gradient from under 100 cm to over 300 cm in the downwind area near the lakes, depicting the lake-effect snow belts from measurements at climatological stations during 1951-1980. The highest totals are associated with steeper terrain that causes enhanced lift and more intense snowfalls on the leeward side of the lakes. For instance, the highest annual snowfall in the state of New York between 1961 and 1990 was near Boonville, situated in the Tug Hill region just west of the Adirondack Mountains and due east of Lake Ontario (Doesken and Judson 1997). At this location, the 30-year average snowfall was 577 cm (Doesken and Judson 1997). Due to the elevation dependence of lake-effect snowfall, average amounts are much lower immediately inland, where elevation is low. Fetch, the distance over which the wind traverses a lake, and elevation are the primary determinants of the mean seasonal distribution of snowfall around the Great Lakes.

The formation of lake-effect precipitation is well-understood (Niziol et al. 1995). Cold air flows over a large unfrozen lake, a surface that is moist and warm. The cold air

gains instability and moisture, and vertical motion of the air increases. Lapse rates steepen and convective clouds develop. These clouds build until reaching an inversion, typically near the 850 hPa level. Instability increases as cold, dry air aloft mixes with relatively warm, moist air near the air-lake interface. The combination of lift and moisture generates high snow efficiencies downwind of the lake. Since Arctic air outbreaks often trigger lake-effect precipitation, the evaporative cooling is sufficient to rapidly change any rain to snow despite above freezing surface temperatures (Lackmann 2001). Variables most critical for lake-effect snow are strong thermal instability and low-level wind direction and shear (Tardy 2000; Liu and Moore 2004; Theeuwes et al. 2010). For intense lake-effect snowfalls, minimal low-level shear and mean boundary layer wind parallel to the major axis of the lake is necessary (Tardy 2000; Theeuwes et al. 2010). Theeuwes et al. (2010) found that snowfall increases exponentially with an increase in lake temperature, because a capping inversion was broken allowing for additional moisture transport. Synoptically, a low pressure area that moves northeastwardly rather than eastward is a precursor of lake-effect in the Great Lakes region (Liu and Moore 2004).

Software created by the Buffalo NWS office to forecast lake-effect snow is BUFKIT (BUFfalo's forecasting toolKIT). The BUFKIT program can display mesoscale model data and allows the user to choose a value for lake surface temperature. In its configuration file, the user can adjust many other parameters. One example is the height of the lake-effect steering winds to calculate shear; for an intense lake-effect storm at low elevation sites, one might chose 700 hPa as the top and 850 hPa as the midpoint. Use of

0 to 4 km shear allows the user to diagnose modes of convection, as lake-effect snowfall will tend to be single banded with low shear, and multiply banded with higher directional shear.

The lake index is an indication of the absolute stability of the lower atmosphere (Mahoney et al. 1997). Similar to the lifted index, the lake index is computed by using the lake temperature as the beginning of a parcel's ascent dry or moist adiabatically and comparing the 850 hPa temperature to that of the environment. Increasing the lake temperature linearly increases the instability when convection is taking place in a lake-effect snow event, since the capping inversion tends to be near or just above 850 hPa. A similar parameter, lake-induced convective available potential energy (CAPE), is also used in BUFKIT. Lake-induced CAPE is a calculation of CAPE when modifying the environmental surface temperature. If one considers the warming effect of the lake on a parcel of air at the surface, higher CAPE results from larger temperature differences between the lake and the overlying air. The Hydrometeorological Prediction Center has a tool for evaluating prospects for precipitation, including lake-effect snow (HPC 2013). Their lake-effect snow criteria include cold air advection, 1000-850 hPa shear less than 30°, and skin temperature (radiometric surface temperature) and 850 hPa temperature difference greater than or equal to 10°C. They also evaluate the mean omega between 500 and 700 hPa, location of the 1300 m thickness line in the 1000-850 hPa layer and the relative humidity in that layer, the 0°C boundary layer height, and location of the -10°C and -15°C isotherms.

Validation of mesoscale modeling using a variety of meteorological parameters allows a forecaster to use models to predict lake-effect snowfall with confidence. With increasing computer power, higher resolution weather models can produce lake-effect snow bands; however accuracy in placement and intensity remains a problem (Ballentine et al. 1998; Theeuwes et al. 2010). On their own, models do not have as much skill as human forecasters, who recognize certain patterns and local climatologies that lend themselves to a lake-effect snowfall in specific locations and times of day. Model performance has been evaluated for lake-effect snowfall events on various criteria, including band location, intensity, width, and orientation. The first two are of particular interest, as they are most crucial to get accurate snow amounts, and are described in great detail by Ballentine and Zaff (2007). In their Cooperative Program for Operational Meteorology (COMET) Partners project, the Weather Research and Forecasting (WRF) model mean absolute error was calculated for all hours, experiments, and cases of the Lake Ontario study. They recommended that an 8 km grid spacing be used operationally to forecast lake-effect snowfall, but noted that a locally run WRF at 12 km resolution could also work well and can be run in one-eighth the time as a 6 km WRF.

The RUC13 has also been used in lake-effect snowfall studies. In a modeling study aimed at determining why a southward shift in snowfall bands was observed in western New York, Arnott (2010) utilized RUC13 data for low-level winds. The results indicated that the root cause of the shift was overly strong low-level winds predicted downwind of the eastern Great Lakes.

Two other mesoscale models, the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5) and WRF model, were used to simulate lake-effect snow events with shallow convection parameterized using the Kain-Fritsch 2 cumulus scheme (Theeuwes et al. 2010). Snowfall was underestimated, with maximum 24 hour snowfalls totaling 31% (WRF) and 43% (MM5) of the observed snowfall. The band of snow generated by the models not only was not intense enough, but the spatial error was enough to place nearly all the snow outside of Buffalo which actually received 207.3 cm (81.6 in) of snow over 7 days.

Ballentine et al. (1998) used the MM5 and showed that although higher spatial resolution improves accuracy, 15 km or even 20 km grid spacing was sufficient to produce lake-effect snow. Part of their study involved the simulation of specific humidity and precipitation in 15 km grids. Six-hour precipitation maxima were well simulated relative to observations and there were appropriate moisture plumes downwind of Lake Ontario. A statistical approach was used by Burrows (1991). The study verified 24 hour forecasts using the CART (Classification and Regression Trees) method, utilizing 129 derivatives of temperature, wind, vertical velocity, and geopotential height at 6 hour intervals. Burrows (1991) found that predictands related to low-level convergence had the largest impact on the forecast and that the best results occurred with very light snowfalls (under 5 cm).

A significant challenge is in determining whether or not a snowfall is pure lake-effect, that is, a snowfall which would not occur without the lake being present. Colloquially, there is little distinction between lake-effect and lake-enhanced snow.

However, lake-enhanced snow, which may be associated with a surface low pressure system or an Arctic frontal passage, will not have the same type of vertical storm structure as a pure lake-effect event. Note that a common precursor to heavy lake-effect snow is for a synoptic scale storm to push through, generating winds on the back side with wrap around lake-enhanced snow. Only as the low-pressure system departs and dry, cold air filters across the region does it become purely lake-effect snow – that is, isolated, narrow convective bands that are no longer transient. In some situations, lake-effect snowfall can begin soon after the conclusion of synoptic snow; in other situations, lake-effect snowfall is delayed.

2.2 Snowfall Measurement and Forecasting

Common approaches to creating snowfall climatology datasets are to use a set of criteria to identify lake-effect events (Miner and Fritsch 1997; Lackmann 2001), then generate both lake-effect and non-lake-effect datasets (Liu and Moore 2004), or include a third category (Laird et al. 2009; Dutter 2012). The additional category used has been either lake-enhanced snowfall or mixed snowfall days when both lake and non-lake-effect snowfall takes place.

Snowfall is defined as the maximum depth of freshly fallen snow that accumulates on a snowboard since the previous day as measured with a ruler (Doesken and Judson 1997). The snowboard should be flush with the surface of old snow or the ground and in an open, flat area. The observer is instructed to report a representative value – a visual average around the weather station – and modify the reading if melting,

settling, blowing or drifting of snow altered the accumulation significantly. Measured snowfall can be less than the maximum daily snowfall if a 24-hour measurement is taken, especially if there is high wind or low-density snow. Conversely, if snow is frequently measured and cleared off, the daily snowfall will be overestimated because snow is not given time to settle before it is measured. Considering the somewhat subjective methodology of measuring and reporting snowfall, it is necessary to use data with a standard method of measurement for any kind of snowfall analysis. The primary daily snowfall reports come from National Weather Service observers and are quality-controlled and published by the National Climatological Data Center (NCDC) within local climatological data (LCD). The location of snowfall measurement is often in association with the precipitation measured at an automated surface observing system (ASOS) site. ASOS stations were implemented in the mid-1990s across the United States (NOAA 1998) and resulted in a widespread reduction in snowfall recording (Cosgrove and Sfanos 2004). Therefore, supplementary snowfall reports that come from the Community Collaborative Rain, Hail & Snow Network (CoCoRaHs), spotters, county officials, and media are very useful for climatological purposes. Alternative sources of snowfall data include Cooperative Observer Network (COOP) and Air Force DATSAV2 Surface Climatic Data.

Snowfall is difficult to forecast due to the variability in the snow to liquid ratio (SLR) during an event, and snow microphysics. When the snow begins to accumulate, its composition constantly changes. Snow cover exists as a combination of ice, dry air, water vapor and liquid water. These characteristics allow it to have a highly variable texture,

controlled by temperature, moisture, and wind near the ground (Jordan et al. 2008). Snow density is critical to forecasting snowfall amounts and depends greatly on the synoptic setup. Liquid water has a density of 1000 kg m^{-3}, whereas snow is usually much lighter. A typical mean value of a low density snow is 66.6 kg m^{-3}, resulting in an SLR of 15:1. A higher density event may be 125 kg m^{-3}, or an 8:1 SLR. Given the same QPF, the 15:1 SLR will produce a deeper snowpack compared to the 8:1 SLR. Without the benefit of an SLR climatology, a single snow ratio for all snowfalls is often used. The 10:1 rule is an assumption that the density of snow is 100 kg m^{-3}. This rule is still widely used, despite the knowledge since the late 19^{th} century that the 10:1 assumption is often a poor one (Roebber et al. 2003; Cobb and Waldstreicher 2005; Ware et al. 2006).

The snow density can only be computed if the snow water equivalent is accurate, and unfortunately, the precipitation data available from NCDC are not a true snow water equivalent (SWE). Snowfall caught by a rain gauge will underestimate snow density as wind can deflect snowflakes from the gauge's aperture. The overall effect of wind on fresh snow cover, however, is to fracture crystals, thereby increasing snow density. Areas downwind of the Great Lakes have high SLR. The 1971-2000 average SLR in the Buffalo, NY county warning area (CWA) is 16.3, much higher than adjacent CWA Binghamton’s 13.0 (Baxter et al. 2005). In another lake-effect snow climatology, Burnett et al. (2003) found that snowfall increased at a higher rate than precipitation by studying 15 lake-effect snow sites during the period 1931-2001. These studies support the hypothesis that lake-effect snows tend to have higher snow ratios. However, snow ratios among lake-effect snowfall cases at specific locations have not been well documented.

Dutter (2012) suggests that lake-effect snow may be the most challenging winter forecast problem throughout the Great Lakes and that production of a lake-effect snowfall climatology would serve as a baseline of snow-liquid ratio (SLR) for quantitative precipitation forecasts (QPF) and snowfall forecasts.

Various techniques to forecast snowfall amounts have been used operationally. Many of the earlier ones are ingredients-based methodologies. One such method, the Garcia method, is an empirical method that works with mixing ratios (Garcia 2000). The processes accounted for do not include low-level moisture advection, which is a limitation for predicting snowfall. Roebber et al. (2003) identified and used seven input variables that would account for snow density differences: solar radiation, low-to mid-level temperature, low-to mid-level relative humidity, mid-to upper-level temperature, upper-level relative humidity, mid-level relative humidity, and external compaction. A neural network was used to classify 1650 events at 28 wide-ranging radiosonde sites into low (<9:1 SLR), medium (9-15:1 SLR), and high density (>15:1 SLR) snowfalls. A similar classification approach was used by Barnwell (2011).

The Cobb Method (Cobb and Waldstreicher 2005) is a physically based forecast methodology, as opposed to an ingredients or statistically based one. It expands on the concept of a cross-hair signature, defined as the intersection of relative humidity (with respect to water) > 75%, an omega maximum of $\geq 10\ \mu b\ s^{-1}$, and $-12 \leq T \leq -18°$ C, to predict ideal snowfall efficiency (Waldstreicher 2001). Case studies were reviewed during four winters at eight stations in central NY and northeast Pennsylvania. During advisory-level snowstorms, only 7 out of 75 events had the cross-hair signature.

However, the signature was found in 42 of 55 warning events. For cases in which there was no signature despite warning criteria snowfall, events fell into three categories. When the location of the omega maximum was lower in the atmosphere than the temperature threshold, it was indicative of shallow lift and heavy wet snow. When the omega maximum was above the temperature threshold, it was associated with heavy snow upstream and low density snow. The third grouping was for cases with weak omega, associated with model errors or long duration events.

By utilizing a top-down approach, the Cobb Method follows a snowflake's transformations as it descends (Cobb and Waldstreicher 2005). The Cobb Method can reflect an atmosphere with favorable conditions for dendrite formation at 750 hPa, which is also warm enough at 900 hPa to support riming. Snow ratios are calculated from the vertical velocities, relative humidities, and temperatures for each layer of a cloud column. Each layer is given a snow ratio, determined by temperature of that layer. Cobb and Waldstreicher (2005) developed a temperature relationship based on research done by Dube (2003), Ware et al. (2006), and Baxter et al. (2005). Adapted from the cross-hair signature, the intersection of high omega and dendrite-favoring temperatures is referred to as the snow production zone. This is of prime importance and is weighted most heavily in the algorithm. The exact calculation of the Cobb snowfall method has evolved over time and unfortunately, changes are not well documented. For example, an adjustment from the original Cobb and Waldstreicher (2005) study is apparently the minimum layer relative humidity changing from 90% to 85% in the algorithm (NOAA NWS La Crosse Wisconsin, 2013).

The Cobb Method was tested with typical synoptic snow events in northern New England (Cobb and Waldstreicher 2005) and the Central U.S. (Barnwell 2011) and is currently used as an option for producing snowfalls in BUFKIT. An SLR is generated at each cloud layer based on a curve in which the SLR peaks at around -15.5 °C and falls off dramatically outside of the dendritic snowflake zone (Cobb and Walstreicher 2005). Altogether, the Cobb method has been tested with 128 stations. The Cobb Method may struggle with high-density snows (Barnwell 2011); however, lake-effect snow tends to be very low density. Also, Barnwell found that the majority of snow events have the heaviest weighted layer between 600 and 500 hPa, suggesting that a shift to higher pressures (lower heights) should be expected among lake-effect snowfalls. Although little research on snowfall has utilized the Cobb Method, Cox et al. (2009) reported on a bulk snow ratio technique that involves the Cobb Method run with the RUC13 model. Their method blended the column approach with a surface temperature approach for data points, without snow producing layers. Although this approach is interesting, it is unknown how accurate the resulting snow ratios are.

The Cobb Method may be used with a compaction correction. In previous Cobb Method studies, this correction was not made. The compaction rate, in general terms, is determined by snow drift, metamorphism, and deformation strain (Jordan et al. 2008). Compaction is a function of timing, so for a snowfall ending at 1500 LST, a measurement at 2100 LST would yield a lower snowfall amount than if it was measured at 1500 LST. Since only daily snowfall records are kept in the local climatological data (LCD), measured at 2400 LST, a compaction factor is critical for verification purposes. For the

same time period, any sum of six, three, or hourly snowfalls as calculated by the Cobb Method using any NWP model without use of a compaction correction should yield overestimated daily snowfalls.

CHAPTER 3: METHODOLOGY

3.1 Snow Climatology

In order to determine lake-effect snowfall events, daily snowfalls with accumulations greater than 5.08 cm (2 in) were identified using data obtained from the NCDC for six first-order weather station observations (Fig. 3.1.1): South Bend, IN (SBN); Muskegon, MI (MKG); Sault Ste Marie, MI (ANJ); Cleveland, OH (CLE); Buffalo, NY (BUF); and Syracuse, NY (SYR). These locations were chosen because they represent lake-effect snow locations in six different National Weather Service County Warning Areas. Data were collected for November through March 1995 to 2012 and used to generate both snowfall and snow ratio climatologies. It should be noted there are some months in which snowfall data are unavailable at Muskegon and Sault Ste Marie (Table 3.1). At both locations, manual snowfall measurements ceased in conjunction with installation of the ASOS and eventually began again in future years. Therefore, between 1996 and 2005, there is only snowfall data for four or five of the six study locations.

Lake-effect events for this study were defined using criteria established by Niziol (1987) and Liu and Moore (2004). These criteria include an 850 hPa air temperature and water temperature difference of greater than 13 °C, low directional wind shear from the surface to 700 hPa, an appropriate fetch over the lake of interest, a buffer of 250 km from the station to any low pressure centers, and evidence of six continuous hours of a narrow snow band's existence. Plots of composited three-hourly NCEP North American Regional Reanalysis (NARR) data obtained from the Penn State e-WALL archive (The

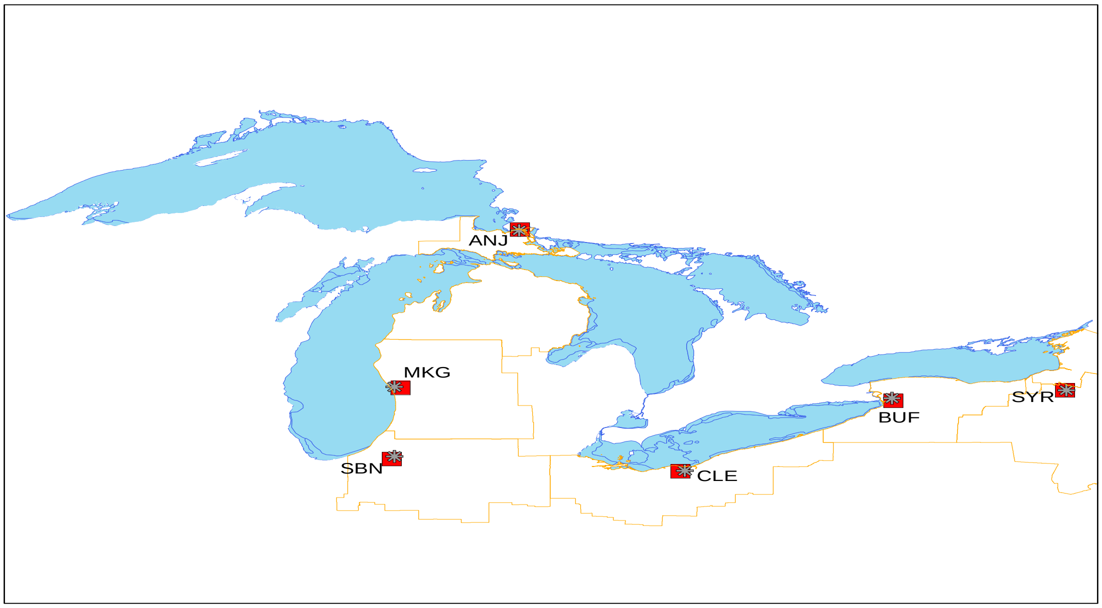

Figure 3.1.1: Study locations; CWAs are outlined in orange, red squares indicate nearest RUC13 grid point to NWS stations (marked in gray asterisks).

Table 3.1.1: Length of snowfall climatology, given in number of months.

	NOV	DEC	JAN	FEB	MAR
SBN	17	17	17	17	17
MKG *	13	13	13	13	13
ANJ **	9	9	8	8	8
CLE	17	17	17	17	17
BUF	17	17	17	17	17
SYR	17	17	17	17	17

*** 11/1996 to 3/2000 is not included (snowfall not reported)***

***** 1/1997-3/1999, 11/2000-3/2005 is not included (snowfall not reported)***

Pennsylvania State University, 2013) were used to identify lake-effect events. To ensure the presence of a vortex located to the north of the Great Lakes for each event, 500 hPa heights were used. The mutual alignment of 700 hPa and 850 hPa heights and surface isobars was used as a proxy for wind direction/shear in the cloud layer where precipitation was falling. Temperatures at 850 hPa were necessary to confirm the $T_{Lake} – T_{Air, 850hPa} > 13$ °C criterion, with daily average lake temperatures obtained from the Great Lakes Environmental Research Laboratory (GLERL) (Great Lakes CoastWatch Node, 2013). The location of the nearest reanalyzed surface low pressure was carefully inspected to avoid including an artificial synoptic low pressure area (one that has no significance on the large scale weather pattern) that could cause a misclassification of snowfall type. To assess the nature of the precipitation bands, composite WSR-88D radar reflectivity images were used (Iowa Environmental Mesonet, 2013). It should be noted that the radar criterion is supplemental and not essential. The radar beam appears to frequently overshoot lake-effect precipitation in Sault Ste Marie due to the station's long distance from the nearest radar. There are also occasional periods with missing/inaccurate reflectivity across the region during lake-effect events, identified using hourly observed precipitation reports and reflectivity from nearby radars.

Snowfalls are defined as non-lake-effect if a large-scale forcing mechanism, such as a surface low pressure system or shortwave trough, is causing the precipitation. Lake-enhanced snowfalls are included in this definition. In most cases, the characteristics of snow as depicted by radar reflectivity are distinct from pure lake-effect events, in that non-lake-effect snowfalls rarely occur in narrow, discrete bands or cells.

For cases in which a portion of a day's snowfall may be a combination of lake-effect and non-lake-effect, the chosen categorization is the dominant one, defined as greater than two-thirds of hours with measurable precipitation. If there is no two-thirds majority, then the day falls into the transitional category. In instances in which there is either no measurable precipitation or only one hour with measurable precipitation, the judgment is based on the trace hours as well. Transitional events count towards neither lake-effect nor non-lake-effect snowfalls; however, they contribute to the overall snowfall climatology statistics.

Precipitation type is an important factor for daily snowfall events. For most events, the LCD publications have sufficient information to determine hourly precipitation type. When it is not clear if mixed precipitation occurs, such as for reports of unknown precipitation, supplementary hourly data from quality controlled LCDs are used to determine the likely precipitation type. Rain to snow, snow to rain, and events with sleet and freezing rain of greater than a trace were used in the study, but the SWE was not maintained. This ensures that snow ratios are not calculated for mixed precipitation events. Any snowfalls meeting the minimum depth criteria, however, are included in the snowfall climatology.

To determine how much snowfall is lake-effect during an average winter season, the data collected in this study are analyzed using a metric introduced in this study, namely, the Lake-Effect Snowfall Intensity Fraction (LESIF). The LESIF is calculated by taking a single station’s mean monthly lake-effect snowfall and dividing it by the sum of mean monthly lake-effect and non-lake-effect snowfall. This is advantageous over

comparing a location some distance away from a lake-effect snow belt with one near a Great Lake to determine the effect of the lakes on snowfall. Also, using a fraction prevents years with fewer events from being underrepresented.

Despite using quality-controlled official measurements, there appear to be biases in SLR within sites. Two examples include Muskegon's frequency of 10:1 SLRs in the 2005 winter season, and Syracuse's snowfall tendency towards extremely high snow ratios, occasionally exceeding 100:1, throughout the study period (Table 3.1.2). Any snow ratios greater than 60:1 were not used in the SLR climatology, similar to the restrictions used in the Baxter et al. (2005) study. Cases with less than .28 cm (.11 in) of liquid precipitation were also not used when calculating snow ratios to account for measurement bias, consistent with previous studies (Baxter et al. 2005; Roebber et al. 2005; Alcott and Steenburgh 2010). Due to these additional criteria, the number of events in the snow ratio climatology is reduced from the snowfall climatology. 775 total events are included, of which 237 are lake-effect snowfalls, 487 are non-lake-effect snow events, and the remaining 51 cases are transitional.

3.2 Cobb Method

The Cobb Method operationally is run to output a snowfall at each time step of a NWP model being used by a forecaster. This snowfall prediction method is based on the modeled snow ratio and quantitative precipitation forecast (QPF). For this study, observed hourly precipitation data are used to generate snowfalls. A compaction factor, which considers the effect of compression, is applied to the snowfall because summation

of hourly snowfalls can produce an overestimation of snowfall. The compaction factor takes the form of an exponential decay:

$$e^{-(a(h-i))^{(1/2)}}$$

where "a" is the compression coefficient = 0.08; "h" is the final hour; and "i" is the current hour (Caribou Snow Amount Tool, 2012). Although this effectively reduces snow depth to consider the settling of snow over time, it does not consider environmental effects, such as wind and sublimation. Use of an NWP model with hourly resolution allows for more precise compaction effects than at coarser temporal resolutions.

An NWP model is needed to provide upper air data for snowfall events identified in the snowfall climatology. The RUC13 was chosen since it produces 1-hr forecasts and has sufficient resolution to produce lake-effect snow (Ballentine et al. 1998). RUC13 analyses are produced via an assimilation cycle, in which a correction is made to the previous 1-hr forecast based on current observations. The sum of the correction and 1-hr forecast produces the 0-hr forecast (Benjamin et al. 2004). Data ingested into the model include satellite derived precipitable water estimates and surface weather observations. Cumulus parameterization is via the Grell-Devenyi scheme modified for use in RUC13. Bulk mixed-phase cloud physics are applied explicitly to predict snow and ice crystals. The RUC13 model was first implemented operationally in 2005. It was subsequently upgraded with 3-D radar assimilation in November 2008 (Benjamin et al. 2008), which is the key reason for the time period of this study.

Table 3.1.2: Sample snowfall events. Those with snow ratios of 10:1 and > 100:1 ratios are bolded. LES = Lake-effect, NON = Non-lake-effect, SPLIT = Transitional.

Day	Month	Type	SWE (cm)	Snowfall (cm)	Snow Ratio
Muskegon 2005-2006 winter season					
23	11	NON	NA	7.874	NA [1]
25	11	SPLIT	1.47	23.4	15.8
1	**12**	**SPLIT**	**0.91**	**9.1**	**10.0**
3	12	NON	0.36	5.6	15.7
7	12	LES	0.69	11.4	16.6
11	12	SPLIT	0.66	7.9	11.9
16	12	NON	0.66	10.2	15.3
20	**1**	**NON**	**1.19**	**11.9**	**10.0**
21	**1**	**NON**	**0.81**	**8.1**	**10.0**
10	**2**	**NON**	**1.02**	**10.2**	**10.0**
6	**3**	**NON**	**0.71**	**7.1**	**10.0**
Syracuse 2009 January & February					
3	1	LES	0.15	8.1	53.3
8	**1**	**LES**	**0.08**	**22.9**	**300.0**
10	1	NON	0.38	6.6	17.3
11	1	NON	0.43	5.6	12.9
13	**1**	**SPLIT**	**T**	**5.6**	**NA**
18	1	NON	0.33	10.7	32.3
21	**1**	**LES**	**T**	**5.3**	**NA**
28	1	NON	1.50	23.6	15.7
31	**1**	**SPLIT**	**0.05**	**6.4**	**125.0**
20	**2**	**LES**	**0.08**	**24.1**	**316.0**
21	**2**	**LES**	**T**	**6.6**	**NA**
23	**2**	**LES**	**T**	**14.2**	**NA**

[1] Snow to rain event with measurable rainfall after snow accumulated.

To generate Cobb Method values for each snowfall event, BUFKIT data derived from 0-hr analysis NCEP RUC13 data for the November-March period of 2008-2012 are used. These data are derived from the nearest grid point to the station observations which are within ten kilometers of the station (Table 3.2.1). An event-to-event comparison between the Cobb Method snowfall and observed snowfall was done for lake-effect and non-lake-effect snowfall separately to see if there is a systematic bias in mesoscale events

compared to synoptic events which have previously been tested by Cobb and Waldstreicher (2005) and Barnwell (2011).

Table 3.2.1: Reference and spatial data for study locations.

Station	**WMO**	**ID**	**Lat**	**Long**	**RUC Lat**	**RUC Long**	**RUC grid point proximity to observing site**	**Typical LES Trajectory**
South Bend, IN	72535	KSBN	41.70	-86.30	41.65	-86.27	8 km SE	NNW-NW
Muskegon, MI	72636	KMKG	43.17	-86.23	43.15	-86.14	10 km ESE	NW-SW
Sault Ste Marie, MI	72734	ANJ	46.47	-84.35	46.49	-84.34	3 km NNE	W-NW
Cleveland, OH	72524	KCLE	41.40	-81.85	41.39	-81.92	8 km WSW	NW-NE
Buffalo, NY	72528	KBUF	42.93	-78.73	42.88	-78.71	8 km SSE	SW-NW
Syracuse, NY	72519	KSYR	43.10	-76.10	43.10	-76.12	2 km W	N-NW

Some events were not evaluated with the Cobb Method based on issues with observed precipitation. The Cobb Method was not used for events in which the observed precipitation type begins as snow, changes in the middle of the event to rain, and ends as snow. Additionally, events were selected only if the sum of observed hourly precipitation equals the liquid equivalent measured at the end of the day. Rain to snow events, since a single period of snowfall accumulation is measured, could be used during hours of snowfall if the daily snowfall exceeded 5.08 cm (2 in).

For all hours in which observed snowfall occurs during an event, the CarSnowTool Beta 5.4 algorithm (NOAA NWS La Crosse Wisconsin, 2013) was run. For hours in which RUC13 snow ratios are not calculated due to a lack of upward vertical velocity within a cloudy layer of the sounding, a snowfall was produced by using the previous hour's Cobb Method snow ratio, or the next hour of observed snowfall if it is a

shorter time interval. The Cobb Method was modified to produce snow ratios when modeled snow is not predicted. This allows for 0-hr analyses to be used in place of 1-hr forecasts and snow ratios to be produced even when the forecast precipitation type is rain. This also introduces a category of events in which snow ratios are produced without a measurable hourly precipitation. A second modification to the algorithm was made in which snow ratios were not produced above 500 hPa, following an adjustment made by Barnwell (2011). For events occurring with deep moisture and lift, this would help increase snow ratios, because the temperatures at this height are much lower than in the snow production zone. Details on the two modifications are given in the Appendix. By using instantaneous fields of vertical velocity, relative humidity, and temperature at the end of the hour in which the precipitation fell, we are assuming these atmospheric conditions are representative of the conditions during the hour of snow accumulation.

Snowfalls in the study are also organized by snowfall amounts for each type. Since the study period for Cobb Method snowfall evaluation is four years, and events with observed precipitation issues are not used, the number of events is much fewer than for the snowfall climatology. There are 55 lake-effect events and 98 non-lake-effect events (Table 3.2.2). The remaining 21 events were transitional. Three groups are used representing light snowfalls between 5.3 and 9.9 cm (2.1-3.9 in), moderate snowfalls between 10 cm and 20.1 cm (4-7.9 in), and heavy snowfalls greater than or equal to 20.1 cm (>=8 in). The moderate snowfall range represents typical NWS advisory level snowfalls in the Great Lakes region, while the heavy snowfall group was chosen to reflect the average minimal warning criteria for 24-hr snowfalls at the six CWAs. The

majority of usable events for the study are light snowfalls, representing 62% and 66% of the total for lake-effect and non-lake-effect, respectively.

Table 3.2.2: Summary of events used in Cobb Method snowfall evaluation.

	Cobb Method Snowfalls					
	Light		Moderate		Heavy	
	# of Events	Total Snowfall	# of Events	Total Snowfall	# of Events	Total Snowfall
Non LES	65	464.1	24	301.6	9	217.2
LES	33	248.7	15	207.5	7	234.2

Cobb Method snow ratios were calculated for all events and compared to those from the snowfall climatology. This comparison could only be made for events meeting the SWE minimum criteria described in section 3.1. Therefore, the number of cases used was reduced from 55 to 40 for lake-effect snowfalls and from 98 to 91 for non-lake-effect snowfalls.

To understand the cause of departures from observed snowfall, two cases were selected to examine the vertical structure of the atmosphere during snowfall. The first event chosen, at Buffalo on 1-2 December 2010, includes both a transitional and lake-effect case. The second event, at South Bend on 2 January 2010, was chosen due to its very high snow ratio. Radar reflectivity was coordinated with observed snowfall and RUC13 analysis sounding data to recapture the evolution of the snowstorms. Cobb Method layer snow ratios were related both to pressure, relative humidity, temperature, omega, and to the cumulative snow ratio (the snow ratio that contributes to snowfall) for each hour of snowfall.

CHAPTER 4: RESULTS

4.1 Snowfall climatology

There are 1272 snowfalls of greater than 5.08 cm (2 in) in the study (Table 4.1.1). Of these, 449 were identified as lake-effect, 729 as non-lake-effect, and 94 transitional. The number of lake-effect snowfalls is similar at five of the six locations, with Syracuse having a much higher number. However, Buffalo has a similar number of non-lake-effect snowfalls as Syracuse. This indicates that Buffalo has a relatively small proportion of lake-effect snowfalls relative to all snowfalls, which may be attributable to a combination of a high frequency of synoptic east coast snowstorms and a less favorable lake-effect location than Syracuse. Since there are fewer years included in the study for Muskegon and Sault Ste. Marie, comparisons between these stations and the other four stations for snow amounts and event totals should not be made.

A higher proportion of snowfall is contributed by non-lake-effect events than lake-effect events at all locations (Table 4.1.2). At Buffalo, Sault Ste Marie, and South Bend, the percentage of lake-effect snowfall is higher than the percentage of lake-effect events. It follows that the average per event snowfall amount is higher for lake-effect snowfalls at these locations.

Table 4.1.1: Summary of snowfall events identified in climatology.

	Lake-effect		**Non-lake-effect**		**Transitional**		**All**	
	# of Events	Total Snowfall (cm)	# of Events	Total Snowfall (cm)	# of Events	Total Snowfall (cm)	# of Events	Total Snowfall (cm)
SBN	66	310.9	89	353.1	9	46.5	**164**	**710.5**
MKG [2]	59	211.5	110	485.0	22	86.3	**191**	**782.8**
ANJ [2]	59	265.0	88	372.5	10	32.3	**157**	**669.8**
CLE	46	177.8	119	492.7	15	59.2	**180**	**729.7**
BUF	68	438.5	146	615.5	15	75.0	**229**	**1129.0**
SYR	151	729.5	177	805.4	23	95.5	**351**	**1630.4**
TOTAL	**449**	**2133.2**	**729**	**3124.2**	**94**	**394.8**	**1272**	**5652.2**

[2] Numbers may be lower due to missing data in study period [see section 3.1]

Table 4.1.2: Proportion of each type of snowfall event identified in climatology.

	Lake-effect		**Non-lake-effect**		**Transitional**	
	Events (%)	Snowfall (%)	Events (%)	Snowfall (%)	Events (%)	Snowfall (%)
SBN	40.2	43.8	54.3	49.7	5.5	6.5
MKG	30.9	27.0	57.6	62.0	11.5	11.0
ANJ	37.6	39.6	56.1	55.6	6.4	4.8
CLE	25.6	24.4	66.1	67.5	8.3	8.1
BUF	29.7	38.8	63.8	54.5	6.6	6.6
SYR	43.0	44.7	50.4	49.4	6.6	5.9
TOTAL	**35.3**	**37.7**	**57.3**	**55.3**	**7.4**	**7.0**

Lake-effect snowfall events occurred on average five times per year at each location with similar seasonal distributions among the stations (Fig. 4.1.1). The number of events and snowfalls provides a monthly account of snowfall "intensity", a term in this paper that will be synonymous with the amount of snowfall per event. Lake-effect intensity at Sault Ste Marie, Buffalo, and Syracuse have similar seasonal patterns. At

each location, intensity is higher in December than January and the magnitude for the mean winter season is higher than the other three locations. For all locations, both the number of events and snowfall amounts peaked in December and January. The odds of an event occurring in one of these months were twice that of November and five times that of March. Syracuse averaged the most events over a winter season with nearly nine and Cleveland had the fewest with around three. These extremes are reasonable given the setup for lake-effect over the eastern Great Lakes; in particular, the climatologically favored west-northwest flow that provides a long fetch from across Lake Ontario to Syracuse produces a much shorter fetch over Lake Erie to Cleveland.

A comparison between the two Lake Michigan stations shows impacts of geography on the snowfall climatology. South Bend appears to have a strong, short lived lake-effect snowfall season, with a low number and intensity of lake-effects snowstorms in November, February, and March (Fig. 4.1.1). Muskegon has a similar distribution, with a greater number of events, especially from January through March. However, the mean intensity of snowstorms is lower than South Bend. Given the shorter fetch over Lake Michigan, the higher frequency, lower intensity snowfalls is likely not a random feature. As for non-lake-effect events, these are more frequent at Muskegon compared to South Bend (Fig. 4.1.1 and 4.1.2). Moreover, these events tend to produce more snowfall, likely as a function of latitude. At Muskegon, 62% of seasonal snowfall is caused by non-lake-effect events, 12% higher than at South Bend (Table 4.1.2). Conversely, lake-effect snowfalls are a larger contributor to seasonal snowfall at South Bend (40%) then Muskegon (31%).

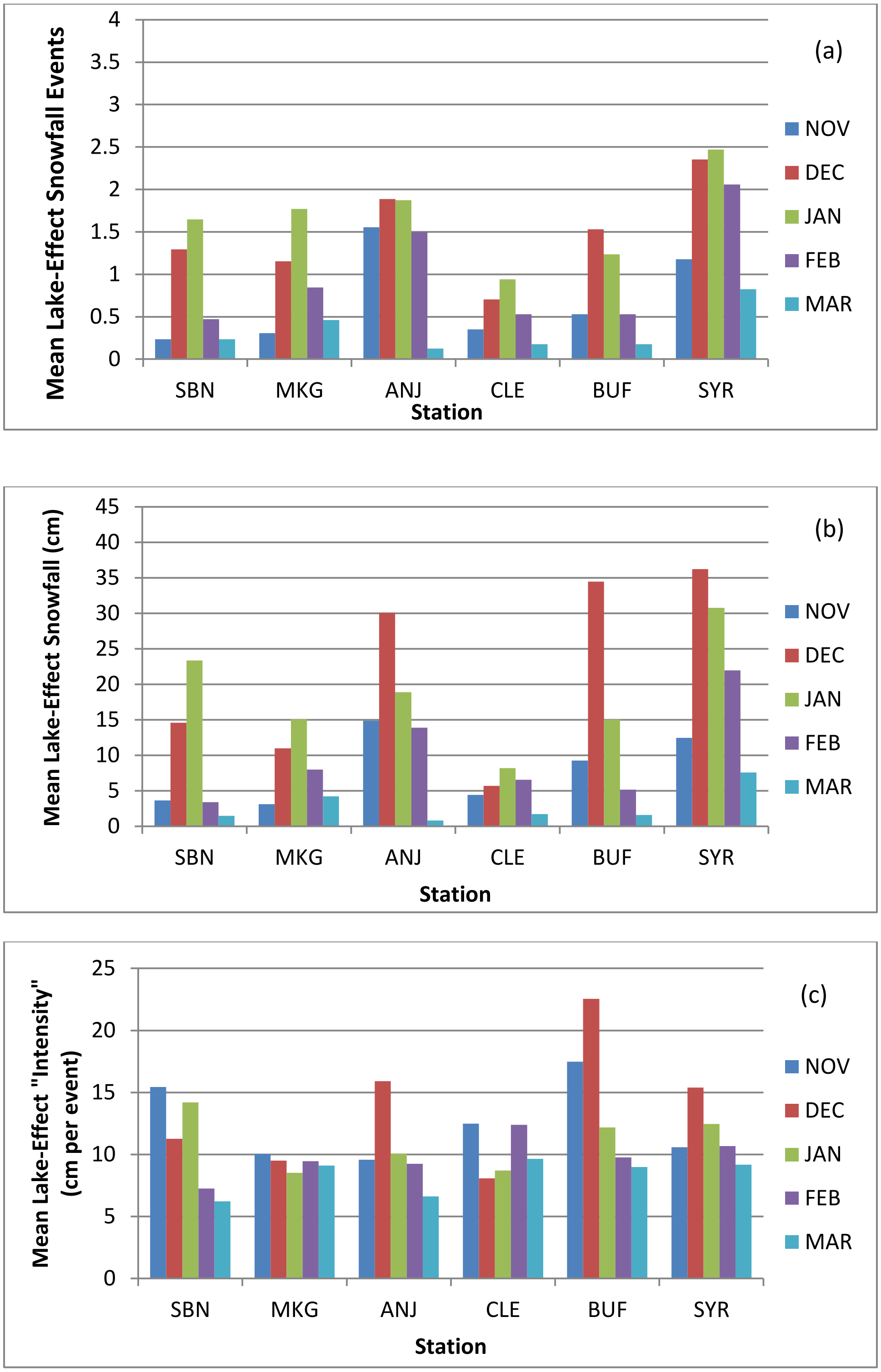

Figure 4.1.1 Monthly lake-effect snowfall climatology for (a) number of events, (b) total snowfall, and (c) “intensity”.

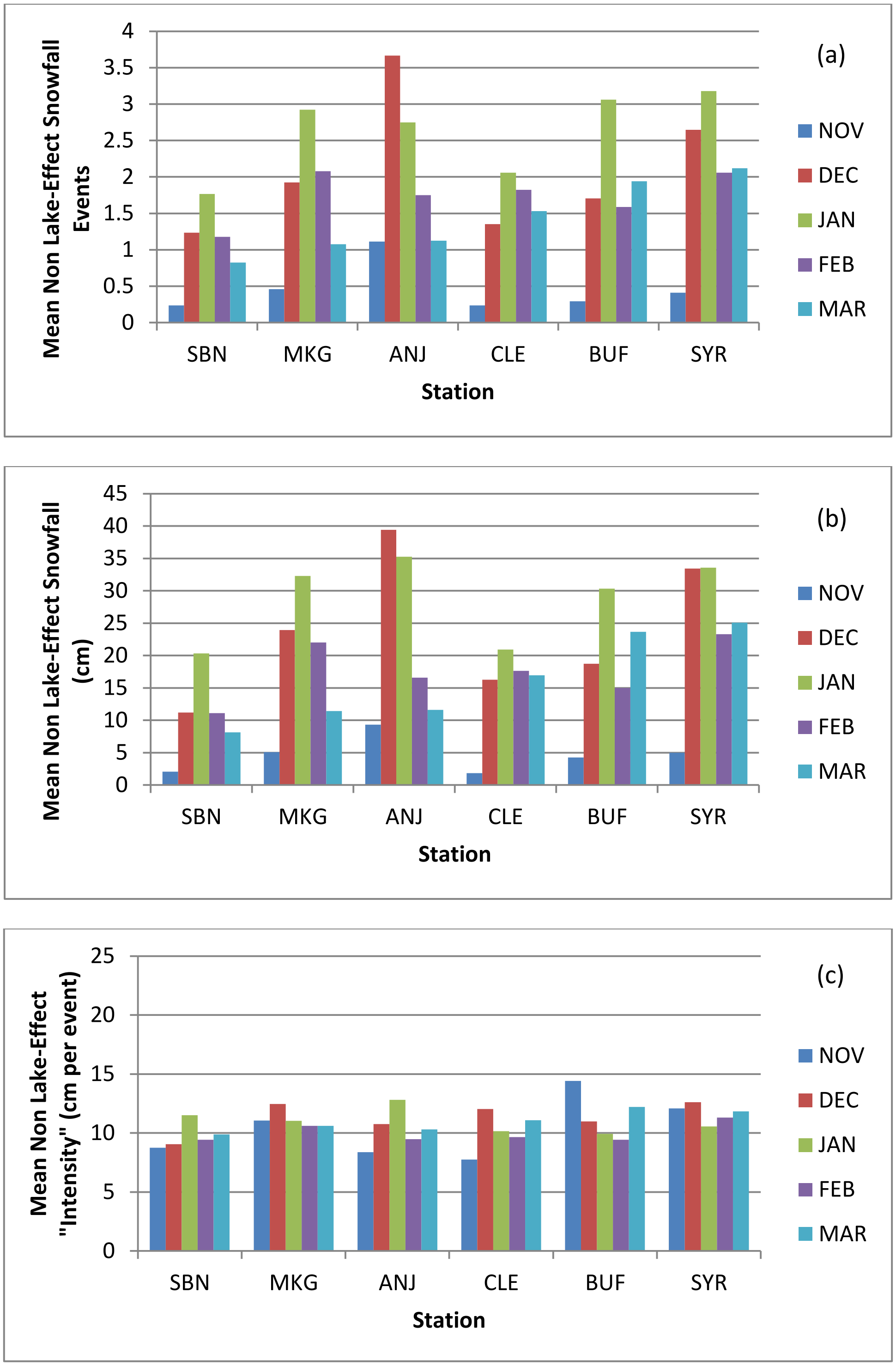

Figure 4.1.2 Monthly non-lake-effect snowfall climatology for (a) number of events, (b) total snowfall, and (c) “intensity”.

All stations have their highest LESIF during November (Fig. 4.1.3). Decreases in LESIF at all locations occurs from November into December, and a decreasing or steady change from February into March. The November mean LESIF is near 0.65 and falls to 0.49 in December, indicating that while only in November do the lakes contribute to the majority of snowfall in these areas, nearly half of the snowfall is December is purely generated by the lakes. In March, the mean LESIF falls to 0.15; only about 15% of snowfall is contributed by the lakes during the late winter. Although a general decline in LESIF occurs through the winter season, the shape of each station's curve varies. For instance, Sault Ste Marie has a significant increase in LESIF during February. Reviewing the cases, a contributor to this unexpected rise is the period of 3-8 February 2007. This case is a long duration lake-effect snowstorm comprising nearly 46% of the February lake-effect snowfall at Sault Ste Marie in the study.

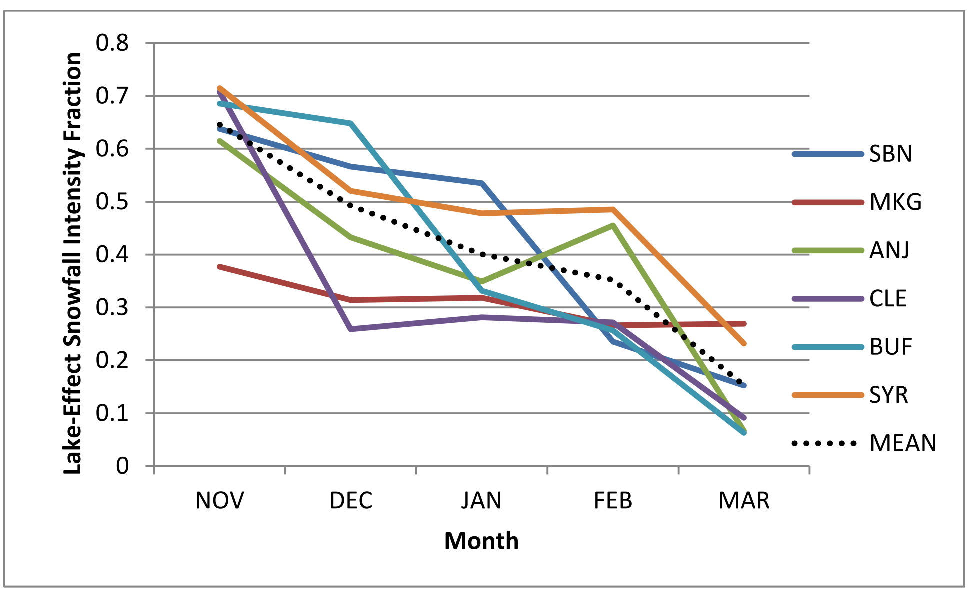

Figure 4.1.3 Ratio of lake-effect snowfall accumulation to non-lake-effect snowfall accumulations (LESIF) for each station during an average winter season.

Interannual variability of snowfall events was examined for each month (Fig. 4.1.4). Muskegon and Sault Ste Marie were not included in this analysis so each winter season has the same number of possible snowfall days. In November, only 7 of the 17 years had a non lake-effect snowfall, and none of these were in the last 6 years of the study. Five years, including the last three years of the study, had no November snowfalls reported at any of the stations. The synoptic pattern for these Novembers featured persistent upper level ridging and few intrusions of polar air. Note that the lack of events does not mean no snow fell in these months, only that the daily snowfall was less than the minimum used for this study. Since the number of events in each year is so small, it is hard to assess if there is a decreasing trend for either snowfall type.

For December, 2000 is particularly snowy, with 31 total events at the four locations. December 2010 had the highest number of lake-effect snowfalls in December (17 events), while the following December there were the fewest lake-effect snowfalls (1). Changes in one type do not coincide with the changes in the other. In January, there is no single year with a preponderance of lake-effect snowfalls. During both 1999 and 2004, however, over 20 non-lake-effect snowfalls occurred during the month.

February is the only month that seems to exhibit an increasing number of snowfall events, especially non lake-effect snowfalls. The lake-effect event increase is largest through 2008-2009 since the last three years of the study have only a combined five lake-effect snowfalls. It remains to be seen if an increase in February lake-effect snowfall events, associated with a delayed freeze-up on the Great Lakes caused by warmer early winter weather, will resume. A reduction in lake-effect snowfalls relative to January is consistent with ice cover, which has a negative effect on turbulent heat fluxes and lake-

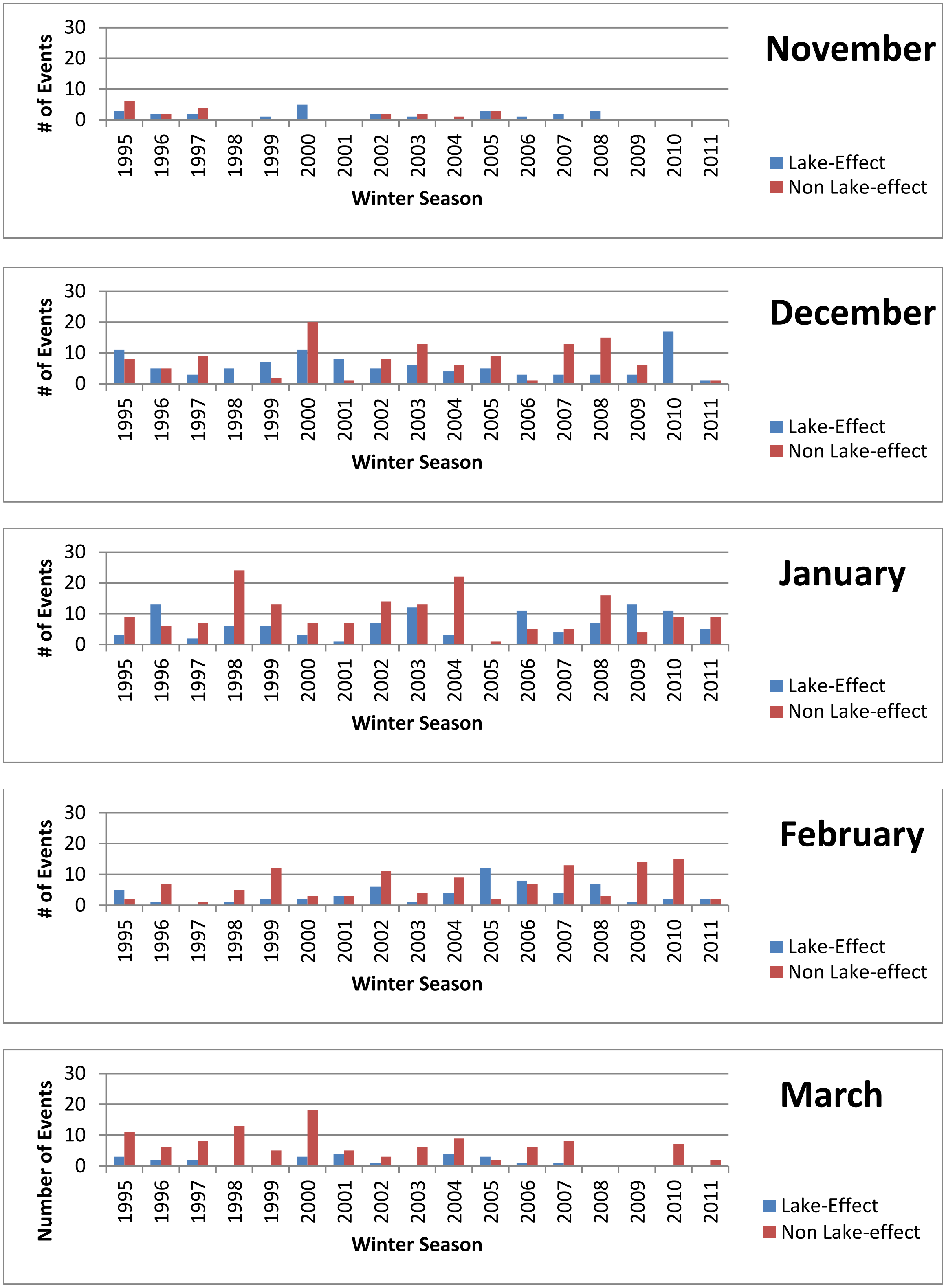

Figure 4.1.4 Monthly lake-effect and non-lake-effect events for each year of the study.

effect snowfall (Cordeira and Laird 2008). Note that the freeze over date is dependent largely on the synoptic scale weather pattern, in which a regime with substantial northwesterly and northerly flow into the region during the late fall will increase the odds of ice cover, especially on the shallower lakes, such as Lake Erie. The deeper lakes, such as Lake Michigan, are less likely to freeze over and in recent years have remained ice-free during the entire winter season. The amount of instability in February is often lower than in January because of lake temperature decreases relative to air temperature, so the potential for heavy lake-effect snowfalls is reduced.

Finally, March snowfalls have been mostly non lake-effect throughout the study period. The lack of lake-effect snowfalls during this month can be mainly attributed to higher air temperatures. Lake-effect events were especially rare in the latter years of the study. Only in the 2005-2006 winter season did the number of lake-effect snowfall events exceed that of non lake-effect snowfall events. That winter was comprised of anomalously mild conditions and infrequent snowfalls through January in the Great Lakes region. This weather pattern maintained a relatively mild lake water temperature, which manifested in numerous lake-effect snowfall events in February, and a few in March, when Arctic air intrusions occurred.

This study's mean snow ratios are 22.5 for lake-effect snowfalls, with non-lake-effect snowfalls averaging a snow ratio near 16.3 (Table 4.1.3). Compared to the results in Baxter et al. (2005), the snow ratios are mostly higher as anticipated, since this study was using only locations near the Great Lakes rather than a CWA average. At ANJ, however, the mean snow ratio is slightly lower than in the Baxter et al. (2005) study. A

Table 4.1.3: Average snow ratios for each location.

Mean Snow Ratios

	Lake-effect	Non-lake-effect	All
SBN	22.1	17.6	20.1
MKG	21.0	15.8	17.5
ANJ	17.9	13.8	15.5
CLE	18.1	14.9	16.2
BUF	21.5	15.8	17.8
SYR	34.2	19.8	23.6
Mean	**22.5**	**16.3**	**18.4**

comparison of cities shows unexpected differences, with surprisingly high density snow ratios at Sault Ste Marie considering it is at the highest latitude. The very low density mean lake-effect snow ratio at Syracuse could actually be even lower when considering that snow ratios could not be calculated for snowfalls with only trace amounts of hourly precipitation, an issue not common at other sites.

Among all locations and all snowfall types, heavy snowfalls have the highest snow ratios (Table 4.1.4). Both moderate and heavy snowfall groups have similarly lower median snow ratios compared to the mean, indicating the presence of positively skewed snow ratios. Light snowfalls have less variability than the heavier snowfall groups. For both lake-effect and non-lake-effect snowfalls, snow ratios are higher with heavier snowfall groups. In Barnwell's (2011) study, the opposite tendency was found in the snowfall amount groupings. Similarly, Ware et al. (2006) found that snow ratios and liquid equivalent were negatively correlated. One reason this physically is reasonable is due to compaction; the weight of heavier snowfalls should apply more force on snow crystals, making the snowfall denser. It is unclear why the observations in this study do

Table 4.1.4: Summary snow ratio statistics.

	Lake-Effect			Non-Lake-Effect			All		
	Light	**Moderate**	**Heavy**	**Light**	**Moderate**	**Heavy**	**Light**	**Moderate**	**Heavy**
Number of Events	109	87	37	273	151	60	405	266	103
Mean Snow Ratio	19.3	23.8	25.4	15.4	17.0	19.2	16.6	19.8	21.4
Median	19.4	21.6	22.6	14.7	14.9	17.1	15.9	17.5	19.1
Mode	20.0	21.4	20.5	10.0	10.0	33.3	10.0	10.0	20.0
St. Dev.	5.7	10.6	11.5	4.8	7.5	8.2	5.4	6.0	9.8
Min	7.4	7.7	7.2	6.2	6.0	8.5	6.2	9.2	7.2
25th %	15.7	16.3	17.0	11.5	11.9	12.7	12.3	13.2	13.4
75th %	22.5	28.7	32.4	18.5	19.5	24.6	20.0	23.6	27.8
Max	34.5	57.3	55.0	31.8	49.2	44.3	34.5	57.3	55.0

not conform to the expected relationship. Both light and moderate snowfall categories had many 10:1 ratios, some of which may be spurious. Comparing lake-effect snowfalls to the full dataset, it is evident that snow ratios increase for all snowfall amount categories (Table 4.1.4). The minimum snow ratios are between 7 and 8:1, giving an indication that not all lake-effect events are comprised of low density snowfall. On the other hand, maximum snow ratios are all lake-effect snowfalls. The variability is higher than for non-lake-effect snowfalls, with a shift towards higher values (Table 4.1.4). Snow ratios of light non-lake-effect snowfalls have a similar interquartile range to their lake-effect counterpart, but have a reduced size for moderate and heavy snowfalls (Table 4.1.4). This suggests that differences in snow density between lake-effect and non-lake-effect snowfalls are most apparent with advisory and warning-level snowfalls as opposed to nuisance snow amounts.

4.2. Cobb Method

Using the snowfall climatology as a background, if the method is reliable, then snowfalls generated by the Cobb Method should be representative of observed snowfalls for the Great Lakes region. The comparison of the Cobb Method snowfalls with observed snowfalls will provide an assessment of the utility of using the Cobb Method to predict lake-effect snowfalls.

4.2.1. Snowfalls

For lake-effect snowfalls, the Cobb Method mostly underestimates daily snowfall observations at all locations (Fig. 4.2.1). The Cobb Method performed worse with light (MAE) is 4.7 cm (Table 4.2.1). Only 4 out of the 55 snowfall events were overestimated

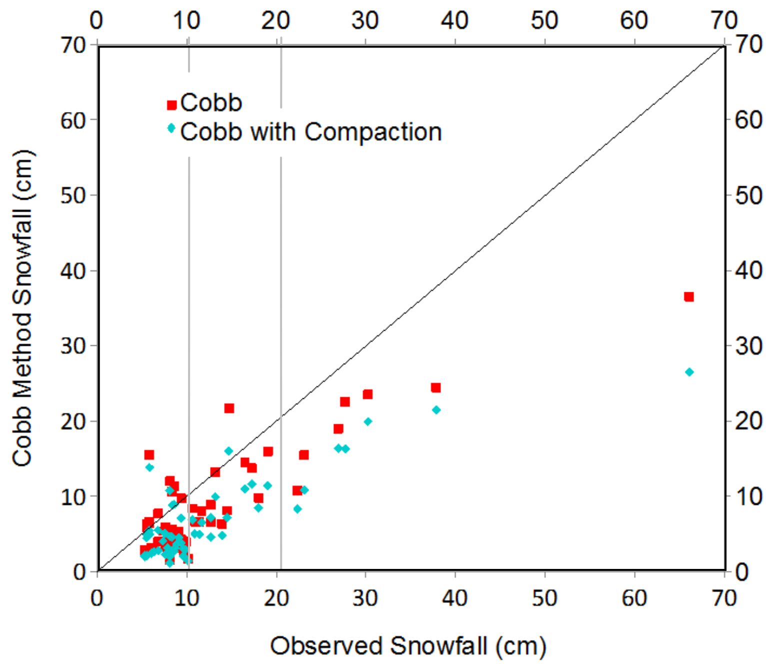

Figure 4.2.1 Lake-effect snowfalls predicted by the Cobb method. Vertical lines divide snowfalls into light, moderate, and heavy snowfalls.

snowfalls compared to moderate and heavy snowfalls. The overall mean absolute error by at least 30%, whereas 33 events were underestimated by that margin (Fig. 4.2.2). About 62% of the snowfalls were within a range of 40 to 80% of observed (Fig. 4.2.3). These results coincide with a 26% bias towards under prediction using the Cobb Method (Table 4.2.2). Applying compaction to the snowfalls increases the overall error from 39.4% to 47.8%. Likewise, error increased for overforecasted snowfalls from 29.3% to 37.8% and for underforecasted snowfalls from 42.6% to 48.9% (Table 4.2.2).

For non-lake-effect snowfalls, the Cobb Method snowfalls are, on average, closer to observations than for lake-effect snowfalls (Fig. 4.2.4). The predicted snowfalls are within 64% of observations, corresponding to snowfall amounts within 3.5 cm (1.4 in.) of

Table 4.2.1 Cobb evaluation for lake-effect snowfalls and non-lake-effect snowfalls. Percent accuracy is given, with mean absolute error provided in parentheses.

		Lake-Effect			Non-Lake-Effect		
		# of Events	Cobb (MAE)	Cobb + Compaction (MAE)	# of Events	Cobb (MAE)	Cobb + Compaction (MAE)
City	SBN	8	56.5 (2.5)	43.6 (2.6)	14	63.3 (3.2)	62.3 (3.7)
	MKG	7	59.3 (2.5)	48.5 (3.4)	11	56.9 (3.8)	66.6 (3.0)
	ANJ	10	50.6 (3.7)	44.3 (4.0)	20	56.8 (3.2)	68.2 (2.3)
	CLE	11	82.1 (4.1)	78.4 (5.7)	21	68.0 (2.8)	78.3 (2.3)
	BUF	6	44.1 (4.4)	43.3 (4.9)	16	60.9 (4.5)	55.9 (5.0)
	SYR	13	60.8 (8.5)	47.4 (11.6)	16	74.7 (3.6)	64.1 (5.2)
Snow Amount	Light	33	55.1 (3.4)	49.2 (3.9)	65	61.3 (2.7)	67.7 (2.3)
	Moderate	15	69.7 (4.2)	58.7 (5.7)	24	66.9 (4.3)	66.3 (4.4)
	Heavy	7	66.5 (11.7)	52.4 (16.3)	9	72.7 (27.3)	60.3 (39.7)
	Overall	55	60.6 (4.7)	52.2 (6.0)	98	63.7 (6.9)	66.7 (9.9)

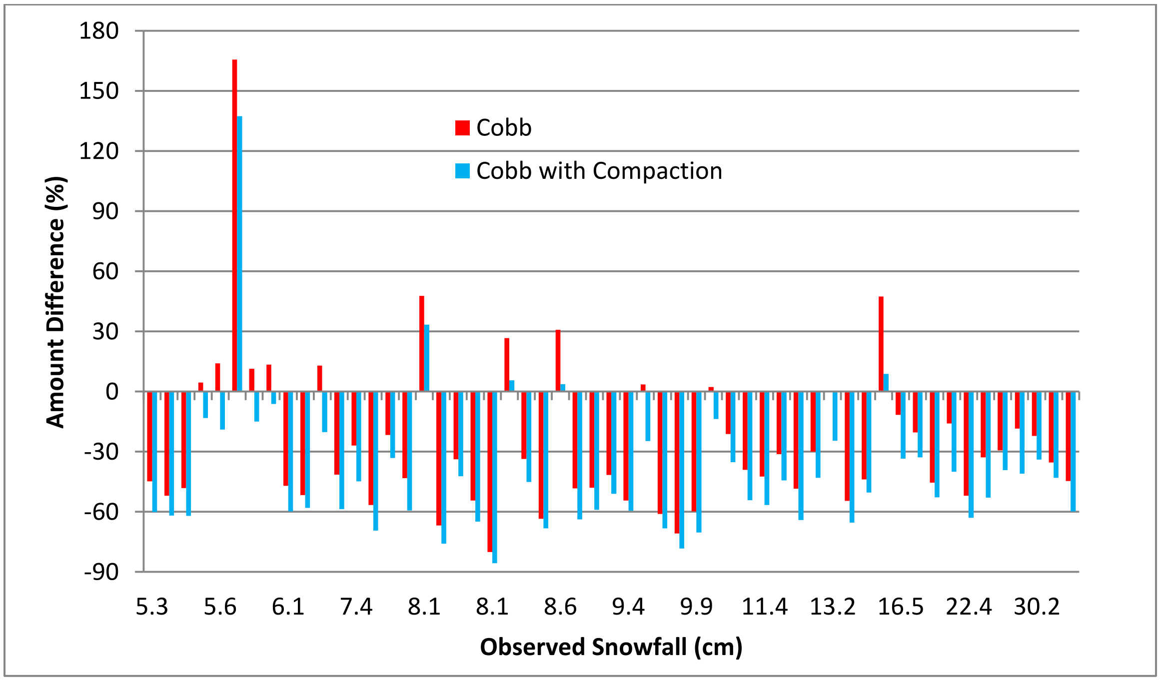

Figure 4.2.2 Percent differences between forecasted and observed snowfalls associated with lake-effect events shown in Fig. 4.2.1.

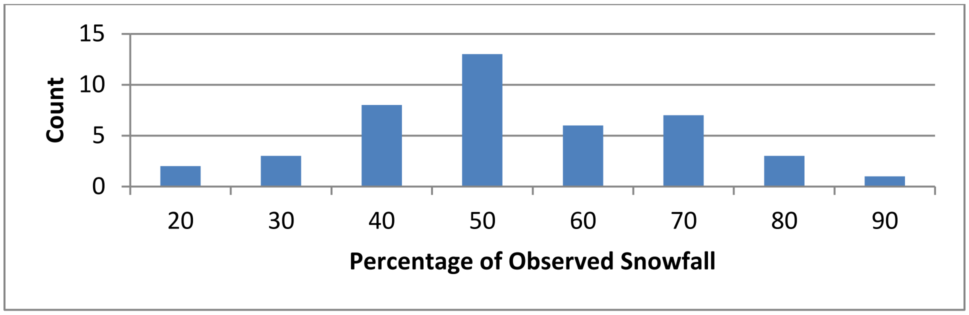

Figure 4.2.3 Histogram of underforecast lake-effect snowfalls.

Table 4.2.2 Comparison of snowfall differences, given in amounts (in cm) and as a percentage, among lake-effect and non-lake-effect events.

	All Events				Overforecast		Underforecast	
	Magnitude		Overall					
	Value	(%)	Value	(%)	Value	(%)	Value	(%)
Lake-Effect	4.7	39.4	-3.6	-25.6	2.3	29.3	5.5	42.6
With Compaction	6.0	47.8	-5.5	-40.1	2.6	37.8	6.3	48.9
Non Lake-Effect	3.5	36.3	0.3	8.7	3.6	43.2	3.3	28.7
With Compaction	3.5	33.2	-2.0	-14.5	2.2	27.2	4.2	36.6

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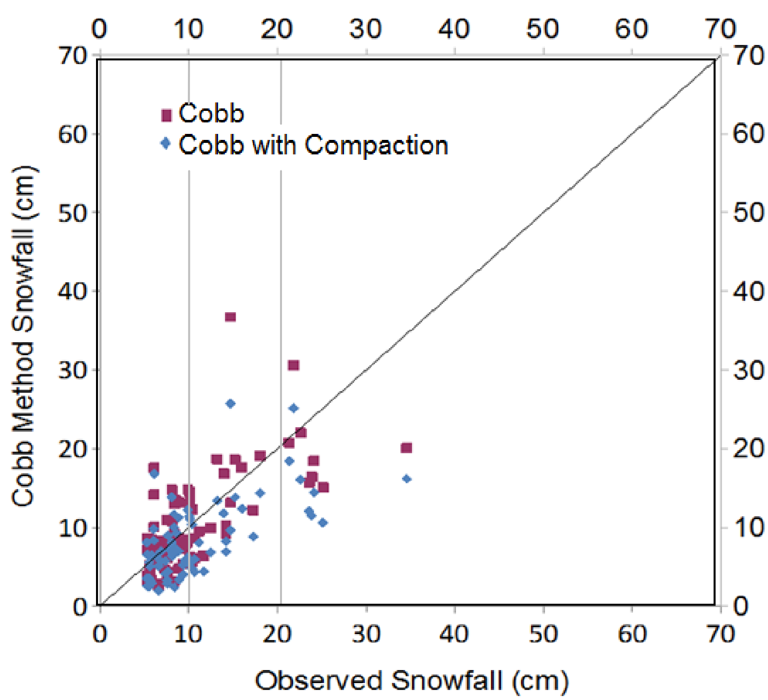

Figure 4.2.4 Non-lake-effect snowfalls predicted by the Cobb method. Vertical lines divide snowfalls into light, moderate, and heavy snowfalls.

observations. This accuracy is lower than the 77.7 %, or 2.8 cm, that Barnwell (2011) found among 50 cases in the Great Plains, but it is higher than for lake-effect snowfalls (Table 4.2.1). However, light snowfalls appear to be mostly overforecast, and by greater than 30% for 25 events (Fig. 4.2.5). Four of the five heaviest snowfalls were underestimated by at least 30%, contributing to the heavy snowfall category averaging 18% less snowfall than what was observed (Table 4.2.1). These results are in contrast to those found by Barnwell (2011). Light snowfalls in his study are underforecast by 20.8% and heavy snowfalls are overforecast by 4.8%. Although Cleveland has the lowest error among the stations, the magnitude of error is surprisingly higher than for lake-effect snowfalls. Applying the compaction factor improves the accuracy for light snowfalls, but increases the error slightly for moderate and heavy snowfalls. Intuitively, the opposite would make sense; compaction due to weight of the snow increases with snow depth. The issue appears to lie in the snowfall observations used in this study. The light snowfalls have lower snow ratios than moderate and heavy snowfalls. Therefore, the snow density is higher and the weight of the snow is relatively light. South Bend, Buffalo, and Syracuse have better results without using compaction. For Buffalo in particular, the relative increase in error is higher than for lake-effect snowfalls. However, non-lake-effect snowfalls at Muskegon, Sault Ste Marie, and Cleveland do improve by around 10% (Table 4.2.1) overall when using compaction.

The forecasted snow amounts were consistently too low for lake-effect events, indicating that the Cobb Method may not work for this type of snowfall. A compaction factor should be applied to the snowfalls since observed snowfalls as used in this study

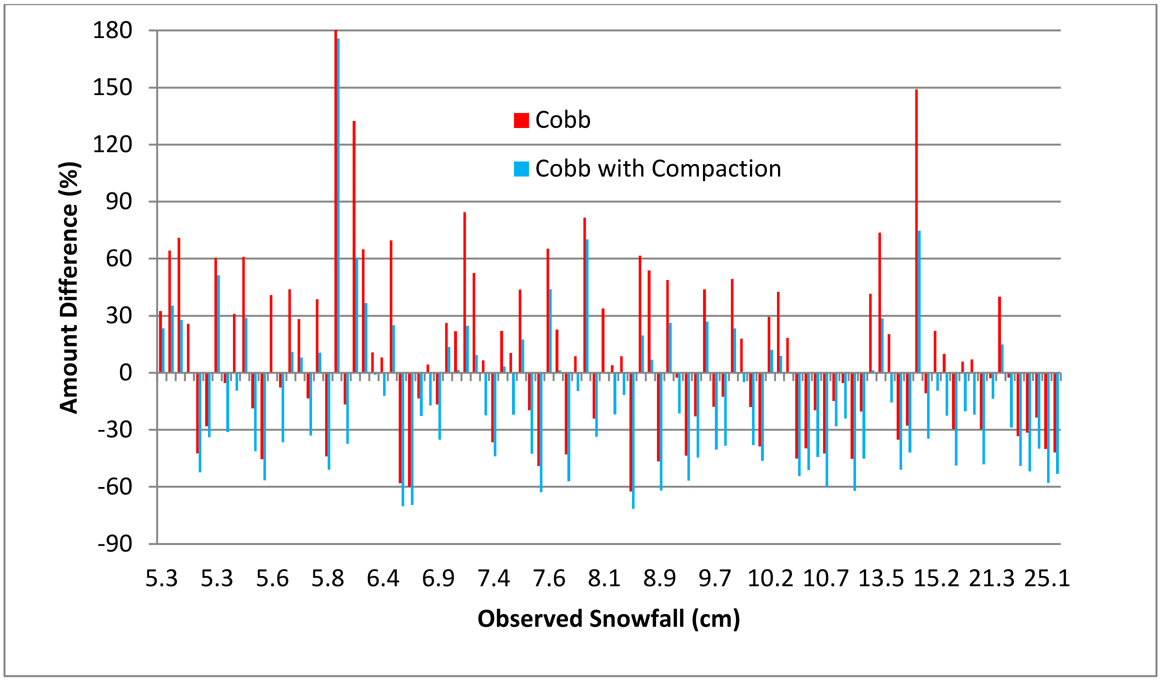

Figure 4.2.5 Percent differences between forecasted and observed snowfalls associated with non-lake-effect events shown in Fig. 4.2.4.

are compacted. Therefore, lake-effect snowfalls may be best forecast with a systematic increase in snowfall intensity to achieve better results closer to observations.

4.2.2. Snow Ratios

The distribution of snow ratios reveals that the forecasted lake-effect snow ratios are negatively skewed, while forecasted non-lake-effect snow ratios are more normally distributed around the mean (Fig. 4.2.6 and 4.2.7). When compared to observed snow ratios, forecasted snow ratios have less spread. Forecasted lake-effect snow ratios depart most noticeably from observed at the upper end, with only one snowfall in the 30:1 ratio bin as opposed to the eleven observed snowfalls in the 30:1 bin or higher. The mode of

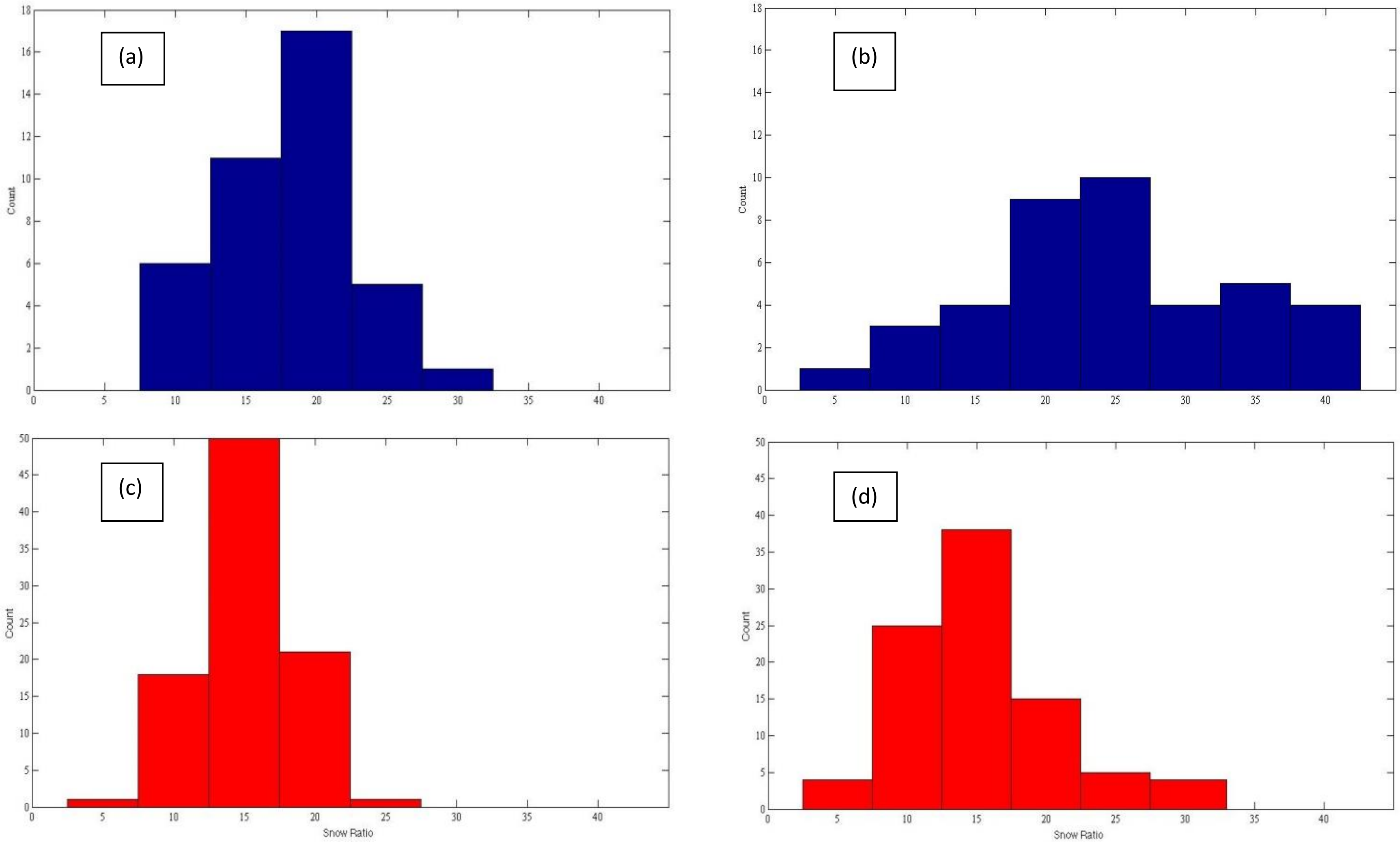

Figure 4.2.6 Histograms of (a) forecasted and (b) observed lake-effect snow ratios and (c) forecasted and (d) observed non-lake-effect snow ratios.

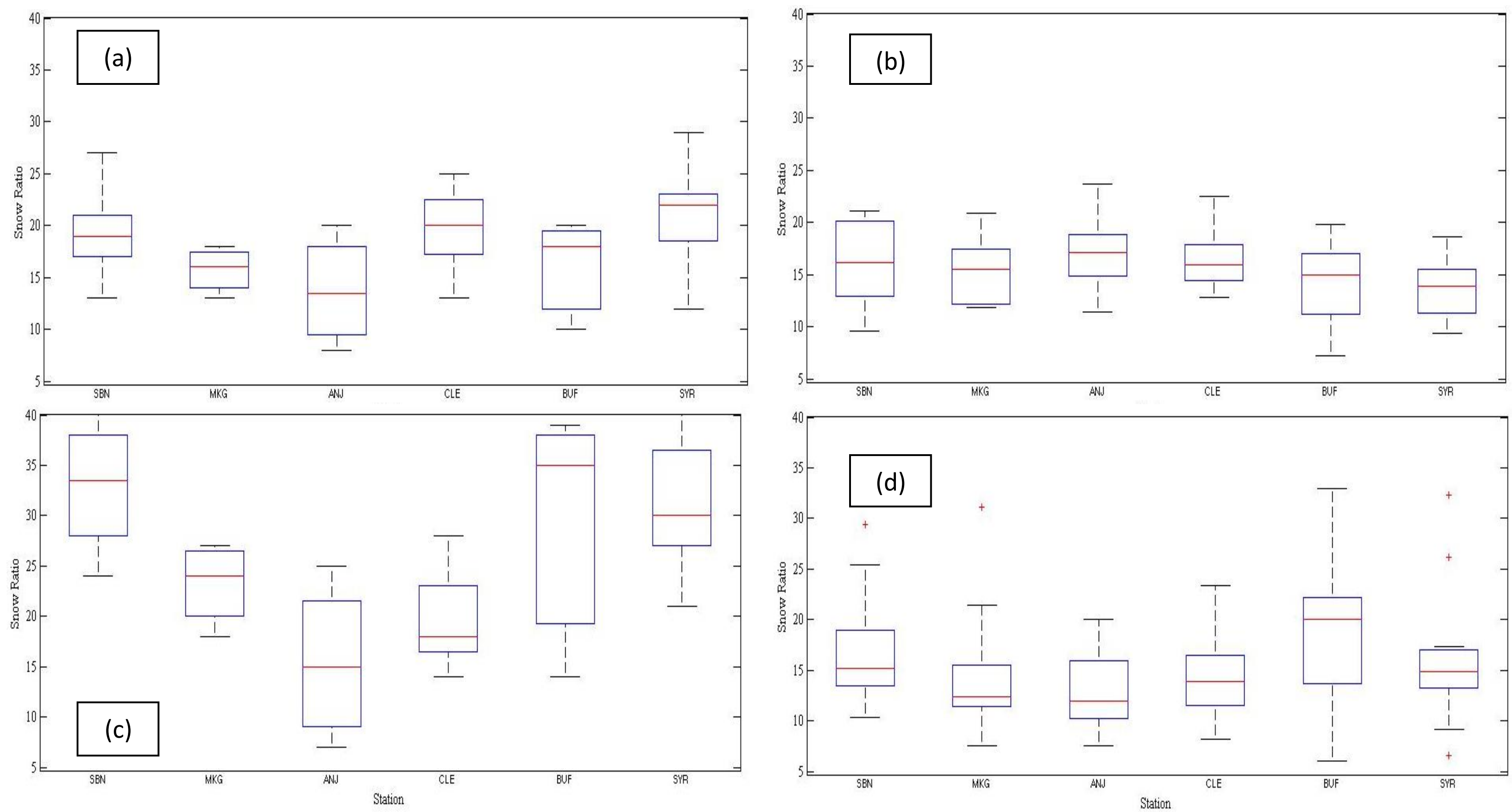

Figure 4.2.7 Boxplots of forecasted (a) lake-effect and (b) non-lake-effect snow ratios and observed (c) lake-effect and (d) non-lake-effect snow ratios at each station. For each plot, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers are 1.5 times away from the interquartile range, and outliers are shown as red plus sign marks.

lake-effect snow ratios is greater, near 25:1, for observations than for forecasts, near 20:1. For non-lake-effect events, both forecasts and observations have a mode near 15:1. Similarly, the distribution of forecasted non-lake-effect snow ratios match observations much better than for lake-effect, with a similar frequency of lower and higher density snowfalls (Fig. 4.2.6 and 4.2.7).

Overall, forecasted snow ratios are higher for lake-effect snowfalls than non-lake-effect snowfalls (Fig. 4.2.8). Forecasted lake-effect snow ratios at Buffalo and Syracuse are negatively skewed, whereas the snow ratios at the other four stations are more normally distributed (Fig. 4.2.8). The snowfalls at Sault Ste Marie have similarly low snow ratios as they did in the snowfall climatology, but the Cobb Method also produces relatively low snow ratios at this station compared to the others. Buffalo and Sault Ste Marie have the largest spread of snow ratios for both observations and forecasts.

Since the snow ratio distributions of observed snowfalls included in the Cobb Method evaluation are similar to that of the climatology, the distribution of forecasted snow ratios should be close to climatology. The differences between lake-effect and non-lake-effect snow ratio distributions, although present, are not reflective of the large observed snow ratio increase associated with lake-effect events. This indicates that the Cobb Method may not be properly forecasting lake-effect snowfalls. To better assess this possibility, two lake-effect snowfalls, part of both the climatology and Cobb Method evaluation, are assessed in detail as case studies.

4.2.3. Case Studies

There were many lake-effect snowfall events that were reviewed as part of the snowfall climatology and used with the Cobb method. Some of these events were multi-day, and those snowfall days as a group are considered as a case. Out of fifty-eight cases, two were selected on the merits of being a “classic” lake-effect snowfall: a single, persistent lake-parallel snow band was situated over one of the study locations, and heavy snowfall resulted from the storm. The first case was selected for the eastern Great Lakes and the second case was selected for the western Great Lakes.

Case 1: An ideal, shore-parallel, lake-effect snow event over Lake Erie occurred on 1-2 December 2010. A single reflectivity band unassociated with a synoptic low appeared on Doppler radar near KBUF at 1900 UTC on the 1^{st}, lasting through part of the 2^{nd} (Fig. 4.2.8). This band was just south of Buffalo the majority of the time, but shifted northward for short periods that coincided with the snowfall measured at the airport. Low pressure derived heavy wet snow fell prior to midday on the 1^{st}, with 7.62 cm (3 in) of non-lake-effect snow falling. Lake-effect snow fell overnight during just a four hour period between 0300 and 0700 UTC on the 2^{nd}, when Cobb Method snow ratios were between 16:1 and 20:1 (Table 4.2.3). Due to a 5.08 cm (0.2 in) precipitation measurement at 2400 LST (0500 UTC), a remarkable 9.7 cm (3.8 in) of snow was predicted in the hour ending at 0500 UTC on the 2^{nd}. During the remainder of the event, only another 2.8 cm was predicted in total, occurring during six non-consecutive hours. Two more periods of snowfall after the overnight snow had much lower snow ratios predicted, ranging between 7:1 and 12:1 (Table 4.2.3). The thermal and moisture profile barely changed between the initial lake-effect snowfall and the subsequent snowfall; what did change

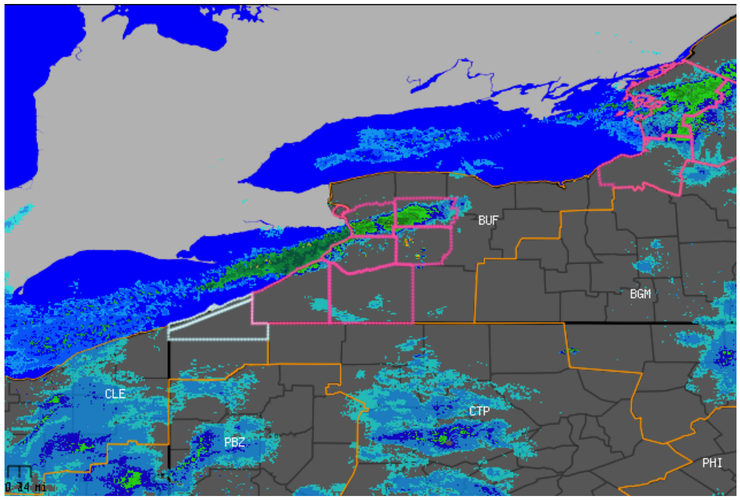

Figure 4.2.8 Radar reflectivity at 0400 UTC 2 December 2012. Pink highlighted polygons show lake-effect snowstorm warnings (Taken from Iowa Environmental Mesonet (2013)).

Table 4.2.3 Hourly snowfall data at KBUF for lake-effect snowstorm beginning at 0400 UTC 2 December.

	Hour ending (LST)	Observed SWE (cm)	Cobb Snowfall (cm)	Compacted Cobb Snowfall (cm)	Observed Snowfall (cm)	Cobb Snow Ratio – > 500 hPa	Cobb Snow Ratio – All Layers
Buffalo - 2010/12/01	9	0.10	0.8	0.6		8	8
	10	0.08	1.1	0.8		12	14
	11	0.15	3.0	2.3		21	20
	12	0.18	3.7	2.8		20	21
	23	0.08	1.4	1.3		18	18
	24	0.51	9.7	9.7		19	19
Transitional		**1.09**	**19.7**	**17.4**	**13.5**	**18.0**	**15.9**
Buffalo - 2010/12/02	1	0.03	0.5	0.3		20	20
	2	0.03	0.4	0.3		16	16
	10	0.13	1.0	0.8		8	8
	11	0.03	0.2	0.2		9	9
	18	0.05	0.4	0.3		7	7
	19	0.03	0.3	0.3		12	12
Lake-effect		**0.28**	**2.8**	**2.1**	**9.7**	**10.1**	**7.5**

was the depth of upward motion through the cloudy layers (Figure 4.2.9). Very near surface layers (lowest 10 hPa) no longer had upward motion diagnosed, but these layers are so thin that the layer weighting only summed to 0.7% of the total snow ratio (Table 4.2.4). Instead, the increase in pressure level, from 809.8 hPa to 837.6 hPa, of the top of the cloud layer is important. This layer had a 43.1% weight and a temperature in the snow production zone, resulting in a 30.7:1 snow ratio (Table 4.2.4). With the vertical extent of snow production slightly closer to the surface, all of the snow growth was at temperatures higher than about -9°C, rather than less than -12°C. Since the uppermost snow layer is weighted so heavily given its relatively large thickness, the impact of the large reduction in snow ratio in that layer is enormous on the cumulative snow ratio. That one layer is responsible for the hourly snow ratio dropping from 16:1 to 8:1. The Cobb Method produced a two-day snowfall of 22.5 cm, very similar to the observed 23.2 cm. However, the first day was overforecast by 6.2 cm (3.9 cm with compaction), and the second day was underforecast by 6.9 cm (7.6 cm with compaction). This case study shows the influence that time of day can have on snowfall observations and verification.

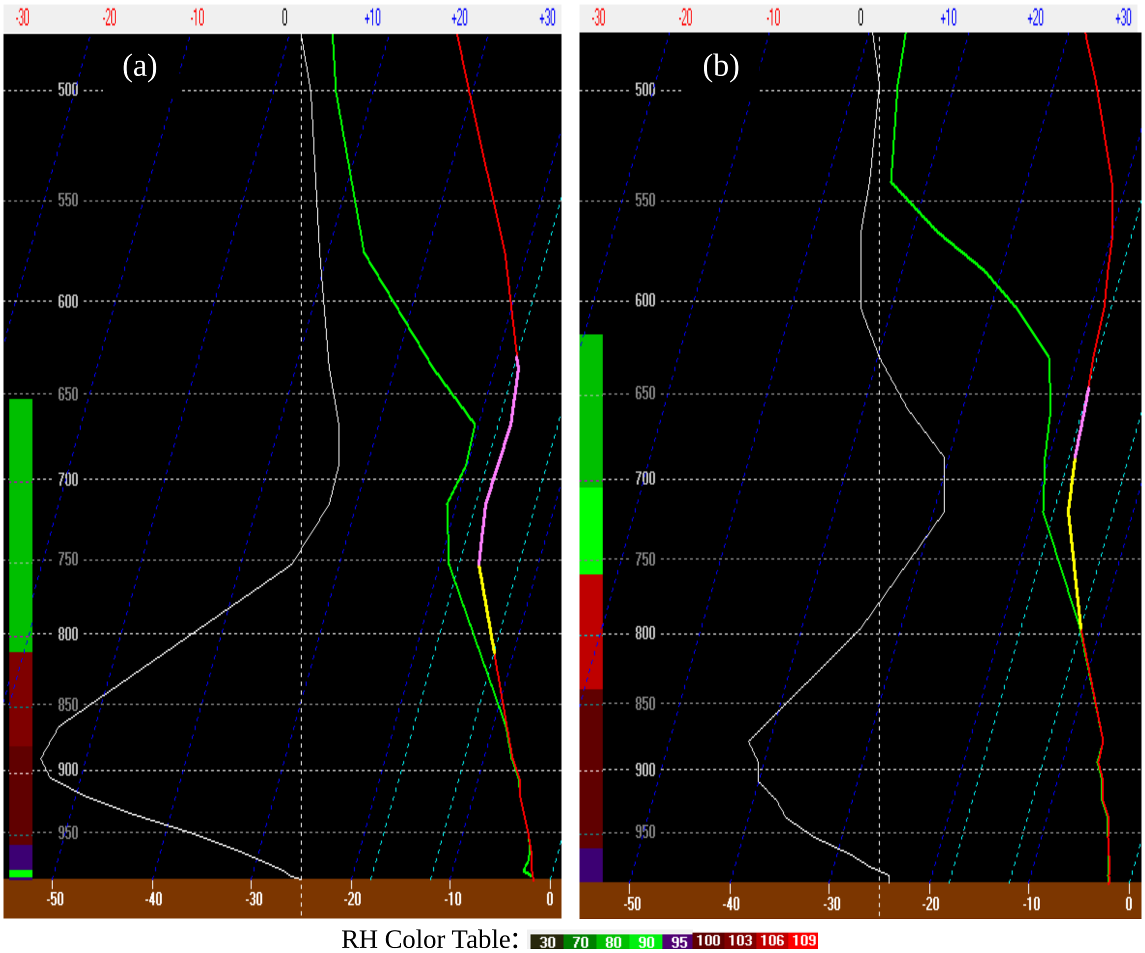

Figure 4.2.9 Skew-T – Log P diagrams for KBUF at (a) 0700 UTC and (b) 1500 UTC on 2010 December 2. Pressure is plotted in hPa, relative humidity with respect to ice is displayed in shaded rectangles, omega ($1x10^{-1}$ hPa s^{-1}) is plotted in white, temperature and dew point are plotted in red and green (°C), and the SPZ is represented by yellow (best snow production) and pink (good snow production) on the temperature sounding.

Table 4.2.4 Partial cobb algorithm output, including only snow layers, for KBUF at 0700 UTC and 1500 UTC on 2010 December 2. The layer with maximum omega in a cloudy layer is bolded.

Layer Average Pressure (hPa)	Relative Humidity with respect to ice (%)	Omega (Pa s^{-1})	Layer Weighting (%)	Temperature (°C)	Snow Ratio
0700 UTC Surface Conditions: Winds from WSW at 1.5 m/s, Temperature is -1C, Snow ratio is 16:1					
809.8	99.1	-1.35	43.1	-12.3	30.7
878.5	107.3	-2.70	18.1	-7.9	7.4
898.4	**105.9**	**-2.75**	**10.5**	**-6.6**	**4.9**
913.1	105.0	-2.50	9.5	-5.6	4.2
927.7	104.2	-2.05	7.6	-4.8	4.3
942.3	103.3	-1.50	5.5	-3.9	4.3
957.0	102.4	-0.95	3.5	-3.1	4.6
969.2	100.5	-0.55	1.3	-2.5	5.9
977.8	97.3	-0.30	0.5	-2.2	6.6
983.9	98.4	-0.15	0.2	-1.9	7.0
987.5	101.4	-0.05	0.0	-1.7	6.7
1500 UTC Surface Conditions: Winds from SSW at 1.5 m/s, Temperature is -2C, Snow ratio is 8:1					
837.6	108.5	-0.80	42.5	-9.3	11.5
886.5	**106.0**	**-1.35**	**13.2**	**-6.5**	**5.5**
901.8	105.2	-1.30	11.6	-6.0	5.2
916.5	104.3	-1.20	10.7	-5.2	4.8
931.3	103.7	-1.05	9.2	-4.4	4.6
946.1	103.0	-0.85	7.4	-3.6	5.0
960.9	102.5	-0.50	4.2	-3.1	6.2
973.2	101.9	-0.20	1.1	-2.6	7.0

Case 2: At South Bend on 1-2 January 2010, an intense lake-effect snowfall event occurred. There was a persistent northerly to north-northwesterly flow and 850 hPa temperatures were below -15°C. With Lake Michigan water temperature at 3.5 °C, the lake index was moderate with lake-induced CAPE of 440 J kg^{-1} at 0900 UTC. The observed daily snow ratio, 39:1, was well above South Bend's climatological average of 22:1 for lake-effect snowfalls (Table 4.1.2). Accordingly, the Cobb Method underpredicted snowfall despite having several hours with 0.8 to 1.0 Pa s^{-1} omega in the snow production zone. In fact, one hour snowfall rates using observed hourly

precipitation were 4.42 cm hr^{-1} (1.74 in hr^{-1}) and 5.16 cm hr^{-1} (2.03 in hr^{-1}) between 0900 and 1100 UTC (Table 4.2.5). While snowfall rates are dependent on the snow ratio and precipitation rate, the snow ratios are dependent on the temperature at which upward motion is greatest in the sounding. For this event, 6 of the 11 snowfall hours occurred with the maxima in omega within a cloud layer occurring at a temperature between -17 and -15°C (Fig. 4.2.10). This area of greatest lift coincided with the snow production zone, resulting in high snow ratios in that layer. Two hours had maxima in omega at a temperature near -23°C, which corresponded with a layer snow ratio of 12:1 to 13:1. Vertical profiles for these hours were ones with best lift above the snow production zone. The remaining three hours were times in which the best lift was below the snow production zone. The layer snow ratios fit well with the snow ratio-temperature relationship produced by Cobb and Waldstreicher (2005) (Fig. 4.2.10). The close fit to the curve provides us with insight to how important the layer with maximum omega is to the cumulative snow ratio that goes into the snowfall calculation.

Table 4.2.5 Heavy, low density snowfall at South Bend on 2 January 2010.

Hour ending (UTC)	Observed SWE (cm)	Cobb Snowfall (cm)	Compacted Cobb Snowfall (cm)	Hourly Cobb Snow Ratio
9	0.06	1.7	1.3	29
10	0.07	2.0	1.5	29

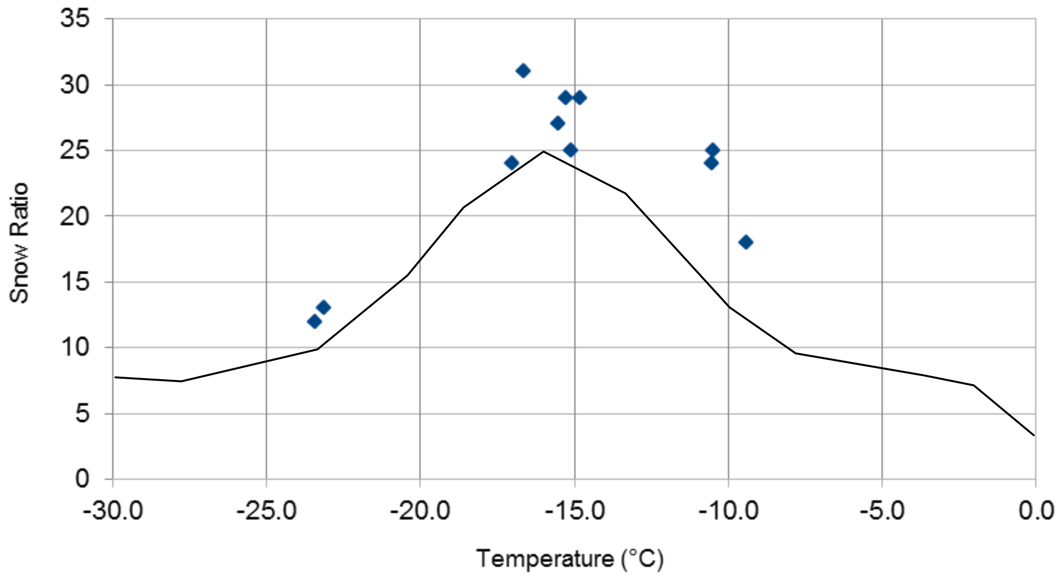

Figure 4.2.10 Cobb Method snow ratios at South Bend are plotted as a function of the temperature at which omega is maximized for each hour of observed snowfall. The solid curve shows the snow ratio as a function of temperature used for calculating cloud layer snow ratios (adapted from Cobb and Waldstreicher 2005). Data is from the lake-effect snowstorm on 1-2 January 2010.

CHAPTER 5: CONCLUSION

Lake-effect snow is a major operational weather forecasting problem. Similarly, forecasting snow amounts is very challenging, even in the near-term. One recent snow prediction technique, the Cobb Method (Cobb and Waldstreicher 2005), is used by the National Weather Service as a tool alongside other techniques such as the Garcia Method (Garcia 2000). The Cobb Method has shown some skill in the central Plains region, and so the goal of this paper was to extend the area of confidence to which it could be used to by testing the technique in a different geographical area. The Great Lakes region was chosen in order to gain an understanding on the limits to how the Cobb Method can be used, since the convective nature of lake-effect snow is challenging for an NWP model. By using RUC13 analysis data, the meteorological fields should be resolved fairly well. However, since vertical velocity is a diagnosed quantity, errors in upward motion are an inherent issue. The Cobb Method assumes that the upper air data in an NWP model is accurate, so the skill of the Cobb Method is degraded to some degree by the inaccuracies in the RUC13 analyses.

Snowfall climatology in the Great Lakes has been limited in the ASOS era, a period of time when NWP model data exists. Snowfall events with daily reports of greater than 5.04 cm (2 in) during 1995-2012 were collected over a representative sample of locations in the Great Lakes region. The study period was sufficiently large to gather over 1200 snowfall events, which were classified into lake-effect, non-lake-effect and transitional categories. Of the snowfall associated with these events, 38% was purely lake-effect and 55% of the snowfall was purely non-lake-effect. The annual mean number

of lake-effect snowfalls was nine at Syracuse, seven at Sault Ste Marie, four and a half at Muskegon, four at South Bend and Buffalo, and two and a half at Cleveland. Across the western Great Lakes, South Bend had a higher LESIF than Sault Ste Marie and Muskegon had the lowest LESIF. For eastern Great Lakes locations, Syracuse has a higher LESIF than Buffalo, with Cleveland having the lowest value of LESIF. When station-specific snowfalls are aggregated by month, no discernible variation is snow amounts gleaned through the study period, but a possible increase in snow amounts in February and decrease in March snowfalls is noted. Mean snow ratios were higher and had greater variance for the lake-effect snowfalls (22.5:1) than non-lake-effect snowfalls (16.3:1). Mean lake-effect snowfall ratios were lowest (around 18:1) at Sault Ste Marie and Cleveland, and much higher at Syracuse (34:1).

The results of this study indicate that to have accurate lake-effect snowfall forecasts using the Cobb Method, an empirically based upward adjustment may be needed for all snow amounts, especially for warning-level snowfalls. The Cobb Method estimates lake-effect snowfalls most accurately at Cleveland and performs the worst at Buffalo. For non-lake-effect snowfalls, events average out to a smaller overestimation of snowfall. Adding a compaction factor improves overforecasted snowfalls. Overall, the accuracy of lake-effect snowfalls is less than for non-lake-effect snowfalls, and non-lake-effect snowfalls are less accurate compared to observations than the snowfalls forecasted by Barnwell (2011) using the NARR. This indicates that using hourly fields may decrease the accuracy of daily snowfalls compared to using 3-hourly fields. As the modeled temporal resolution departs from the observed temporal resolution, more modeled time

steps are needed to equate the forecasts and observations, which may introduce an increased cumulative error effect.

Since observed precipitation was applied to the Cobb Method, and snowfall is the product of snow ratio and precipitation, snow ratios were used as a proxy for snowfall differences between observations and forecasts. The snow ratios of events used in the Cobb Method evaluation are distributed similarly to that of the climatology. Forecasted snowfalls have reduced variability and are more symmetric around the mean. These snowfalls have lower snow ratios, especially for lake-effect events, compared to the observed snowfalls. By examining the layer snow ratios of lake-effect snowfalls produced by the Cobb Method, we were able to connect the atmospheric variables modeled by the RUC13 to the forecasted snowfalls. We found that snowfalls depend highly on the thickness of the cloud layer in which upward vertical velocity occurs.

An important consideration to be made in these Cobb Method verifications is the potential bias in measurement. Considering the snowfall climatology at Syracuse, for instance, there seems to be a tendency towards very high snow ratios, even after removing events with snow ratios greater than 60:1. Since extreme snow ratios are observed in lake-effect snowfall and the Cobb Method does not easily generate very high snow ratios, underproduction of snowfall is reasonable. However, unadjusted Cobb Method output is a sum of hourly snowfalls, which we would expect to inflate daily snowfall relative to observed (presumably compacted) snowfall and relative to what Barnwell (2011) found using a NARR dataset with three hour temporal resolution. It is also possible that the RUC13 is not producing large enough vertical velocities in the

snow production zone relative to observations. To better diagnose the omega field, a repeated methodology using higher spatial resolution would be useful for a future study.

The underestimation of the Cobb Method snowfall for most lake-effect events may be caused in part by the restriction of accumulating snowfall to hours in which greater than a trace of liquid precipitation occurred. The inability of the Cobb Method to produce extreme layer snow ratios of greater than 35 also limits the Cobb Method. Our results are consistent with what Barnwell (2011) found in his study: the Cobb Method has trouble producing snow ratios higher than 20:1 (low density snow), a range of snow ratios that is observed for many lake-effect snowfalls in this study. When forecasted lake-effect snow events have high ratios (such as 25:1 and 30:1), they are typically in events with much higher observed ratios (such as 40:1 and 50:1).

The differences may be also be due to the resolution of the RUC13 model, as the grid spacing is somewhat coarse for depicting the mesoscale circulations associated with lake-effect precipitation. Using the concept of 10 grid points needed to resolve a feature, the RUC13 should only be able to capture portions of the lake-effect bands. The RUC13, like other NWP models, parameterizes boundary layer atmospheric conditions. The Cobb Method relies on the modeled relative humidities, temperatures, and vertical velocities to produce precipitation that may not be parameterized correctly for lake-effect scale. One way to improve the quantitative precipitation forecast (QPF) ability of the Cobb Method during lake-effect snowfalls may involve using a locally run, higher-resolution mesoscale model, such as the 4km WRF or High Resolution Rapid Refresh (HRRR). Another important consideration is the vertical spacing of the layers in the RUC13 sounding. Since the thickness of layers farther away from the surface is increased, model errors at

those heights have a larger impact on the overall snow ratio. A layer above 850 hPa with the same relative humidity and vertical motion as at 950 hPa will always be weighted more. Further research in the convective parameterization of the Rapid Refresh (RAP), the successor of the RUC13, and its possible effects on the Cobb Method output is needed.

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Appendix

The Caribou Snow Amount Tool 5.4 (Cobb) algorithm is a perl script that calculates precipitation type, snowfall, and icefall from BUFKIT files. The user runs the script for a particular NWP model and station ID. The default output is for each hour that the model produces a forecast. The input parameters include surface temperature, wind, snowfall, snow ratio, QPF, sleet, and freezing rain, as well as probabilities of hydrometeor type (snow, ice, rain).

The user can enter a command to change the cloud relative humidity threshold from 85% to a different value, change the temperature by a certain number of degrees at all pressure levels, or see the vertical profile of relevant winter weather parameters, such as relative humidity with respect to ice, wet bulb temperature, vertical motion, and snow ratio. With the latter command, the 0-hour (analysis) profile can be output. Since precipitation does not occur in the model analyses, snow will not be predicted, and therefore the Cobb Method snow ratio will always be zero. A simple change is necessary to calculate a snow ratio for the profile. After precipitation type is determined, there is a conditional statement that calculates a snow ratio only if snow is predicted. By deleting this statement, the modification to produce snowfall with 0-hour RUC13 data and observed precipitation was achieved.

Omitting the snow production above the 500 hPa layer is the second simple modification that was made to the Cobb algorithm. According to Barnwell (2011), the snow amount smart tool used in the Graphical Forecast Editor at NWS forecast offices

removes data above 500 hPa. Considering the shallow convection associated with lake-effect snowfall, it was expected that most of the impact of such a modification would be for non-lake-effect events. Similar to the snow ratio modification, a conditional statement is addressed to achieve this modification. Within the subroutine of calculating snow ratios and snow accumulation, there is an "if" statement that calculates snow ratios when the layer relative humidity with respect to ice exceeds the threshold and the layer omega is negative. By adding a third condition that the layer pressure must be greater than 500 hPa, only layer snow ratios below the 500 hPa layer are calculated.