Using Radar Reflectivity Heights to Forecast the Presence of Large Hail across the Intermountain West

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1 - Background

Hail is a weather phenomenon frequently associated with strong and severe thunderstorms. Hailstorms cause, on average, $1.2 billion of property damage each year (Changnon 1999), which is comparable to the annual damage caused by tornadoes (Kunkel et al. 1999) In the course of a year, over 75 percent of cities in the continental United States will see a hailstorm. Numerous studies have greatly improved the scientific understanding of the physical processes involved in the development of large hail. These are summarized in Knight and Knight (2001). Of particular interest to this study are the processes involved in melting processes which impact the size of hailstones which are able to reach the surface (Rasmussen and Heymsfield 1987).

Additionally, forecasters have developed many tools to help predict large hail events. Radar interrogation tools for anticipating large hail include the Lemon Technique (Lemon 1980), Vertically Integrated Liquid (VIL) Density (Amburn and Wolf 1997), as well as using the VIL product to identify a “VIL of the Day” (Paxton and Sheppard 1993, Wallman 2002). However, Edwards et al (1998) have shown the VIL of the Day technique to have very limited skill in forecasting the presence of large hail. In addition to these techniques, radar algorithms have also been developed to forecast hail size (Witt et al. 1998), although studies such as Vasiloff et al. (1997) and Graham and Nelson (1998) have shown that these algorithms often over-forecast the presence and size of large hail in weaker cells.

More recently, Donavon and Jungbluth (2007, hereafter referenced as DJ07) developed a technique for anticipating the occurrence of large hail by comparing the height of the 50 dBz echo to the freezing level. This technique has shown considerable skill in identifying the potential for large hail within thunderstorms east of the Rockies. However, operational experience has shown that using the values from DJ07 greatly under-forecasts the presence of large hail within the Intermountain West. This study will utilize the methodology utilized in DJ07 to create a modified version more applicable to large hail events across the Intermountain West.

2 - Data and Methodology

To identify large hail cases for this study, the StormData database (NCDC 2010) was searched for reported occurrences of hail of 0.75 inch or greater that occurred between

1996 and 2006 within 120 nautical miles of five WSR-88D sites within the Intermountain West and the Great Basin. These sites were: KMTX (Salt Lake City, UT), KICX (Cedar City, UT), KLRX (Elko, NV), KGJX (Grand Junction, CO), and KESX (Las Vegas, NV). Additionally, all cases from the KRGX radar that occurred in Nevada and all cases from the KRIW (Riverton, WY) radar that occurred in Southwest Wyoming were used. California cases under the KRGX (Reno, NV) radar umbrella and events under the KRIW umbrella outside of southwest Wyoming were not used because the environments in these cases differed too much from the other Great Basin cases. The cases and RDAs used in this study are shown in Figure 1.

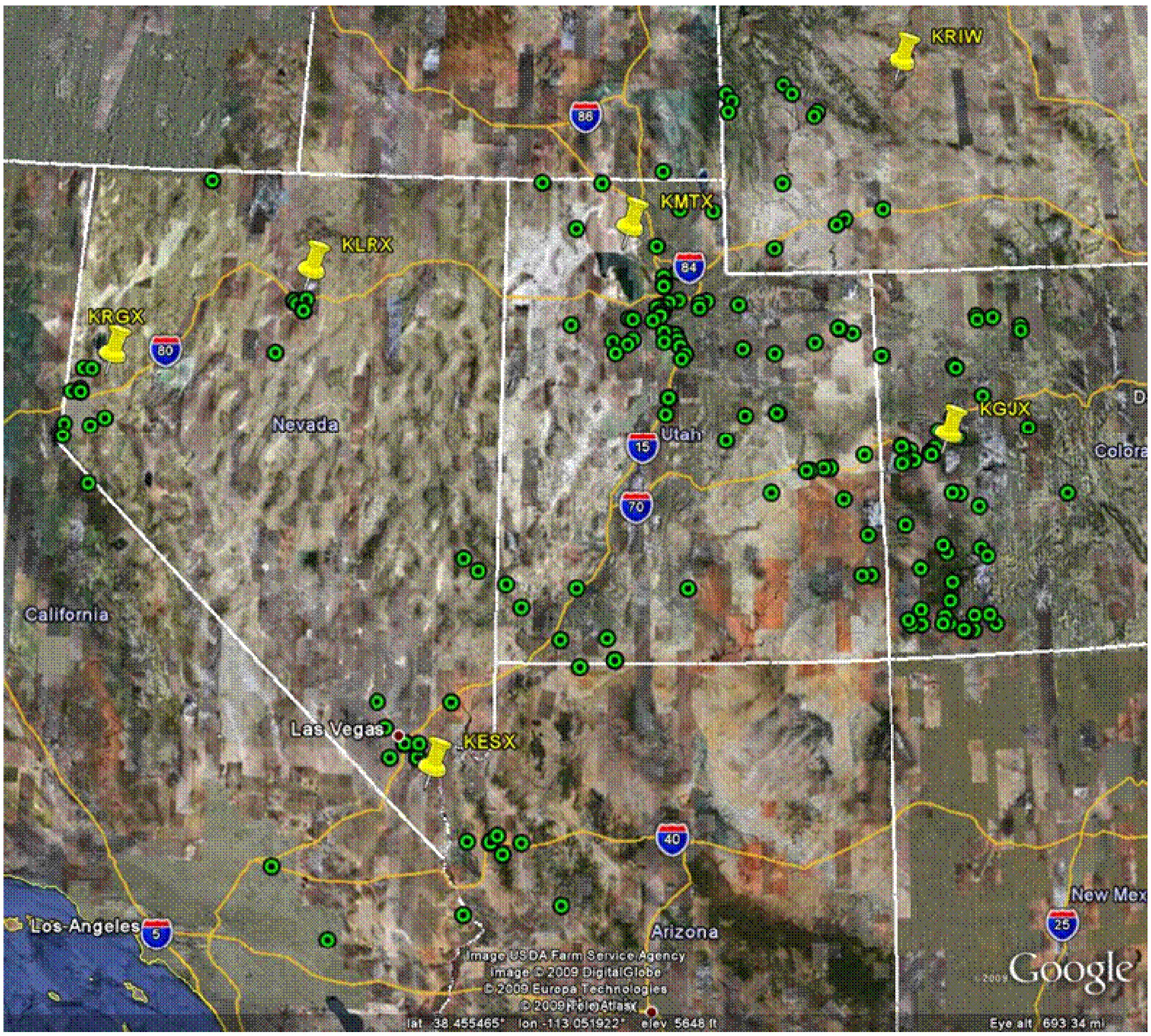

Figure 1: A map indicating the location of each large hail case utilized in the study along with the location of each RDA used. Each case is represented by a green circle while each RDA is represented by a yellow push pin icon.

Archive II data for each case was downloaded from the National Climatic Data Center and then analyzed using NCDC's Weather and Climate Toolkit. Each hail producing storm was isolated using the latitude and longitude included with the StormData report. Then, the greatest height of the 50, 55, 60, and 65 dBz echoes with each storm were identified for the thirty minute time period from 20 minutes before through 10 minutes after the time of the report, as given in StormData. Any report that could not be associated with at least a 50 dBz echo was removed from the data set. Reflectivity heights were recorded in feet above MSL. Heights above ground level (AGL) were avoided due to the potential of introducing large errors as a result of estimating the elevation for the location from which the report was received. In other words, errors relative to the reporting sites' elevation would carry over to the reflectivity heights AGL and could potentially skew the data.

Finally, for each storm, the closest sounding, both in geographical distance and time, was retrieved from the University of Wyoming online database. RAOB software was then used to plot each sounding and retrieve the freezing level, wet bulb zero level (both in feet above MSL), and the 500 mb temperature. Cases were thrown out if the closest observed sounding was not available near the time of the event, or if only a partial sounding that did not include the previously mentioned parameters was found.

In cases where multiple large hail reports were found to be associated with one storm, only the largest hail report was used. This was done to eliminate weighting of cells from which many reports were received. Additionally, a small number of cases in which the reports appeared egregiously large given the observed environmental conditions or storm structure were not included in the analysis.

Given the sparse population of the Intermountain West, no attempt was made to examine the potential false alarm rate of this large hail detecting technique. With such a limited spotter network, it can be assumed that the lack of a report of large hail does not necessarily indicate that the large hail did not occur. Therefore, this study focused on the likelihood that the technique would identify the potential for large hail in cases when it was indeed observed.

Using this methodology, 198 cases were examined for the study. The events were stratified by the radar umbrella under which they occurred, as well as by hail size. 65% of the cases come from two radars: KMTX and KGJX (Table 1), and 42% of the cases were for reports of hail between 0.75 and 0.88 inches (Figure 2).

Radar	**Number of Cases**
KMTX	66
KGJX	63
KESX	26
KRGX	15
KICX	12
KRIW	11
KLRX	5

Table 1: Chart showing the number of cases used from each radar.

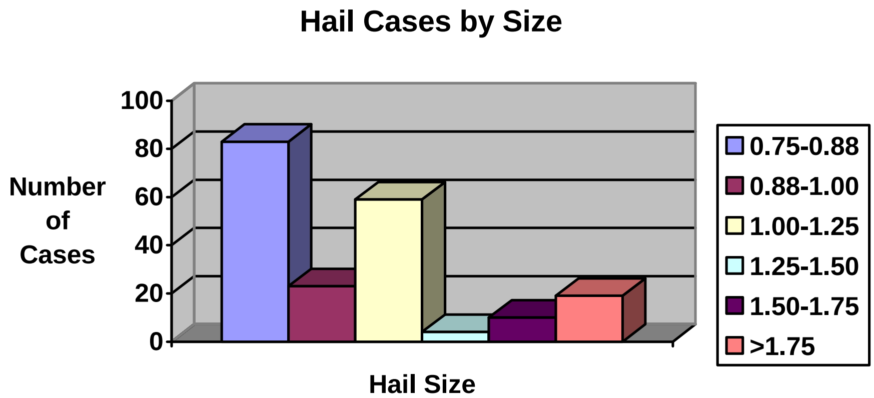

Figure 2: Histogram showing the number of cases for different ranges of hail size. The largest hail report in the study was 4.00 inches near Rangely, Colorado.

3 - Results

a. Reflectivity Heights versus Freezing Level

Scatter plots were developed for reflectivity values of 50, 55, 60, and 65 dBz vs freezing level and wet-bulb zero height. Quantile regression techniques were then used to determine the 20^{th} percentiles for each of these plots. The 20^{th} percentile represents a value where, at a given freezing level, 80 percent of the reflectivity height observations associated with large hail events fall above and 20 percent of the reflectivity height observations fall below. For all freezing level values in the study, the 20^{th} percentile is represented as a linear approximation. In this Intermountain West study, the 20^{th} percentiles were used, as opposed to the 5^{th} and 10^{th} percentiles utilized in the DJ07 study, because of the larger spread in reflectivity heights associated with large hail for a given freezing level in the western U.S. cases. In other words, for a given freezing level, there was a wider range of reflectivity heights associated with large hail in the Intermountain West study compared to DJ07. A similar analysis was completed relating wet-bulb zero heights to the maximum height of the 50, 55, 60, and 65 dBz returns. The skill was found to be similar whether reflectivity heights were compared to the freezing level or the wet-bulb zero height. The scatter plots presented here were generated utilizing freezing level heights because that data is typically more readily available for operational use.

A scatter plot was developed for 50 dBz echo height vs. freezing level (Figure 3). All cases within the dataset were associated with a 50 dBz echo, as this was one of the thresholds set in the quality control of the data for inclusion in the study. The points indicating large hail reports have been assigned different icons based on the size of the hail report. The 20^{th} percentile line has also been plotted on figure 3. For the 50 dBz criterion, the equation for the 20^{th} percentile (A) is:

Y = 26.1 + 2.0462(X-13.2) and slope = 2.0462

While Figure 3 indicates an approximately linear relationship between 50 dBz height and freezing level, the correlation appears to improve as hail size increases. The majority of outlier events are associated with hail between 0.75 and 1.00 inch. Conversely, events with hail greater than 1.50 inches are closely packed along and just above the 20th percentile line. Additionally, the clustering of events in the scatter plot seems to indicate that the relationship is more linear at lower freezing levels than at higher freezing levels. However, this may be due to the smaller amount of events observed at lower freezing levels.

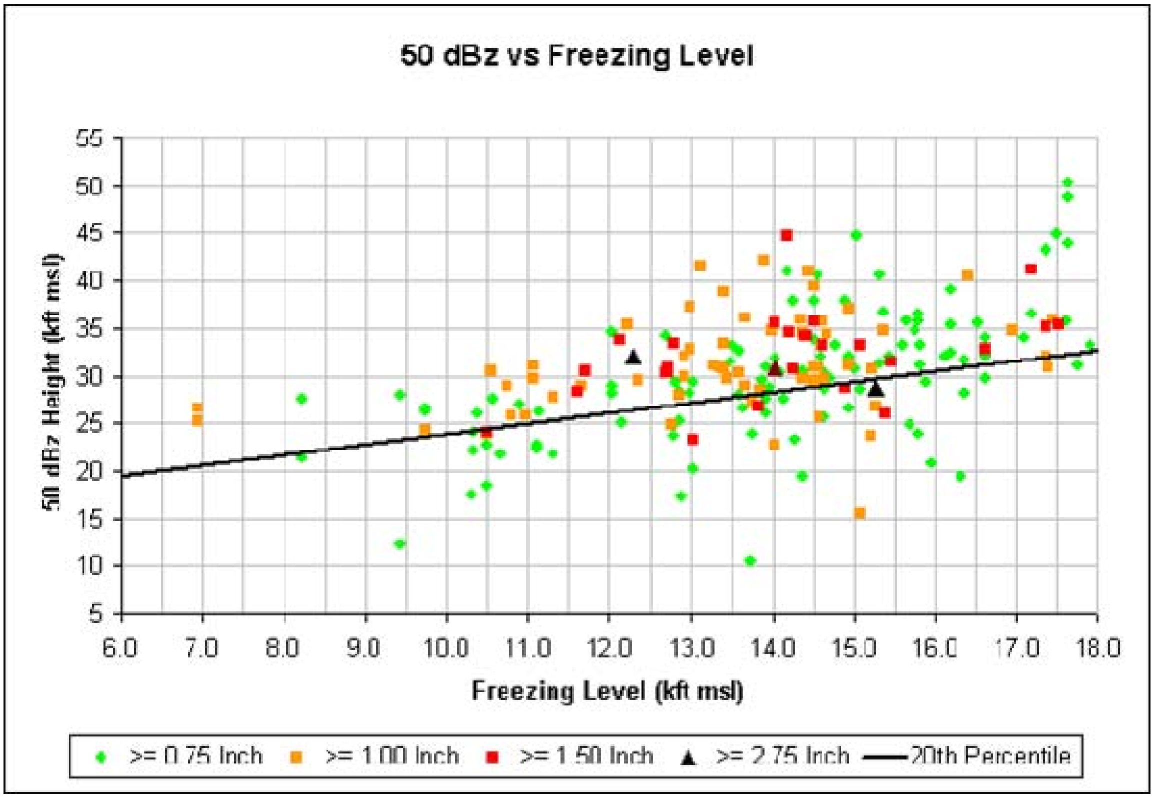

Figure 3: A plot of the maximum height of 50 dBz echoes versus freezing level for each case in the study. Different symbols are used to represent different hail sizes.

Within the dataset, 94% of cases were associated with a 55 dBz echo (187 of 198 cases). Figure 4 shows the scatter plot developed for 55 dBz echo height vs. freezing level. For the 55 dBz criterion, the equation for the 20th percentile (B) is:

Y = 23.28 + 1.7081(X-14.3) and slope =1.7081

Looking at Figure 4, one sees that there is still an approximately linear relationship when comparing 55 dBz height and freezing level. However, outliers are more apparent, especially those that fall below the 20th percentile line. Also, the outliers tend to appear more frequently at lower freezing levels than in Figure 3, so unlike the relationship between the 50 dBz echoes and freezing level, the relationship between the 55 dBz echoes and freezing level does not appear to be more linear at lower freezing levels.

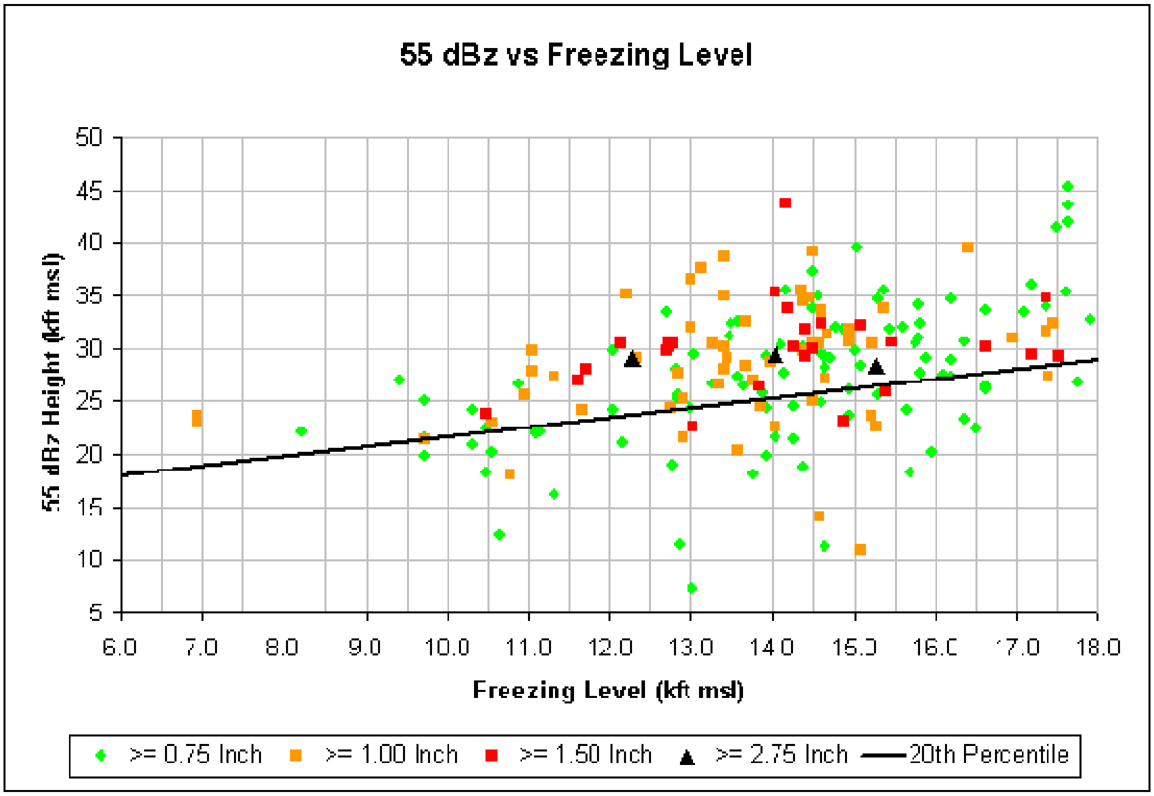

Figure 4: A plot of the maximum height of 55 dBz echoes versus freezing level for each case in the study.

Figure 5 shows the scatter plot developed for 60 dBz echo height vs. freezing level. In the study, only three quarters (75%) of cases were associated with a 60 dBz echo (148 of 198 cases). With fewer cases, there is less of a linear correlation between echo height and freezing level on the scatter plot. For the 60 dBz criterion, the equation for the 20^{th} percentile (C) is:

$$Y = 18.3 + 1.2373(X-14.4) \text{ and slope} = 1.2373$$

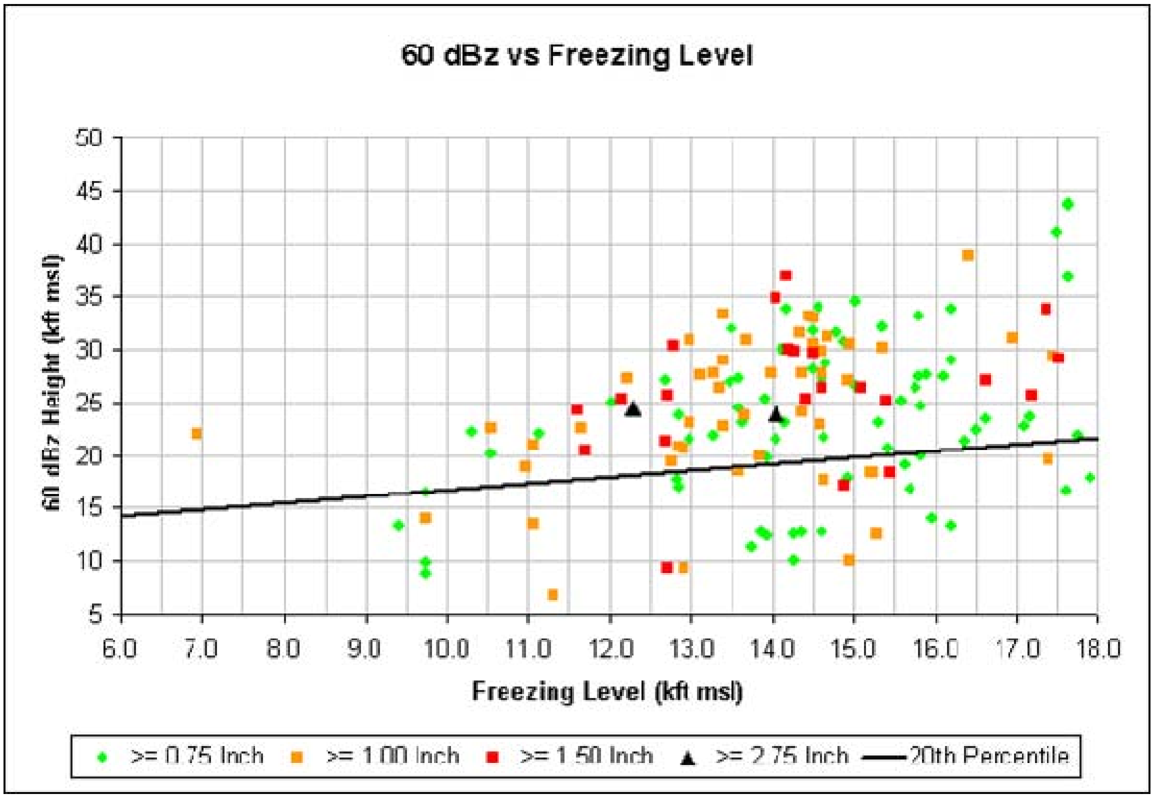

Figure 5: A plot of the maximum height of 60 dBz echoes versus freezing level for each case in the study.

Only 35% of cases (69 of 198 cases) were associated with a 65 dBz echo. Although 65 dBz returns are likely associated with the presence of hail, the data set used did not reveal a relationship between the height of a 65 dBz echo at a given freezing level and the presence of large hail. This may be a result of the small sample size in the data set.

b. Adjustments for one inch hail criteria

In 2010, the National Weather Service change the minimum hail criterion used to issue Severe Thunderstorm Warnings from 0.75 inch to one inch. Because of this, new scatter plots comparing the reflectivity heights of 50, 55, and 60 dBz echoes with freezing level were created for the 93 cases in the data set associated with events involving hail one inch or greater in diameter. 20^{th} percentile regression lines were also created for each plot. Of these cases, all were associated with a 50 dBz echo, 98% (91 of 93 cases) were associated with a 55 dBz echo, and 80% (74 of 93 cases) were associated with a 60 dBz echo. These scatter plots and quantile regressions are shown in Figures 6 through 8.

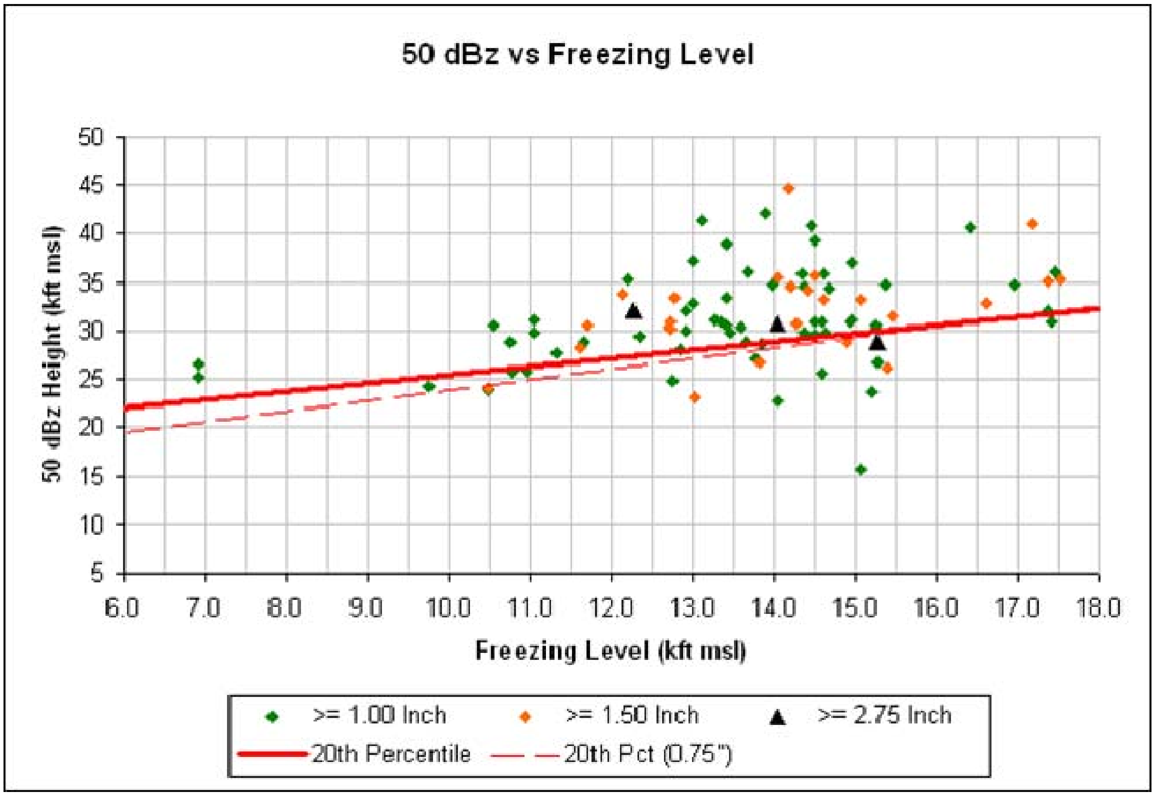

Figure 6: A plot of the maximum height of 50 dBz echoes versus freezing level for cases in the study associated with hail one inch or greater in diameter.

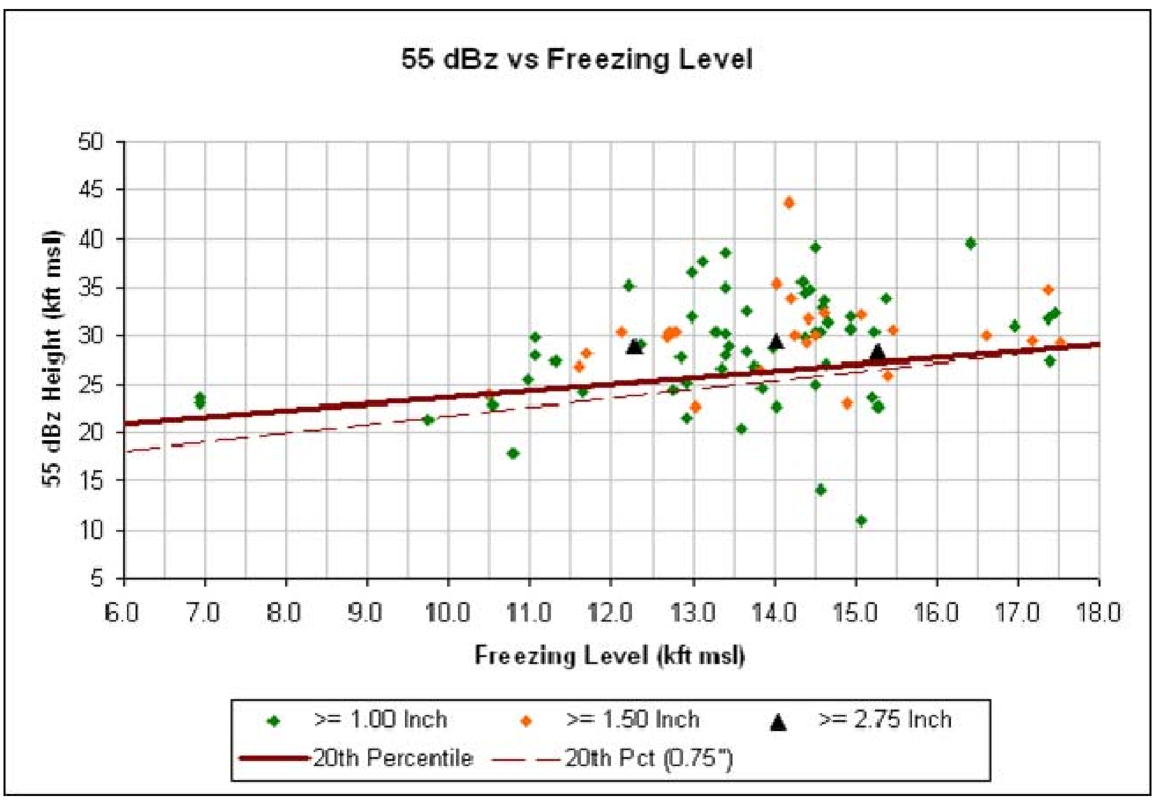

Figure 7: A plot of the maximum height of 55 dBz echoes versus freezing level for cases in the study associated with hail one inch or greater in diameter.

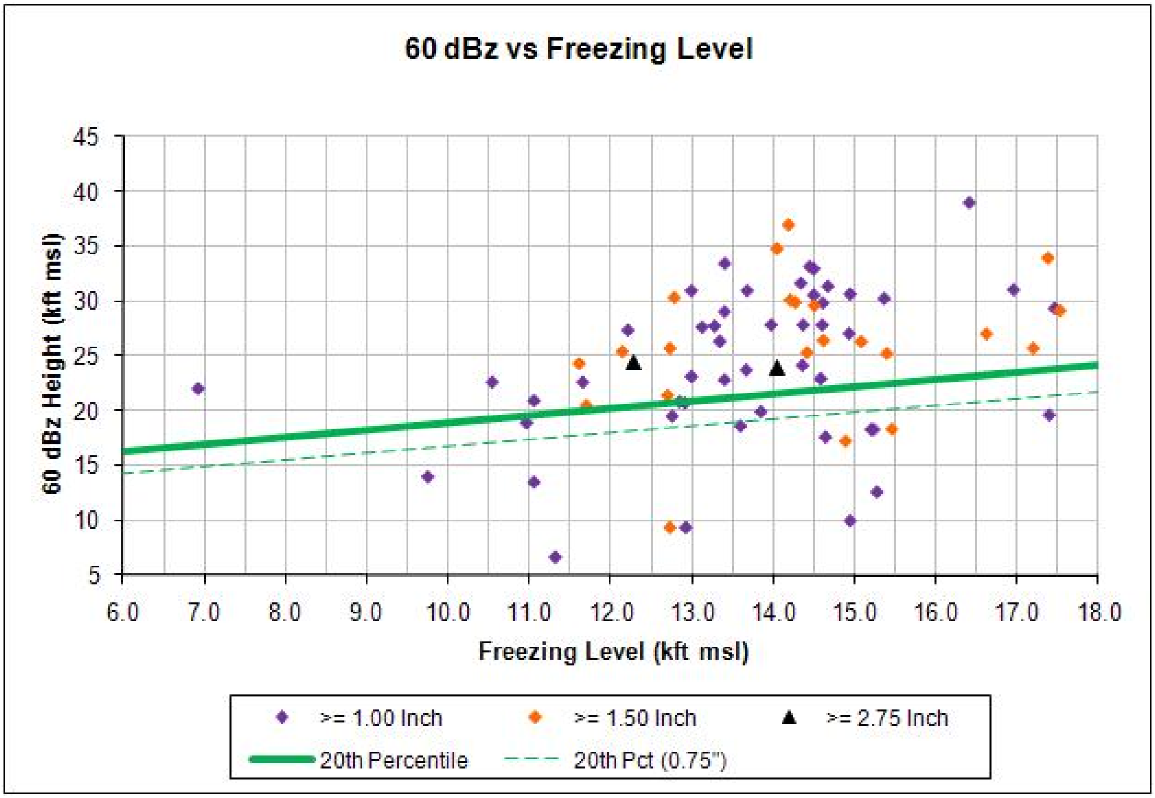

Figure 8: A plot of the maximum height of 60 dBz echoes versus freezing level for cases in the study associated with hail one inch or greater in diameter.

c. Other techniques

To test its potential for indicating the presence of large hail, Vertically Integrated Liquid (VIL) (reference) was retrieved for KMTX cases. However, it was found to be poorly correlated with hail size and thus was not investigated for the remaining radar sites. Storm Top Divergence was also investigated for the KMTX cases, but it showed poor skill in detecting large hail, and was often not observed at all in pulse storm events.

4 - Discussion

In order to aid in forecasting the presence of large hail, a composite plot of the 20th percentile for 50, 55, and 60 dBz echo heights was developed for both the original data set and the subset of cases associated with hail one inch or greater in diameter (Figures 9 and 10). The 20th percentile line associated with the 60 dBz echo in figure 10 is indicated by a dashed line as the relationship between 60 dBz echo heights and freezing level was only weakly linear in the subset of data. Therefore, confidence is low with respect to the reliability of that 20th percentile line. Confidence in the presence of large hail increases as each of these thresholds is met. However, there were several cases in which very narrow reflectivity cores met the aforementioned thresholds, but were only associated with small hail. This may be because thunderstorms with narrower cores tend to be more short-lived than those with wider cores, allowing for less time for hail to develop before the core collapses.

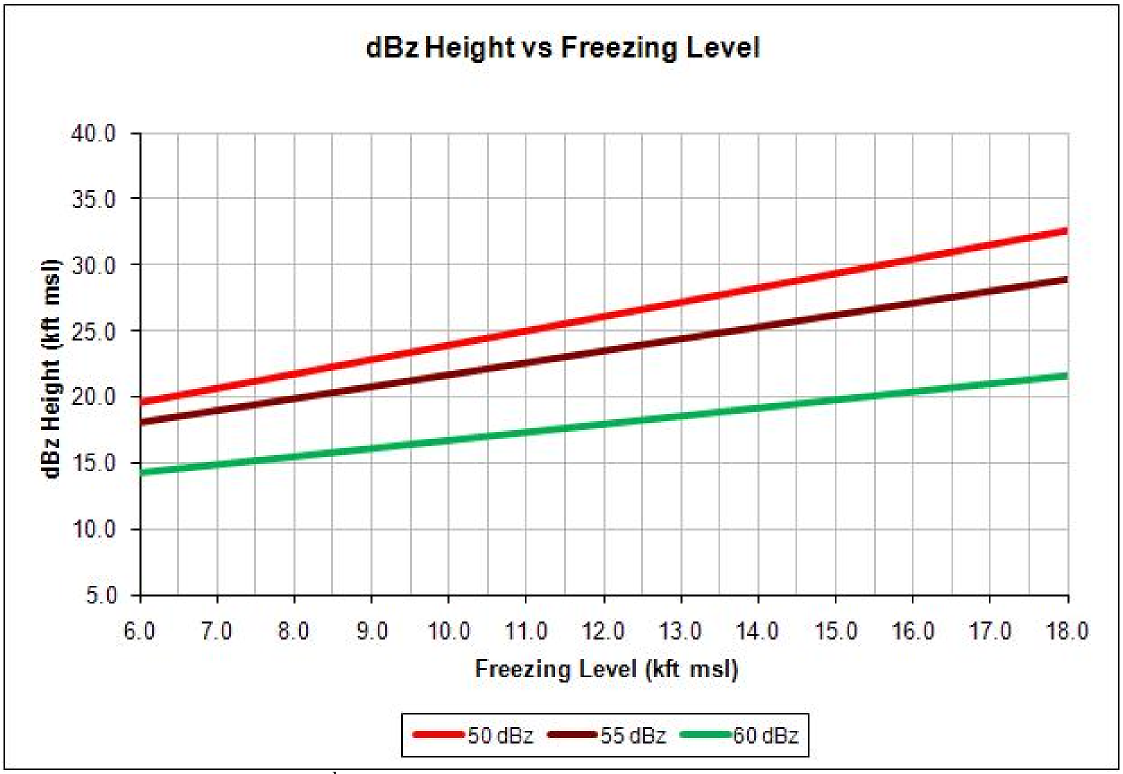

Figure 9: A plot of the 20th percentile lines for the entire data set previously depicted on figures 3, 4, and 5.

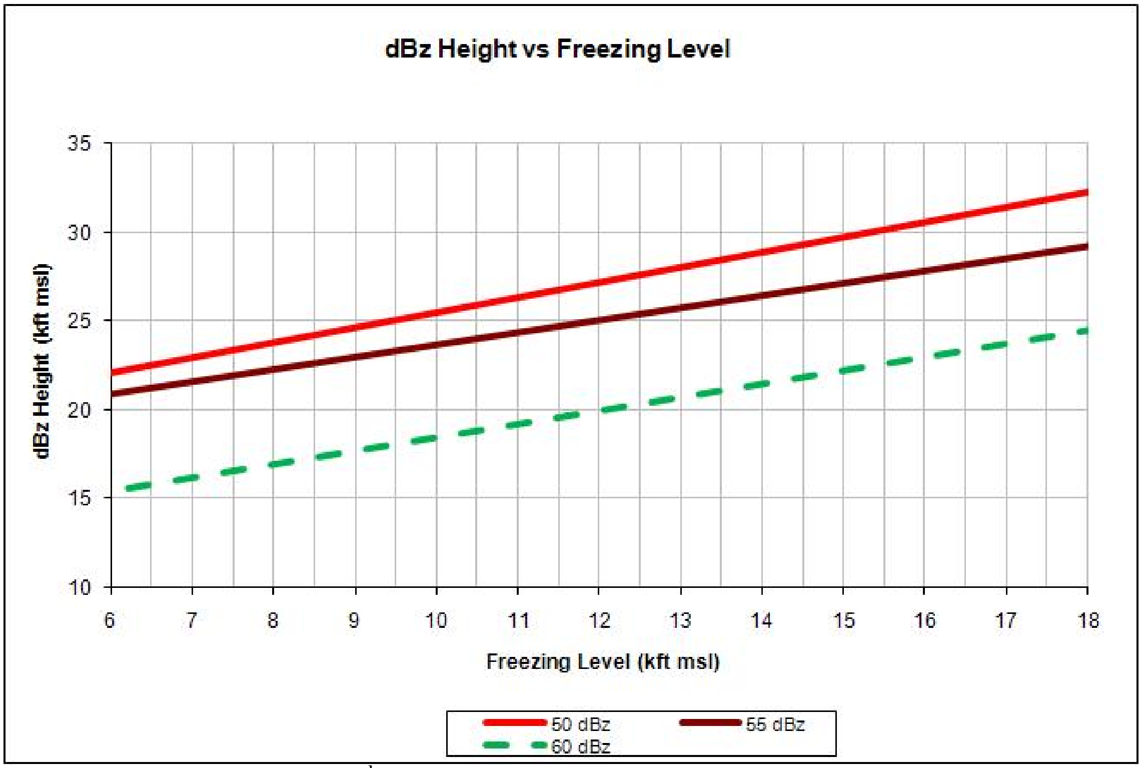

Figure 10: A plot of the 20th percentile lines for cases involving events containing hail one inch or greater in diameter, previously depicted on figures 6, 7, and 8.

Although the approach utilized in this paper mirrored that of DJ07, the freezing levels associated with the presence of large hail at a particular reflectivity height were significantly lower than those in DJ07. The DJ07 focused on Midwest cases, which were all associated with freezing levels much lower than those typically found in the Intermountain West. The slope of the regression line for the 50 dBz height versus freezing level in that study is much steeper than the one found in the Intermountain West study (3.38 versus 2.05). Thus, extrapolating the line in the DJ07 study to the freezing levels found in hail cases in the West would give much higher freezing level thresholds than were found to be true in the Intermountain West study. Therefore, it is of interest to consider why the difference in thresholds exists between the two studies. In an effort to accomplish this, the dataset was further broken up, in order to investigate theories which might explain the lower hail thresholds observed in this study when compared to the DJ07 study.

a. Season

The large hail cases within the dataset were broken up into warm (June through August) and cool (all other months) seasons, in order to see if the technique showed greater skill in a particular season. The warm and cool season were determined in order to try and look at differences between cases likely associated with the American Southwest Monsoon, and other cases more likely associated with Pacific cold fronts. The results of this are shown in Figure 11.

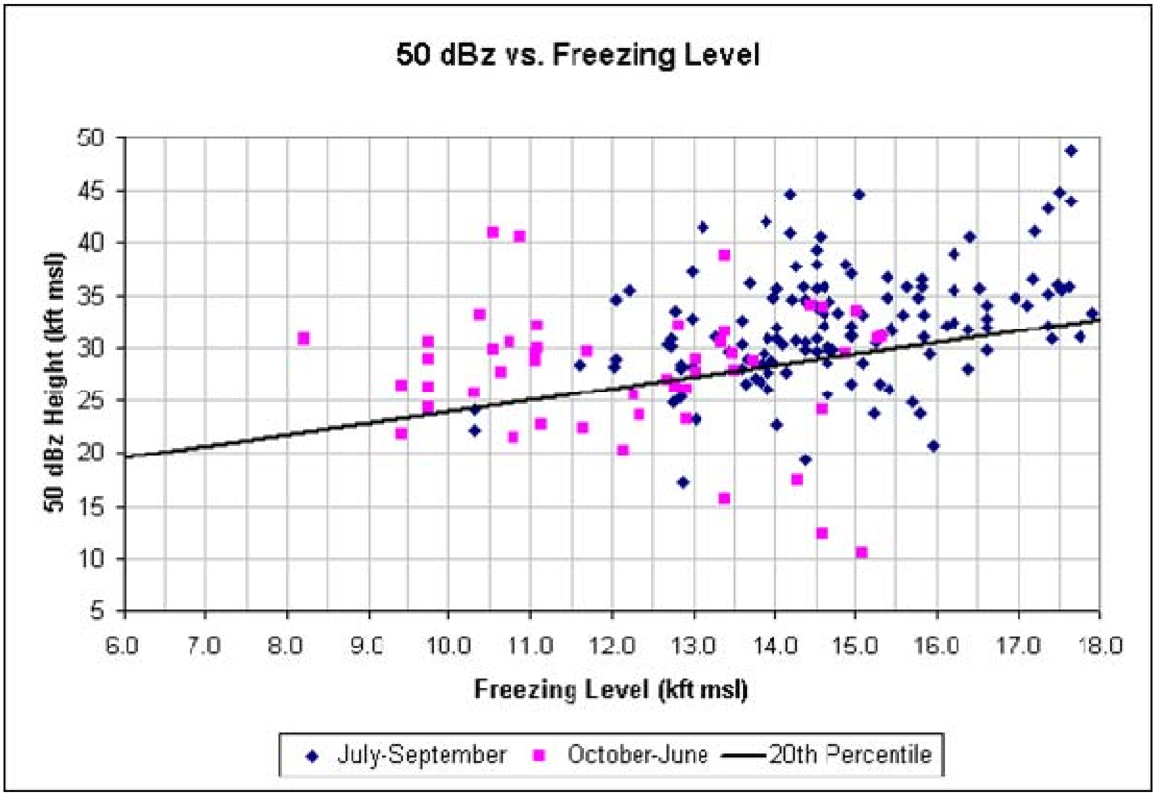

Figure 11: A plot of the maximum height of 50 dBz echoes versus freezing level for each case in the study. Cases occurring during the warm season (July through September) are indicated in blue, while cases occurring during the cool season (October through June) are indicated in magenta.

Hail cases were found to be associated with higher freezing levels during the warm season as opposed to the cool season. This was expected, as freezing levels are typically higher during the monsoon months, and lower during the cool season. Breaking the cases up by season showed no impact on the 50 dBz methodology, as the cool season cases fell within the lower end of the freezing level spectrum, while the warm season hail cases fell within the upper end of the freezing level spectrum. Warm season events appear to be better clustered than the cool season events, showing a more linear relationship. Thus, the method seems to have a bit more skill in the warm season than the cool season.

B. Elevation

Terrain across the West was hypothesized to have an impact on the size of hail reaching the surface, resulting from shorter residence times within the melting layer for large hail falling at higher elevations. This may have a significant impact on how much melting of large hail occurs, thus resulting in a better chance for large hail to reach the surface, and could account for the difference in slope of the regression lines in DJ07 and the Intermountain West study.

To test this theory, the dataset was divided into 4 groups based on the elevation from which the hail report was received: 3 kft MSL and lower, 3-5 kft MSL, 5-7 kft MSL, and cases above 7 kft MSL. This is depicted in Figure 12. The idea was that if the theory were true, a disproportionate number of the hail events at the lower end of the dBz spectrum for each freezing level would be events which occurred at higher elevations.

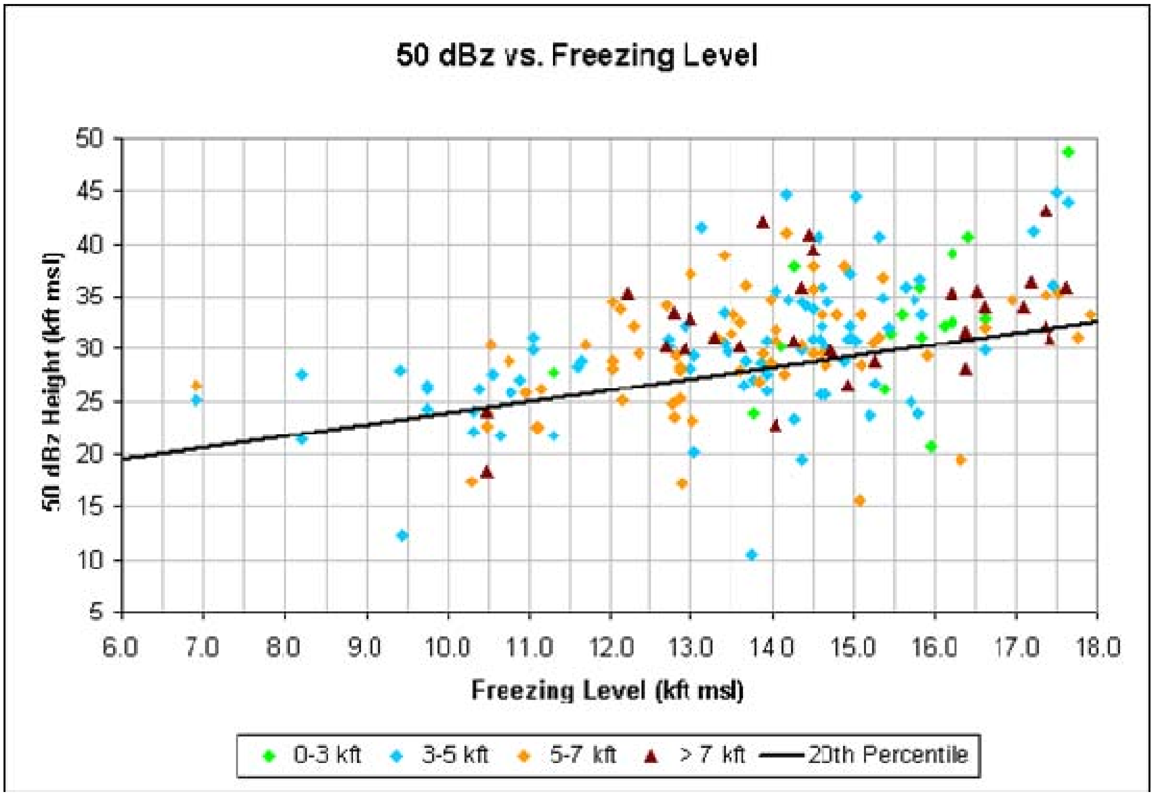

Figure 12: A plot of the maximum height of 50 dBz echoes versus freezing level for each case in the study. The different colors of dots indicate different elevation ranges.

However, the scatter plot depicting elevation showed considerable spread across the spectrum. In fact, many of the cases in the 3-5 kft range were found in the lower end of the spectrum, while most of the cases above 7 kft were found in the upper end of the spectrum. Therefore although smaller hailstones, which are more prone to melting, may be more likely at higher elevations, the study showed no correlation between elevation and the presence of large hail. Larger hailstones seemed to be less impacted by residence time within the melting layer than expected, although this may also be an artifact of the sample size.

C. Dry sub-cloud layer

Rasmussen and Heymsfield (1987) showed three factors which impact melting of hailstones. They are: smaller hailstones melt proportionally faster than large hailstones, hail melts faster in warmer environments, and relative humidity plays an important role in the rate of melting of the hailstones. Specifically, they found that hail melts faster in moist environments than in dry environments. The sub-cloud layer within the Intermountain West is often drier than the more moist environments often found in the

Midwest. This drier air across the West likely gives hailstones a better chance of reaching the surface before melting, and likely explains the differences observed between this study, and the DJ07 study. Additional investigation correlating core heights, freezing level, and relative humidity in the sub-cloud layer may yield additional insight into whether this is truly the cause of these differences, but is beyond the scope of this study.

5 - Summary and Conclusions

Scatter plots were developed for 50, 55, and 60 dBz reflectivity heights vs. freezing level. Quantile regression techniques were then used to develop a 20th percentile line for each set of data (where the 20th percentile line represents a value where, at a given freezing level, 80 percent of the reflectivity height observations associated with large hail events fall above and 20 percent of the reflectivity height observations fall below). A composite chart was then developed using the 20th percentile line for each of the 50, 55, and 60 dBz values, in order to aid forecasters in determining whether a thunderstorm is capable of producing large hail.

The values in this study were significantly different than those developed by DJ07 for cases east of the Rockies. These differences appear to result from drier sub-cloud layers often found across the West, as opposed to those typically found east of the Rockies. This drier sub-cloud air results in less melting, which may allow hailstones to reach the surface with greater diameters than observed further east for similar observed freezing level and dBz height.

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It is important to mention that this study did not address the false alarm rate associated with the use of these guidelines for forecasting the presence of large hail in a cell. The frequency with which storms reach the reflectivity height thresholds set forth by the study without producing large hail is currently unknown. Despite that, the technique detailed in DJ07 and modified in this study for cases west of the Rockies has been used operationally to reliably forecast the presence of large hail. However, it should always be used as a guideline in combination with other hail forecasting indicators not included in this study, such as three body scatter spikes and the presence of a large mesocyclone. The results of this study should be one of many tools used to make the best possible forecast of the probability of large hail associated with particular storms.

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Radar data was investigated utilizing NOAA's Weather and Climate Toolkit developed by NCDC (http://www.ncdc.noaa.gov/oa/wct/).

Upper air soundings were interrogated utilizing The Universal Rawinsonde Observation (RAOB) program from Environmental Research Services (http://www.raob.com/).

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