The Influence of Environmental Variables on Hailstone Material Properties

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Abstract

Hailstorms across the United States cause more than $10 billion annually in property losses with major events exceeding $1 billion in losses. The increase in hailstorm losses has outpaced advances in detection, forecasting, and damage mitigation. The ability to forecast with any detail the maximum hail size, concentration, and the true damage potential remains a challenge. Until recently, there were limited quantitative data on hailstone strength. Hailstones were qualitatively referred to as "hard", "soft", or "slushy". The strength of hail influences the amount of damage a given hailstone can produce, at a given impact kinetic energy. The strength of hail is likely function of several factors: the temperatures at which the ice grains were produced, residence time within the hail growth zone, and any imperfections that can lead to crack propagation when under compression (i.e. the interface between layered structures from alternating growth regimes, expansion cracks, large bubble features, etc.)

The Insurance Institute for Business & Home Safety (IBHS) has performed compressive strength tests and detailed physical measurements on over 2,000 hailstones during their annual field research program from 2012-2016. This study examines thermodynamic and kinematic variables and their influence on hailstone mass-diameter relationships, axis ratios, and compressive strength. Twenty thunderstorms cases, the majority of which are supercells that contained sufficient sample sizes of hailstone strength from several locations across the hail swath were analyzed. Proximity soundings from the Rapid Refresh (RAP) archived model analysis fields were reconstructed to represent the storm inflow environment. In general, kinematic variables (i.e. shear vector, storm-relative flow) exhibited a greater correlation to mean and maximum hailstone strength than thermodynamic proxies for updraft strength.

1. Introduction

Hailstorms are responsible for nearly ten billion dollars in insured losses on an annual basis (MunichRe, 2017; Gunturi and Tippett, 2017; Lepore et al., 2017). The growing amount of damage from an often-overlooked hazard of severe convective storms argues that a better understanding of this hazard is imperative. The broad, synoptic-scale conditions that support large hail potential have been documented in the historical literature. The fundamental microphysics behind hail growth processes and the basic characteristics of hailstones have also been given considerable research attention (i.e. axis ratios, mass, density) (Browning, 1963; Browning, 1976; Heymsfield et al., 2014; Knight and Knight 2001; Knight et al., 2008; Macklin, 1977; Ziegler et al., 1983). Throughout the historical literature hailstones are often referred to as “hard”, “soft”, and even “slushy”, yet until recently no quantitative measurements have been shown to support these assumptions. Additionally, there is little knowledge explaining how or why hail strength varies from storm to storm. Some hypotheses suggest that the source region of the embryos within a thunderstorm could affect strength, the trajectory a hailstone takes through the growth region, and alternating growth regimes (e.g. dry v. wet growth) and the hailstone structure they produce may play a role. All remain untested. The study presented here couples hailstone strength data with numerical weather prediction model analysis field to investigate the environmental characteristics that best explain the general differences in hailstone strength between 20 different thunderstorms.

The recent work of Giammanco et al. (2015) was the first to perform a quantitative compression test of natural hailstones in the field. It was found that hailstones do acquire different strengths, (Brown and Giammanco 2012; Giammanco and Brown, 2014 ; Giammanco et al., 2015; Giammanco et al. 2017). This research was driven through the need for more representative laboratory hail impact tests for building materials. It was hypothesized that the damage/impact modes on asphalt shingles (the most widely used roof cover material in the United States) associated with dimensionally identical hailstones must differ because of differing strength characteristics (Brown and Giammanco 2013). Through laboratory testing three distinct visible impact modes were found to occur using laboratory ice spheres that mimicked different natural hailstone strengths. The three modes are, a “hard bounce”, a “hard shatter” and “soft” impact (Standohar-Alfano et al., 2017). The two primary test protocols for a building material’s impact resistance, Underwriters Laboratory 2218 and FM Approvals 4473, do not account for the strength properties of natural hailstones (Underwriters Laboratories, 2012; FM Approvals, 2005). Both test methods fail to simulate the actual structure of hailstones and just merely obtain some estimate of the correct impact energy. UL2218 uses steel ball bearings of four varied sizes (classes) to test impact resistance, which most certainly do not replicate the impact physics of a real hailstone impact. The FM4473 protocol uses pure water ice spheres as an attempt to capture some fraction of reality, but still fails to realize the different internal structure of hailstones.

With the above said, it is important to note that the strength of a hailstone alters from case to case and these two testing methods fail to realize that discrepancy. In addition, since the material properties change, it is important to know how they change and what environments are conducive to stronger hail and which support generally weaker hailstones. This could help identify regional differences through environmental analyses and determine what roof cover products may be most appropriate for a given region to help reduce losses from hailstorms.

2. Data

2.1 Hailstone Strength

Hailstone strengths have been measured in a multi-year hail field research program carried out by the Insurance Institute for Business & Home Safety (IBHS). Hailstones were subjected to a compression test in the field. The peak force at the point each hailstone fractured was captured and used to estimate a uniaxial compressive stress. This metric was used a proxy for strength (Giammanco et al., 2015). For the dataset used in this study, most thunderstorm cases included multiple measurement locations across the swath of hail. Many hailstones were measured and tested at each location. The hailstone measurements were then aggregated together for each thunderstorm case. The storm mode for each was classified as right moving, left moving, embedded supercells, QLCS or just simply labeled as marginally severe. For the events shown here, most were supercells.

When considering the 20 cases in the analysis dataset, a quantifying metric was used to divide the raw data into what is mentioned later as strong, moderate and soft. Strong representing the storms that produced hailstones with a mean uniaxial compressive stress greater than 1.1MPa, which represents the 75th percentile and greater. As for moderate, its extent was between the 25th and 75th percentiles, represented by between 0.58 and 1.1 MPa and soft being represented by a mean compressive stress of less than 0.58 MPa or the 25th percentile and less. These breakpoints also generally corresponded to the different impact mode regimes observed in laboratory testing. For the purposes of this work we use the mean compressive stress to represent the strength of natural hail.

2.2. Inflow Soundings

The storm-scale environment characterization was conducted using RAP model analysis soundings, following the approach of Smith et al. (2012) and Potvin et al. (2010) Radar data were used to assist in identifying an appropriate location for the representative inflow model sounding for each case. This model has 13km grid spacing and 37 sigma levels at 25mb increments from 1000mb up to 100mb. This model was selected because data were available from the beginning of the field program in May 2012. The selected model analysis time was the closest hour prior to the target thunderstorm crossing over the deployment roadway. Inflow soundings were subjectively analyzed for each case. The subjective review involved looking for convective contamination from thunderstorm outflows either from the incipient storm or nearby convection, unexplained shapes to the wind profile other than that of the surrounding synoptic environment, and saturation of the thermodynamic profile, indicating the presence of clouds in the model. In addition, the surface observation point was scrutinized for any effects of a surface cold pool. If either of the sounding had either a wind direction not consistent with the synoptic environment or a surface cold pool was present, then a new sounding location was selected, and the process was repeated (Brooks, 2009; Doswell and Evans, 2003)

For 18 of the 20 cases, the collected sounding was within the ”goldilocks zone” defined as being in that ~40-80km distance from the storm (Potvin et al., 2010). The main reason for being outside that zone was because not all the targeted storms were isolated and to get a better representation of the pre-storm environment, a distance outside the ‘goldilocks zone’ was chosen. In addition, based on this previous work, the thermodynamic profile is much more sensitive to sounding location relative to the storm than that of the kinematic profile, it may be possible that a different sounding location my change the results of the thermodynamic section below.

3. Data Analysis

3.1 Thermodynamics

After collecting “ideal” soundings for each case, the following thermodynamic indices were calculated:

- SBCAPE
- MUCAPE
- MLCAPE
- DCAPE
- Hail growth layer CAPE (-10 to -30° C layer)
- SRH from 0-3km
- Supercell composite parameter (SCP)
- Significant hail parameter (SHIP)
- 0-6km Bulk Shear
- Surface lifted index
- Precipitable water
- 700 – 500mb lapse rate
- Height of the 0˚C isotherm
- Cloud layer shear

Table 1 – Correlation and P-value for each thermodynamic variable described above when related to the mean hailstone strength.

Correlation and P-value for Thermodynamic Variables		
Variable	**P-value**	**Correlation**
SBCAPE	0.837	0.049
Height 0 Isotherm	0.425	0.189
SRH 0-3km	0.595	0.127
Surface LI	0.645	-0.110
PWAT	0.548	0.143
Hail Growth Layer Depth	0.878	-0.037
CAPE	0.842	0.048
Hail Growth Layer CAPE	0.921	0.024
0-6km Shear	0.577	0.133
DCAPE	0.313	0.238
700-500mb Lapse Rate	0.874	0.038
SCP	0.782	0.066
SHIP	0.558	-0.140
SR Wind Direction	0.222	0.286
SR Wind Magnitude	0.870	0.039
SR Wind U	0.292	0.248
SR Wind V	0.494	-0.162
Cloud Layer Shear	0.191	0.305
Cloud Layer Shear U	0.245	0.273
Cloud Layer Shear V	0.676	0.100

A correlation and significance test were performed for each thermodynamic variable where each of the sounding variables were

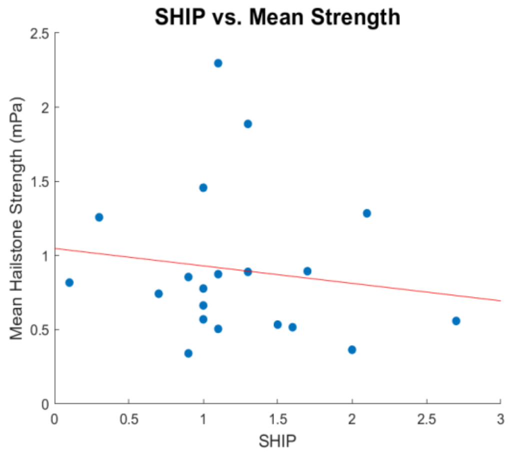

Figure 1 - Mean hailstone strength related to SPC's SHIP.

correlated to the mean of hailstone strength for each case (Table 1).

None of the thermodynamic variables evaluated in Table 1 showed any significance in their relationship to hailstone strength at the 95% confidence interval (none less than 0.05 for p-value). With the lack on any identifiable correlation between mean hailstone strength and the thermodynamically-based variables, it does not appear likely that thermodynamics alone

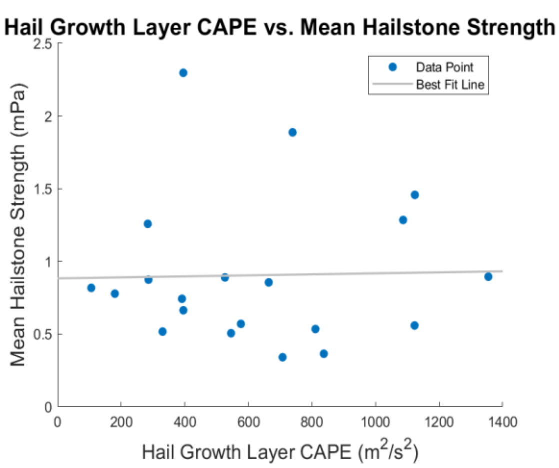

Figure 2 - CAPE in the hail growth layer related to the mean hailstone strength for each case.

dictate strength. The Significant Hail Parameter (SHIP; SPC 2018), which is a probabilistic predictor for seeing significantly sized hail (>2in), does not appear to be useful in predicting hailstone strength (Figure 1). Its associated p-value is 0.5575 giving it almost no relationship to hailstone strength. It was hypothesized that instability within the hail growth zone could play a role in hailstone residence time, thus affecting strength but the results shown in Figure 2 do not support this.

3.2 Kinematics

With little evidence of a relationship between thermodynamic variables and hailstone strength, the wind profile was investigated. By taking the composite wind profile for each strength category and rotating it to the 0-6km bulk shear vector (Figure 3), an analysis of the kinematic profiles was completed. The average storm relative wind direction and magnitude themselves do not show significant trends, but by decomposing the mean kinematic quantities into their respective U- and V-components as well as the magnitude at each sigma level, illuminated where the wind profile plays a role in the strength of hailstones. The storm relative winds were computed using outputs from the Bunker's method (Bunkers et al., 2000) for determining storm motion and subtracting that from the environmental wind profile. For each strength group, soundings were composited to examine the mean structure of the wind profile.

Figure 3a shows there is a clear separation in the magnitude of the composite wind profiles in the upper level of the atmosphere primarily between 350hPa and 200hPa, even though there is some divergence of the wind profile beginning around 400hPa. The increase in magnitude of the composite winds coupled with hailstone strength increases indicates that stronger hailstones may be associated with improved storm-scale ventilation aloft. One could assume this is indicative of updraft variance in the form of shape, size, strength or some combination of the three. There is another location where there are meaningful differences in the composite profiles for the three groups. Within the storm-relative inflow layer, between about 850hPa and 750hPa increased flow was found for the strong hailstone class. The storm relative wind magnitude increase within this level is driven primarily in the V-component direction. Conceptually, this would suggest there is an increased amount of low-level air entering the storm from the right of the bulk shear vector. In addition, there is more variance in the V-component of the wind vector as mean hailstone strength increases. Figure 3b also shows that as the hailstone strength increases, the V-component profile acquires a more pronounced ‘S’ shape. The U-component, specifically across the mid and upper levels is better behaved and exhibits a general increase. (Figure 3c) There is however, a general trend of the overall U-component of the SR wind increasing with increasing hailstone strength (Figure 6b). This means that the U-component averaged over the entire profile must also be greater as hailstone strength increases. This is particularly true in the upper levels of the atmosphere which helps to explain why the magnitude increases with increasing strength in Figure 3a. Understanding that these are

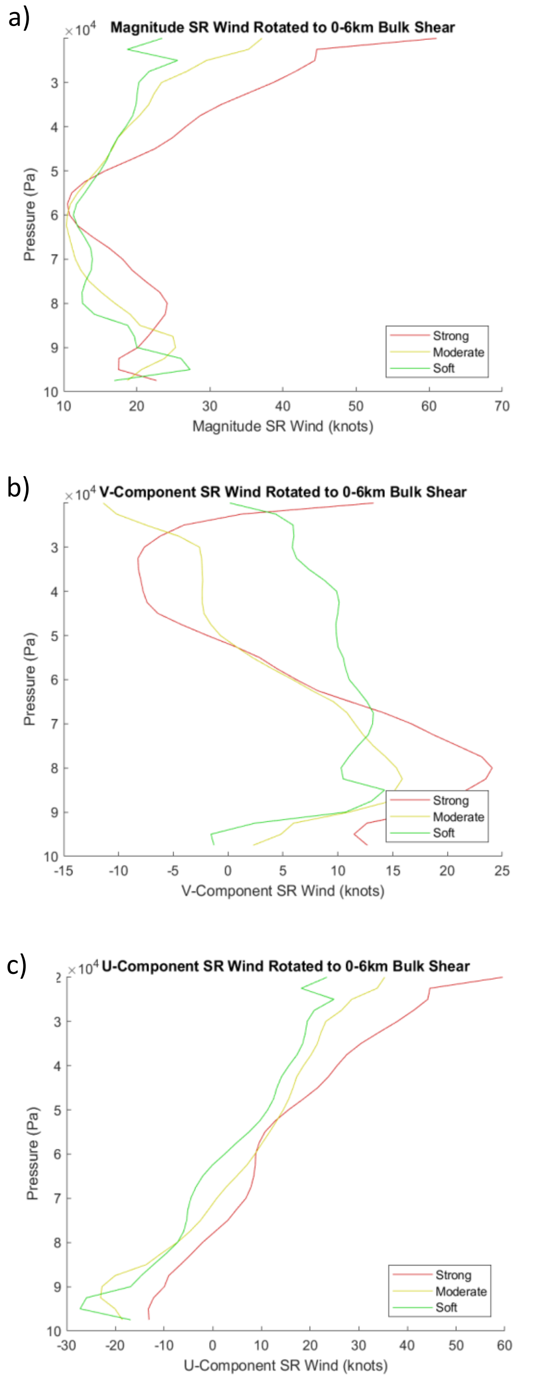

Figure 3- Composite storm relative wind profiles rotated to be along the 0-6km Bulk Shear Vector Strong, Moderate and Soft denoting the different compressive strengths of the hailstones. Strong (>1.1MPa), Moderate (0.58-1.1MPa) and Soft (<0.58MPa)

composite wind profiles, for further analysis, the levels of interest were investigated for each individual case with the upper level denoted by the average wind vector between ~25-125hPa below the estimated EL and the lower level denoted by the average wind vector between ~100-200hPa above the surface. One other interesting note in Figure

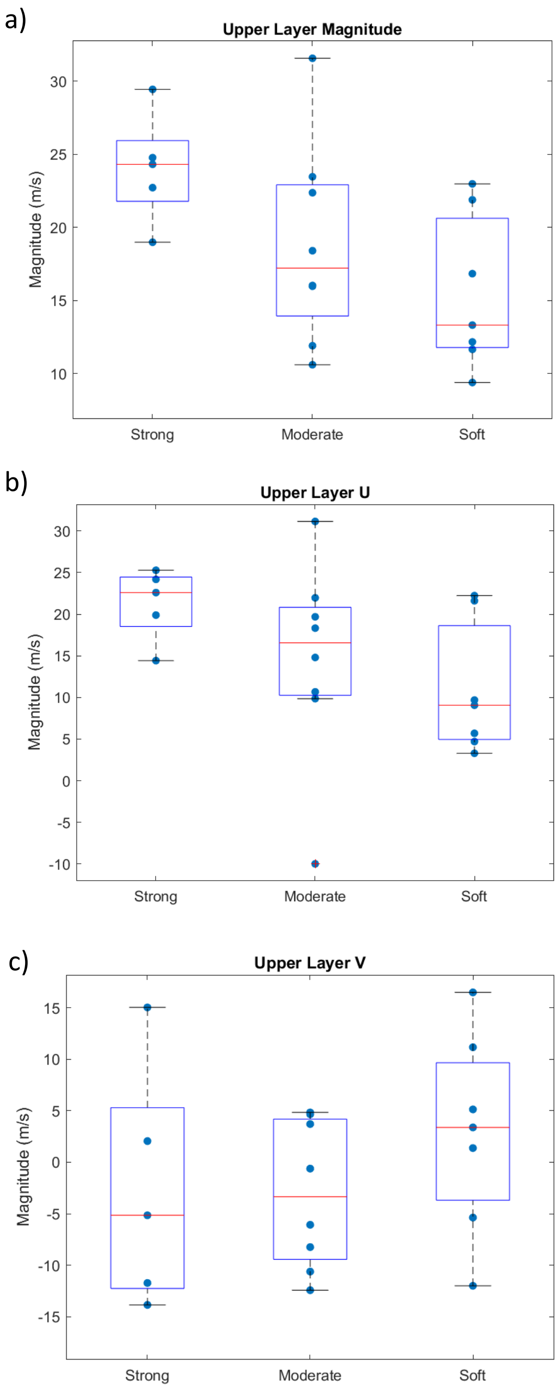

Figure 4- Upper Layer (UL) magnitude, U- and V-components, respectively.

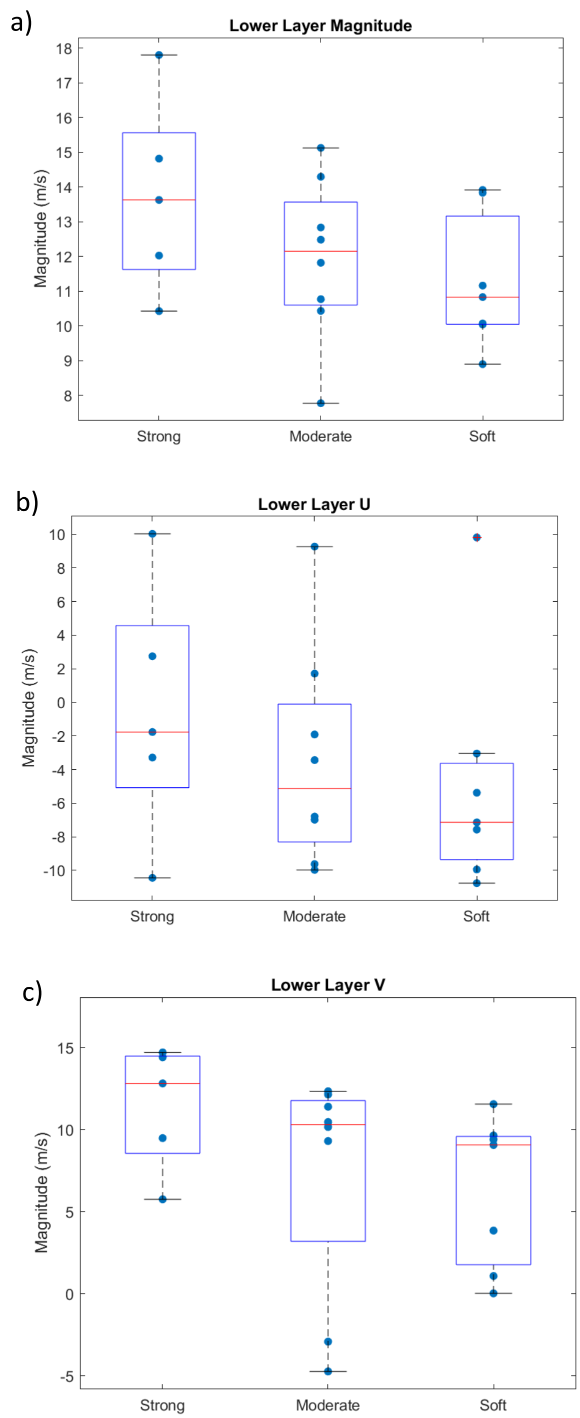

Figure 5- Same as in figure 4 but with Lower Layer (LL).

3c is that the height of the absolute value of the minimum U-component wind decreases as hailstone strength increases.

Because of clear differences in the wind profile shown in Figure 1 at ~100-200hPa above surface (LL) and ~25-125hPa below EL (UL), the profiles were scrutinized further. Figure 4a and b, show a general uptrend in UL magnitude and the UL U-component, respectively, as the mean strength of hailstones increases. Figure 4c, however shows a general downward trend as mean strength increases. Since the strong and soft categories cover almost the same range, its interpretation is not relevant.

Figure 5a illustrates a consistent increase in LL magnitude as mean strength increase and as a result, a significant trend was identified.

In addition, the maximum value for each strength class increases in an exponential fashion. As for the LL U-component, there is a small positive trend based on median values; however, because of the large variability in the U-component for all classes it was difficult to discern if a true relationship was present (Figure 5b, Table 2) As for the LL V-component (Figure 5c), there is a clear increase in the maximum value for each class' composite profile. Additionally, there is a slight upward trend in the maximum attained value with hailstone strength category.

Boxplots of the average V-component (Figure 6a) and U-component (Figure 6b) of the rotated SR winds from the surface up to the equilibrium level (EL) were created. Since the mean V-component is somewhat consistent for all three classes, it can be ruled out as being a meaningful predictor of mean hailstone strength (Table 2). In addition, the average U-component tends to increase with hailstone strength as shown by the median and is particularly

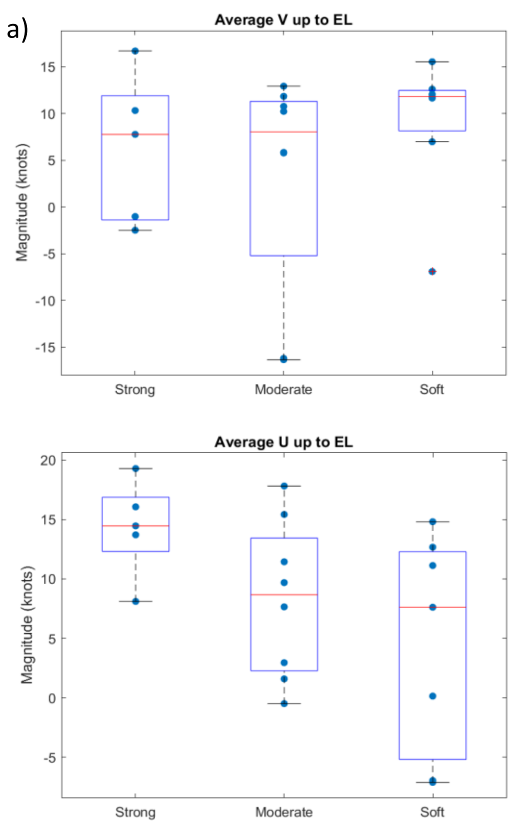

Figure 6- Average U- and V-components from the surface to the equilibrium level (EL)

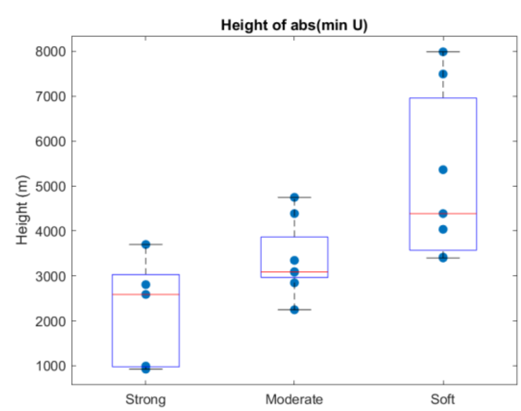

Figure 7- The height at which the absolute value of the U-component attains a minimum value.

Table 2- Correlation and P-value for each of the described variables above. All significance tests were run against the mean recorded hailstone strength. Yellow and green boxes in the p-value column representing significance of 0.10 or less and 0.05 or less, respectively.

Correlations and P-values for Linear Fitted Model		
Variable (x-axis)	Correlation	P-Value
Magnitude Upper Layer	0.453	0.045
Magnitude Lower Layer	0.519	0.019
U Upper Layer	0.354	0.125
V Upper Layer	-0.187	0.431
U Lower Layer	0.308	0.187
V Lower Layer	0.339	0.143
Average U	0.424	0.062
Average V	-0.107	0.655

evident when comparing the minimum or maximum values of each category.

Table 2 provides a summary of the correlation and p-values from Figures 4, 5 and 6. From the table, there are three variables that have rather significant trends, the magnitude of UL wind, magnitude of LL wind and average U wind.

As previously shown, the difference in the height of the absolute value of the minimum U-component of the rotated SR wind noted in Figure 1c, it is crucial to get a better understanding of the difference when related to hailstone strength. From Figure 7, it is very clear that the height increases with a decrease in hailstone strength. This trend can be concluded because of the lower extent, upper extent and median decreasing as hailstone strength increases. The p-value of this dataset was 0.0052 which makes this a powerful piece of data and it also explains a significant trend is present.

4. Conclusions

The environmental variables from model analysis proximity soundings were used to determine if hailstone strength was dependent on the storm-scale environment. The thermodynamic quantities computed from the proximity soundings showed no meaningful trends related to hailstone strength. While the storm-scale thermodynamics certainly influence updraft character and are a factor in maximum hail size, to an extent, they do not appear to be a driving factor when considering hailstone strength. In addition, when reviewing the composite wind profiles for each of the given mean strength categories, it was apparent that clear differences in the profiles were present. It was found that three variables, the UL magnitude, the LL magnitude and the average value of the U-component up to the EL were statistically correlated with mean hailstone strength. The height at which the absolute value of the U-component attained a minimum value was also found to have a correlation to the observed mean hailstone strength.

The analysis presented here argues that the kinematics of the storm relative environment should be treated with as much if not, more importance than the thermodynamics in determining hailstone strength characteristics. In addition, the motion of the storm is another factor that could potentially influence hailstone strength, through augmenting the low-level inflow environment. As a result, it can be said that storm mode matters, with supercells being the prolific producers of hail. Beyond that, the small nuances within the environment matter for shaping hailstone strength.

5. Future Endeavors

The results from this study show that the storm-scale kinematic environment helps determine the average hailstone strength. The next question to be asked is why? And what is transpiring within a thunderstorm and the hail growth region to yield stronger or weaker hail. The vertical wind shear is known to play a role in embryo source region locations as well as the path that a hailstone takes through the storm (Dennis and Kumjian 2017). Relating the results of the Dennis and Kumjian (2017) study to those found here resulted in the following research questions:

- Does the elongation of the updraft along the shear vector impact the strength of the hailstones in the same way that it does with their size due to different length trajectories?
- Is it possible that with an elongated updraft that a hailstone can reside at colder temperatures within the hail growth region for an extended period?

Storm-scale modeling of hailstone trajectories using idealized cases can be used to test the hypotheses posed here.

By quantifying the hailstone trajectories, and its residence time within different temperature bins in the hail growth zone, a better understanding of how these shifts in the kinematic wind profile play a role in hailstone strength may be concluded. The results shown here also argue that continued observations and testing of hailstones is sorely needed to help understand the complex processes at work. This is vital for improving how we forecast, detect, and ultimately mitigate the impact of this often overlooked but costly hazard.

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