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Total Precipitable Water as It Relates to Hailstone Diameter and Its Potential for Improving Hailstone Diameter Forecasting

Lyn Comer
Atmospheric Science
The University of North Carolina Asheville
One University Heights
Asheville, NC 28804 USA

Faculty Advisor: Dr. Christopher Godfrey

Abstract

In the past, vertically integrated liquid water (VILW) and liquid water content (LWC) were used as predictors for hailstone diameter. However, forecasts using these values as primary predictors display little or no skill. Further research on the growth of hailstones produced the HAILCAST model, which was later integrated into the Weather Research and Forecasting (WRF) model to produce the WRF-HAILCAST model. This model included updated hail formation physics including differing hail densities for wet versus dry growth and mass growth due to water vapor deposition and condensation. Despite these updates, the WRF-HAILCAST model falls short in hailstone diameter prediction. Due to its connection with the severity of storms and the amount of precipitation produced, total precipitable water (TPW) may be a viable candidate for further improvement of these forecasts. Hailstone diameter data from the Severe Hazards and Analysis Verification Experiment (SHAVE) from 2014 is compared with the TPW data from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) 40-year reanalysis archive to determine a correlation between TPW and hailstone diameter. This study found that TPW does not hold a strong positive correlation with hailstone diameter. However, a range of TPW does correlate with ranges of hailstone diameters and was shown to be statistically significant. Since TPW can be measured before a hailstorm occurs these relationships will lead to greater insight for predicting hailstone diameter.

1. Introduction

Hailstorms are localized severe storm events that can damage crops and property, costing billions of dollars in losses, in addition to posing a risk for bodily injury. For example, the "Mayfest" hailstorm was one of the most expensive thunderstorm events in U.S. history[1]. This storm produced hail up to 114 mm (4 in.) in diameter, caused over $2 billion in damage, and 109 hail-related injuries[2]. Although there have been improvements over the last 20 years in forecasting hail size, much improvement is still needed. Therefore, the purpose of this research is to evaluate the relationship between hailstone diameter and TPW, the effectiveness of TPW as a forecast parameter, and its potential usefulness in improving hailstone diameter predictions.

Historically, predictions of hailstone size have shown little or no skill[2]. Current hail forecasting methods produce only a "nowcast" based on current conditions because they can only be applied to a storm that already exists and has been detected by radar[3]. As a result, there is a minimal lead time to prepare for a hailstorm event. Edwards and Thompson suggest that an effective hailstone size forecasting method requires thermodynamic variables to be accessible not only during a hailstorm but also before the event occurs[2].

Vertically integrated liquid water (VILW) has also been used as a predictor for hailstone size. Initially, VILW appeared promising for improving hailstorm forecasting[4]. Ensuing studies found otherwise. In fact, Edwards and Thompson found that VILW and other common hailstone size predictors were producing forecasts with little to no skill[2]. In particular, the study revealed that despite VILW performing similarly to other predictors in the dataset, it is not an accurate measure for predicting hailstone size alone due to large predictive errors[2].

Attempting to resolve this issue, the HAILCAST hail growth model was developed and later integrated into the Weather Research and Forecasting (WRF) model. Adams-Selin and Ziegler added updated hail physics to the integrated model, including different hailstone densities for wet and dry growth, mass growth by vapor deposition or condensation, and others[3]. Over a one-year period, the study found that 66% of the time the WRF-HAILCAST hailstone diameter forecast was within 0.5 in. of the observed hailstone diameter if WRF successfully forecasted convection.

While this model holds better verification than previous methods, there is still much to be desired in the accuracy of hailstone size forecasting. Total precipitable water (TPW) is the depth water would stand if all the water vapor in a column of air was condensed[5]. TPW varies across the United States both regionally and monthly. According to Reitan, extreme variations in TPW may be linked to deviation from the typical precipitation for a given location[5]. Additionally, a case study in Alberta, Canada, showed that there is a particular range of TPW correlating with storms that produced strong tornadoes, weak tornadoes, or severe storms producing large hail[6]. This indicates that TPW could potentially be a factor for determining the type of severe storm produced. Therefore, the Storm Prediction Center (SPC) could use TPW as a forecast parameter for predicting tornado strength, precipitation totals, and hail diameter size. This research will explore TPW and its relationship with hailstone diameter size using statistical analysis as well as its value for improving forecasting techniques.

The next section of this paper provides information on the data and methods used for this research including the origin of the data and the statistical techniques used. Section 3 will cover the results with accompanying figures produced by this study. Section 4 discusses the results and their implications for forecasting hailstone diameter. Finally, section 5 summarizes the conclusions found and provides suggestions for further research.

2. Data and Methodology

Two data sets were integrated and evaluated. The Severe Hazards Analysis and Verification Experiment (SHAVE) project executed by the National Oceanic and Atmospheric Administration (NOAA) Hazardous Weather Testbed collected data detailing the average and maximum hailstone diameter measured for each hailstorm occurrence across the contiguous United States from 2006-2015. For simplicity, only the years 2006-2009 were used for this study. The hailstone average and maximum diameter measurements were conducted by citizens in the path of a hailstorm after receiving a phone call from the SHAVE team. As a result, there could be errors within the data set as the measurements were not taken by trained professionals.

However, since the purpose of this study is to develop a baseline correlation between hailstone diameter and TPW the measurements need only be representative, not exact. In addition, this is one of the largest data sets for hailstone size measurements, as collecting such microscale data holds a unique challenge. The TPW amounts (kg/m^2) were taken from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) 40-Year Reanalysis Project which uses a coarse grid resolution of 40 km. While this resolution is very coarse in comparison with the size of a hailstorm it is the most accessible data due to the lack of radiosondes and fine TPW measurements. Finding a relationship between the hailstone diameters and coarse TPW data, while not ideal, would likely be the most useful for forecasters simply due to accessibility. Using the latitude and longitude information proved from the SHAVE project measurements, the TPW amounts at the nearest locations were pulled from the NCEP/NCAR Reanalysis data. The time for the TPW measurement was taken as the closest measurement to the time of the hailstorm occurrence. Since TPW on a large scale such as 40 km does not change quickly or vary significantly from nearby locations, this data method is sufficient for this study. Using this integrated data set, a statistical analysis was performed to determine the correlation between TPW and hailstone diameter.

The data were divided into 3 groups: small, medium, and large hailstones. Diameters less than 1 inch are considered "small" hail. Hailstones 1-2 inches in diameter are considered "medium" hail, and "large" hail have diameters greater than 2 inches. For simplicity and best representation, this was done for the average diameter of the hailstones only. Kruskal-Wallis tests were performed to determine if there was a difference between the mean TPW of any of the three groups.

Since there are three classes of hailstone sizes there are $K*(K-1)/2$ possible pairwise comparisons, where K is the number of classes. These pairwise comparisons are small versus medium average hailstone diameters, small versus large average hailstone diameters, and medium versus large average hailstone diameters. The Kruskal-Wallis chi-squared value was 17.855 with 2 degrees of freedom and a p-value of 0.0001327. Since the p-value is less than $\alpha=0.05$ it can be concluded that there is a significant difference in means at the 5% level between at least one of the groups. Once a significant difference between the mean TPW among the groups was detected follow-up tests were used to determine which of the three groups has a difference in distribution. To determine which test would best suit the data, histograms of the data for each of the classes were created. The histograms are shown below in Figure 1.

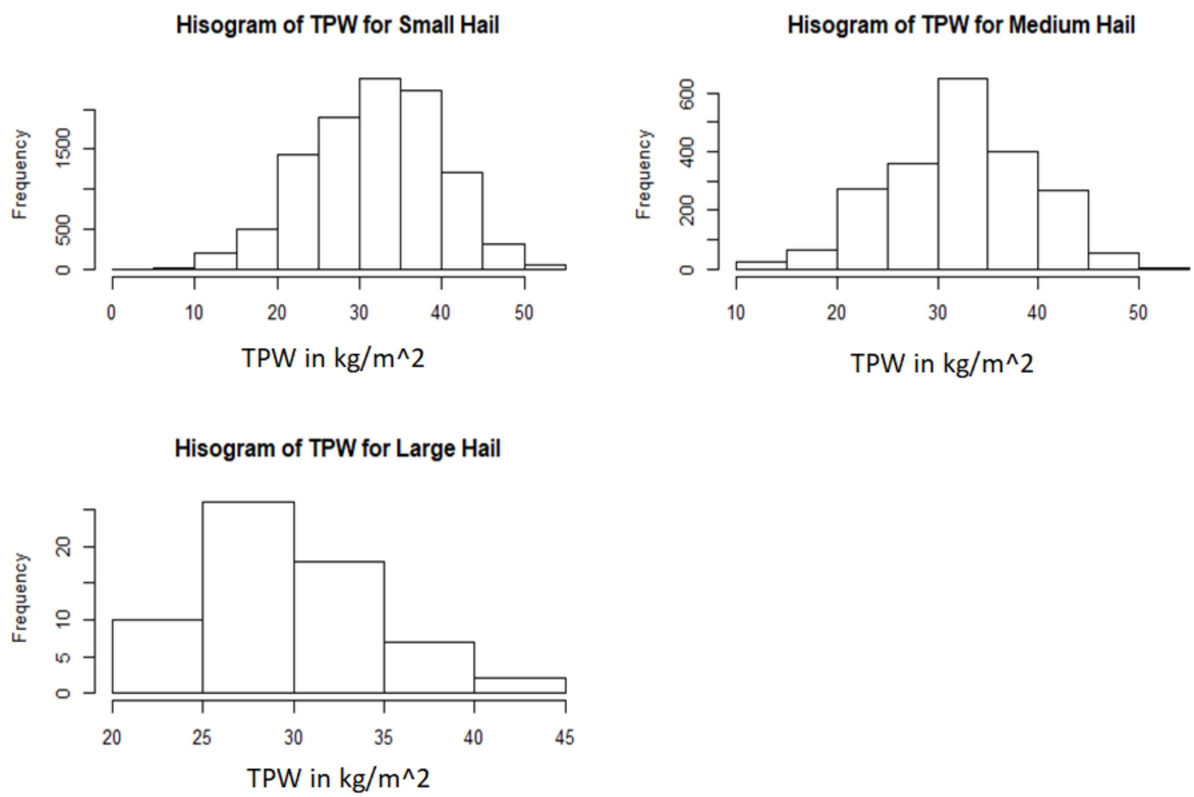

Figure 1: Histograms for small, medium, and large hailstone TPW amounts.

Based on these histograms and normality tests the data for small and large hailstone diameters do not follow a normal distribution while the data for medium hailstone diameters does. As a result, Wilcoxon Rank-Sum tests with continuity correction and permutation tests using 1000 permutations and a difference in medians were conducted for all three groups of small, medium, and large hailstone diameters. For simplicity, the same statistical methods were applied to all three of the groups since applying statistical tests using the median on a normal distribution such as for the medium-sized hailstone group would not impact the outcome since the median is equal to the mean for normal distributions. The results of these tests are discussed in the next section.

3. Results

The integrated data are compared for correlation in Figure 2. The multiple R-squared value was calculated as 0.001, leading to a correlation coefficient, or R-value, of 0.03.

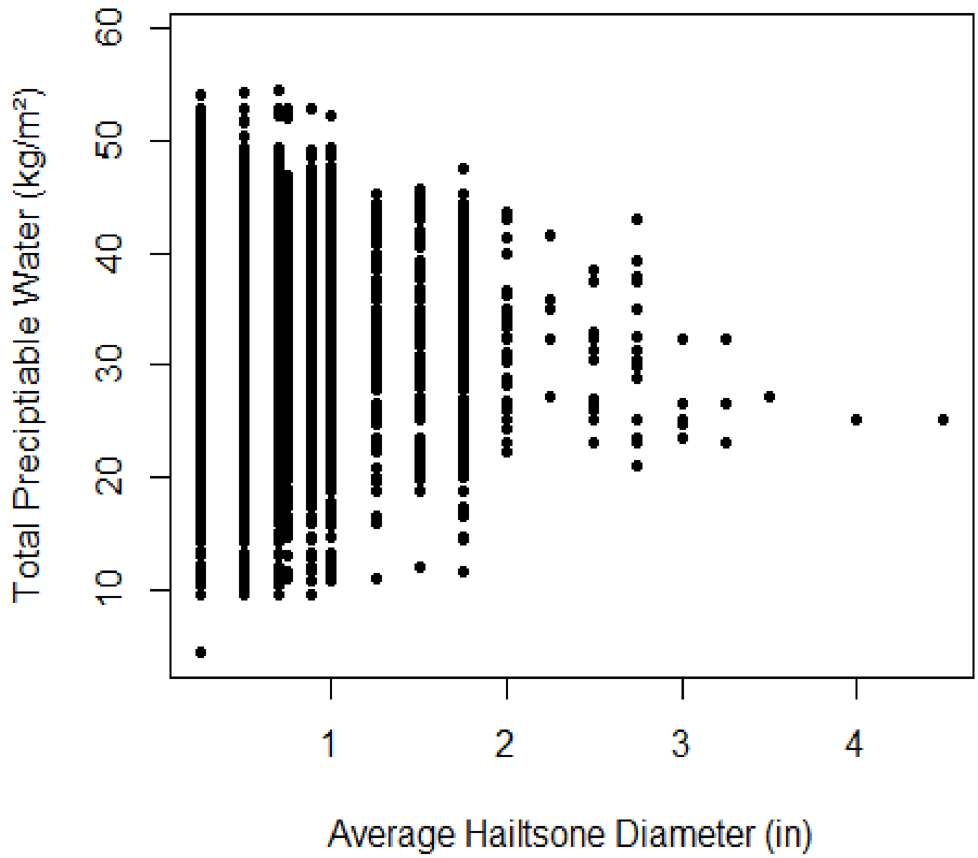

Figure 2. The average hailstone diameter in inches versus the total precipitable water amount in kg/m^2 in the U.S. for the years 2006-2009.

From a purely statistical standpoint, the R-value indicates a very small positive correlation. In fact, the correlation coefficient is so small that it is almost negligible. This shows that for this study TPW on a large grid has an extremely limited correlation with hailstone diameter. This is not surprising considering that the TPW in the location of a thunderstorm may greatly differ from the large-scale measurements. However, notice from Figure 2 that there appears to be a range of TPW that is required for larger hailstone diameters. No hailstones larger than two inches in diameter were produced with a TPW value under 20 kg/m^2 or above 50 kg/m^2. This means that higher TPW does not necessarily indicate a larger hailstone diameter, but rather, a particular range of TPW may correspond to a range of potential hailstone diameter. This is confirmed through the Wilcoxon Rank-Sum tests with continuity correction and permutation tests using 1000 permutations and a difference in medians conducted for all three groups of small, medium, and large hailstone diameters.

From the Kruskal-Wallis test, a p-value=0.0001327 was achieved. Since this p-value is less than $\alpha=0.05$ it can be concluded that there is a difference in means between the diameters in at least one of the groups. As a result, follow-up tests were performed to determine which of the groups have a difference in distribution. From the histograms in Figure 1, it was determined that not all the datasets followed a normal distribution, meaning that Wilcoxon Rank-Sum tests and permutation tests using a difference in medians would be ideal to perform pairwise comparison tests. Since there were three groups, three follow-up pairwise comparison tests were performed, multiplying the p-values produced by 3 using the Bonferroni p-value adjustment. A null hypothesis of no difference in TPW between pairs was used for all the tests.

Table 1. Comparison of the Wilcoxon Rank-Sum test and permutation test p-values for the three pairwise comparisons. All p-values greater than α=0.05 are highlighted in red indicating no statistical significance and all p-values less than α=0.05 are highlighted in green indicating statistical significance.

	Wilcoxon Rank-Sum test p-value	Permutation test p-value
Small and medium hailstones	0.06801	1.491
Small and large hailstones	0.0017082	0
Medium and large hailstones	0.00016725	0

From the Wilcoxon Rank-Sum test comparing small and medium hail, the Bonferroni adjusted p-value was 0.06801. Since this p-value was greater than α=0.05, it can be concluded that there was no difference in the distributions of the small and medium-sized hailstones' total precipitable water amounts. This was confirmed through the permutation test using a difference in medians for small and medium-sized hail. This permutation test produced an adjusted p-value of 1.491. Since the p-value is greater than α=0.05, we fail to reject the null hypothesis, meaning that there is no difference in TPW between small and medium hailstones.

From the Wilcoxon Rank-Sum test comparing small and large hail, the Bonferroni adjusted p-value was 0.0017082. Since this p-value was smaller than α=0.05, there was a difference in the distributions of the small and large-sized hailstones' total precipitable water amounts. This was confirmed through the permutation test using a difference in medians for small and large-sized hail. This permutation test produced an adjusted p-value=0. Since the p-value is less than alpha=0.05, we reject the null hypothesis, meaning that there is a difference in TPW between small and large hailstones.

From the Wilcoxon Rank-Sum test comparing medium and large hail, the Bonferroni adjusted p-value was 0.00016725. Since this p-value was smaller than α=0.05, there was a difference in the distributions of the medium and large-sized hailstones' total precipitable water amounts. This was confirmed through the permutation test using a difference in medians for medium and large-sized hail. This permutation test produced an adjusted p-value=0. Since the p-value is less than α=0.05, we reject the null hypothesis, meaning that there is a difference in TPW between medium and large hailstones.

4. Discussion

While there may not be a strong direct correlation between TPW and hailstone diameter, the relationship between a range of TPW and hailstone diameter is worth noting. As a result, further analysis was performed on the typical hailstone diameters found in the United States. Table 2 breaks the total number of hail events recorded in the SHAVE project from 2006-2009 into sections based on a one-inch range of diameter. This is done for both the average and the maximum hailstone diameters for all storms.

Table 2. The total number of hail events recorded in the SHAVE project from 2006-2009 sections into one-inch ranges of diameter.

	1-2 in	2-3 in	3-4 in	4-5 in	>5 in
Number of events using max diameter.	4080	422	48	43	1
Number of events using average diameter.	2053	85	14	3	0

Table 2 shows that the majority of hail events produce hailstones with diameters less than 2 inches. Based on this information in order for TPW to be a generally useful forecasting parameter, it must show statistically significant differences between the small and medium hailstone size groups. This is further supported by the boxplot in figure 3, showing that most hailstone diameters are less than 1 inch.

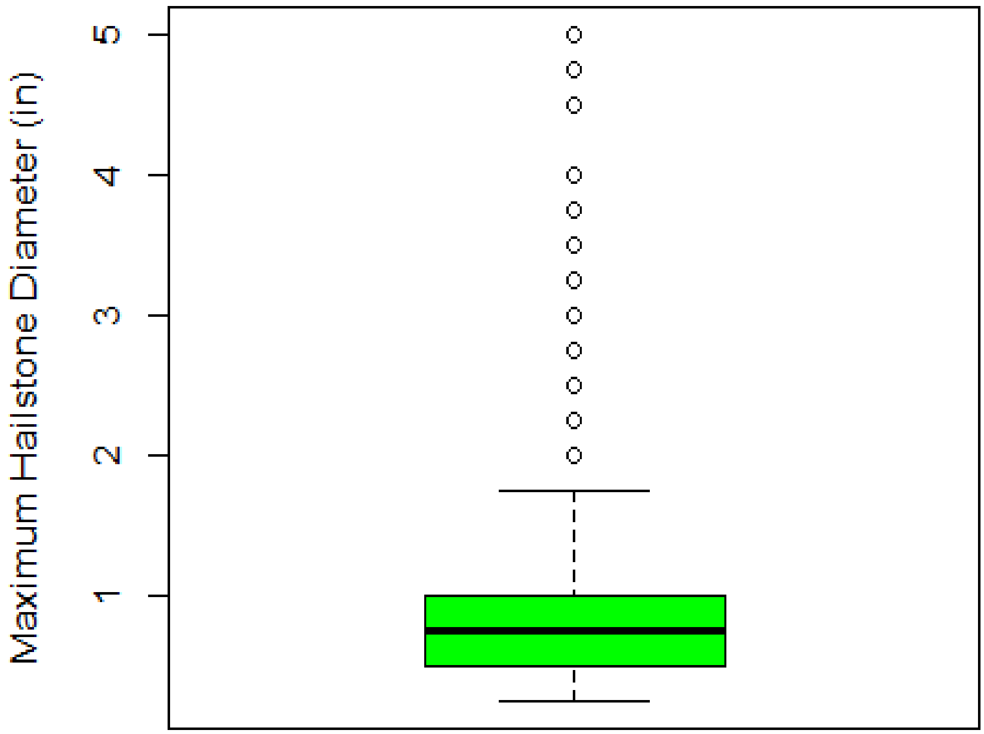

Figure 3. Boxplot of hailstone diameters in the U.S. from 2006-2009.

As a result, in order to effectively improve hailstone size forecasting, one would seek to improve the forecasting of smaller hailstone diameters, as the frequency of occurrences is much higher. TPW does not demonstrate itself as a good predictor for this purpose since there was no statistically significant difference in TWP for small and medium-sized hailstones. However, TPW could be used as an indicator when other predictors are showing a hailstone diameter above one inch. Essentially, TPW would be an effective forecast parameter if used in conjunction with other predictors for larger hailstone diameters such as those utilized in the WRF-HAILCAST model. Since larger hailstones have the potential to cause greater damage, improving forecasting in this area is beneficial.

Additionally, TPW could potentially be used as a forecasting indicator when differentiating between small and large-sized hailstones or medium and large-sized hailstones. Since the damages and injuries resulting from hailstones increase as the size of the hailstone increases, these measures indicate that TPW could be useful when attempting to forecast the size of the average hailstone that a storm will produce. In particular, TPW was shown to be significantly different between small hail (less than 1 inch in diameter) and large hail (greater than 2 inches in diameter) and between medium hail (1-2 inches in diameter) and large hail (greater than 2 inches in diameter).

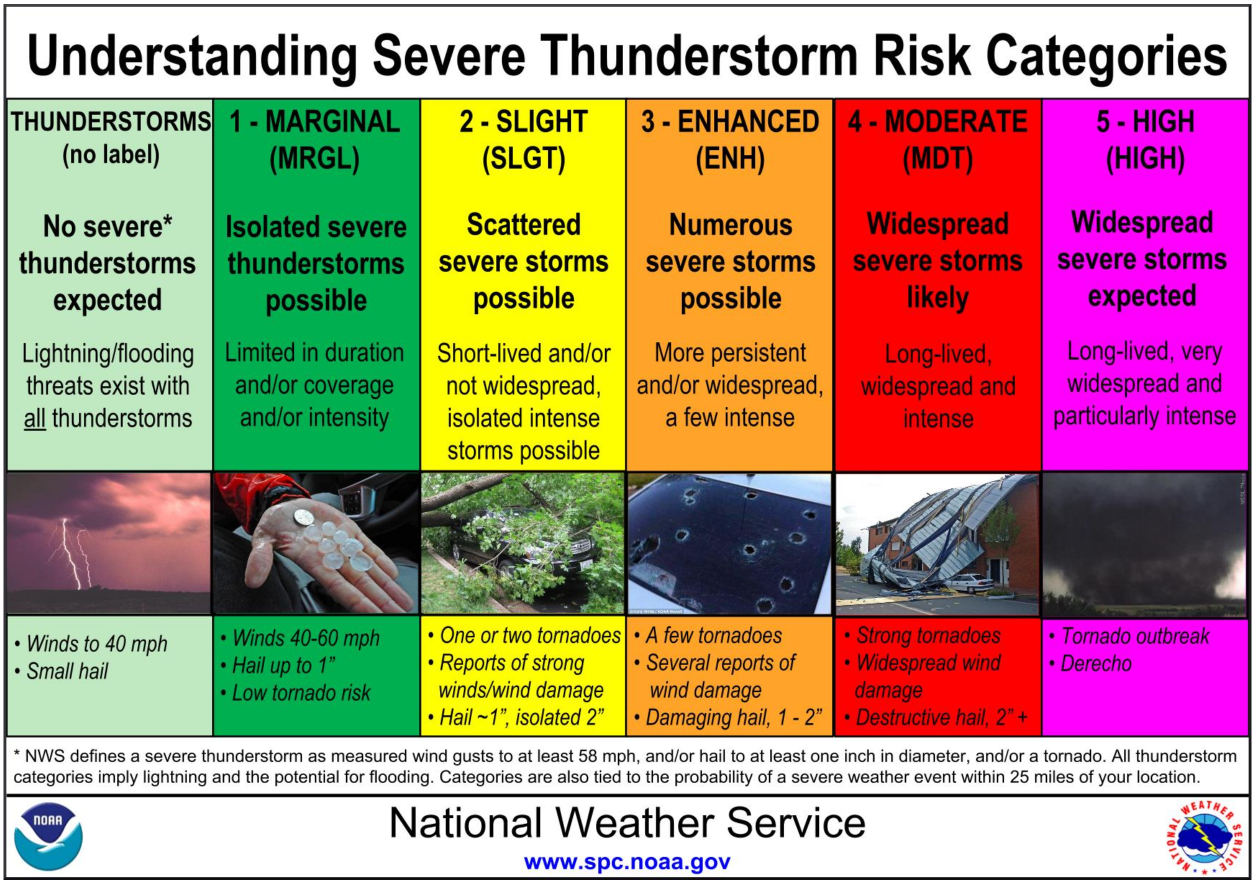

Figure 4. SPC Severe thunderstorm risk categories[7].

It is also worth noting that the SPC uses hailstone diameters for classifying its severe thunderstorm categorical risks as shown in Figure 4. Note that for the slight risk of scattered severe storms possible, hail of approximately 1 inch in diameter is one of the criteria. For enhanced risk of numerous severe storms possible, damaging hail of 1 to 2 inches is a criterion. And for moderate risk of widespread severe storms likely, destructive hail of greater than 2 inches in diameter is listed as a criterion. The NWS defines a severe thunderstorm as any storm that produces one or more of the following elements: a tornado, damaging winds, or speeds of 58 mph (50 knots) or greater, or hail 1 inch in diameter or larger. The SPC further defines significant severe thunderstorms as any storm that produce one or more of the following elements: a tornado that produces EF2 or greater damage, wind speeds of 75 mph (65 knots) or greater, or hail 2 inch in diameter or larger[7]. This means that TPW could be used to help produce the severe thunderstorm categorical risks for enhanced and moderate categories and for determining whether a storm will be severe or significant severe since there is statistical significance for TPW values of medium and large hailstone diameters.

Since TPW is a thermodynamic variable that can be measured before a storm occurs this could help improve lead times in hailstone diameter forecasting and severe storm categories by providing an additional indicator of hailstone size for medium and large hailstones. Therefore, if used alongside other variables, TPW could improve the forecasting of larger hailstones.

5. Conclusion

Forecasting the diameter of a hailstone is an intricate process that still has much room for improvement. Over the past few decades, individual predictors such as VILW have not been successful for this type of forecasting. Today’s slightly more effective models involve a compilation of thermodynamic variables. One variable that has not been including in these models but can be observed before the hailstorm event occurs is TPW.

After thorough analysis, this study found that TPW does not hold a strong direct positive correlation with hailstone diameter. However, a range of TPW values corresponds with certain larger ranges of hailstone diameters with no hailstone diameters over two inches occurring with a TPW under 20 kg/m^2 or above 50 kg/m^2. Therefore, if used alongside other variables, TPW could improve the forecasting of larger hailstones. Additionally, TPW clearly shows capability in determining whether a storm will produce severe (1-2 inches in diameter) or significant (greater than 2 inches) hail by the SPC's definitions. To confirm this, more studies would need to be completed that examine the ranges of TPW as they correlate to large hailstone diameters and the usefulness of TPW in the SPC definitions of severe and significant. A specific dataset of large hailstone diameters would be beneficial in conducting future studies. Further research on other potential variables must be discovered and tested to attempt the overall improvement of hailstone diameter forecasting.

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7. References

1. NCDC, 1995: *Storm Data*. Vol. 37, No. 5, 268 pp.
2. Edwards, R., and R. L. Thompson, 1998: Nationwide comparisons of hail size with WSR-88D vertically integrated liquid water and derived thermodynamic sounding data. *Wea. Forecasting,* **13**, 277–285.
3. Adams-Selin, R. D., and C. L. Ziegler, 2016: Forecasting hail using a one-dimensional hail growth model within WRF. *Mon. Wea. Rev.,* **144**, 4919–4939.
4. Amburn, S.A. and P.L. Wolf, 1997: VIL density as a hail indicator. *Wea. Forecasting,* **12**, 473–478.
5. Reitan, C. H., 1960: Distribution of precipitable water vapor over the continental United States. *Bull. Amer. Meteor. Soc.,* **41**, 79–87.
6. Dupika, M. L., and G. W. Reuter, 2006: Forecasting tornadic thunderstorm potential in Alberta using environmental sounding data. Part II: Helicity, precipitable water, and storm convergence. *Wea. Forecasting,* **21**, 336–346.
7. NOAA. 2020: SPC Products. SPC, Accessed 1 April 2021, https://www.spc.noaa.gov/misc/about.html