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Verification of the Cobb Snowfall Forecasting Algorithm

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VERIFICATION OF THE COBB SNOWFALL FORECASTING ALGORITHM

by

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Forecasting storm total snow accumulation is one of the most difficult aspects of meteorological forecasting. The forecaster has to interpret three main variables in order to forecast snowfall accurately. These forecasting variables are the duration of the snowfall, the amount of liquid water the storm will produce, and the snow density or snow ratio. With the advancement of computer models in recent history, the need for a quick and easy interpretation of these variables has grown, and to improve on previous forecasting techniques' disadvantages with including the three snow forecasting variables. The Cobb Method snowfall forecasting algorithm utilizes model data and interprets all variables of snowfall forecasting and quickly produces snowfall amounts for storm events. By using past model and observational data, model forecast errors can be eliminated, and a better interpretation of the Cobb Method's accuracy can be determined compared to observations. The results indicate that the Cobb Method is 77.7% accurate to observations without considering errors in observational data. Dividing the study data into three groups of snowfall totals and three groups of snow ratios, the Cobb Method is still shown to have accuracy between 70% and 80%. In an attempt to improve the Cobb Method, two simple linear modifications were made. The two modifications show similar results; underforecasted amounts become more

accurate to observations while near exact and overforecasted amounts become more overforecasted. This study shows that the Cobb Method is a step in the right direction towards more accurate snowfall forecasting, and with increased research on the variables affecting snowfall and more accurate model data, the difficulties of forecasting snowfall amounts will become much easier.

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1. Introduction

Accurately forecasting storm total snowfall accumulation is a difficult problem in weather forecasting. In order to accurately forecast snowfall amounts, the forecaster must know the duration of the snowfall, the amount of liquid water the storm will produce, and the snow density or snow ratio. The snow ratio is the liquid equivalent of the measured snowfall accumulation, and the snow ratio is inversely proportional to snow density. One of the more difficult problems of the three unknowns is forecasting the correct snow ratio, which can vary in both space and time, and the processes that govern snow ratios are not simple or well understood. In general, a 10:1 snow ratio (10 inches of snow is equal to 1 inch of liquid water equivalent) is assigned to obtain the amount of snow that will accumulate. However, snow ratio values can vary anywhere from 3:1 to 100:1 (Ware et al. 2006). According to recent snow ratio studies by Roebber et al. (2003) and Baxter et al. (2005), the average U.S. climatological snow ratio is approximately between 13:1 and 15:1. Assigning a 10:1 snow ratio or even a single climatological average snow ratio, especially to the entire duration of a snow event, will not produce accurate conditions in most cases.

Another facet of snowfall forecasting is the use and misuse of operational "rules of thumb" or techniques that do not apply to all winter weather storm systems. An ingredients-based methodology (IM) for snowfall forecasting was developed by Wetzel and Martin (2001), and showed improvements, since the methodology allows the forecaster to apply many variables over the entire vertical atmospheric layer. However, no forecasting technique applies atmospheric variables to forecast snow ratios, or incorporates how snow develops within the cloud column within individual timesteps for the snow event.

In an attempt to solve the snowfall forecasting problem, Cobb and Waldstreicher (2005) developed the Cobb Method of snowfall forecasting. The Cobb Method snowfall forecasting algorithm considers the duration of snowfall, liquid water produced by the storm, and changes in the snow ratio through time and space. The algorithm can be applied to forecasting models and can quickly produce storm total snowfalls. Instead of assigning a single snow ratio to the entire event, snow ratios over the duration of the storm calculated by the Cobb Method can vary, and this can produce a much more accurate snowfall forecast. Forecasters can also use the Cobb Method to interpret how much snow will fall during specific periods of the event, instead of simply applying a cumulative snowfall total and snow ratio for the entire event.

Unfortunately, at present only limited scientific evaluations have been made for the Cobb Method, so its reliability is still uncertain. Therefore, this study aims to assess the accuracy of the Cobb Method. Model forecast dependence will be removed by using past observations. One of the main disadvantages of all snowfall forecasting techniques, including the Cobb Method, is they all suffer from model forecast inaccuracies. Obviously, the Cobb Method can only produce results as accurate as the model predicting the event. By eliminating forecasting errors in the model data and using observations to essentially forecast what already happened, any errors associated with model inaccuracy can be ignored, and the accuracy of the Cobb Method itself can be better interpreted. Any inaccuracies of the Cobb Method with respect to specific snow ratios and therefore snowfall amounts will be shown through statistical analyses. The results of this study will allow forecasters to use the Cobb Method algorithm with greater confidence by understanding the accuracies and inaccuracies in the algorithm when forecasting snowfall totals.

2. Background

Forecasting snowfall is not only a function of the amount that accumulates, which can be attributable to the duration of the snow event and the rate to which the snow falls, but also the density of the snow itself. First, the duration, or length of time the snow will fall has to be known. Second, the amount of liquid water the storm will produce, or the quantitative precipitation forecast (QPF), needs to be accurate. Third, it is difficult to accurately predict snow ratios, and assessing for changes in those snow ratios as the system evolves (Cobb and Waldstreicher 2005). However, even having one of these three factors completely accurate, for example the QPF, errors in forecasted snow amounts could be as large as a factor of 10 simply because of errors in forecasted snow ratios (Roebber et al. 2003). Accounting for the correct snow ratio and having accurate QPF will greatly increase snowfall forecast accuracy.

The forecaster has to interpret duration, a model's QPF, then determine what the storm snow ratio will be, and traditionally, a 10:1 snow ratio is used. A mean snow ratio of 10:1 is a good approximation, and although 10:1 works in some cases, many geographic regions and storm-specific cases are not accurately represented by this ratio. Baxter et al. 2005 stated that many different studies (e.g., Henry 1917; LaChappelle 1962; Grant and Rhea 1974; Doesken and Judson 1996; Super and Holroyd 1997; Judson and Doesken 2000; Roebber et al. 2003) have shown that this 10:1 assumption does not apply to all locations, and can vary depending on the atmospheric conditions for the forecast period. With snow totals greater than 5.1

cm (2 in), snow ratios can be anywhere from 2:1 as a lower bound and an upper bound up to 50:1 (Roebber et al. 2003). The United States mean observed values of snow ratios from Baxter et al. (2005) showed a climatological range of about 12:1 to 15:1 with an average of 13.5:1, slightly lower than what Roebber et al. (2003) found (15.6:1). For the region used in this study, Baxter et al. (2005) found a mean snow ratio around 13:1, with 25^{th}, 50^{th}, and 75^{th} percentile snow ratio values around 9:1, 12:1, and 15:1 respectively.

Forecasting techniques have tried to improve on this 10:1 assumption by using different atmospheric variables and “rules of thumb” to forecast snowfall. Synoptic climatology methods (e.g. Goree and Younkin 1966; Browne and Younkin 1970) forecasted heavy snowfall based upon a location 6.5° to 7° latitude downstream and 2.5° latitude to the left of the track of the 500 hPa vorticity maximum, or 167 km (90 nm) to the left of the 850 hPa low center over a 12-hour period. The Cook method (Cook 1980) forecasts the area of heavy snow by locating the warmest temperature at 200 hPa (in °C) and the coldest temperature within 15° latitude upstream of the forecast region then subtracts these values. The snowfall amount is determined by taking about half of the warm air advection (WAA) at 200 hPa. Temperatures at 700 hPa are used to modify the forecast if needed. The Magic Chart (Sangster and Jagler 1985; Chaston 1989) forecasts snowfall by first finding the 700 hPa net vertical displacement (NVD) of air that is over the forecasted region currently, and what will be advected into the region over the next 24 hours. The highest snowfall amounts are where the greatest net vertical displacement (in hPa) overlays with a temperature region of -3°C and -5°C at 850 hPa. The Garcia Method (Garcia 1994) predicts snow amounts for a 12-hour period using average mixing ratios (in g kg $^{-1}$) on an isentropic surface. The 700-750 hPa pressure level on the appropriate isentropic surface over the forecast region is located, and the mixing ratio value currently over the region is averaged with the maximum mixing ratio value advecting into the region over the next 12 hours. This value is multiplied by 2 to get the snowfall amount forecasted for the region. The LEMO method (Gordon 1998) relates the maximum 500 hPa vorticity value to a maximum snowfall amount using a simple procedure. All of these techniques are also described in Wetzel (2000).

Major difficulties with these methods are that the methods may not forecast snowfall correctly in many cases. The methods were implemented due to similarities in the weather patterns for the forecast period, and were heavily dependent on the locations of synoptic features (850 hPa low, 500 hPa vorticity, 200 hPa temperature advections, 700 hPa temperature, etc). The methods also did not focus on the important physical elements that are vital to a more accurate snowfall forecast, such as duration, liquid water, and changes in snow ratio over time. The previous forecasting techniques were also developed prior to the abundance of Numerical Weather Prediction (NWP) model data, can only be utilized within a 12 to 24 hour forecast timeframe to the event, and the methods are rarely accurate beyond the first 3 to 6 hours of that timeframe (Wetzel and Martin 2001). Using these previous forecasting techniques tends to focus on just a few levels or atmospheric variables, and does not accurately assess all factors effecting not only snowflake formation, but also evolution through the descent. For example, the Cook method works for some events because the WAA in the upper levels is usually a good indicator of cyclogenesis and the strength of the weather system in the lower levels. However, the whole atmosphere is not included in the method (except for the 700 hPa temperature used to modify the technique) so important variables in snowfall formation and descent are not accounted for. The Garcia method accounts for moisture availability and lift using isentropic surfaces at 700 hPa, which is appropriate for mid-level moisture and snow formation. However, what about below this level? Is the atmosphere dry below 700 hPa causing the snow to fall through this layer to not continue to grow, or to even mostly sublimate? After sublimation and eventual column saturation, will the storm progress further in time to finally allow, or increase accumulating snowfall amounts? These methods do allow some adjustment for the forecaster to conclude (like using the 700 hPa temperature in the Cook method, or adjusting for low level moisture with the Garcia method), however no single snowfall forecasting technique includes all variables necessary for a proper atmospheric evaluation.

Recent forecasting studies have moved away from the traditional "rules of thumb" and began applying real physical processes of the atmosphere to differentiate storms that affect a region. Wetzel and Martin (2001) developed an ingredients-based methodology (IM) for forecasting snowfall based upon the earlier works of ingredients-based approaches for flash flood forecasting (Doswell et al. 1996) and snowfall (Nietfeld and Kennedy 1998). It was noted, however, that the ingredients-based snowfall work done by Nietfeld and Kennedy (1998) was only used as a "conceptual model" rather than for operational use (Wetzel 2000). The Wetzel and Martin (2001) IM approach to snowfall forecasting has many advantages over the previous techniques since five variables are all accounted for in real time: forcing, moisture, instability, precipitation efficiency (or how cloud microphysics effect the precipitation rate), and temperature (Wetzel and Martin 2001). Previous forecasting techniques do not assess for all five of the ingredients (Table 2.1). The "left to forecaster" (LtF) in Table 2.1 indicates that the variable is not part of the technique, however, forecasters have the option to make adjustments to the results by adding in the influence of that respective variable. No one technique accounts for more than two variables used in the ingredients based methodology (Table 2.1), although certain ingredients may be inadvertently implied. For example, the Magic Chart uses net vertical displacement of air parcels and may consider the stability since the more unstable the parcel, the greater the vertical displacement even though that ingredient is "left to the forecaster" (Wetzel 2000). Regardless of included ingredients or implied, no previous technique included all five of these variables to more accurately forecast snowfall.

Although the IM is more accurate than previous methods, an easier, numerical weather prediction (NWP) model based algorithm would make snowfall

Table 2.1. The 5 variables of the ingredients based methodology and previous techniques' ability to account for each ingredient (taken from Wetzel and Martin 2001). LtF corresponds to "left to forecaster", meaning the forecaster must go outside the forecasting technique in order to account for that variable.

	Synoptic Climatology	Cook Method	Garcia Method	Magic Chart	LEMO
Forcing for Ascent	No	No	LtF	Yes	No
Moisture	No	No	Yes	Ltf	No
Instability	No	No	No	No	No
Efficiency	No	No	No	No	No
Temperature	No	Yes	No	Yes	No

forecasting not only faster and more accurate, but would incorporate all of the variables generated by the NWP model much more quickly than accounting for these variables individually. Furthermore, the difficulty of snowfall forecasting is not only forecasting the amount of snow, but how much liquid water will fall from the storm, and what will the snow ratios be from the beginning to the end of the event. Roebber et al. (2003) stated that it would be beneficial to create an integrated, and well-verified method for forecasting snow from NWP models, and until then, converting liquid water to snow through the diagnosis of snow ratio is the only way to forecast snowfall. Roebber et al. (2003) also stated that in-cloud vertical motions were not included in their study, and would greatly improve their results. Despite the drawback of the absence of vertical motion, a web-based diagnostic of snow ratio (found at http://sanders.math.uwm.edu/cgi-bin-snowratio/sr_intro.pl) based upon the neural network technique of Roebber et al. (2003), was implemented online. The technique outputs the probabilities that the storm snow ratio will be within the three categories of below average (<9:1), average (9:1 to 15:1), and above average (>15:1). This is a useful tool using model data, however, being able to see snow ratios during the duration of the snow event would be very useful, instead of just one assigned probability of a range of snow ratios. Also adding in vertical motions would aid in the forecast process.

The Cobb method (Cobb and Waldstreicher 2005) was developed with the goals of efficiency, simplicity, and accounting for duration, changes in snow ratio, vertical velocities, and changes in liquid water. The main goals of the method are to deviate away from the 10:1 snow ratio assumptions, to associate the effects of vertical motions on snow formation, and include the evolution of the snow through the cloud, and over time. The physical quantities from the IM are all included in the calculation and output of the algorithm. The Cobb method utilizes the snow ratios associated with the different observed crystal types described in Dube (2003), and the cross-hair signature of Waldstreicher (2001). Dube (2003) found that the highest snow ratios are associated with dendrites and rimed crystals. Dendrites and rimed crystals are also associated with lower snow densities (Table 2.2). Snow ratios or snow crystal densities (Figure 2.1) are primarily a function of temperature and humidity. The higher the supersaturation, or higher the relative humidity, the lower the density of the snow crystal at that temperature (Figure 2.1). Fakuta and Takahashi (1999) showed two peaks of low-density crystals (Figure 2.2) when studying snow crystal densities. Crystals were grown under controlled conditions for ten minutes, and the observed density with respect to temperature was determined.

The cross-hair signature (Waldstreicher 2001) exposes the relationship between vertical motion maxima of at least 10 $\mu b\ s^{-1}$ correlated with the dendrite-favored temperature region between -12° to -18°C. The goal of this signature is to forecast rapid snow accumulation and efficient snow production. Waldstreicher (2001) determined that if the cross-hair signature is observed in two of three successive NWP model runs, significant snowfall can be expected. For 55 winter storm warning events, 76.36% of the events had a cross-hair signature, and for 75

Table 2.2. Snow ratios associated with snow crystal types adapted from Dube (2003).

Snow Crystal Type	***Snow Ratio***
Stellar Dendrites	> 25:1
Dendrites/Needles	18:1 – 25:1
Mixed Dendrites, Plates/Needles	12:1 – 18:1
Slightly Rimed Dendrites/Columns or Plates	9:1 – 12:1
Significantly Rimed Crystals	5:1 – 9:1
Ice Pellets/Snow Grains	3:1 – 5:1

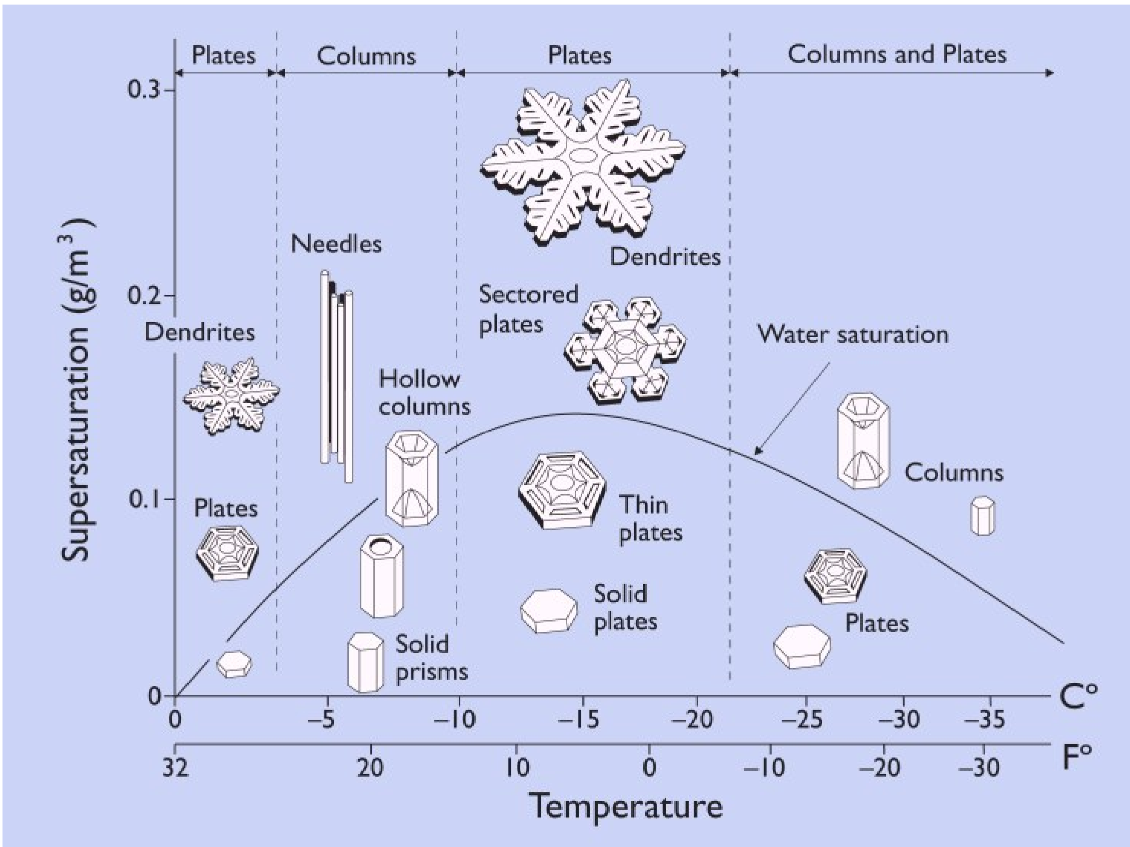

Figure 2.1. Formation temperature and saturation for snow crystal types at specific temperatures and levels of supersaturation (taken from Libbrecht 1999).

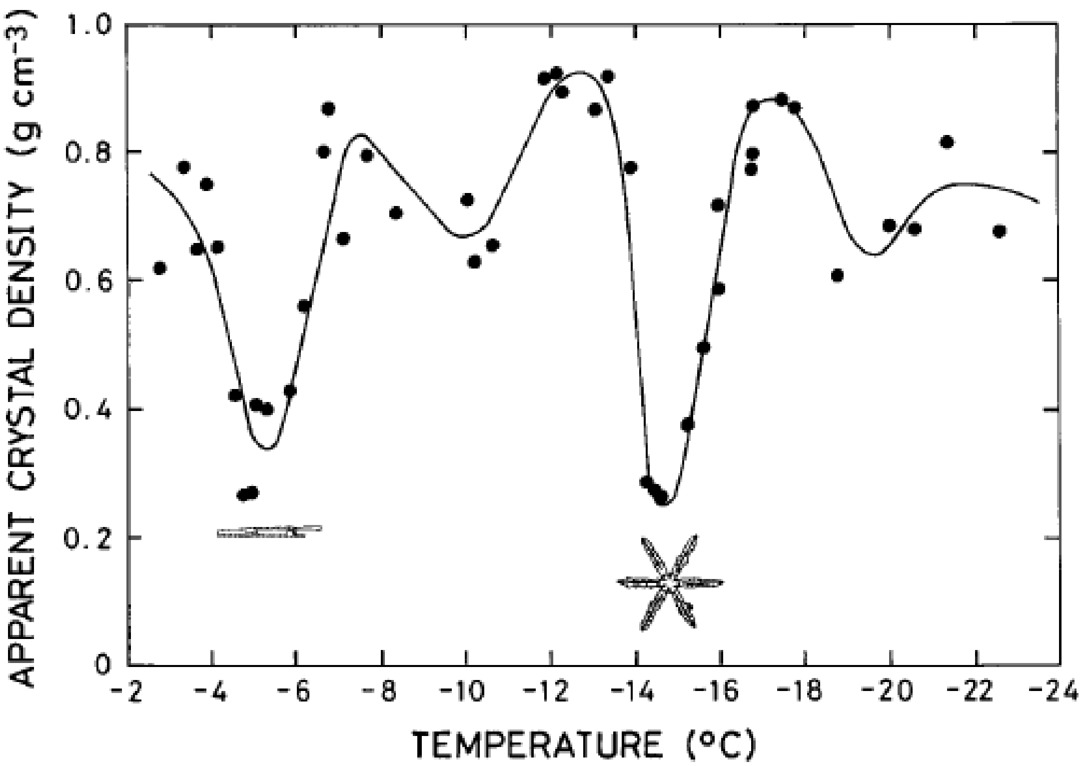

Figure 2.2. Snow crystal densities as a function of temperature (taken from Fakuta and Takahashi 1999).

winter weather advisory events, only 9.46% of the events had a cross-hair signature (Waldstreicher 2001). Therefore, the cross-hair approach was determined to distinguish between winter weather advisory and winter storm warning events. The usefulness of this technique's interpretation of vertical motion maxima and dendritic growth temperatures are implemented in the Cobb Method. Taking the results from Dube (2003), Baumgardt (1999), the cross-hair approach from Waldstreicher (2001), and some interpolation from Fakuta and Takahashi (1999), the Cobb method interpolates snow ratio primarily as a function of temperature (Figure 2.3).

Cobb and Waldstreicher (2005) stated that vertical motion is not only related to the rate of precipitation production (assuming saturated conditions), vertical velocity effects how long snow crystals can remain in a layer and to what degree supersaturation can persist. Cobb and Waldstreicher (2005) also describe a region called the Snow Production Zone (SPZ) which is described as a region between -12°C to -18°C that is excellent at producing low-density dendritic snow crystals with high crystal growth rates (Figure 2.4). At this temperature range many ice deposition nuclei are active in supporting crystal growth rather than supercooled water droplet formation. Combining the snow production zone with high values of vertical motion would coincide with high snow ratio (low-density) dendritic snow crystals, and high snowfall rates, and is supported by the studies of Waldstreicher (2001), Baumgardt (1999), and Dube (2003) (Cobb and Waldstreicher 2005).

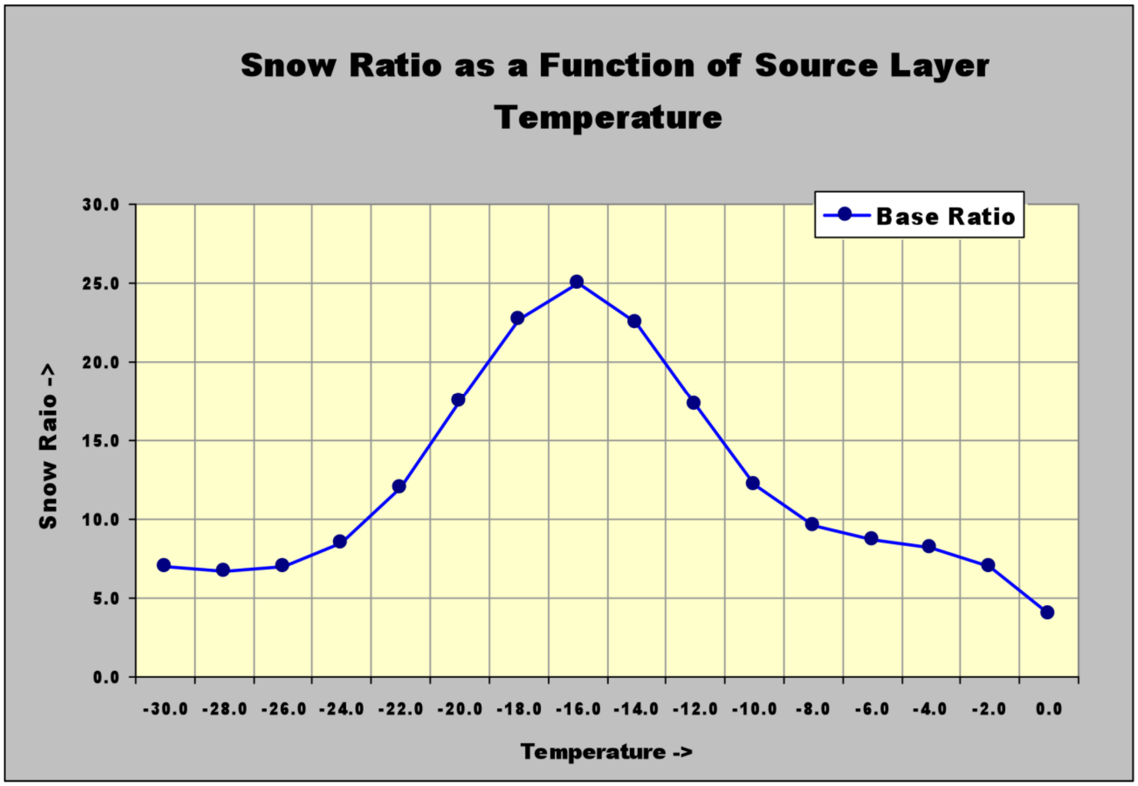

Figure 2.3. Snow ratio as a function of temperature used for calculating cloud layer snow ratios in the Cobb method (taken from Cobb and Waldstreicher 2005).

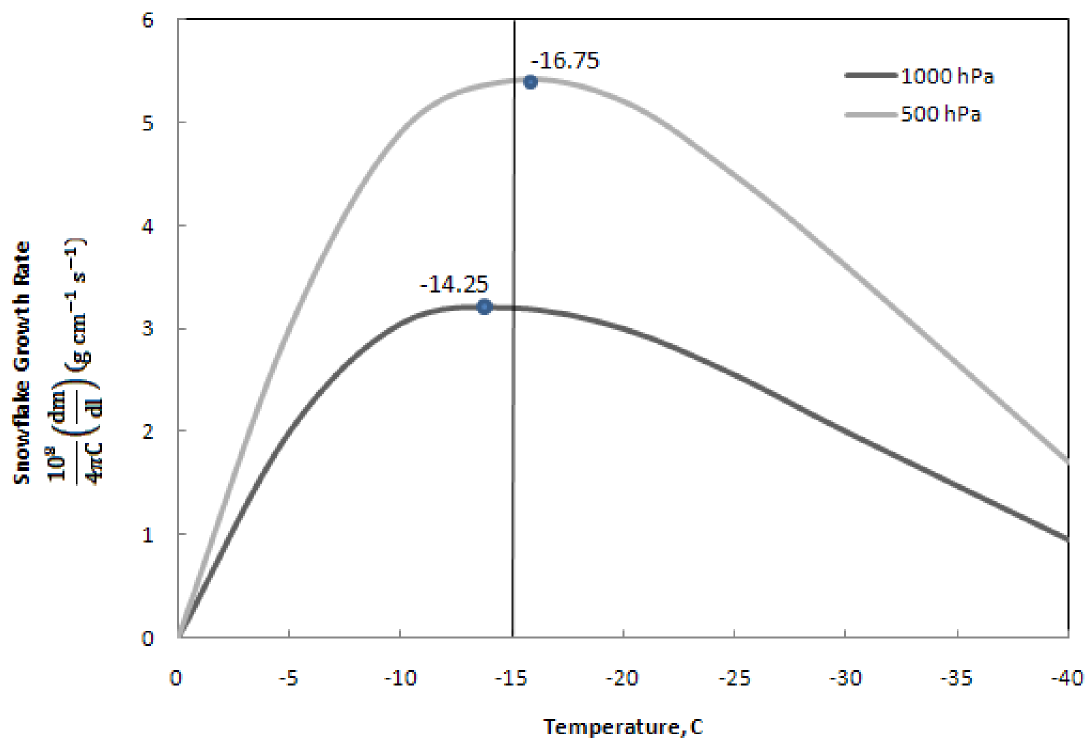

Figure 2.4. Normalized snow crystal growth rates with respect to temperature adapted from Byers (1965)

Waldstreicher (2001) and Cobb and Waldstreicher (2005) stated two important relationships between the snow production zone and vertical motion maxima either above or below that region. First, if vertical motion maxima are above the zone, moderate density plates and columns are likely to form and possibly fall through the zone and grow branches increasing their snow ratio, decreasing snow density. Second, if vertical motion maxima are below the SPZ, supercooled water droplets will be found and riming would dominate crystals falling through the layer producing lower snow ratio values (higher densities), or no snow at all depending on the temperature.

The Cobb method algorithm incorporates vertical velocities, relative humidities, and temperatures from NWP data to determine snowfall totals. Snow ratios are calculated from the vertical velocities, relative humidities, and temperatures for each layer of a cloud column. To calculate a surface snow ratio, each layer snow ratio is weighted and summed. Snowfall amount for a time period is the surface snow ratio multiplied by the model QPF. Each time period can be summed up over the entire event timeframe to get the storm total snowfall.

To calculate the weighted snow ratio for each time period, the Cobb Method algorithm uses 4 steps listed below:

1) The algorithm first finds the maximum upward vertical velocity (UVV) within a cloud layer. A cloud layer in a NWP model is a layer with a relative humidity with respect to ice greater than or equal to 90%.

2) A weighting factor is then calculated. The weighting factor includes the UVV (ω, or layer average upward vertical motion), max UVV (ω_{max}, or maximum upward vertical motion within the cloud), and the thickness (Φ_2 - Φ_1, where Φ is the geopotential height) of the layer being calculated.

$$\textit{Weighting Factor} = \omega\,(\omega/\omega_{max})^2\,(\Phi_2 - \Phi_1) \quad (1)$$

These layer-weighting factors are summed over all layers and used in step (4).

3) The snow ratio is interpolated from each layer calculated in step (2) with a relationship based upon temperature for each layer(Figure 2.3).

4) Finally, the weighted contribution of the layer's snow ratio is calculated:

$$WSR = SR(T) * (LWF / \Sigma \textit{ Layer Weighting Factors}) \quad (2)$$

Where WSR is the weighted snow ratio, SR(T) is the snow ratio with respect to temperature interpolated from Figure 2.3, and LWF is the individual layer weighting factor. The weighted layer snow ratios are then summed to get the snow ratio used to multiply by the QPF for that time period, and a snowfall total is outputted.

Cobb and Waldstreicher (2005) also state a few important assumptions for this algorithm. The weighting factor from step (2) is calculated this way because the layer with the most vertical motion will have the largest contribution to the total snow ratio. Adding in this weighting factor enables the algorithm to better include the extremities within snow ratios (Cobb and Waldstreicher 2005). The other two assumptions of the algorithm are the same as many other forecasting techniques, that the NWP model produces accurate vertical motions and QPF for the event.

3. Methodology

No matter how accurate the snowfall forecasting method, algorithm, or rule of thumb may be, if the NWP model does not provide accurate output, your forecasted snowfall amounts will not be accurate. There is no way to be certain if the difference lies within the NWP model or the forecasting technique when there are differences between the technique and observations. Therefore, NWP model data cannot be used for testing the accuracy of a forecasting technique. In order to determine the strengths and weaknesses of a snowfall forecast technique, in this case, the Cobb method, NWP model forecast error needs to be eliminated or at least ameliorated to the extent possible. Removing the error is accomplished by using reanalysis model data and observations from previous measurements. By using reanalysis data and observations, the most accurate atmospheric and surface data can be used to analyze the Cobb Method.

Using the North American Regional Reanalysis (NARR; Mesinger et al. 2006) dataset, assuming these data represent current conditions, and surface observations from the National Climate Data Center (NCDC) U.S. local climatological data (LCD) publications, the goal was to produce a hindcast. The timeframe of this study is from 1979 to 1993 for two reasons: the NARR dataset begins in 1979, and the implementation of the Automated Surface Observing System (ASOS) stations began in 1993 which ended human measurement of precipitation.

To test the Cobb Method in the central part of the United States, five stations were chosen. The central United States locations were chosen due to their close proximity to each other, their location relative to climatological synoptic patterns that affect the area, and they are far away from abundant moisture sources. The close proximity of the locations allows for a slightly different perspective for each synoptic storm. Three stations are located within the Omaha-Valley NWS CWA (Lincoln, NE, Omaha-North, NE, and Norfolk, NE), one within the Hastings NWS CWA (Grand Island, NE), and one located within the Des Moines NWS CWA (Des Moines, IA). These locations were chosen because they include hourly measured liquid precipitation that could be implemented as "QPF" into the simulated model data. Grand Island and Des Moines were chosen because they are upstream and downstream of the Omaha-Valley CWA. In the case of a typical synoptic pattern for this region, Grand Island would be near the beginning stage of the synoptic storm. Des Moines may enable the synoptic storm to develop further, downstream of the other four sites. The Des Moines location might also allow more moisture for the storm, and provides another condition to test the method. A wide variety of synoptic winter storms affects this area, and would allow for events with different contributing atmospheric variables to affect the Cobb Method.

There are 10 storms within the study period that meet the following classifications: All five locations report snowfall greater than 48.3 mm (1.9 in) during the same storm, and one of the five stations has to report at least 127 mm (5 in) of snowfall. The first requirement, having snowfall greater than 48.3 mm, is similar to the standards used by Roebber et al. (2003) and Baxter et al. (2005) of 50.8 mm (2 in), and all stations had to report at least 2.8 mm (0.11 in) of liquid equivalent precipitation. The minimum reported snowfall was dropped to 48.3 mm (1.9 in) due to two of the events having a station reporting that amount, increasing the number of events. Requiring one station to have a minimum of 127 mm (5 in) of snowfall also ensures that there will be a greater variability in snowfall totals over the ten storms in order to get a better range to test the method. The snowfall amounts are 6-hour new snow measurements according to National Weather Service (NWS) requirements. The 6-hour snow accumulation measurements are summed up to yield a 24-hour snowfall accumulation, reported on the LCD monthly data sheet, and the 24-hour snowfall accumulations are the snowfall amounts used for comparison to Cobb Method snowfall accumulation forecasts.

In addition, if one of the stations reports any other type of precipitation (freezing rain/drizzle, ice pellets/sleet, or rain) in the middle of the event, the event is not used. If there is precipitation other than snow during the middle of the event, it is unclear whether the reported liquid precipitation for the 3-hour period is attributable to snow or another form of precipitation, and therefore cannot be used. However, it is possible for precipitation type to be reported other than snow during the beginning or end of an event and still be included in the study. If precipitation other than snow occurs at the beginning of an event and then switches to snow, the event is included in the data set from the time of the precipitation type switch. If the precipitation type switches from snow to something other than snow at the end of the event, the event is determined by the time when the precipitation type switched. In both cases, the liquid precipitation is only accumulated when the precipitation type is snow. This eliminates the question of precipitation other than snow affecting liquid equivalents, and thus another possible source of error not attributable to the method itself. Furthermore, if a station reported a trace of liquid precipitation during an hourly observation, it is not counted or approximated in any way towards the total storm precipitation.

Once the storms are established, NARR data are obtained and used to create BUFKIT files for use in the Cobb Method. Since the measured liquid precipitation from the LCD is hourly, the observations are totaled up over 3-hour increments in order to match the temporal resolution of the NARR dataset. The NARR data and LCD precipitation observations are combined and outputted to BUFKIT files. The BUFKIT files are then used with the Cobb method, and snowfall accumulation are obtained.

To analyze the Cobb Method compared to observations, the data are interpreted from the 10 storms for the 5 locations (50 events). The 50 events were also analyzed by snowfall amount and snow ratio. The snowfall amount and snow ratio categories were divided into three groups with fairly reasonable characteristics and, for the most part, equal number of events within each group, and not having an overwhelming majority of events in any one group. To see if there's a snowfall total bias, the data are divided into three snowfall total groups relative to the Cobb Method amounts obtained in this study. The first snowfall total group is light snowfalls less than 7.62 cm (3 in), the second is moderate snowfalls between 7.62 cm (3 in) and 12.70 cm (5 in), and the third is large snowfalls greater than 12.70 cm (5 in). The second category is to analyze observational snow ratios with snow ratios found using the Cobb Method, with the Cobb Method snow ratios being divided into three groups. The groups within the snow ratio category are high-density Cobb Method snow ratios from 3:1 through 10.9:1, moderate density Cobb Method snow ratios from 11:1 through 12.9:1, and low-density Cobb Method snow ratios greater than 13:1. By sorting the data by the Cobb Method forecasted totals rather than the observations, biases can be found within the Cobb Method, and the forecaster can adjust the snowfall total forecast based upon data that are already visible before the event.

For all categories, the actual snow ratios from observations are provided with the weighted Cobb snow ratio interpretation. The Cobb actual snow ratio is found by taking the total water from observations and the snow total amount the Cobb Method predicted. The weighted Cobb snow ratio is found by first weighting the 3-hourly snow ratios to the amount of water for that respective three hour period, then averaging all values during the duration of the storm. Ten to one snowfall totals were also added to the measured snowfall and Cobb forecasted snowfall totals to see what a 10:1 snow ratio would have forecasted for each event.

The last section of the Cobb Method analysis provides some insight to simple changes that may improve the snowfall forecasts. Since the Cobb Method largely relies on vertical velocities and temperatures assigned to specific layers of the atmosphere, the focus of this section will rely on these variables. Based upon the data from the events, two simple modifications are applied to the Cobb Method algorithm to assess what changes will occur. The first change is to delete all data above 500 hPa, then run the Cobb Method algorithm and check the results. The reasoning for this change was that the Cobb Method assigns all cloudy layers less than -24°C a snow ratio of 10:1, and this ratio seemed to be an extremely high snow density for that region of the atmosphere. The lack of moisture at the heights associated with temperatures that cold would suggest that errors in Cobb Method forecasts could be attributed to this problem. Also, the NWS has a snow amount smart tool used in the Graphical Forecast Editor (GFE) that uses the Cobb Method in some cases. When used, the data above 500 hPa are also removed by the snow amount smart tool when calculating the forecasted snow. The second change added to the Cobb Method algorithm is with the same 10:1 snow ratio assumption at temperatures less than -24°C, but for this change, the 10:1 snow ratio is changed to a higher snow density value. In this case, a value of 12.7:1 is used since it is very similar to the climatological average snow ratio found for the study region. If the values within the Cobb Method are slightly different because of a 10:1 snow ratio assumption, assigning these layers of the atmosphere to a climatological average snow ratio may improve snowfall forecasts.

4. Results

4.1 All Locations

The 50 events presented here have similar characteristics (Figure 4.1.1, Table 4.1.1) to the snow ratios found by Roebber et al. (2003) and Baxter et al. (2005), and the events for this study are a representative sample which conclusions can be drawn from. The number of observations and stations in this study are considerably less than the studies of Roebber et al. (2003) and Baxter et al. (2005). It should be noted that the previous studies were for the entire continental U.S. and not just for the forecast area used in this study of Eastern Nebraska and Iowa. Data from the Omaha-Valley CWA from Baxter et al. (2005) are included for direct comparison to the data from this study (Table 4.1.1).

The Cobb Method forecasted snow ratios and observed snow ratios are also similar (Figure 4.1.2). The Cobb Method mean snow ratio value at 12.3:1 is slightly lower than the observed snow ratio mean of 14.1:1 (Table 4.1.2), which is consistent with the snowfall amount statistics showing the mean Cobb Method snowfall amounts tend to be slightly less than observations. The Cobb Method and observations have a higher mean snow ratio over the median, showing the skewness of observations towards higher snow ratios (Table 4.1.2). However, the skewness of observations towards higher snow ratios over the Cobb Method is greater; the 25th percentile values are very similar between the Cobb Method and

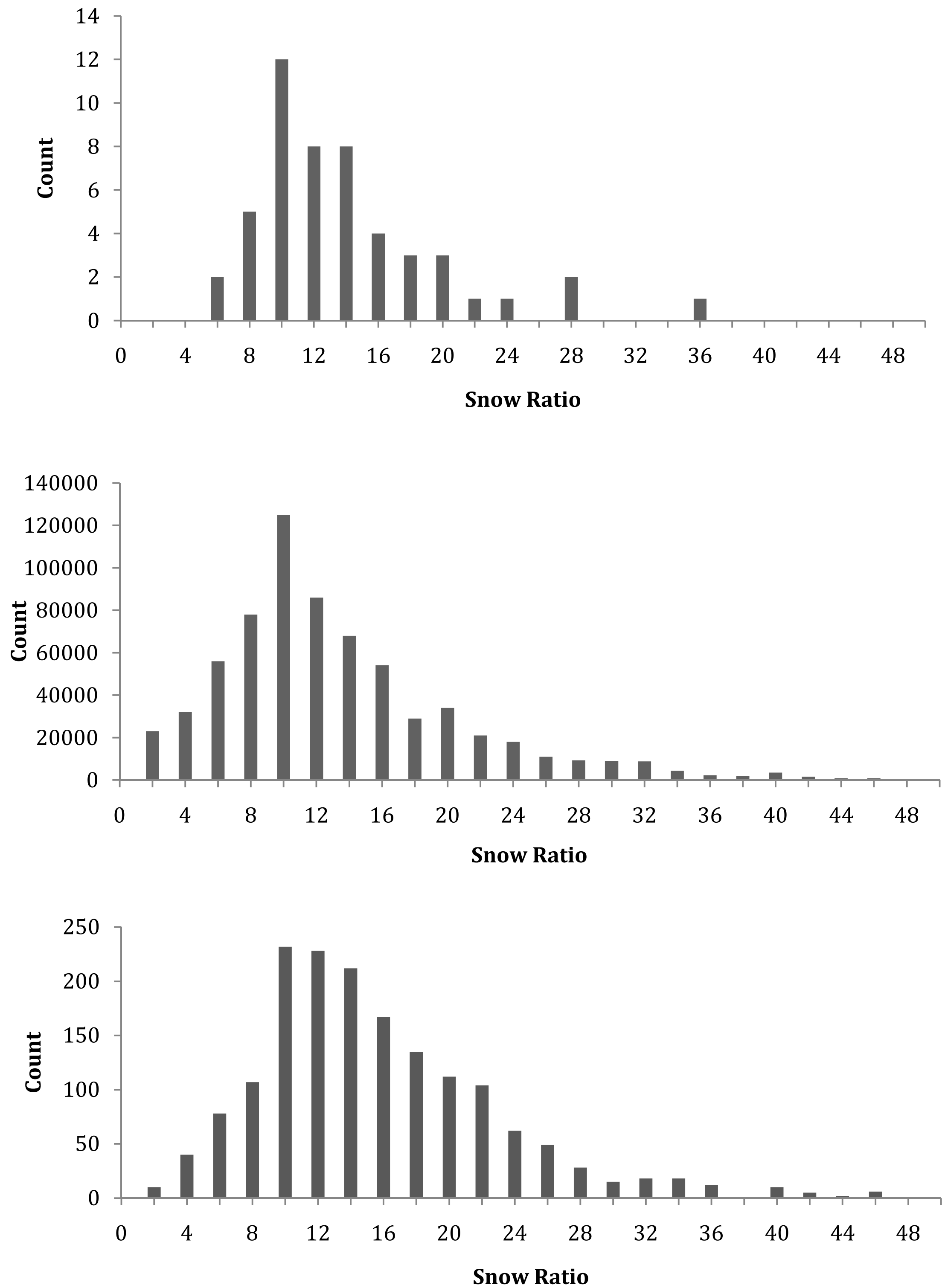

Figure 4.1.1. Histograms of snow ratios for the current study (top), Baxter et al. (2005) (middle), and Roebber et al. (2003) (bottom).

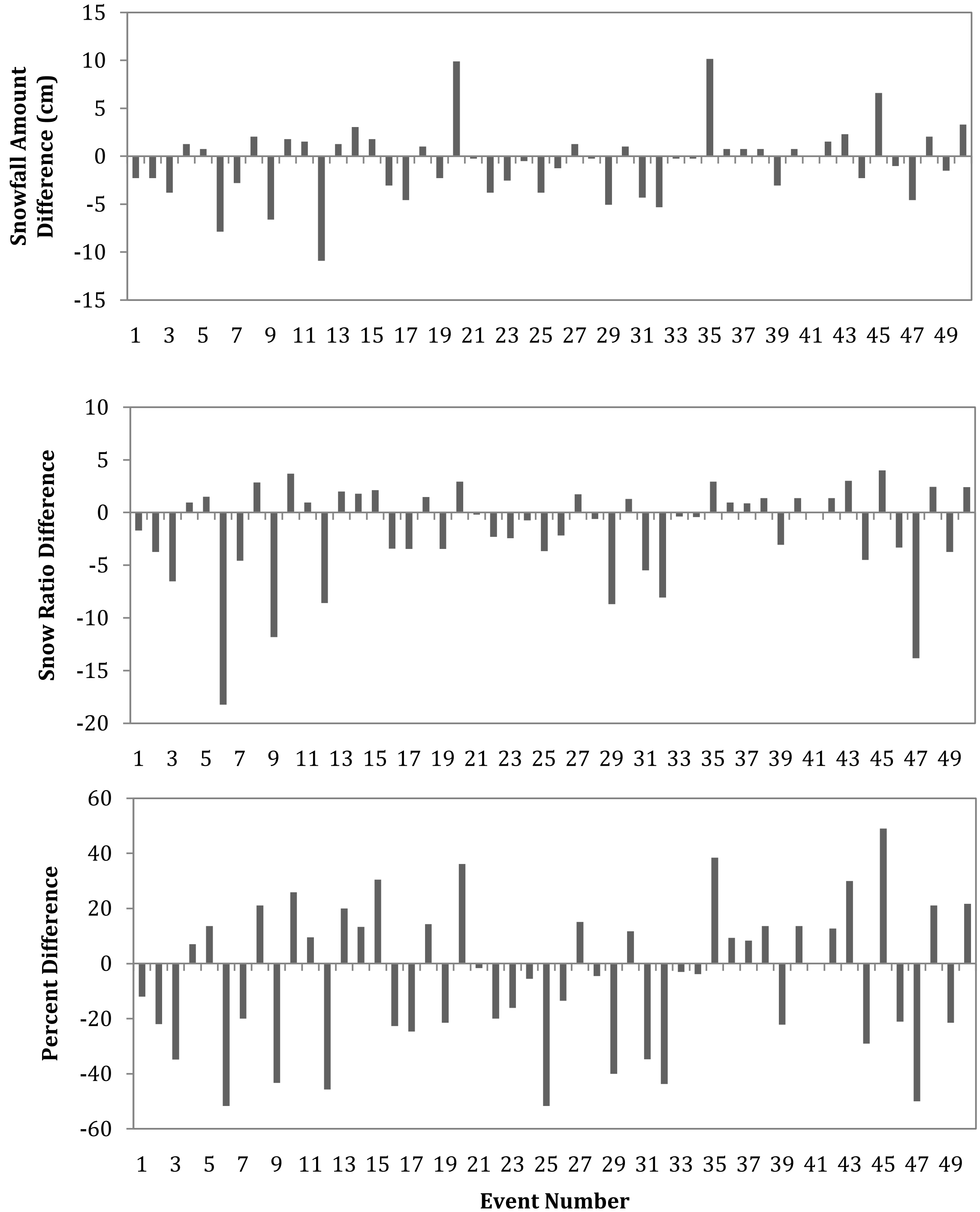

Figure 4.1.2. All events snowfall amount (top), snow ratio (middle), and percent (bottom) differences between actual observations and Cobb forecasted totals. Values greater than 0 correspond to Cobb overforecasting observations, and values less than 0 correspond to Cobb underforecasting observations.

Table 4.1.1. Snow ratio statistics for previous studies and the current study.

	Current Study Obs (NE & IA)	Current Study Cobb (NE & IA)	Baxter et al. (2005) (Omaha CWA)	Baxter et al. (2005) (All U.S.)	Roebber et al. (2003) (All U.S.)
Mean	14.05	12.34	12.60	13.53	15.60
Median	13.38	12.16	11.40	12.14	14.10
Mode	10.00	12.50	-	10.00	10.00
Std Dev	5.50	2.40	6.20	7.05	-
25th %	10.61	11.01	8.90	9.26	-
75th %	15.83	13.28	15.80	16.67	-
Obs	50	50	9224	668,832	1650 Events
Stations	5	5	-	7760	28

Table 4.1.2. Snowfall amount and snow ratio statistics for all events.

	Snowfall		Snow Ratio	
	Cobb (cm)	**Obs (cm)**	**Cobb**	**Obs**
Mean	11.25	11.87	12.34	14.05
Median	8.76	10.29	12.16	13.38
Mode	8.13	5.59	12.50	10.00
Minimum	3.56	4.83	3.41	6.97
Maximum	37.34	27.43	18.33	35.29
Std. Dev.	6.99	5.56	2.40	5.50
25th Perc.	7.43	7.68	11.01	10.61
75th Perc.	13.14	15.24	13.28	15.83

observations, but the 75th percentile value of the Cobb Method is less than observations (Table 4.1.2). The Cobb Method does not have a higher range of snow ratios compared to the observations (Table 4.1.2), which is opposite of the snowfall amount statistics.

When considering snowfall amounts for all 50 events, the Cobb Method and observed snowfall amounts are quite similar. The Cobb Method forecasted snowfall amounts have a mean of 11.3 cm, observed snowfall amounts have a mean of 11.9 cm, and a median much closer to the mean than Cobb Method forecasted snowfall amounts (Table 4.1.2). The range of observed snowfall amounts is around 22 cm and the range of Cobb observed snowfall amounts is around 35 cm indicating that the Cobb Method, although skewed towards lighter snowfall totals, has a much broader standard deviation of snowfall totals over observations (Table 4.1.2). The skewness of the Cobb Method towards lower snowfall totals over observations is also shown with the 25th and 75th percentile values (Table 4.1.2), which show the 25th percentile values to be much closer together (.25 cm difference) when compared to the 75th percentile value (2.1 cm difference).

The differences between the Cobb Method forecasted snow ratios and observed amounts show the Cobb Method to only have a difference of 22.3%, which corresponds to 2.8 cm (1.1 in) for snowfall amounts and 3.5 units for the snow ratios (Figure 4.1.2, Table 4.1.3). Most of the difference lies with an underforecasting bias by the Cobb Method of 25.2% (Table 4.1.3). The 25.2%

Table 4.1.3. All events average differences for both amounts (in cm) and percentages. Overforecast and underforecast amounts are Cobb forecasted amounts compared to the actual observation measurements.

	All Points				Overforecast		Underforecast	
	Magnitude		Overall					
	Value	(%)	Value	(%)	Value	(%)	Value	(%)
Snowfall (cm)	2.8	22.3	-0.6	-4.9	2.6	20.1	3.2	25.2
Snow Ratio	3.5	22.3	-1.7	-4.9	2	20.1	4.8	25.2

difference corresponds to an underforecasting error of 3.2 cm (1.3 in) of snowfall or 4.8 units of the snow ratio (Table 4.1.3). When considering overforecasting, the Cobb Method overforecasts observations by 20.1% on average, which corresponds to 2.6 cm (1.0 in) of snowfall or 2 units of the snow ratio (Table 4.1.3).

The comparisons between the Cobb Method and observations provide useful information on the accuracy of the Cobb Method. Overall, there is a slight bias for the Cobb Method to underforecast observations by about 5% (Table 4.1.3). More detailed results may provide answers to any biases within the Cobb Method since underforecasted and overforecasted differences to observations are very similar. By going back to the three fundamental questions with snowfall forecasting: how long will the snow occur, what is the liquid water content of the snow, and what is the density of the snow, any biases of the Cobb Method can be exposed. Further analysis of the data through separating the data by snowfall amounts and snow ratios may allow biases within the Cobb Method to be exposed for not only snow densities, but for events with varying amounts of snowfall.

4.2 Snowfall Totals

The second category of analysis divides the 50 forecasted snowfall events according to the Cobb Method into three groups; light snowfalls less than 7.62 cm (3 in), containing 13 events, moderate snowfalls between 7.62 cm (3 in) and 12.70 cm (5 in), containing 23 events, and heavy snowfalls greater than 12.70 cm (5 in), containing 14 events. Dividing the Cobb Method data by snowfall amounts allows for any biases to be shown with Cobb Method snowfall totals compared to observation snowfall totals.

For the 13 light snowfall events, three events are overforecasted by the Cobb Method, and ten are underforecasted (Figures 4.2.1 and 4.2.2, Table 4.2.1) when compared to the observations. Most of the differences in accumulation are very small, with most differences under 3 cm (Figure 4.2.2). The average difference appears large at 27.1%, but the corresponding average difference in amounts is only 2.5 cm (Table 4.2.2). Light snowfall events as a whole have a underforecasting bias of 2.2 cm, or roughly 21% difference between Cobb Method forecasted snowfall amounts and observations (Table 4.2.2). The amounts and corresponding percent differences show that even though the percentages seem high, the amount differences are small between observations and Cobb Method snowfall amounts. Since light snowfall amounts correspond to events less than 7.62 cm (3 in), an overall percent difference of around 21% or 2.2 cm, which is not very significant when forecasting snowfall amounts (Table 4.2.2).

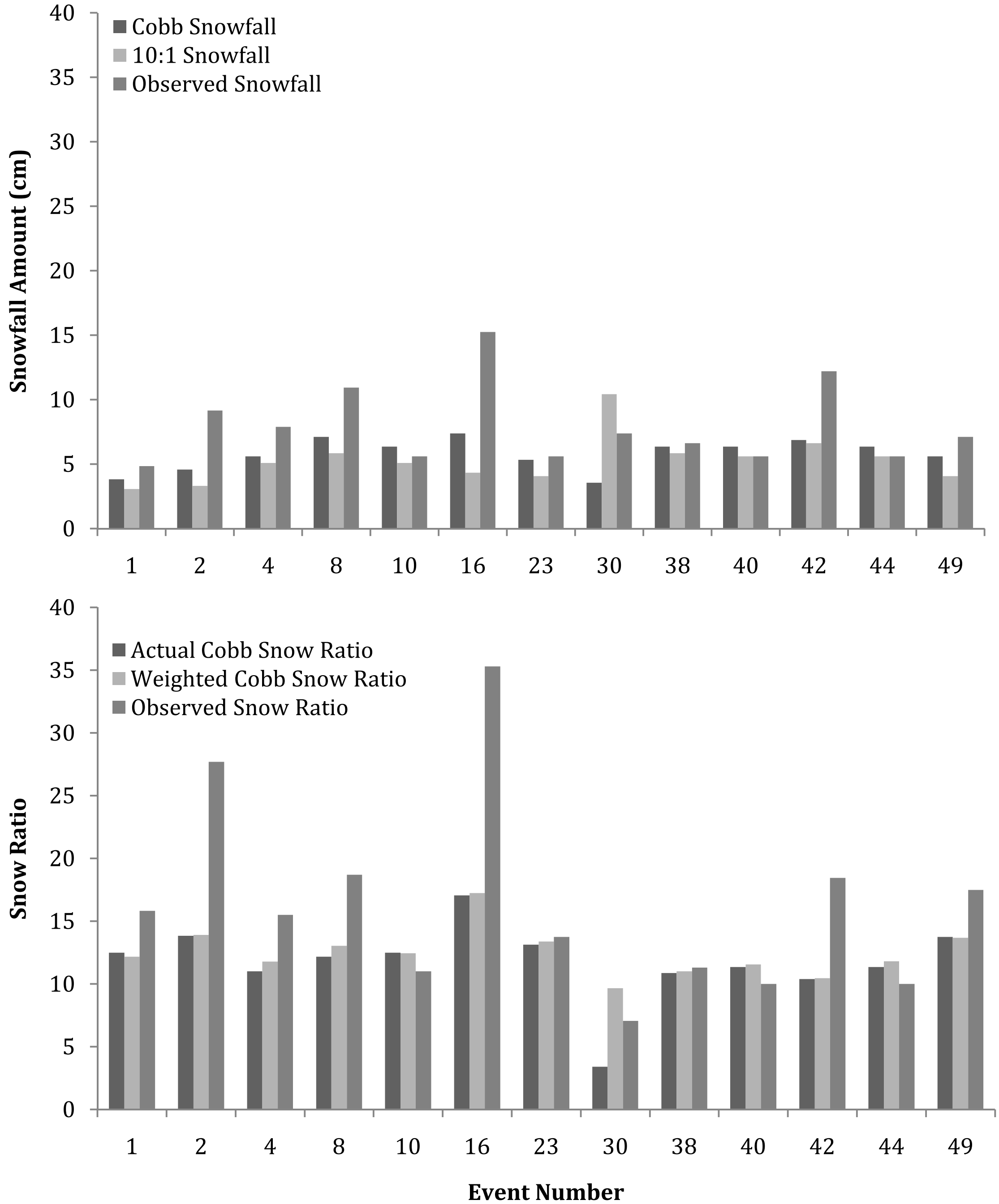

Figure 4.2.1. Light snowfall event amounts (top) and snow ratios (bottom).

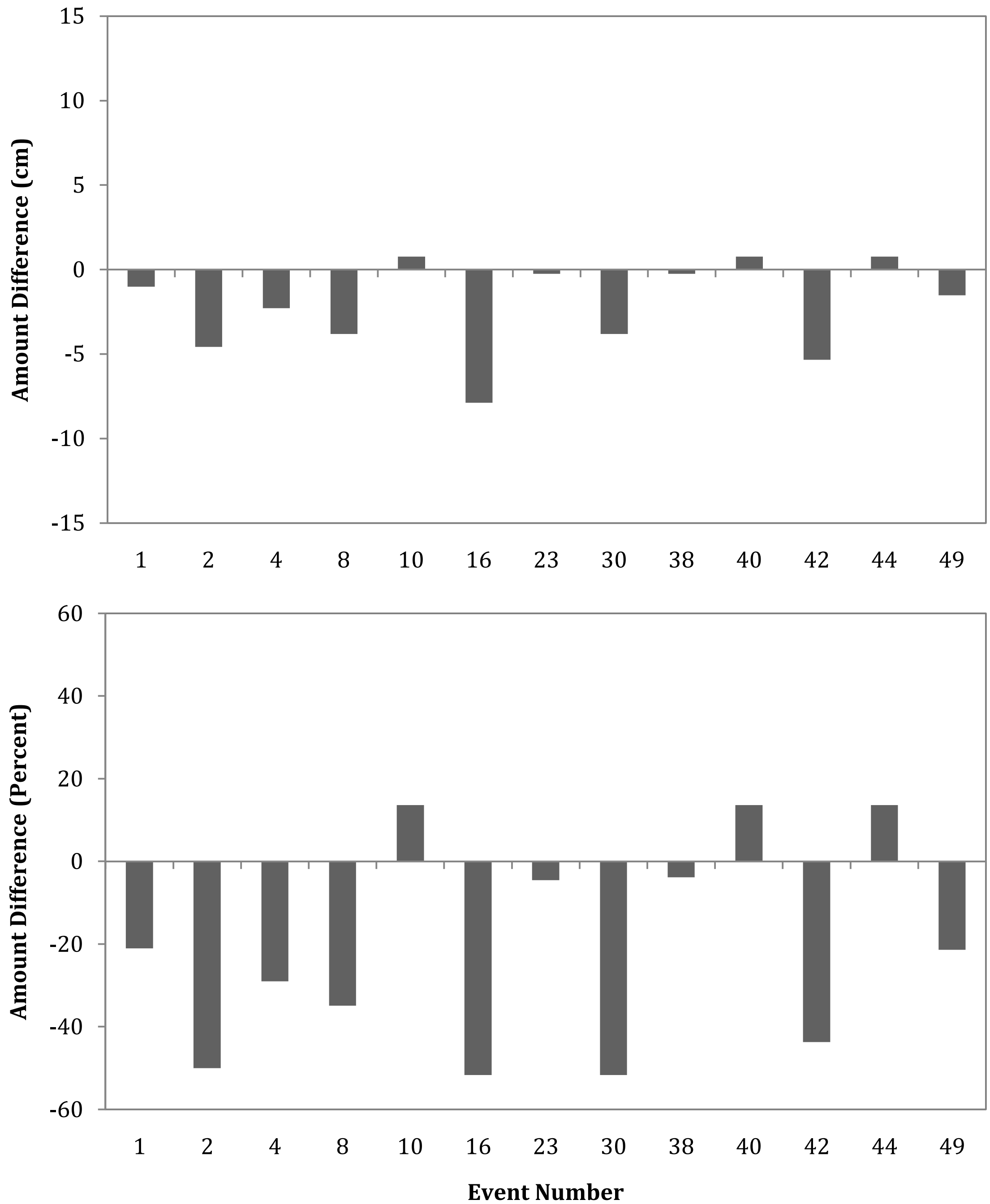

Figure 4.2.2. Light snowfall event snowfall amount differences (top) and percent differences (bottom) between actual observations and Cobb forecasted totals. Values greater than 0 correspond to Cobb overforecasting observations, and values less than 0 correspond to Cobb underforecasting observations.

Table 4.2.1. Snowfall amount statistics for all three groups

	Light Snowfall		Moderate Snowfall		Heavy Snowfall	
	Obs (cm)	Cobb (cm)	Obs (cm)	Cobb (cm)	Obs (cm)	Cobb (cm)
Mean	8.0	5.8	9.9	9.2	18.8	19.7
Median	7.1	6.4	9.4	8.6	18.3	17.1
Mode	5.6	6.4	9.7	8.1	15.2	-
Minimum	4.8	3.6	5.8	7.6	11.9	13.0
Maximum	15.2	7.4	15.2	11.7	27.4	37.3
Std. Dev.	3.1	1.2	2.6	1.3	4.8	8.1
25th Perc.	5.6	5.3	8.3	8.1	15.4	14.2
75th Perc.	9.1	6.4	11.6	10.0	21.9	19.9

Table 4.2.2. Light, moderate, and heavy snowfall event differences for both amounts (in cm) and percentages. Overforecast and underforecast amounts are Cobb forecasted amounts compared to the actual observation measurements.

	All Points				Overforecast		Underforecast	
	Magnitude		Overall					
	(cm)	(%)	(cm)	(%)	(cm)	(%)	(cm)	(%)
Light	2.5	27.1	-2.2	-20.8	0.8	13.6	3.1	31.2
Moderate	2.1	19.8	-0.7	-1.8	1.5	18.9	2.9	22.6
Heavy	4.4	22.0	0.9	4.8	4.7	23.5	4.1	20.0

When considering snow ratios for light snowfall events (Figure 4.2.1 and Table 4.2.3), the observed snow ratios have a higher median and much higher 75th percentile value when compared to the mean Cobb Method snow ratio values. The higher median and 75th percentile value for the observations indicates that the actual and weighted Cobb Method values are slightly skewed towards higher density snow ratio events. All observed snow ratios also show a much higher standard deviation compared to both actual and weighted Cobb forecasted snow ratios, indicating a smaller range of snow densities from the Cobb Method (Table 4.2.3). The skewness of both actual and weighted Cobb Method snow ratios towards higher density snow ratios indicates why the snowfall amounts for light snowfall events have a lower mean and median compared to observations (Table 4.2.1).

Events 2, 16, 30, and 42 are the events that show the most difference between Cobb and observed light snowfall events. These events are investigated further to determine possible explanations for the large differences. Event 30 corresponds to the Des Moines snowfall event from 30-31 March 1985. During this event, Des Moines receives 1.04 cm (.41 in) of liquid water on the 31st and the station reports snow during the entire day. This event has a very low observed snow ratio of 7:1, indicating the low snow ratio could have been caused by having liquid precipitation during the period. The 30th is not used because the station reports ice pellets, rain, and freezing rain on that date. The temperature at midnight is 0°C, and

Table 4.2.3. Light snowfall event snow ratio statistics.

	Observation Actual SR	**Cobb Actual SR**	**Cobb Weighted SR**
Mean	16.3	11.8	12.5
Median	15.5	12.2	12.2
Mode	10.0	12.5	-
Minimum	7.1	3.4	9.7
Maximum	35.3	17.1	17.2
Std. Dev.	7.8	3.1	1.9
25th Perc.	11.0	11.0	11.6
75th Perc.	18.5	13.1	13.4

the station reports freezing rain and snow, and at 03 LST, the temperature is -0.1°C and reporting snow. However, the Cobb Method forecast values seemed to lag behind the observations, assuming the observations are correct, and the Cobb Method reports freezing rain for the first 3-hour period of 31 March instead of snow. During that 3-hour period from 00 to 03 LST, 0.66 cm (.26 in) of liquid water is reported at Des Moines, and since the Cobb Method outputs freezing rain during that time, this liquid water is not attributed to snowfall. Only .38 cm (.15 in) of the 1.04 cm (.41 in) total liquid water is attributed to snow according to the Cobb Method for the rest of the event. Since the temporal resolution is only 3-hourly, and the change from freezing rain to snow could occur any time over that 3-hour period, it is impossible to interpret that period of the event. However, this resolution problem can be viewed as a Cobb Method problem, and must be included in the overall statistics and consideration of the analysis. Especially during early or late winter, snowfall events in this region can sometimes start as rain and switch over to snow, and in order to get a true test of the Cobb Method, events like these are important to consider and should remain in the event data set.

Event 2 and event 42 are from the Omaha-North station during the 9-10 February 1981 and 2-3 December 1990 snowfall events, respectively. Event 2 shows a 50% difference between observed snow amount and the Cobb Method forecast snow amount, however from the beginning of the study domain in 1979 until around the timeframe of this event, the LCDs of the Omaha-North station reported many traces within the hourly precipitation data. This seems out of the ordinary since the nearby stations report either more liquid precipitation, or less snowfall than the Omaha-North station. The possible difference in Omaha-North's measured liquid precipitation is enforced with the event from 9-10 February 1981 when compared to the surrounding stations. Omaha-North reports .33 cm (.13 in) of liquid water, 9.1 cm (3.6 in) of snow, and the Cobb Method forecasts 4.6 cm (1.8 in) of snow. The most comparable station, Lincoln, reports 0.3 cm (.12 in) of liquid precipitation, 4.8 cm (1.9 in) of snow, and the Cobb Method forecasts 3.8 cm (1.5 in) of snow. Norfolk reports nearly the same snowfall as Omaha-North at 9.7 cm (3.8 in), with .84 cm (.33 in) of liquid precipitation, which is more than 2.5 times the liquid precipitation reported at Omaha-North. Therefore, the difference in values can be attributed to an unknown observation discrepancy and not necessarily a Cobb Method forecasting problem.

Similar to event 2, event 42 shows the observations taken at Omaha-North to not fit the storm event as expected when compared to the observations of the surrounding stations. Event 42 is from the same storm of 2-3 December 1990 as the moderate snowfall difference of event 41, and approximately the same difference is observed between the stations. Omaha-North (event 42) and Lincoln (event 41, moderate snowfall event) report 12.2 cm (4.8 in) and 12.4 cm (4.9 in) with .79 cm (.31 in) and .66 cm (.26 in) of liquid precipitation, respectively. When compared to Grand Island with 6.6 cm (2.6 in) of snow and .58 cm (.23 in) of liquid precipitation and Norfolk with 8.4 cm (3.3 in) of snow and .69 cm (.27 in) of liquid precipitation, it would seem that there could be a problem within either the recorded snowfall total, or the amount of liquid precipitation. The Cobb forecasted amounts for Grand Island and Norfolk are within .25 cm (.1 in) for both stations, and the difference for Lincoln is 4.3 cm (1.7 in) and for Omaha-North it is 5.3 cm (2.1 in). When examining the data, it would seem that the Omaha-North station and/or the Lincoln station observations for these events appears inaccurate, however, since there is no way of knowing if the observations are correct, the event has to remain within the study.

Within the moderate snowfall category there are 23 events with 11 overforecasted amounts, 11 underforecasted amounts, and one event with no difference between the Cobb Method forecasted amounts and observations (Figures 4.2.3 and 4.2.4). Overall, moderate snowfalls show the greatest accuracy out of the three snowfall total groups when considering percent differences (Table 4.2.2). The mean difference is smallest between Cobb Method forecasted snow amounts and observed snow amounts within moderate snowfalls (Table 4.2.4). The average difference in magnitude is 19.8% (2.1 cm) with underforecasting having the higher magnitude at 22.6% (2.9 cm) (Table 4.2.2). Even though underforecasting has the higher difference value, overall the moderate snowfall category contains no overwhelming over or underforecast difference (Table 4.2.2).

When looking at the snow ratios for moderate snowfall events, observations and Cobb Method snow ratios show the most similarity compared to the other two snowfall groups (Table 4.2.4). The median, mode, minimum, and both percentile

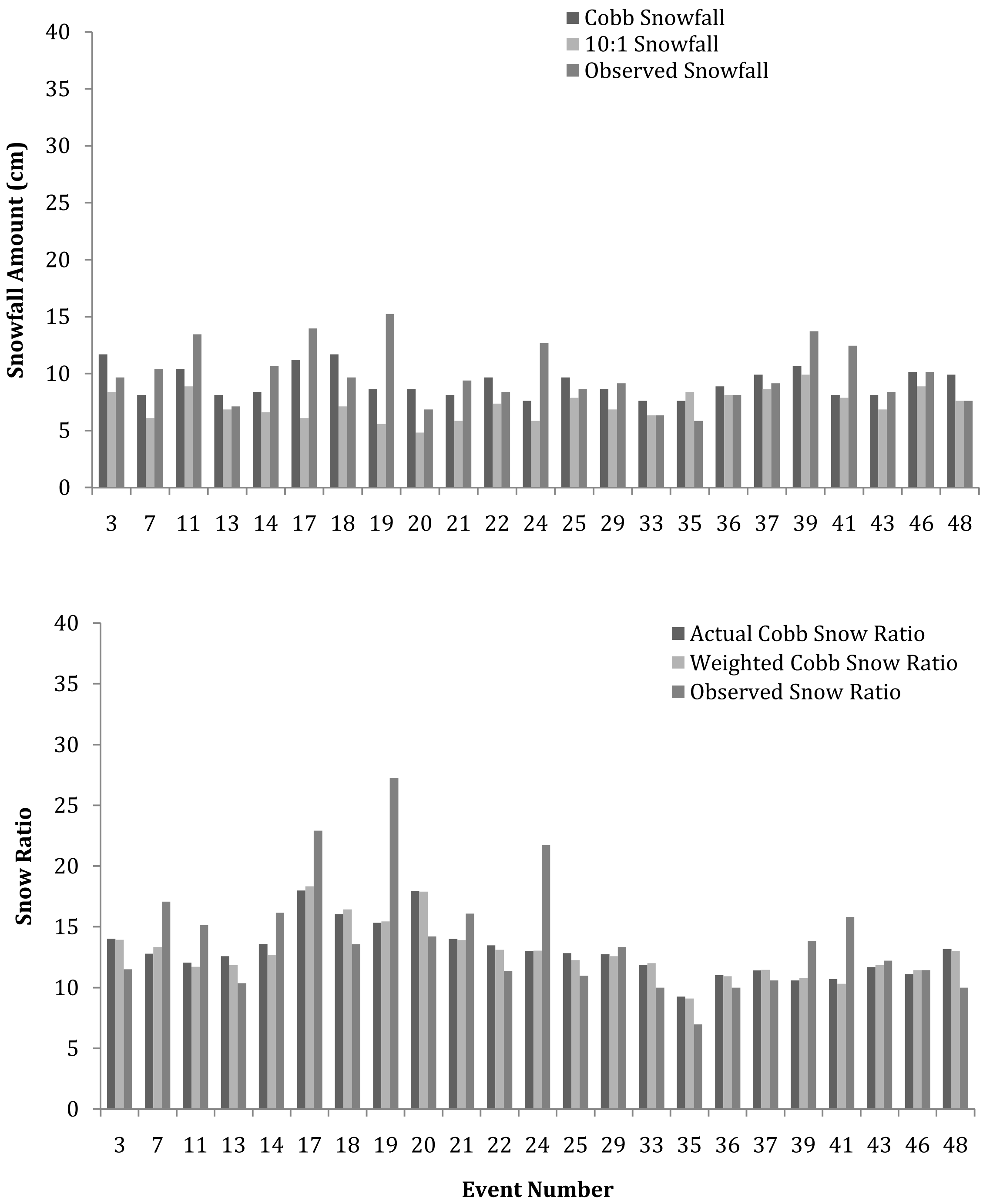

Figure 4.2.3. Moderate snowfall event amounts (top) and snow ratios (bottom).

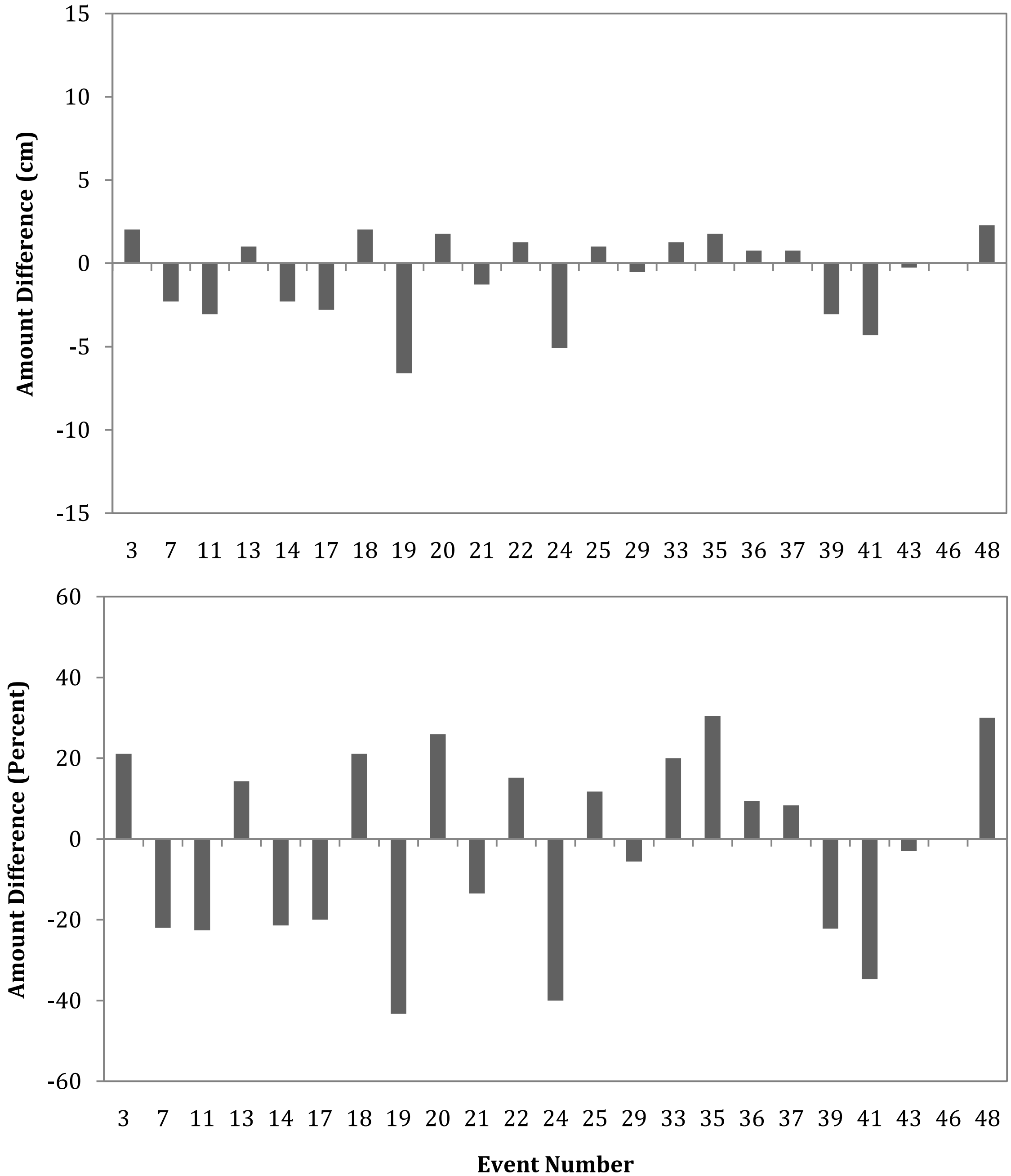

Figure 4.2.4. Moderate snowfall event snowfall amount differences (top) and percent differences (bottom) between actual observations and Cobb forecasted totals. Values greater than 0 correspond to Cobb overforecasting observations, and values less than 0 correspond to Cobb underforecasting observations.

Table 4.2.4. Moderate snowfall event snow ratio statistics.

	Observation Actual SR	Cobb Actual SR	Cobb Weighted SR
Mean	14.0	12.7	13.5
Median	13.3	13.0	14.0
Mode	10.0	10.0	14.0
Minimum	7.0	8.0	10.0
Maximum	27.3	18.0	19.0
Std. Dev.	4.7	2.6	2.5
25th Perc.	10.8	10.5	12.5
75th Perc.	15.9	14.5	14.5

values show that the Cobb Method performs very well within the moderate snowfall category (Table 4.2.4). The Cobb Method actual snow ratio shows slightly better accuracy when compared to the Cobb Method weighted snow ratio since the 25th percentile values, median, mode, and minimum values are very similar between observations and the Cobb Method actual snow ratio. Both Cobb Method snow ratio categories should be similar to observations in the moderate snowfall event group since the moderate events contain not only the most events out of all three snowfall event categories, but also the moderate events are in the "middle" of the dataset. Having the data that are near the average of all the events would greatly aid an algorithm such as the Cobb Method, since it performs averaging within its calculations and there aren't any snowfall amount outliers within the moderate category.

The largest difference found within these 23 events is event 19, where there is a 43% (6.6 cm) underforecasted difference between the Cobb Method forecasted amount and the observation (Figure 4.2.4). Event 19 is from Grand Island during the 20 December 1983 storm event, which is the same event as event 16 from Lincoln in the light snowfall category. Grand Island has similar differences as Lincoln during the event. Grand Island reports .56 cm (.22 in) of liquid precipitation and 15.2 cm (6.0 in) of snow, and the Cobb Method forecasts 8.6 cm (3.4 in) of snow. Since Lincoln reported 15.2 cm (6.0 in) and Grand Island reported 15.2 cm (6.0 in) as well, and approximately the same liquid water is reported, it is possible that the snow was much drier than Cobb forecasted. This event is a very cold event, with surface temperatures at Grand Island and Lincoln averaging -24°C and -22°C respectively, supporting a drier, lower density snowfall. The lower surface temperatures help explain why the snow ratio is a very low-density snow, and could indicate a low-density snow ratio bias within the Cobb Method. The Cobb Method has a difficult time producing snow ratios higher than 20:1.

Event 24 is the second largest difference and is also an underforecasted amount. The data are from the 8-10 January 1985 event at Grand Island, and appears more likely to be a measurement problem since Grand Island has the most snowfall of the five stations with 12.7 cm (5 in), however, does not report the highest liquid water equivalent. It is possible that a lower density snowfall did fall at Grand Island, however, when comparing directly with Lincoln, the closest station, both stations reports .58 cm (.23 in) of liquid water, but Lincoln reports 3.3 cm (1.3 in) less snowfall than Grand Island. Furthermore, Omaha-North reports .74 cm (.29 in) of liquid water, which is more than Grand Island's liquid water observation, and only 8.4 cm (3.3 in) of snow is reported at Omaha-North, and thus adds more reason to question the observations at Grand Island for this event.

There are 14 events within the heavy snowfall event category with 8 overforecast amounts, and 6 underforecast amounts (Figures 4.2.5 and 4.2.6). The heavy snowfall event group is the only category where there is an overforecasting bias (Figure 4.2.6, Table 4.2.2). The largest differences in amounts are within heavy snowfall events, which is to be expected, since the large amounts have no upper

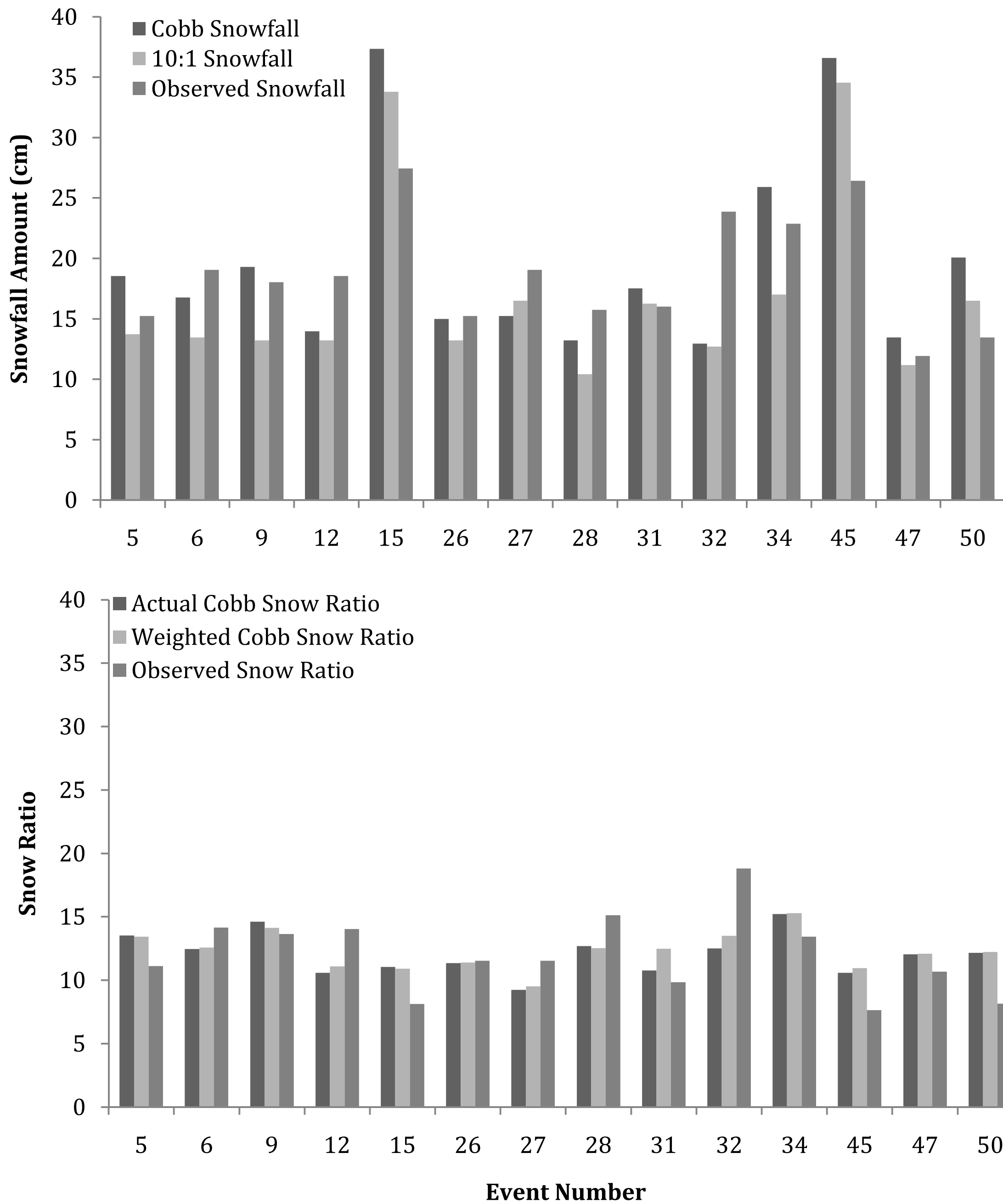

Figure 4.2.5. Heavy snowfall event amounts (top) and snow ratios (bottom).

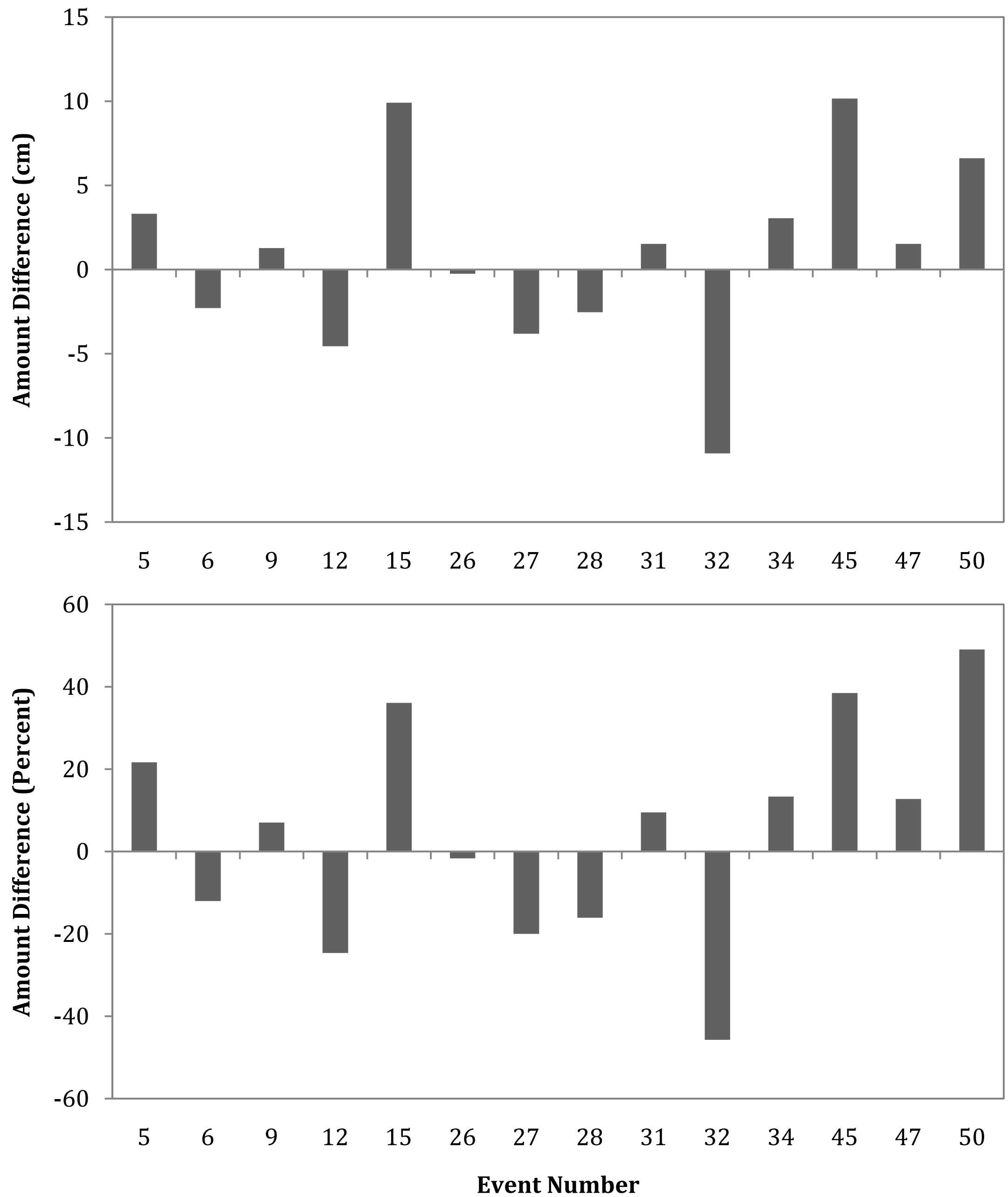

Figure 4.2.6. Heavy snowfall event snowfall amount differences (top) and percent differences (bottom) between actual observations and Cobb forecasted totals. Values greater than 0 correspond to Cobb overforecasting observations, and values less than 0 correspond to Cobb underforecasting observations.

bound. However, the percent difference in magnitude is only 22% still showing relatively high accuracy by the Cobb Method (Table 4.2.2).

When considering snow ratios in the heavy snowfall category, the mean Cobb actual snow ratio is approximately the same as the observed snow ratio, with both values being about 12:1 (Table 4.2.5). Also, the observation snow ratio median being less than the mean within light and moderate snowfalls' mean and median snow ratio values (Table 4.2.2 and Table 4.2.4, respectively) shows the same trend in the heavy snowfall group (Table 4.2.5). In contrast to heavy snowfall observations, the Cobb Method actual snow ratio median is greater than the mean, indicating that the Cobb Method snow ratios are slightly skewed towards higher snow ratio values (Table 4.2.5). The weighted Cobb Method snow ratios, however, show the median to be less than the mean just like the observations. The standard deviation of snow ratios is smallest within the heavy snowfall events for the Cobb Method than observations (Table 4.2.5) even when compared light and moderate snowfall snow ratios (Table 4.2.2 and Table 4.2.4), indicating a decrease in variance of snow ratios as the Cobb forecasted snowfall amounts increase. The heavy snowfall event category snow ratios also show that out of all three snowfall categories, the Cobb Method weighted snow ratio values are greater than observation values except for the maximum and standard deviation (Table 4.2.5). This is to be expected since the Cobb Method weighted snow ratios depend on how much liquid water the storm produces, and heavy snowfall events largely produce the most precipitation.

Table 4.2.5. Heavy snowfall event snow ratio statistics.

	Observation Actual SR	Cobb Actual SR	Cobb Weighted SR
Mean	12.0	11.9	13.4
Median	11.5	12.5	12.5
Mode	11.5	13.0	12.0
Minimum	7.6	9.0	10.0
Maximum	18.8	15.0	18.0
Std. Dev.	3.1	1.9	2.6
25th Perc.	10.1	10.3	11.3
75th Perc.	13.9	13.0	15.8

The largest differences between the Cobb Method forecasted amounts and observations are found within events 15, 32, 45, and 50 (Figure 4.2.6). Events 15, 45, and 50 are all overforecasting differences, while event 32 is an underforecasting difference. Events 15, 45, and 50 help to show heavy snowfall events are the only group with a larger overforecasting bias.

Events 15, 45, and 50 are all Des Moines events. In order for the Cobb Method to forecast correctly, a snow ratio between 7:1 and 8:1 are required for these events. Snow ratios between 10:1 and 12:1 were the actual Cobb Method forecast snow ratios for Des Moines. However, like most Des Moines observations in this study, a snow ratio of less than 10:1 is reported, and six out of 10 events had a snow ratio of 10:1 or less at Des Moines. This would indicate that, if there are observation problems, that either Des Moines has a tendency to over-report liquid water, or incorrectly measure snowfall. Assuming that the measurements of both snow amounts and liquid water are relatively correct may be attributed to Des Moines' location. Des Moines has a more favorable location for additional available moisture from synoptic systems compared to the other four locations. The Cobb Method appears to have a difficult time forecasting high density or high moisture snow ratios. These events will be addressed more closely with other high-density snow ratios in section 4.3.

Event 32 is from Omaha-North during the 28 March 1987 snowfall event. The Cobb Method forecasted 13.0 cm (5.1 in) of snow for Omaha-North, and the observations are 23.9 cm (9.4 in) of snow, and 1.27 cm (.50 in) of liquid precipitation. When considering the corresponding snow ratios (Figure 4.2.5), a 10:1 snow ratio is not forecasted by the Cobb Method. This is due to the Cobb Method reporting rain and freezing drizzle for the first nine hours of 28 March at Omaha-North. The LCD observations do not report this precipitation, however, fog is reported for the first three hours, and snow the following six hours. Therefore, the Cobb Method lost .23 cm (.09 in) of liquid precipitation during the event, and according to the Cobb Method, only 1.04 cm (.41 in) of liquid precipitation is attributable to the snow forecast amount of 13.0 cm (5.1 in). The corresponding snow ratio forecast by the Cobb Method is 12.4:1. The reason for the Cobb Method predicting rain instead of snowfall is due to the surface temperatures changing from 3.3°C at 00 LST to 0°C at 03 LST, and since during the last six hours of 27 March the LCD of Omaha-North reported rain, the switchover from rain to snow could have happened any time during that 3-hour timeframe. Since the temporal time step of both the LCD and the Cobb Method are 3-hourly, being able to discern when the switchover happened is impossible. It is also important to consider that snow can accumulate at the surface with above and near freezing temperatures, and the Cobb Method may not be able to consider such events. The lack of moisture can be considered as a problem with the Cobb Method, which needs further analysis to be able to interpret changes within the model data.

It is important to note that compaction of the snowfall totals are not accounted for within the observations in this study. The Cobb Method forecasted snowfall amounts are accumulated at 3-hour intervals to get storm total snowfall, and the observational data are measured every 6 hours before summed to get a 24-hour snowfall amount used within this study. The evidence for compaction was evident with the mean snow ratio data of Roebber et al. (2003) with a climatological snow ratio of 15.6:1 and Baxter et al. (2005) with a climatological snow ratio of 13.5:1. Ware et al. (2006) stated that the different means are most likely attributed to the different measurement intervals of snowfall, with the Roebber et al. (2003) study using 6-hour interval measurement data, and Baxter et al. (2005) using 24-hour interval measurement data. Baxter et al. (2005) should have a lower average snow ratio due to the longer interval between measurements causing more snow compaction before the next measurement, decreasing snowfall amounts and thus, snow ratios. The overforecasted snowfall amounts by the Cobb Method to observations could in fact become less overforecasted if observational measurements are taken at 3-hour intervals, since the Cobb Method in this case does not factor in compaction of the snowfall. The increased frequency of observations would decrease the effect of compaction of the snow, and would raise observational snowfall measurements. This may decrease the difference between the Cobb Method and observations for overforecasted events, and since the largest amount differences are with larger storm snowfall totals, the Cobb Method could be more accurate than shown with this study.

Also, the Cobb Method assumes that all snow falling on a land surface will not melt and will accumulate over time. Snow occurring near or above freezing at the surface will likely experience some form of melting effects that will decrease the observational snowfall measurements. All of the individual 3-hour Cobb Method snowfall amount forecasts that are totaled to yield a storm total snowfall amount do not have a melting factor applied. Therefore, surface melting may lead to Cobb Method snowfall being higher than observations, and thus, may account for some of the overforecasting event differences found in this study.

In summary, the Cobb Method forecast snowfall amounts indicate that with increasing snowfall amounts, the Cobb Method changes from underforecasting to overforecasting when compared to observations (Figures 4.2.2 and 4.2.6). Also, the Cobb Method forecast snowfall amount means are less than the observations for light events, about the same for moderate events, and surpass mean snowfall amounts for heavy snowfall events (Table 4.2.2) indicating that snowfall amounts change from underforecasting to overforecasting as snowfall amount increases. For light snowfall events, the overforecasting percentage is the smallest (13.6%) of the events while the underforecasting percentage (31.2%) is the largest of the events (Table 4.2.2). This is to be expected, since smaller snowfall amounts can have much lower density snow approaching 100:1 (Roebber et al. 2003, Ware et al. 2006), and the Cobb Method appears to have a difficult time producing lower density snowfalls greater than 20:1. The moderate snowfall event category has a slight bias to underforecasting, however a similar underforecasting and overforecasting percentage is observed when compared to light snowfalls (Table 4.2.2). The heavy snowfall events have a slight bias to overforecasting (Table 4.2.2). The overforecasting bias with heavy snowfall events could be attributed to higher density snowfalls with plenty of moisture, because as snowfall amounts increase, the mean snow ratios decrease (Tables 4.2.2, 4.2.4, 4.2.5). Higher density snow ratios with varying snow amounts are observed for Des Moines, and the Cobb Method does a relatively good job predicting these snow ratios. However, the Cobb Method rarely produces snow ratios of less than 8:1 for any 3-hour period, and thus, for very "wet" snows that Des Moines appears to receive, a high snow density bias may exist within the Cobb Method. There also could be a compaction factor for observations for heavy snowfall events, causing the Cobb Method to have an underforecasting bias with heavier snow events. With heavier snowfall amounts, the weight of the snow can cause snowfall accumulation measurements to be less than what the Cobb Method has forecasted due to different measurement frequencies, and can have a larger effect with larger snowfall accumulations. The compaction effect would not be as dramatic for moderate or light snowfall events due to the snowfall accumulations having smaller totals, yielding less weight towards compaction.

4.3 Snow Ratios

The third category of analysis divides the data by Cobb Method forecasted snow ratios, and needs to be examined because density of the snow is an integral part of the Cobb Method and snowfall forecasting. There are 50 measured snowfall events by Cobb Method forecasted snow ratios, and are divided into three groups; high-density snowfalls with snow ratios from 3:1 through 10.9:1, containing 12 events, moderate-density snowfalls with snow ratios from 11:1 through 12.9:1, containing 21 events, and low-density snowfalls with snow ratios greater than 13:1, containing 17 events.

For the 12 high snow density events, four events are overforecasted by the Cobb Method, and eight are underforecasted (Figures 4.3.1 and 4.3.2, Table 4.3.1). The magnitude of the differences between the Cobb Method snow ratios and observations is the highest difference percentage at 27.9% (Table 4.3.2). This is largely due to the overwhelming underforecasting percentage of 28.9% and the overall percent difference of -13.2% (Figure 4.3.2).

The high-density snow ratios have the highest mean snowfall amounts for both the Cobb Method and observations when compared to the other two groups (Table 4.3.3). Also, the high-density snow ratio group has the highest standard deviations of snowfall amounts between the groups, indicating that high density snow ratios contain the greatest variability with Cobb Method forecasted snow totals and observations (Table 4.3.3).   The broad range and high standard deviation is indicated by high-density snowfalls containing not only the smallest Cobb

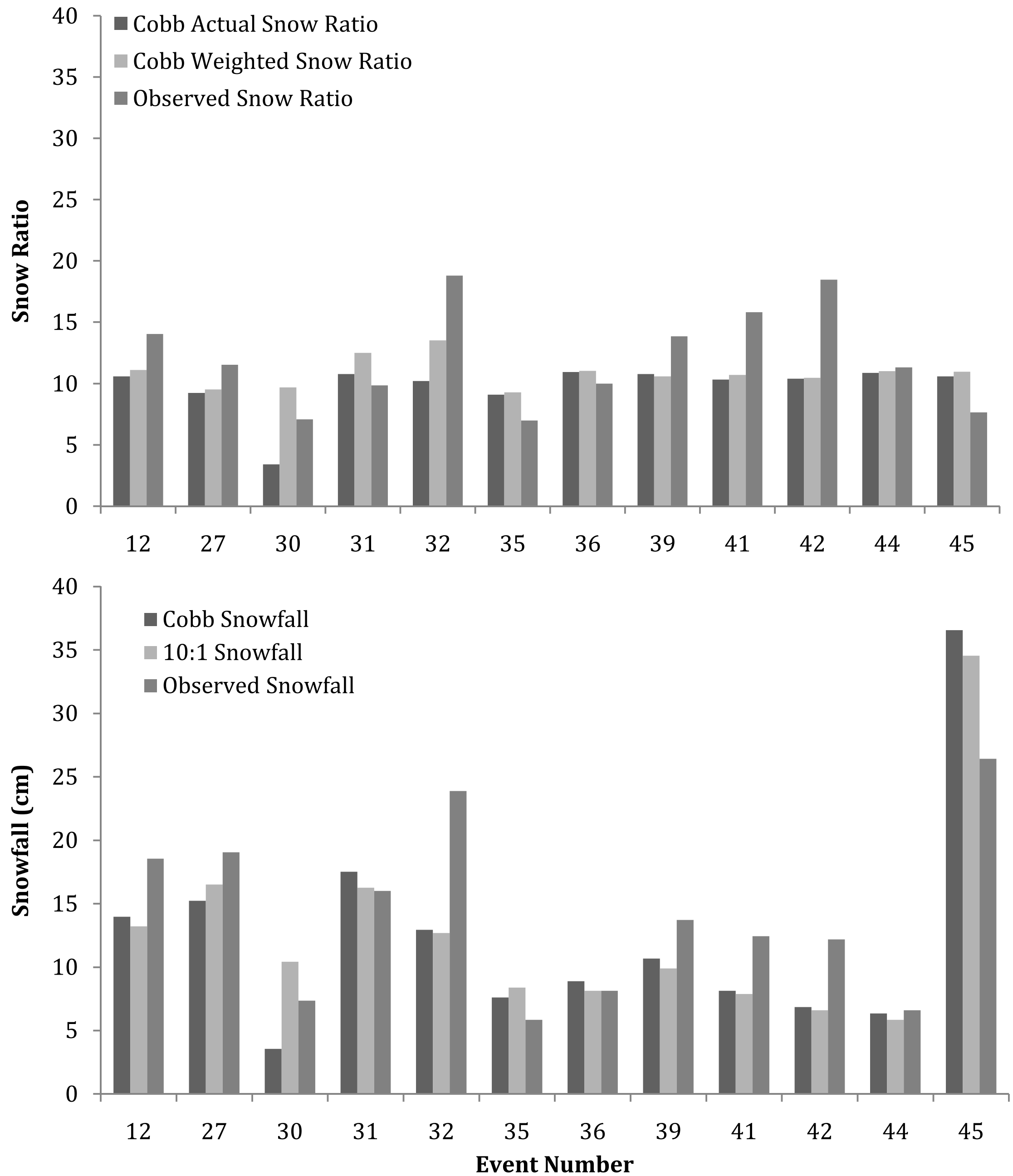

Figure 4.3.1. High-density snowfall event snow ratios (top) and their corresponding snowfall amounts (bottom).

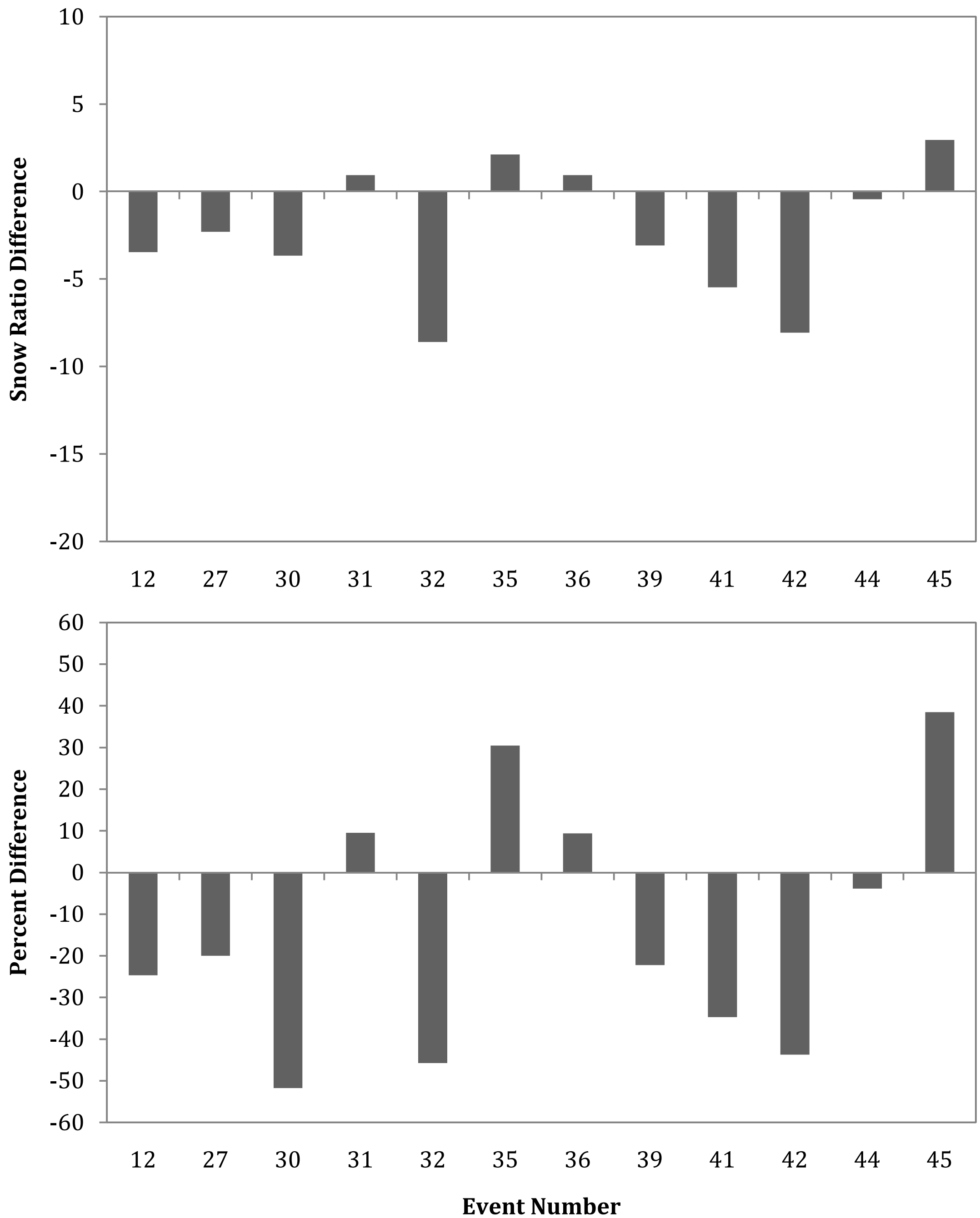

Figure 4.3.2. High-density snowfall event snow ratio differences (top) and snow ratio percent differences (bottom) between actual observations and Cobb forecasted totals. Values greater than 0 correspond to Cobb overforecasting observations, and values less than 0 correspond to Cobb underforecasting observations.

Table 4.3.1. High-density snowfall event snow ratio statistics.

	Observation Actual SR	Cobb Actual SR	Cobb Weighted SR
Mean	12.1	9.8	10.9
Median	11.4	10.5	10.8
Mode	#N/A	#N/A	#N/A
Minimum	7.0	3.4	9.3
Maximum	18.8	10.9	13.5
Std. Dev.	4.1	2.1	1.2
25th Perc.	9.3	10.0	10.3
75th Perc.	14.5	10.8	11.0

Table 4.3.2. High, moderate, and low snowfall event snow ratio differences and percent differences. Overforecast and underforecast amounts are Cobb forecasted amounts compared to the actual observations.

	All Points				Overforecast		Underforecast	
	Magnitude		Overall					
	Value	(%)	Value	(%)	Value	(%)	Value	(%)
High	3.5	27.9	-2.3	-13.2	1.7	21.9	4.2	28.9
Moderate	2.1	17.2	-0.4	1.2	1.8	19.3	2.7	16.7
Low	5.1	24.8	-2.9	-6.5	2.4	19.4	7.5	29.6

Table 4.3.3. Snowfall amount statistics for all three groups.

	High Density		Moderate Density		Low Density	
	Obs (cm)	Cobb (cm)	Obs (cm)	Cobb (cm)	Obs (cm)	Cobb (cm)
Mean	14.18	12.36	10.8	11.1	11.6	10.7
Median	13.08	9.78	9.1	8.6	9.7	8.6
Mode	#N/A	#N/A	5.6	6.4	15.2	11.7
Minimum	5.84	3.56	4.8	3.8	5.6	4.6
Maximum	26.42	36.58	27.4	37.3	22.9	25.9
Std. Dev.	6.79	8.65	5.4	7.2	4.6	5.6
25th Perc.	7.94	7.43	7.1	7.1	8.4	7.6
75th Perc.	18.67	14.29	13.5	13.2	15.2	11.7

forecasted snow amount at 3.6 cm (1.4 in), but also the second largest Cobb forecasted snow amount at 36.6 cm (14.4 in). The Cobb Method weighted snow ratio has slightly closer values to observations when compared to the Cobb Method actual snow ratio (Table 4.3.1). Similar to heavy snowfall events from the previous section, one would expect high-density snow ratio events to have more moisture and precipitation, and thus, the liquid water dependent Cobb Method weighted snow ratios are closer to observed values.

The largest differences between the Cobb Method high-density snow ratios and observed snow ratios are events 30, 32, 42, and 45 (Figure 4.3.2). Events 30, 32, and 42 are underforecasted, and event 45 is overforecasted by the Cobb Method when compared to observations (Figure 4.3.2). Events 30 and 42 are with light snowfall amounts, and events 32 and 45 are heavy snowfall events (See section 4.2). None of the high-density large snowfall differences are within the moderate snowfall category.

There are 21 events within the moderate-density snowfall category, containing 10 overforecasted amounts, 10 underforecasted amounts, and one event that is forecasted correctly to the observation (Figures 4.3.3 and 4.3.4). Moderate-density snow ratio events have a snow ratio difference of only 2.1 (17.2%) and moderate-density snow ratio events are the only group to have an overforecasting bias (Table 4.3.2). Also, the moderate-density snow ratios have the smallest percent difference when considering overforecasting or underforecasting, with an

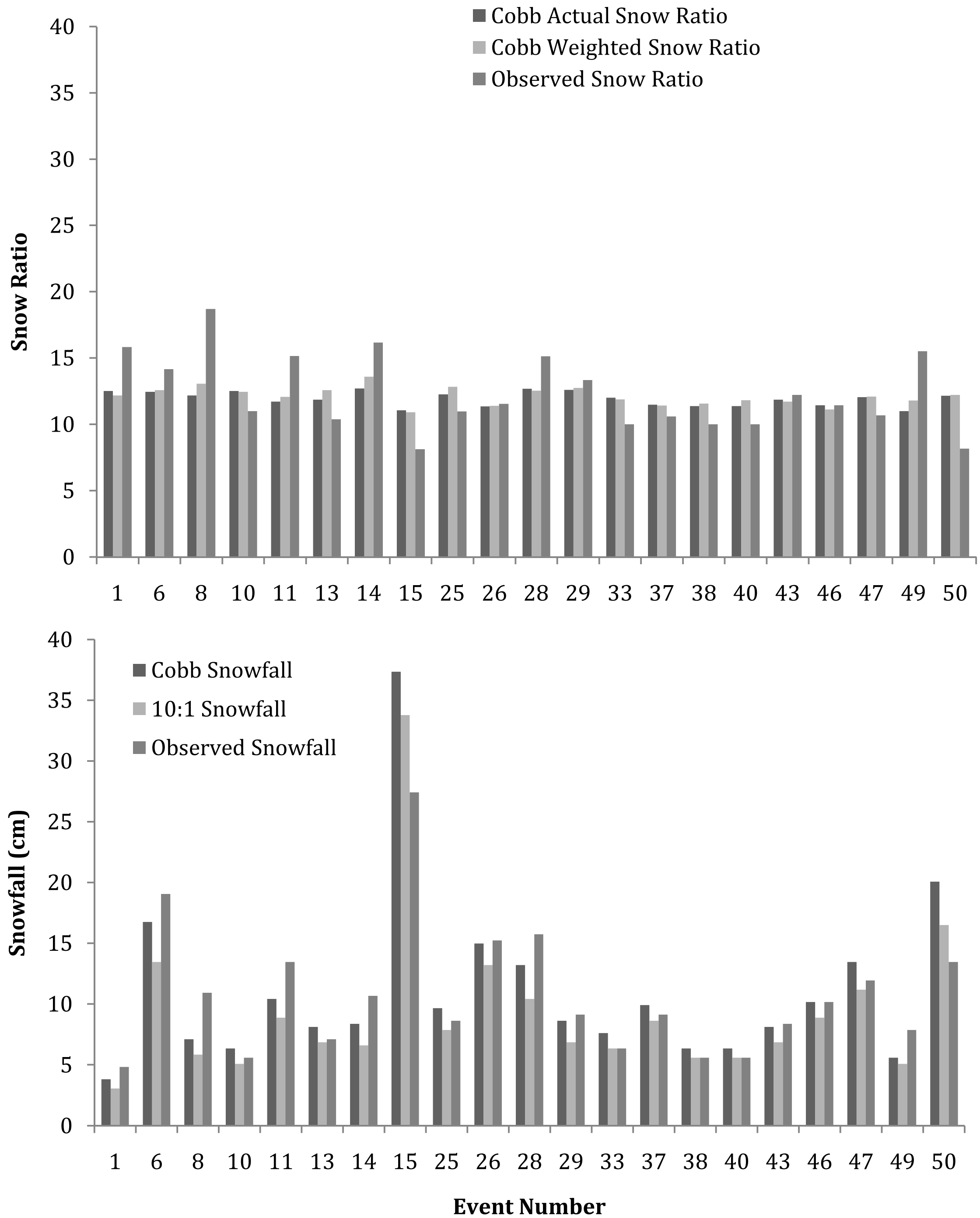

Figure 4.3.3. Moderate density snowfall event snow ratios (top) and their corresponding snowfall amounts (bottom).

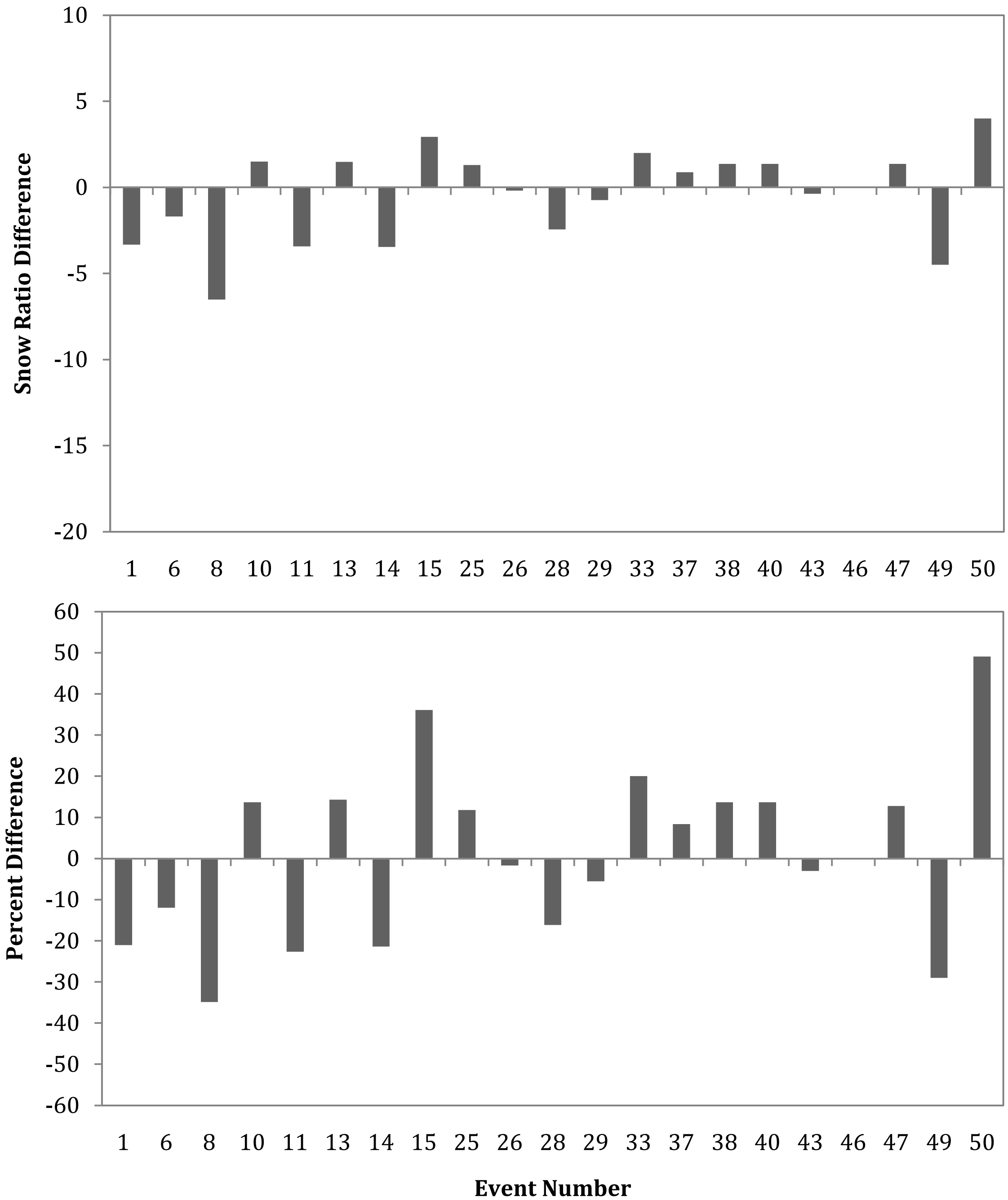

Figure 4.3.4. Moderate density snowfall event snow ratio differences (top) and percent differences (bottom) between actual observations and Cobb forecasted totals. Values greater than 0 correspond to Cobb overforecasting observations, and values less than 0 correspond to Cobb underforecasting observations.

underforecasting percent difference of 16.7% (Table 4.3.2).

The moderate-density snow ratio group (Table 4.3.4) shows the mean Cobb snow ratios and observed snow ratios are around 12:1. The biggest differences between the Cobb Method and observations, however, are within the standard deviations and the maximum values of snow ratios (Table 4.3.4). The standard deviations of both actual and weighted Cobb Method snow ratios does not exceed 1, indicating a much smaller variance when compared not only to the other three groups, but moderate-density observed snow ratios as well (Table 4.3.4). Also, the moderate-density actual and weighted Cobb snow ratios only have a range around 2:1, while observed snow ratios have a much larger range of 11:1, again indicating the smaller variance of the Cobb Method moderate-density snow ratios. The small variability in the moderate-density snow ratio statistics suggests that the Cobb Method does a very good job with forecasting snow ratios around the climatological average.

The snow amount differences between the Cobb Method snowfall and observed snowfall within the moderate-density snow ratio group are only 0.3 cm, which is the smallest difference of the three snow ratio groups (Table 4.3.3). The 25^{th} and 75^{th} percentile Cobb Method snowfall amounts and observed snowfall amounts within the moderate-density snow ratio group are also very similar, with 25^{th} percentile values of 7.1 cm, and 75^{th} percentile values around 13 cm (Table 4.3.3). Similar to the other three snow ratio groups, the range of Cobb Method snow

Table 4.3.4. Moderate-density snowfall event snow ratio statistics.

	Observation	**Cobb**	**Cobb**
	Actual SR	**Actual SR**	**Weighted SR**
Mean	12.3	11.9	12.1
Median	11.4	12.0	12.1
Mode	10.0	12.5	#N/A
Minimum	8.1	11.0	10.9
Maximum	18.7	12.7	13.6
Std. Dev.	2.9	0.5	0.7
25th Perc.	10.4	11.4	11.7
75th Perc.	15.1	12.5	12.6

amounts is larger than the observed snow amounts for the moderate-density snow ratio group (Table 4.3.3).

The largest differences within the moderate-density snow ratio events are events 8, 15 and 50 (Figure 4.3.4). The Cobb Method snow ratio for event 8 underforecasts the observed snow ratios, while events 15 and 50 are overforecasted. Event 8 is associated with the light snowfall category, and events 15 and 50 are associated with heavy snowfall events. Events 15 and 50 are discussed in the previous section with the snowfall amounts, however event 8 has not yet been addressed. Event 8 is from Norfolk on 16 December 1981, and shows a common problem with snowfall measurements in Norfolk. The measurements of liquid water may not be accurate since the liquid water measurement does not match up with the other four locations during the storm, however the measurements conveniently add up to be exactly 10:1. When retrieving events from the Norfolk LCDs, many snowfall events have a snow ratio of 10:1 not only for a few days, but sometimes the monthly data is exactly 10:1 for every snowfall event. It is possible that many of these events were 10:1, however it is extremely unlikely that every snow event for an entire month had only 10:1 snow ratio events. Event 8 at Norfolk may not have the correct liquid water measurement, and the difference between the Cobb Method forecasted snowfall and observations may be attributed to this

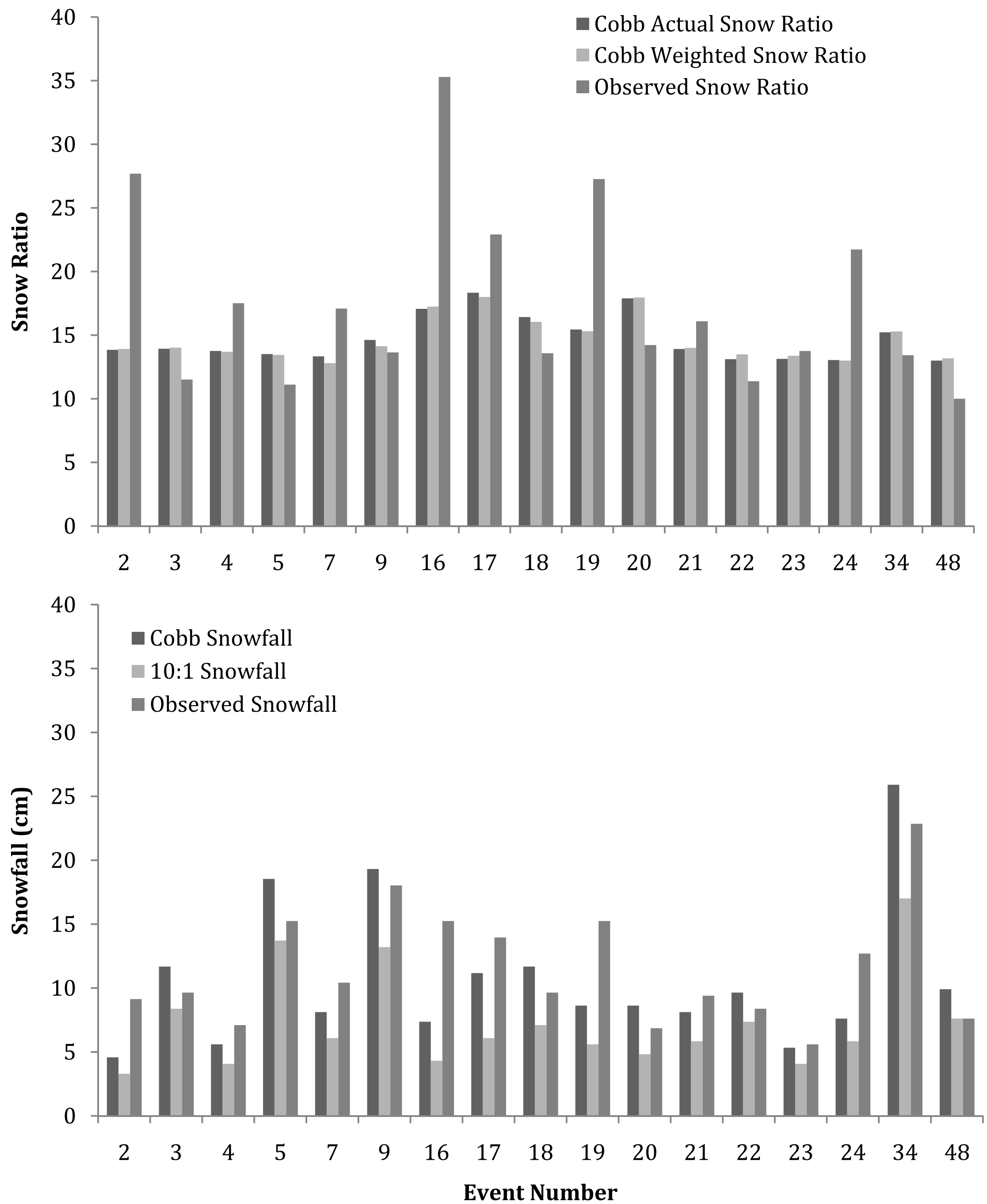

Figure 4.3.5. Low-density snowfall event snow ratios (top) and their corresponding snowfall amounts (bottom).

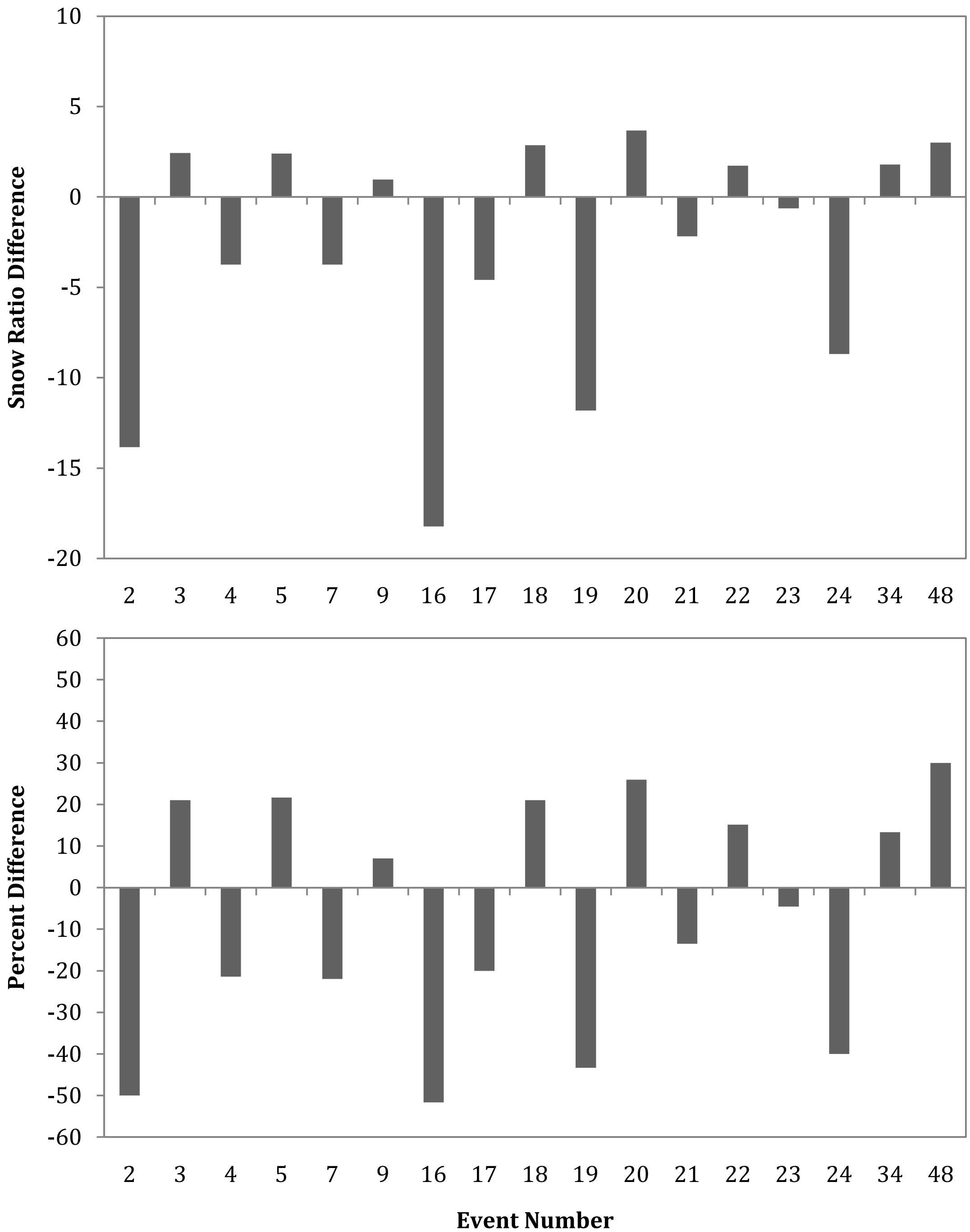

Figure 4.3.6. Low-density snowfall event snow ratio differences (top) and percent differences (bottom) between actual observations and Cobb forecasted totals. Values greater than 0 correspond to Cobb overforecasting observations, and values less than 0 correspond to Cobb underforecasting observations.

measurement issue. Therefore, like many of the other problematic events, event 8 was not removed from the data set.

The differences found for the low-density snowfall events (Figures 4.3.5 and 4.3.6) show a trend towards underforecasting. There are 17 low-density snowfall events, with 8 overforecasted events, and 9 underforecasted events (Figure 4.3.6). The overforecasted and underforecasted snow ratio difference values are the largest among the three groups (Table 4.3.2). The underforecasting percentage is also the greatest among the three groups at 29.6% (Table 4.3.2). Low-density snowfalls have the largest difference between standard deviations and means of Cobb snow ratios and observed snow ratios when compared to the other two groups, and the range of observed snow ratios is much larger than Cobb snow ratios (Table 4.3.5). The maximum value for observed low-density snow ratios is approximately 35:1, and the Cobb maximum actual and weighted snow ratios are about 18:1, which is the largest difference between Cobb to observed snow ratios compared to the other groups (Table 4.3.5).

The snowfall amounts for low-density snow ratios are also similar to high-density snow ratio events, but are slightly closer to observations compared to high-density snowfall amounts (Table 4.3.3). The low-density snow ratio mean and median for the Cobb Method snowfall amounts and observed snowfall amounts show slightly better similarity to observations over high-density snowfall amounts (Table 4.3.3). The low-density snowfall amounts are the closest to observations out of the three groups, having the smallest difference between the ranges of Cobb

Table 4.3.5. Low-density snowfall event snow ratio statistics.

	Observation Actual SR	Cobb Actual SR	Cobb Weighted SR
Mean	17.5	14.7	14.6
Median	14.2	13.9	14.0
Mode	#N/A	#N/A	#N/A
Minimum	10.0	13.0	12.8
Maximum	35.3	18.3	18.0
Std. Dev.	7.1	1.8	1.7
25th Perc.	13.4	13.3	13.4
75th Perc.	21.7	15.5	15.3

snowfall amounts and observed forecasted amounts (Table 4.3.3). The smaller range of Cobb snowfall amounts and observed snowfall amounts is reflected in the differences between the standard deviations, which is also smallest between the three groups (Table 4.3.3). Cobb forecasted snowfall totals, like the other two groups, has a larger range than the observed snowfall totals (Table 4.3.3).

The largest differences associated with low-density snow ratios are events 2, 16, 19, and 24 (Figure 4.3.6). All of the largest difference events mentioned are underforecasting snow ratios when comparing the Cobb Method forecasted snow ratios to observed snow ratios. Events 2 and 16 are light snowfall amounts, and events 19 and 24 are moderate snowfall amounts. None of the largest differences within low-density snow ratio events are within the heavy snowfall amount category.

Low-density snow ratios show the greatest difference values between Cobb snow ratios and observed snow ratios (Table 4.3.2). High-density snow ratios also have the highest overforecasting percentage, and low-density snow ratios have the highest underforecasting percentage. This would indicate that the Cobb Method, when considering only snow ratios, appears to lessen observed snow ratios by "averaging" the snow ratios. Although the snowfall amounts in all three snow ratio groups show the Cobb to have a higher range and standard deviation for snowfall values, the standard deviations of all three groups' Cobb snow ratios are much smaller than observed snow ratios (Tables 4.3.1, 4.3.3, 4.3.4, and 4.3.5). It is also important to note that, when considering differences in the values of snow ratios, low-density events have the largest differences in both underforecasting and overforecasting (Table 4.3.2). This would indicate either that the Cobb Method has a hard time discerning the snow ratios when low-density events occur, or the observers have difficulty measuring and interpreting low-density events. Excluding the errors in observations, which happen during all events, The Cobb Method snow ratios for all three categories do not produce the range that the observations produce (Tables 4.3.1, 4.3.4, 4.3.5). The "averaging" effect is clearly visible here, and would indicate that extreme high-density or low-density values will not be produced when using the Cobb Method.

4.4 Possible Modifications to The Cobb Method

It has been shown that the differences between observations and the Cobb Method are fairly small. Questions do arise when the differences are large and systematic in nature between the Cobb Method and observations. There are many variables to consider when looking for differences within snowfall conditions, however, the primary focus within this study will be on the temperatures and vertical velocities within the Cobb Method. Since the Cobb Method uses vertical velocities for weighting layers and temperature for assessing what snow ratio will be given to that layer, the initial focus to possibly improve the results of the Cobb Method should be with these two variables.

One probable difference could be within the temperature to snow ratio assignments themselves. The Cobb Method assigns a 10:1 snow ratio to all layers having an average temperature less than -24°C, regardless of pressure level. This 10:1 ratio seems to be too low of a snow ratio for such cold temperatures, since the 10:1 snow ratio usually corresponds to a higher density snow and warmer temperatures. From Fakuta and Takahashi (1999) snow densities as a function of temperature seem to show a decreasing trend in snowflake density below -21°C (Figure 2.2), however the figure does not go past -24°C. Plates and columns are shown to exist at temperatures lower than -24°C, and such snowflakes have a snow ratio ranging from around 9:1 up to 18:1 (Figure 2.1, Table 2.2). It is therefore assumed that assigning 10:1 as the snow ratio for all temperatures below -24°C appears to not cover all snowflake densities. The relationship between temperature and snow ratio at temperatures less than -24°C are not known, and Ware et al. (2006) stated that no studies were found to address this issue. However, Heymsfield (1986) found that aggregation is very important at temperatures between -25°C to -36°C in convective anvils, allowing ice crystals to grow with decreasing altitude to sizes of up to 1 cm. For this study, on average, temperatures below -24°C exist above 500 hPa (Figure 4.4.1). Above 500 hPa to the top of the troposphere, especially in winter, there may not be enough moisture to support such a high-density snow ratio of 10:1 within a cloud.

The Cobb Method also weights the vertical velocities with the highest vertical velocity layer having the greatest weight in the final snow ratio. Within a model's cloudy layer, which is any layer that has a 90% relative humidity, there are many values of vertical velocity. The values of vertical velocity are within model-defined layers of the cloud, and the Cobb Method assigns importance to these layers through the magnitude of vertical velocities. The higher the value of upward vertical velocity, the larger the weighted contribution to snowfall formation, and the larger the contribution to the final storm snow ratio according to the Cobb Method. When the temperature threshold of -24°C is met, the 10:1 snow ratio is used. If colder than -24°C, less dense snow could actually form, causing the Cobb Method to use an inappropriate snow ratio of 10:1. There are a lot of occurrences of maximum vertical velocities occurring at a temperature less than -24°C (Figure 4.4.2), which are the maximum vertical velocities within the cloud column for each respective 3-hour timeframe for each event.

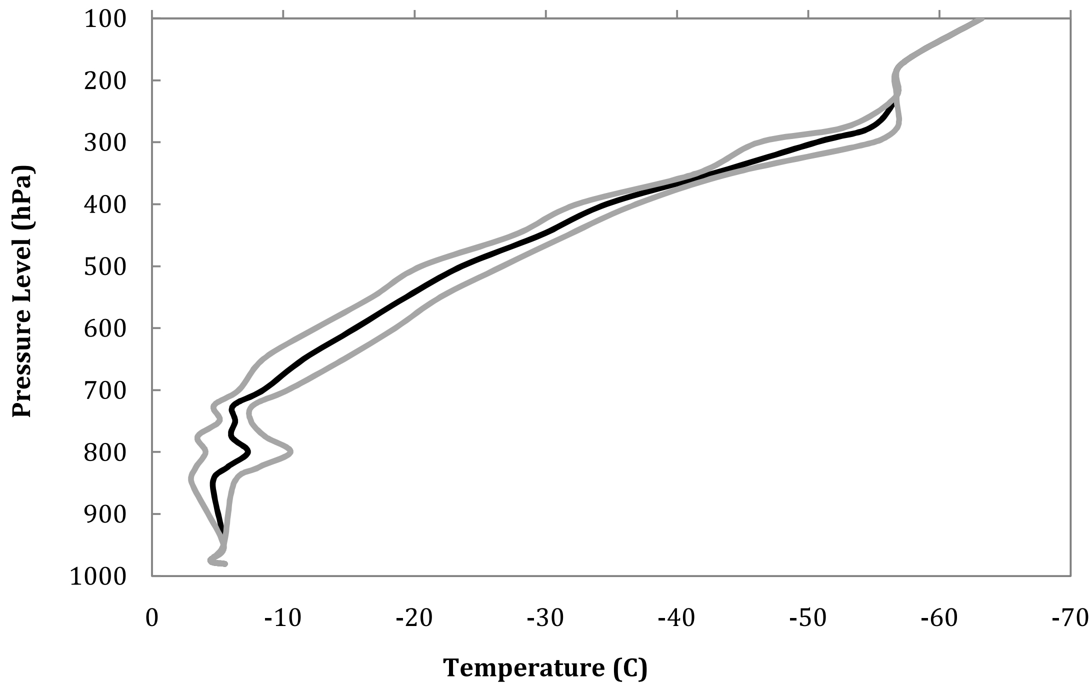

Figure 4.4.1. Plot of the average temperature (Black) that the 3-hour maximum vertical velocity occurs at each pressure level. The upper and lower bound of the standard deviations (Gray lines) is also plotted.

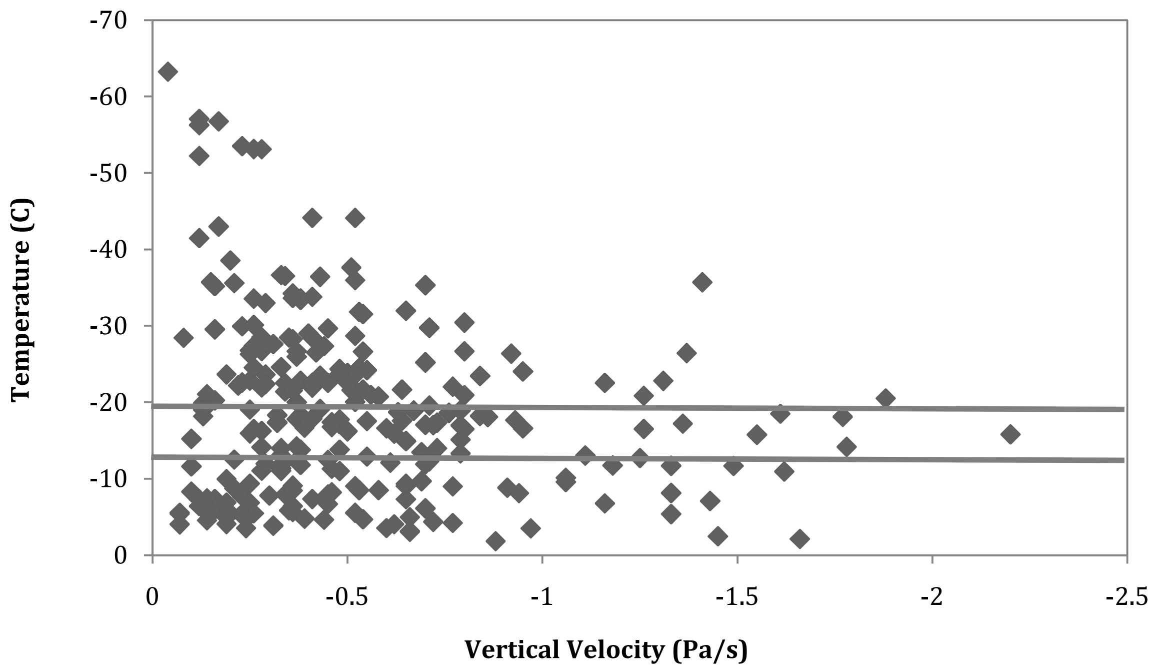

Figure 4.4.2. Plot of the 3-hour maximum vertical velocity values and the temperature they occurred. The dendritic growth zone, or SPZ referred to by Cobb and Waldstreicher (2005), is indicated between the solid lines on the graph.

When using the 50 cases in this study, the highest average maximum vertical velocity values are within 800 to 500 hPa (Figure 4.4.3). The number of times a maximum vertical velocity value occurs at each pressure level (Figure 4.4.4) shows a narrow peak between 500 and 600 hPa. The number of maximum vertical velocities indicates that the most significant contributions to snow ratios, and therefore snow amounts, largely comes from the middle levels of the troposphere. Contributions below 800 hPa and above 500 hPa do not have as much of an impact when compared to the middle levels, however there are enough occurrences outside the 800 to 500 hPa range to affect the results of the Cobb Method.

Two modifications were done to the Cobb Method in order to test the assumptions that temperatures below -24°C can produce lower density snow ratios greater than 10:1. The first modification is changing the 10:1 assumption to a higher snow ratio, since the Cobb Method underforecasts snow ratios by 4.8:1 when considering all 50 events(Table 4.1.3). By doing this, snowfall totals and snow ratios could possibly be more accurately represented to produce a drier or lower density snow. For the hypothesis of changing the snow ratio, a good start to a possible change of the 10:1 snow ratio assumption is using the climatological average for the region. The climatological average snow ratio for the Omaha-Valley CWA according to Baxter et al. (2005) is 12.7:1 (Table 4.1.1). The second modification is to eliminate all data above 500 hPa, the colder temperatures causing 10:1 snow ratio assumptions would be eliminated, and may improve forecasted snowfall totals and snow ratios. Eliminating data above 500 hPa in the Cobb Method is the technique

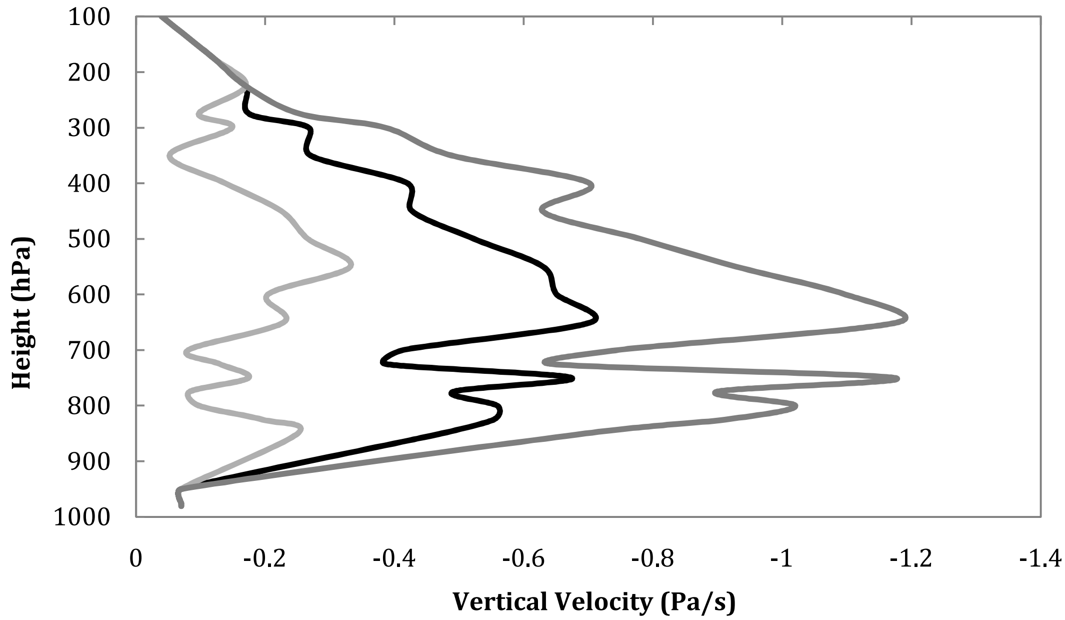

Figure 4.4.3. Plot of the average maximum vertical velocity (Black line) of each 3-hour event at each pressure level it occurs. The upper and lower bound of the standard deviations (Gray lines) is also plotted.

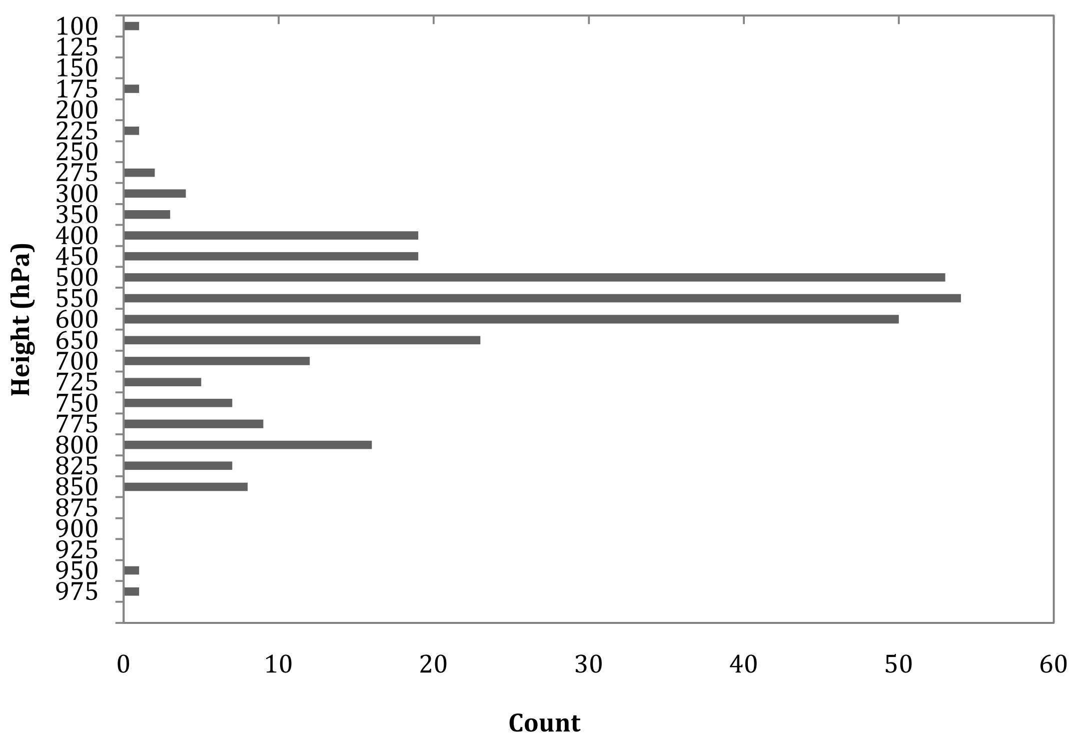

Figure 4.4.4. Plot of the number of occurrences the maximum vertical velocity occurs in each 3-hour event at each pressure level.

used by a version of the Snow Amount Smart Tool used in the Graphical Forecast Editor (GFE) by the National Weather Service.

To see the effects of the two modifications to the Cobb Method, nine events are chosen based upon the original Cobb Method forecasted snow ratios. The three categories described in section 4.3, high-density, moderate-density, and low-density snow ratios, are investigated to see how the modifications affect specific events. Three events from each of the snow ratio categories are used; one overforecasted by the Cobb Method, one underforecasted by the Cobb Method, and one near or exactly forecasted by the Cobb Method. There are nine events; four from Lincoln, two from Norfolk, two from Grand Island, and one from Des Moines (Table 4.4.1).

All of the nine events showed an increase in the 3-hourly snow ratios and snow totals (Table 4.4.2, Table 4.4.3, Table 4.4.4) and corresponding storm total snowfalls (Table 4.4.5) between the original Cobb Method and the two modifications. Removing data above 500 hPa and changing all 10:1 assumptions below -24°C to 12.7:1 have approximately the same effect on the Cobb Method. The underforecasted snowfall amounts get closer to snowfall observations (Table 4.4.5), and the snow ratios (Table 4.4.2, Table 4.4.3, Table 4.4.4) show a slight increase.

The three high-density snowfall events show the least amount of change when looking at all nine events (Table 4.4.5). The near exact event, 2-3 December 1990 at Grand Island, and the underforecasted event, 2-3 December 1990 at Lincoln,

Table 4.4.1. Summary of the events used for the modification analysis.

Density	Type of Forecast Difference		
	Under	Near Exact	Over
High	Lincoln Event 41	Grand Island Event 44	Lincoln Event 31
Moderate	Lincoln Event 1	Lincoln Event 46	Des Moines Event 15
Low	Grand Island Event 24	Norfolk Event 23	Norfolk Event 3

Table 4.4.2. Data showing the selected high-density event observations, original Cobb Method forecasted values and the modified Cobb Method forecasted values. Snow ratio values (SR) are rounded to the nearest value by the Cobb Method output.

	Original Cobb				Remove Above 500		Modify 10:1 to 12:1	
Location & Time	Water	Temp	SR	Snow	SR	Snow	SR	Snow
LNK 28 MAR 12Z	0.05	-1.7	13:1	0.8	13:1	0.8	14:1	0.8
LNK 28 MAR 15Z	0.30	-3.3	14:1	4.3	16:1	5.1	16:1	5.1
LNK 28 MAR 18Z	0.20	-5.0	15:1	3.0	16:1	3.3	16:1	3.3
LNK 28 MAR 21Z	0.25	-5.0	12:1	3.0	13:1	3.3	13:1	3.3
LNK 29 MAR 00Z	0.43	-5.0	11:1	4.6	11:1	4.6	11:1	4.6
LNK 29 MAR 03Z	0.15	-5.6	11:1	1.8	12:1	1.8	12:1	1.8
GRI 02 DEC 18Z	0.28	-2.2	11:1	3.0	11:1	3.0	11:1	3.0
GRI 02 DEC 21Z	0.25	-2.8	11:1	2.8	11:1	2.9	12:1	3.0
GRI 03 DEC 00Z	0.05	-3.3	11:1	0.5	12:1	0.5	12:1	0.5
LNK 02 DEC 18Z	0.13	1.1	10:1	1.3	10:1	1.3	11:1	1.3
LNK 02 DEC 21Z	0.25	0.0	10:1	2.5	10:1	2.5	11:1	2.8
LNK 03 DEC 00Z	0.18	-1.1	11:1	1.8	11:1	1.8	11:1	1.8
LNK 03 DEC 03Z	0.08	-1.7	11:1	0.8	12:1	1.0	12:1	1.0
LNK 03 DEC 06Z	0.10	-1.7	12:1	1.0	13:1	1.3	13:1	1.3
LNK 03 DEC 09Z	0.05	-1.7	12:1	0.5	12:1	0.5	12:1	0.5

Table 4.4.3. Data showing the selected moderate-density event observations, original Cobb Method forecasted values and the modified Cobb Method forecasted values. Snow ratio values (SR) are rounded to the nearest integer by the Cobb Method output.

	Original Cobb				Remove Above 500		Modify 10:1 to 12:1	
Location & Time	Water	Temp	SR	Snow	SR	Snow	SR	Snow
DSM 01 FEB 15Z	0.46	-5.0	15:1	7.1	16:1	7.6	16:1	7.6
DSM 01 FEB 18Z	0.28	-3.9	11:1	3.0	11:1	3.0	11:1	3.0
DSM 01 FEB 21Z	0.13	-2.2	10:1	1.3	10:1	1.3	11:1	1.3
DSM 02 FEB 00Z	0.69	-2.8	9:1	6.4	9:1	6.4	10:1	6.6
DSM 02 FEB 03Z	0.38	-3.3	8:1	3.3	8:1	3.3	9:1	3.6
DSM 02 FEB 06Z	0.30	-2.8	10:1	3.0	10:1	3.0	10:1	3.0
DSM 02 FEB 09Z	0.28	-2.8	13:1	3.6	16:1	4.6	15:1	4.1
DSM 02 FEB 12Z	0.18	-3.3	11:1	1.8	11:1	1.8	11:1	2.0
DSM 02 FEB 15Z	0.10	-3.9	10:1	1.0	10:1	1.0	10:1	1.0
DSM 02 FEB 18Z	0.10	-4.4	11:1	1.0	11:1	1.0	11:1	1.3
DSM 02 FEB 21Z	0.23	-3.9	12:1	2.8	12:1	2.8	12:1	2.8
DSM 03 FEB 00Z	0.18	-4.4	11:1	2.0	11:1	2.0	11:1	2.0
DSM 03 FEB 03Z	0.08	-5.6	12:1	1.0	12:1	1.0	12:1	1.0
LNK 05 JAN 00Z	0.05	-7.8	13:1	0.8	13:1	0.8	13:1	0.8
LNK 05 JAN 03Z	0.20	-8.3	11:1	2.3	11:1	2.3	11:1	2.3
LNK 05 JAN 06Z	0.51	-7.8	11:1	5.6	16:1	7.9	16:1	7.9
LNK 05 JAN 09Z	0.13	-7.8	11:1	1.5	11:1	1.5	11:1	1.5
LNK 10 FEB 06Z	0.05	-10.6	12:1	0.5	12:1	0.5	13:1	0.8
LNK 10 FEB 09Z	0.05	-12.2	13:1	0.8	14:1	0.8	14:1	0.8
LNK 10 FEB 12Z	0.03	-16.1	13:1	0.3	16:1	0.5	14:1	0.3
LNK 10 FEB 15Z	0.10	-16.7	11:1	1.3	12:1	1.3	13:1	1.3
LNK 10 FEB 18Z	0.08	-17.2	13:1	1.0	14:1	1.0	14:1	1.0

Table 4.4.4. Data showing the selected low-density event observations, original Cobb Method forecasted values and the modified Cobb Method forecasted values. Snow ratio values (SR) are rounded to the nearest value by the Cobb Method output.

	Original Cobb				Remove Above 500		Modify 10:1 to 12:1	
Location & Time	Water	Temp	SR	Snow	SR	Snow	SR	Snow
OFK 09 FEB 18Z	0.08	-13.3	10:1	0.8	13:1	1.0	13:1	1.0
OFK 09 FEB 21Z	0.05	-12.2	17:1	1.0	18:1	1.0	18:1	1.0
OFK 10 FEB 00Z	0.05	-13.9	15:1	0.8	17:1	0.8	16:1	0.8
OFK 10 FEB 03Z	0.23	-13.3	14:1	3.3	15:1	3.6	15:1	3.3
OFK 10 FEB 06Z	0.08	-14.4	17:1	1.3	18:1	1.3	17:1	1.3
OFK 10 FEB 09Z	0.08	-17.2	19:1	1.5	21:1	1.5	19:1	1.5
OFK 10 FEB 12Z	0.20	-17.8	12:1	2.3	14:1	3.0	14:1	2.8
OFK 10 FEB 15Z	0.15	-18.9	13:1	2.0	14:1	2.0	14:1	2.0
OFK 09 JAN 03Z	0.03	-10.0	14:1	0.3	17:1	0.5	15:1	0.3
OFK 09 JAN 06Z	0.10	-10.0	12:1	1.0	15:1	1.0	14:1	1.0
OFK 09 JAN 09Z	0.13	-10.0	13:1	1.8	14:1	1.8	14:1	1.8
OFK 09 JAN 12Z	0.03	-9.4	10:1	0.3	10:1	0.3	12:1	0.3
OFK 09 JAN 15Z	0.05	-8.9	15:1	0.8	15:1	0.8	15:1	0.8
OFK 09 JAN 21Z	0.08	-6.7	15:1	1.0	16:1	1.3	16:1	1.3
OFK 10 JAN 03Z	0.03	-8.3	14:1	1.0	14:1	0.3	14:1	0.3
GRI 10 FEB 03Z	0.13	-12.8	13:1	1.5	14:1	1.8	14:1	1.8
GRI 10 FEB 06Z	0.13	-13.3	14:1	1.8	15:1	1.8	14:1	1.8
GRI 10 FEB 09Z	0.10	-15.6	16:1	1.8	18:1	1.8	17:1	1.8
GRI 10 FEB 12Z	0.05	-18.3	10:1	0.5	12:1	0.5	12:1	0.5

Table 4.4.5. Snowfall totals (SN) and snow ratios (SR) for the events in Tables 4.4.2, 4.4.3, and 4.4.4. All snow and water values are in cm.

*	Location	Obs. SN	Obs. Water	Obs. SR	Cobb SR	Cobb SN	12.7 SR	12.7 SN	+/- SN	500 SR	500 SN	+/- SN
	HIGH DENSITY											
O	LNK 28-29 Mar 1987	16.0	1.63	9.8:1	10.8:1	17.5	13.7:1	18.9	1.4	13.5:1	18.8	1.3
E	GRI 02-03 Dec 1990	6.6	0.58	11.3:1	10.9:1	6.3	11.7:1	6.5	0.2	11.3:1	6.4	0.1
U	LNK 02-03 Dec 1990	12.4	0.79	15.8:1	10.3:1	7.9	11.7:1	8.7	0.8	11.3:1	8.4	0.5
	MOD DENSITY											
O	DSM 02-03 Feb 1983	27.4	3.38	8.1:1	11.1:1	37.3	11.5:1	39.4	2.1	11.3:1	38.9	1.6
E	LNK 04-05 Jan 1991	10.2	0.89	11.4:1	11.1:1	10.2	13.3:1	12.4	2.2	13.3:1	12.4	2.2
U	LNK 09-10 Feb 1981	4.8	0.30	15.8:1	12.5:1	3.8	13.6:1	4.1	0.3	13.6:1	4.1	0.3
	LOW DENSITY											
O	OFK 09-10 Feb 1981	9.7	0.84	11.5:1	13.9:1	11.7	15.8:1	13.7	2.0	16.3:1	14.2	2.5
E	OFK 09-10 Jan 1985	5.6	0.41	13.9:1	13.4:1	5.3	14.3:1	5.6	0.3	14.4:1	5.8	0.5
U	GRI 09-10 Feb 1981	7.1	0.41	17.5:1	13.8:1	5.6	14.3:1	5.8	0.2	14.8:1	5.8	0.2

both show improvements when the modifications are implemented (Table 4.4.5). Grand Island had originally a Cobb Method forecasted value of 6.3 cm (2.5 in) and an average snow ratio of 10.9:1. Modifying the 10:1 assumption to 12.7:1 increased the snowfall to 6.5 cm (2.6 in) with an average snow ratio of 11.7:1, and deleting the data above 500 hPa has 6.4 cm (2.5 in) of snow with an average snow ratio of 11.3:1 (Table 4.4.5). Slightly higher increases in snowfall totals are shown in the Lincoln event, with the modifications increasing snowfall by 0.8 cm (0.3 in) for the snow ratio modification, and 0.5 cm (0.2 in) for the deletion of data above 500 hPa (Table 4.4.5).

The largest change within high-density snowfall events is the overforecasting event, 28-29 March 1987 at Lincoln. The Cobb Method already overforecasted observations by 1.5 cm (0.6 in), and the modifications added an additional 1.4 cm (0.6 in) by the snow ratio modification, and 1.3 cm (.5 in) by deleting data above 500 hPa (Table 4.4.5). The additional snowfall would create an even larger overforecasted amount.

Moderate-density snow ratios have the largest overall snowfall changes observed between the Cobb Method and both Cobb Method modifications between the three snow density categories. The largest change within the moderate-density snow ratios is the near exact event of 4-5 January 1991 in Lincoln (Table 4.4.5). The Cobb Method originally forecasted correctly with the observations at 10.2 cm (4.0 in), however, the modifications made the correct forecast an overforecast with an additional 2.2 cm (0.9 in) to the original Cobb Method snowfall (Table 4.4.5).

Snow ratio averages increase from 11.1:1 in the original average Cobb Method to both modifications having a snow ratio of 13.3:1 (Table 4.4.5). The overforecasting event, 2-3 February 1983 in Des Moines, has similar increases between the original Cobb Method and the modifications as the exact forecasting event, with the snow ratio modification adding 2.1 cm (0.8 cm) and the deletion of data above 500 hPa adding 1.6 cm (0.6 in) to the original Cobb Method snowfall (Table 4.4.5). The snow ratio averages increase from the original Cobb Method value of 11.1:1 to having the snow ratio modification having 11.5:1, and the deleting of data above 500 hPa having an average snow ratio of 11.3:1 (Table 4.4.5). The underforecasting event from 9-10 February 1981 in Lincoln only improves by 0.3 cm (0.1 in) for both modifications (Table 4.4.5). Snow ratio averages increase from an original Cobb Method value of 12.5:1 to both modifications having an average snow ratio of 13.6:1 (Table 4.4.5).

The low-density snow ratio modifications have increasing changes occurring with overforecasts as well. The overforecasting event from Norfolk on 9-10 February 1981 has an original Cobb Method forecast of 11.7 cm (4.6 in) with an average snow ratio of 13.9:1, and observations have 9.7 cm (3.8 in) of snowfall (Table 4.4.5). The snow ratio modification has a snow ratio of 15.8:1 and adds 2.0 cm (0.8 in) of snowfall, while the deletion of data above 500 hPa has a snow ratio of 16.3:1 and adds 2.5 cm (1.0 in) of snowfall to the original Cobb Method snowfall (Table 4.4.5). The near exact event from Norfolk on 9-10 January 1985 is the only modification that changed the Cobb Method snowfall to be the same as the observations. The observations have 5.6 cm (2.2 in) of snowfall, and the original Cobb Method snowfall was 5.3 cm (2.1 in) of snowfall (Table 4.4.5). The 12.7:1 snow ratio modification increased the original Cobb Method snowfall to 5.6 cm (2.2 in) which was the exact observation measurement (Table 4.4.5) and also increased the snow ratio to 14.3:1. The underforecasted event is from Grand Island on 9-10 February 1981, and is originally underforecasted by 1.5 cm (.6 in) of snow (Table 4.4.5). Both modifications add an additional 0.2 cm (0.1 in) of snow, which is a very small improvement (Table 4.4.5).

The two modifications to the Cobb Method are not large modifications, however, changes are observed. Events that are underforecasted will improve and become closer to observations since snow ratios will increase due to the absence of data above 500 hPa, or the 10:1 assumption for temperatures lower than -24°C will be 12.7:1. Events that were forecasted exactly to observations or close to them will become overforecasted events, and events that are overforecasted will become more overforecasted. Even though the underforecasted events improved slightly, the modifications made to the Cobb Method cannot be applied since the changes to overforecasted events made the differences much larger (Table 4.4.5). Therefore, these modifications to the Cobb Method will only improve underforecasted amounts, and make exact forecasted and overforecasted amounts more inaccurate. The modifications to the Cobb Method resemble an exponential change in the sense that underforecasted events barely improve, and overforecasted events greatly increase and become more overforecasted. In order to improve on the Cobb

Method, much more research is needed in order to determine what changes will benefit all categories of snowfall. The changes implemented in this study further show that there is not a simple fix or relationship between the variables that affect snow ratio, and this was shown in Roebber et al. (2003).

Since the relationships between the unknown variables that govern snow ratios are largely unknown, a simple modification will not benefit all types of snowfall events. For example, one simple change within the Cobb Method or any method may benefit lower density snowfall events, and perform poorly for higher density snowfall events and vice versa. Also, it is assumed that formation of ice crystals at temperatures below -24°C would have an absence of abundant moisture since these temperatures are largely at higher altitudes in the atmosphere. With the absence of higher moisture content, one would expect the snow ratios at such cold temperatures to have a lower crystal density. This may be true, however, Doesken and Judson (1997) stated that ice crystals that form at such cold temperatures actually could have a higher density, since the crystals are smaller and pack tightly when they accumulate on the surface. Even if the crystals do form with a lower density, when they accumulate at the surface and observations are taken, the snowfall total and corresponding snow density measured could be represented by different snow ratio characteristics nearly opposite to where the crystals formed. Therefore, much more research is needed in order to get a better grasp on which atmospheric variables can better assist the Cobb Method and future snowfall forecasting algorithms.

5. Conclusion

Snowfall forecasting is one of the most difficult forecasting challenges in meteorology. The three most important factors in snowfall forecasting are the duration of the snowfall, the amount of liquid water the storm will produce, and the snow density or snow ratio. For most traditional forecasting, a snow ratio of 10:1 is assumed in order to forecast how much snow will fall from a given amount of liquid precipitation. Recent studies of snow ratio climatologies have shown 10:1 to be common, but below the average snow ratio for most of the United States. In order to aid in the snowfall forecasting challenge, the Cobb Method was developed, and incorporates the three important factors while improving on the 10:1 snow ratio assumption.

The results of this study show that the Cobb Method does a decent job forecasting snowfall, although there are a few items to consider. The results show the Cobb Method produces snowfall and snow ratio differences around 20% to 30%, on average, giving results that are 70% to 80% accurate to observations. It is important to note that the differences in Cobb Method values are calculated based on observations, and the observations may not be completely accurate. Assuming the observations have some error, say around 10% to 15%, the Cobb Method may have even more accurate forecasts given the most accurate data possible.

When looking at all 50 events studied, the Cobb Method and observational data produce results similar to snow ratio climatologies of Roebber et al. (2003) and Baxter et al. (2005). The Cobb Method has a snowfall total mean of 11.3 cm and a snow ratio mean of 12.3:1, while observations within this study have a snowfall total mean of 11.9 cm and a snow ratio mean of 14.1:1. The Cobb Method forecasts have a smaller range and standard deviation of snow ratios when compared to observations, however, the Cobb Method has a larger range and standard deviation for snowfall totals when compared to observations. This would indicate that for snow ratios, the Cobb Method tends to average out extreme values, and produces a much larger variation of snowfall totals compared to observations due to the absence of averaged-out extreme values. All 50 events also have an overall magnitude forecasting accuracy of 77.7% (2.8 cm snowfall total difference, 3.5:1 snow ratio difference). When the Cobb Method underforecasted snowfall events, accuracy is 74.8% (3.2 cm snowfall total difference, 4.8:1 snow ratio difference), and when the Cobb Method overforecasted, accuracy is 79.9% (2.6 cm snowfall total difference, 2:1 snow ratio difference).

When the data are divided into light, moderate, and heavy snowfalls, light snowfalls have the highest underforecasting differences in terms of percentage, while heavy snowfalls have the largest differences in magnitude for both underforecasting and overforecasting between Cobb Method forecasted values and observations. Looking at percent differences and mean values, the Cobb Method forecasts a larger range than the observations produce. Light, moderate, and heavy snowfall events have a Cobb Method mean snowfall amount of 5.8 cm, 9.2 cm, and 19.7 cm respectively, while observations have 8.0 cm, 9.9 cm, and 18.8 cm respectively. This reveals that overall, the Cobb Method underforecasts light snowfall events, comes close to observations for moderate events, and overforecasts observations for heavy events. The overforecasting bias towards heavy events could partly be attributed to compaction of snowfall in the observations. The Cobb Method data has 3-hourly snowfall accumulations summed to get a storm total snowfall, while observations have 24-hour snowfall accumulations. This difference could cause the observational snowfall to compact, causing decreased snowfall accumulations compared to the Cobb Method. The compaction effect of observational snowfall amounts will have a greater effect with larger snowfall accumulations, thus increasing the differences between Cobb Method forecasts and observations. Light to moderate snowfall amounts may not be affected as much by compaction than heavier snowfalls. Compaction may also play a role in the snow ratio densities.

Dividing the data into three snow ratio categories of high-density, moderate-density, and low-density, highlights the accuracy of the Cobb Method with high-density snow ratios being 78.1% accurate and low-density snow ratios being 70.4% accurate. When looking at magnitude differences, low-density snow ratios have the highest differences for both underforecasting at 2.4:1 and overforecasting at 7.5:1. Since the highest differences are in the low-density category, a higher range of snowfall amounts would be supported, and is reflected in the snowfall amounts' statistics. The general tendency for snow ratios is the opposite of snowfall amounts in the sense that the standard deviation and range are less than the observations. Since the snowfall amounts still have a larger range and standard deviation compared to observations when the data are divided by snow ratio, it is likely that the over-averaging property of the Cobb Method causes extreme high and low values to be blended out. The extreme high and low blended out values could bring the Cobb Method forecasted snow amounts and snow ratios closer to observations. This point is also reinforced by the similar statistics to the Cobb Method forecasted snow ratios and observations for moderate-density snow ratio events, and the small underforecasting and overforecasting value and percent differences between Cobb Method forecasted snow ratios and observations.

Two modifications to the Cobb Method show that simple changes to the algorithm may improve one or two of the snow categories, but do not improve forecasts for all types of snow events. The two modifications implemented are changing the 10:1 snow ratio assumption below the temperature of -24°C within the Cobb Method algorithm, and deleting the data above 500 hPa before calculating the output from the Cobb Method. The climatological average snow ratio for the Omaha-Valley, NE CWA of 12.7:1 was assigned to the 10:1 snow ratio, and was taken from Baxter et al. (2005). Both of the modifications are implemented due to the theory that such high altitudes and/or cold temperatures are unable to support such high-density snow ratios, and thus, by changing the Cobb Method algorithm to support this theory, improvements could be shown. The changes implemented seem to change the output almost systematically, and only improve underforecasted amounts. Snowfall totals that were near-exact, exact, or overforecasted now have higher Cobb Method snow ratios and increased snowfall amounts, and become more inaccurate to observations. This reinforces the results of Roebber et al. (2003) and Ware et al. (2006) stating that the variables affecting snow ratio are very complex and require much more research. A simple linear-like change to the Cobb Method by modifications presented here to such a complex forecasting problem has shown not to be effective for all types of snow events.

The results of this study show the Cobb Method to be a step in the right direction towards forecasting snowfall. The Cobb Method is an easy to use model algorithm and takes important atmospheric variables into effect when forecasting snowfall. More research is needed, however, in order to determine which variables have the greatest effects on snowfall forecasting and improving the Cobb Method, or even creating a new snowfall algorithm. This study has shown that the Cobb Method produces accurate results, however, a much larger study may be needed to assess the accuracy of mountain, lake effect, and even snowfall events with substantial convective lift. Further analysis of how the Cobb Method performs under these situations could provide more insight into what variables affect snowfall accumulation, and the development of an improved snowfall forecasting algorithm.

6. References

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