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**A CLIMATOLOGY OF SIGNIFICANTLY SEVERE HAIL
IN THE NORTHEAST UNITED STATES FROM 2011-2022**

A Thesis in
Meteorology and Atmospheric Science

by
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ABSTRACT

An analysis of NOAA Storm Events Database hail reports from 2011 to 2022 was conducted for the northeastern United States to identify cases of significantly severe (≥ 2 in or 51 mm in maximum dimension) hail. For each of the 167 cases observed, we also examined NEXRAD level-II data to identify convective storm mode (e.g., right-moving supercell, QLCS, etc.) and behaviors including storm splitting or mergers. Using these datasets, we performed a climatology for these events, compiling an array of statistics which included maximum reported hail size, report quantity, duration of severe (1.00 to 1.99 in or 25-50 mm) and significantly severe hail, hail report time of day and year, extent of the hail reports swath, storm motion before and during significant hail production, and tornadoes produced (if any). ERA5 reanalysis data was obtained for each case to analyze thermodynamic and kinematic environments, including computing common severe weather indices like the Significant Hail Parameter (SHIP). These data were used to create composite soundings and hodographs for each convective storm mode and other categories of statistical interest.

With an average severe hail duration of roughly one hour, many of these cases were not short-lived or isolated. A few of the higher-impact events generated millions of dollars in damage over swaths greater than 100 miles (160 km) in length. The results both align with previous studies analyzing significant hail environments but also highlight a few differences unique to the northeast. This will not only aid forecasters in predicting future events in this region but also inform commercial businesses and insurance companies, such that mitigation strategies can be developed to limit property losses from these uncommon, yet prolific hailstorms.

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LIST OF ABBREVIATIONS AND ACRONYMS

BWD: bulk wind difference

CAPE: Convective Available Potential Energy, MU-: Most Unstable, ML-: Mixed Layer

cm: centimeter

km: kilometer

LH: Linear Hybrid (Smith et al 2012 convective storm mode classification)

m: meter

NARR: North American Regional Reanalysis

NCEI: National Centers for Environmental Information

NEXRAD: Next Generation Weather Radar (WSR-88D Doppler Radar)

NOAA: National Oceanic and Atmospheric Administration

NWS: National Weather Service

QLCS: Quasi-Linear Convective System

RM & LM: Right-mover & left-mover (cyclonic & anticyclonic supercell respectively)

SED: Storm Events Database

sfc: surface

SHIP: Significant Hail Parameter

sig hail: significantly severe hail ($\geq 2.00''$ or 51 mm in diameter)

sm: statute miles

SMV: storm motion vector

SPC: Storm Prediction Center

SR: storm-relative

SRH: storm-relative helicity

TBSS: Three-Body Scattering Signature

v_r : radial velocity

WFO: Weather Forecast Office

Z_{DR} : differential reflectivity

Z_H and Z_V : radar reflectivity factor at horizontal (_H) and vertical (_V) polarization

ρ_{hv} : co-polar correlation coefficient

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Hail causes an average of \$20 billion in damages across the United States annually in recent years (Bowen et al. 2024), significantly up from \$2.4 billion during the 1990s (Changnon 1999). It kills crops and livestock, totals cars and can lead to traffic accidents, and punches holes in the roof and siding of homes and businesses. The Midwest and Great Plains are notorious for producing some of the largest hail in the world (Gutierrez and Kumjian 2021) and frequently see large hail events (Allen et al. 2017; Murillo et al. 2021); however, large hail also occurs outside this region, in lesser-thought-of locations around the world (e.g., Allen et al. 2020). Along with the central U.S., central Argentina, southern Europe, and southeastern Asia all experience 3-12 or more hail days annually, but almost the entire eastern half of the U.S. also falls into the lower end of this range (Prein and Holland 2018).

The northeast U.S. is one of the most populated stretches of the country, with many sprawling metropolitan areas. With such large population density, the Northeast is particularly susceptible to hail damage, especially considering most of the region is unprepared to deal with large hail, given its perceived rarity. Indeed, Ohio and Pennsylvania were number six and seven, respectively, of the top ten states with hail damage incidents in 2024 (Porter 2024). In 2021, Maryland, Pennsylvania, and Ohio had similar or *greater* instances of property damage from large hail as states like Kansas and Oklahoma (Keegan 2022)¹.

In part, the perceived rarity arises from the fact that highly unstable, sheared environments thought to favor hailstorms (like those found in the U.S. Great Plains; Allen et al. 2020) are generally less common in the Northeastern U.S. (e.g., Lombardo and Colle 2011). Further, studies of pre-convective environments in other regions of the world (e.g., Europe), have demonstrated that their average hail environments differ significantly from those in the U.S. (e.g., Taszarek et al. 2021). In order to combat this perceived rarity of

¹ And interestingly, as shown later in this paper, 2021 was the *least* active year for large hail in the Northeast in the entire study period, highlighting even more how common hail damage is in this region.

Northeastern U.S. hailstorms and adequately compare environments and storm behaviors of Northeast large-hail events to those in other regions, this study embarks on a climatology of significantly severe hail (≥ 2 in or 51 mm, hereafter referred to as “sig hail”) for this understudied region.

1.1 Hail Report Data

Severe hail (1.00 to 1.99 in or 25-50 mm) and sig hail are reported to the National Weather Service (NWS) local Weather Forecast Offices (WFOs) from a plethora of sources, including trained spotters, law enforcement, emergency management, NWS employees, social media, newspapers, amateur radio, storm chasers, the general public, and more (Allen and Tippet 2015). Though the report source is expansive, it is greatly affected by population density, more so than tornado and wind reports that can be evaluated post-event by storm surveys, even in remote areas. Allen and Tippet (2015) found that hail reports clustered around high population centers and road networks, making it virtually impossible to complete an unbiased spatial analysis of reports. Along with such population bias, biases in report size are also well documented. For example, Schaefer et al. (2004) explored the hail report dataset from the NWS from 1955-2002 and show that 98.3% of the 154,702 reports are precisely ten unique sizes, owing to reporters using objects of standard size as a comparison. Ironically, an ongoing social science experiment shows that the public’s quantitative estimates of hail maximum dimension are more accurate than when asked to compare to a reference object (Allen et al. 2024). Although such individual judgment skews reports, as technology and public awareness have advanced, the quantity and accuracy of reports have increased, largely due to the availability of posting photos and videos of hail on social media, which can be harvested for quantitative information (e.g., Eisenbach 2023).

Despite these limitations, spatial hail report data were useful in this study for temporal and environmental analyses, along with providing additional context for case studies. As described in the next chapter, these reports underwent additional careful quality control screening prior to use in this study.

1.2 Large Hail Climatology

Owing to the prevalence of hail report biases, some authors have turned to more objective approaches for constructing hail climatologies. Cintineo et al. (2012) constructed such a hail climatology in the U.S. for the 2007-2010 period using a radar-derived quantity called the maximum expected size of hail (MESH; Witt et al. 1998), which is now computed as part of the multi-radar multi-sensor (MRMS; Smith et al. 2016) suite of products. Annual severe hail days reached a maximum of 9-12 through all of Nebraska and Kansas, most of Oklahoma and South Dakota, western Texas, and eastern Colorado and New Mexico. In contrast, most of the Northeast was characterized by roughly 1-2 severe hail days, except for a corridor extending from central Maryland through the Hudson Valley of New York, where roughly 4-5 severe hail days per year occurred in the southern portion, and 2-3 occurred in the northern portion. A similar result was found in a follow-up study by Murillo et al. (2021) using an updated MESH configuration applied to the four-dimensional space-time composite NEXRAD data known as GridRad (e.g., Homeyer and Bowman 2022). Over a 23-year period, Murillo et al. (2021) found 2-4 annual severe hail days for all of Ohio and Pennsylvania, all of Maryland except for the Chesapeake peninsula, and all of New York except for the Adirondacks and just downstream of Lake Erie. Their study also found the peak for the central and high plains was slightly higher at 12-14 days, over a similar spatial extent as Cintineo et al. (2012). Another MESH study with finer temporal resolution was conducted by Wendt and Jirak (2021), which analysed annual severe hail *hours* across the U.S. A similar bullseye was located over northwestern Kansas and western Nebraska, with >30 severe hail hours a year. Over the Northeast, 5-10 annual hail hours occurred across northern Virginia and West Virginia, southern and central Ohio, western and central Maryland, and southern Pennsylvania. All states east of the Mississippi River and north of Florida saw the same range. Further north, however, a fast drop off existed, with only 2-3 hours expected in southern and central New York and eastern New Jersey, 1-2 hours in western and northern New York and all of New England, with the exception of northeastern Maine and coastal Massachusetts and Rhode Island, which saw only 0.5-1 annual hour.

Of interest to operational forecasters is the ability to anticipate severe hail based on pre-convective environmental conditions, either from proximity soundings or model reanalyses. For example, Johnson and Sugden (2014) compiled environmental data from Rapid Update Cycle (Benjamin et al. 2004) model analysis to differentiate between “lower-end severe hail” (≤ 1.25 in, 32 mm) and sig hail. They found a marginal increase in most unstable CAPE (MUCAPE) with hail size, from a mean of 2010 J kg⁻¹ to 2789 J kg⁻¹ for the 2.00-3.25 in (51-83 mm) and ≥ 3.5 in (89 mm) bins, respectively, but large overlaps between all adjacent hail-size categories still existed. Steep 700-500-hPa lapse rates are also known to favor large hail production (e.g., Taszarek et al. 2017, Warren et al. 2021). However, Johnson and Sugden (2014) found more “non-traditional” parameters like hail growth zone (HGZ) thickness and bulk wind difference (BWD, or “shear”) above 6 km showed moderate skill for distinguishing between the 1.50-1.75 in (35-44 mm), the 2.00-3.25 in (51-83 mm), and ≥ 3.5 in (89 mm) bins. Conversely, when using the ECMWF Reanalysis V5 (ERA5, Hersbach et al. 2020) analysis proximity soundings and a machine learning approach, Gensini et al. (2021) found the 0-6 km BWD to be one of the most important parameters, as well as the storm-relative helicity (SRH) in the 3-6 km and HGZ layers.

This latter finding suggests that the specifics of the *storm-relative* hodograph are most important for maximizing hail size, which has major support in the recent literature (e.g., Kumjian and Lombardo 2020; Lin and Kumjian 2022; Nixon and Allen 2022). Dennis and Kumjian (2017) used Cloud Model 1 (Bryan and Fritsch 2002) to perform idealized simulations of hailstone growth in supercell storms within fixed thermodynamic profiles and varying hodographs. They found that increasing the zonal (u) component of deep-layer shear widens updrafts in the east-west direction, leading to more hail production and longer hail residence times within the HGZ of a supercell, ultimately increasing the maximum potential hail size. When considering even larger hail sizes, Gutierrez and Kumjian (2021) showed that storms producing gargantuan hail (≥ 6 in or 152 mm) featured large (>10 m s⁻¹) storm-relative winds in the lowest 2 km above ground level (AGL). When combined with large (>2000 J kg⁻¹) values of MUCAPE, these environments suggest wider updrafts. In contrast, they found that conventional severe convection environmental parameters like

0-6 km BWD, and 0-3 km storm-relative helicity (SRH) showed little use in predicting these events. The story with all these studies is similar: While there are parameters to *help* operational forecasts of these events, we still have not discovered a strong enough pattern to be able to predict these events with full confidence, or such a pattern may not even exist.

Large hail climatologies that focus specifically on the Northeast U.S. are few. In a study of the environments of Northeast severe thunderstorm events, Hurlbut and Cohen (2014) found 67 reports of sig hail during the period from 1999-2009. Summer (June-August) was the peak season for all severe weather reports. Using observed proximity soundings created from the Universal Rawinsonde Observation program, they calculated from a 126-sample size a 25th to 75th percentile distribution of roughly 500 to 1600 J kg⁻¹ of mean-layer CAPE (MLCAPE) for sig hail events and 12.5 to 19 m s⁻¹ of 0-6-km BWD. Interestingly, neither of these variables distinguished well between events of sig hail versus non-sig hail. Lombardo and Colle (2011) also define (coastal) Northeast convective parameters for severe storms within convective storm mode categorizations using the North American Regional Reanalysis (NARR; Mesinger et al. 2006). The cellular mode composites of 49 samples showed a 25th to 75th percentile range of MUCAPE of roughly 750 to 1600 J kg⁻¹ and 8 to 16 m s⁻¹ of 0-6-km BWD.

1.3 Doppler Radar Characteristics of Large Hail

Dual-polarization capabilities were incorporated into every WSR-88D Doppler radar in the nationwide network by 16 May 2013 (NWS), allowing radars to send vertically polarized electromagnetic waves simultaneously with the “traditional” horizontally polarized electromagnetic waves. New polarimetric radar variables, including differential reflectivity (denoted as Z_{DR} , the difference between Z_H and the vertical equivalent Z_V when both are expressed in decibels) and co-polar correlation coefficient (denoted as ρ_{hv} , a measure of the consistency of shapes of scatterers within the sampling volume), are particularly useful in deciphering regions of hail within a thunderstorm (Kumjian 2013a). Z_{DR} approaching zero dB ($Z_H - Z_V = 0$ dB) suggests spherical scatterers and thus large hail (non-spherical large hail *typically* tumbles chaotically, and the resulting population of hailstones scatters

isotropically and is thus “seen” as spherical by the radar), whereas raindrops, especially large ones, are larger in the horizontal dimension and have greater relative permittivity, resulting in positive Z_{DR} (Kumjian 2013b). Very large hail can produce dramatically lower ρ_{hv} (<0.85) compared to rain (≥ 0.97), especially if it is irregularly shaped, because ρ_{hv} diverges from unity as the sizes of the scatterers differ and produce increased variability in backscatter differential phase (Kumjian, 2013b). Additional dual-polarization artifacts aid in Doppler radar detection of hail, including the three-body scattering signature (TBSS; Zrnić 1987), which protrudes radially outward from the hail core in the opposite direction to that of the radar site, and has extremely low values of ρ_{hv} (<0.5 , Kumjian 2013c). However, determining the exact hail size from any radar variables probably is not possible (Kumjian et al. 2024). Even in the extreme cases of gargantuan hail, radar analysis depicted similar structures and maximum values in Z_H as in cases of smaller hail (Blair et al. 2011; Allen et al. 2020; Gutierrez and Kumjian 2021). The only radar-derived quantity useful for significant size delineation was rotational velocities within the parent supercell storms. Rotational velocities were found to be much larger in gargantuan hail cases (31.3 m s^{-1}) than in giant hail (4 in or 102 mm) cases (median of 24 m s^{-1}), which were also larger than in sig hail cases (Blair et al. 2011).

Scrutinizing these variables and artifacts was key to understanding the evolution of the thunderstorms that produced sig hail analyzed in this study, and in confirming/revising hail report data. In the next chapter, we discuss how these data are used in the analysis.

CHAPTER 2

DATA AND METHODS

This chapter details the methods and data used to compile the climatology of significantly severe hail in the Northeastern U.S. For this study, the Northeast region was defined as Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, Delaware, Maryland, and Washington, D.C. Additionally, only portions of Ohio, West Virginia, and Virginia were included (Figure 2.1), which differs from other definitions of the “Northeast” in previous studies (Cerniglia and Snyder 2002; Bunkers et al. 2006; Lombardo and Colle 2011; Hurlbut and Cohen 2014). This serves to both include all counties within the Cleveland and Pittsburgh WFOs, and to smooth the geographic area of interest as to avoid arbitrarily cutting it off at state borders (only the northern half of the Sterling WFO was retained). Additionally, these regions appear climatologically similar to the southern and central Northeast, with derived radar parameters suggesting similar instances of annual severe hail days (Cintineo et al. 2012; Murillo et al. 2021; Wendt and Jirak 2021).

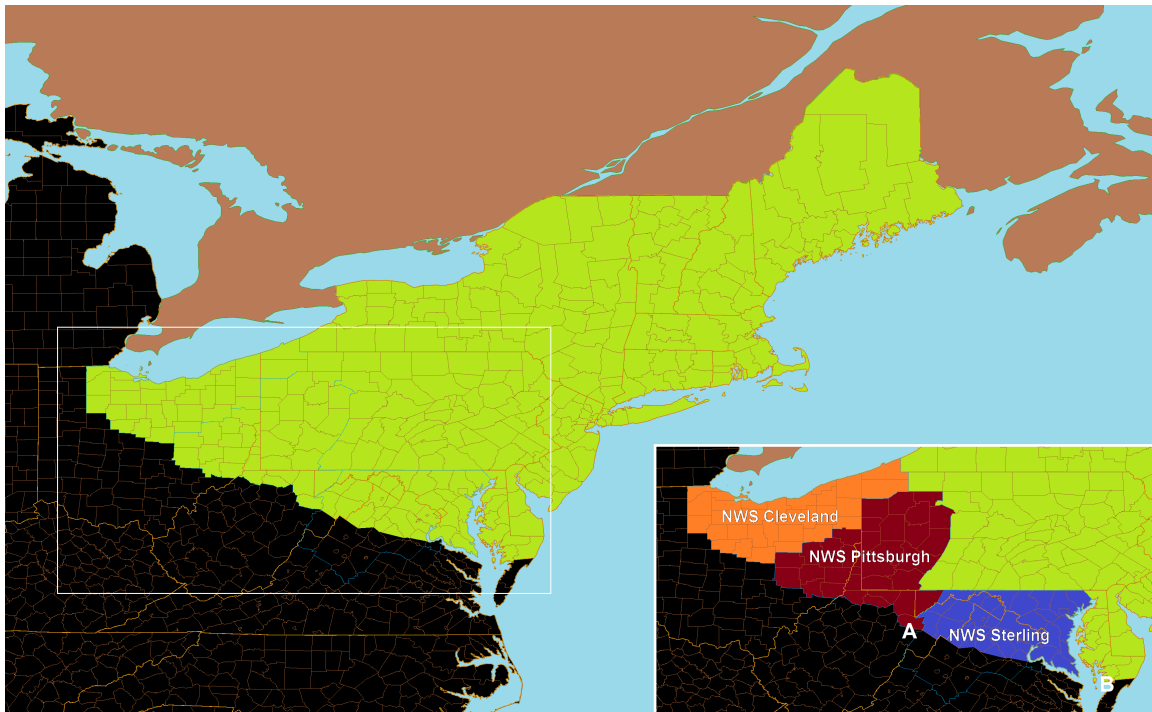


Figure 2.1. A map defining the Northeast region. Portions of Ohio, West Virginia, and Virginia were added to include the entirety of the Pittsburgh and Cleveland WFOs, and the northern half of the Sterling WFO, denoted by the subfigure.

The period from 2012-2022 was initially chosen for the analysis to include the entire era in which the WSR-88D radars had been upgraded to dual-polarization capabilities and to remain within the time period of improved severe weather reporting, as suggested by Allen and Tippett (2015). Subsequently, 2011 was added because of its abundance of cases, providing additional samples for the climatology.

2.1 Collecting Data, Defining Cases, and Refining Errors Using Doppler Radar

Hail reports were collected from both the Storm Prediction Center's *Storm Reports* page (https://www.spc.noaa.gov/climo/reports/110323_rpts.html; will hereafter refer to as "SPC reports") and NOAA's Storm Events Database (Schaefer and Edwards 1999; will hereafter refer to as SED). SPC reports are mostly preliminary data, while data from SED are refined with additional accuracy. For example, SED filters out repeated reports and reports that are spatially close together (somewhere between 0.02° and 0.01° latitude/longitude and closer), whereas SPC reports do not. Repeated reports occur when multiple reports are made by the public from the same town or city ("Town X"). Often, the public will not indicate their exact location within Town X, so the location included in the database is automated to the "center" of Town X. To more accurately depict the number of reports for each case, these repeated reports were identified from the SPC reports and retained. To make it visually obvious that there was >1 report in Town X in the case images (Appendix A), the coordinates for these reports were dithered, or arbitrarily modified by less than 0.01° latitude/longitude. (The clustered reports in Cases 2 and 53 in Appendix A are great examples of this.)

Another limitation of SPC reports is the lack of duration information, whereas the SED often adds a duration if it was known. In addition, SED will occasionally add a third and fourth decimal place to latitude/longitude for higher precision, correct a time or location that was inaccurate in the preliminary report, add an event narrative with information useful to correcting other errors, or add additional delayed reports from post-event analyses. Swath data were also available in SED for roughly 10 Cases, displayed as a "Begin

Lat/Lon” and “End Lat/Lon,” much like is done for tornado paths. In these instances, additional hail report points were manually added between the start and end location of the swath at a spatial resolution $>0.01^\circ$ but $<0.05^\circ$ to differentiate from repeat reports².

Next, the reports were separated into Cases and Events. A Case was defined as a single thunderstorm updraft that produced at least one sig hail report. If multiple, separate thunderstorm updrafts produced sig hail reports on the same day, each thunderstorm was considered a separate Case and the whole day was considered one Event. The cutoff time for Events was chosen to be the local sunrise time for each Case instead of the SPC definition of 1200 UTC (only Case 25 was close to this time). To determine whether reports were associated with a single thunderstorm updraft, archived level-II radar data from the WSR-88D network were consulted. The preliminary reports data were loaded into the NOAA Weather and Climate Toolkit (<https://www.ncdc.noaa.gov/wct/>) and labeled by the time of the report, with sig hail marked specially. Data for the radar site(s) of interest were imported from Amazon Web Services (<https://s3.amazonaws.com/noaa-nexrad-level2/index.html>). Animations of the lowest-level PPI scans of radar reflectivity factor at horizontal polarization (Z_H) were constructed for the time period in which the Case(s) was observed to determine what hail reports were associated with the Case in question. Once a preliminary loop of Z_H with hail reports was rendered, the final step was to correct the remaining location and time errors manually. This was accomplished through the scrutinization of dual-polarization variables at varying elevation angles via the methods described in Kumjian (2013a-c). The two most common errors, which both occurred in nearly every case, were (i) a lack of duration for all reports, and (ii) a report delay time of 5-15 minutes. If, for example, one report would have a 5-min duration and the rest would not, this was likely caused by limitations of both the SED and SPC report datasets and not by observation, though multiple radar variables were analyzed to ensure it would make sense to add a duration or even modify the reported duration slightly. Delayed hail reports were likely due to the observer reporting the hail after it had stopped falling. These reports

² Case 4 was the only exception, as adding additional reports at this spatial resolution would have resulted in hundreds of additional reports. This unique case had 12 swaths, some of which were over 40 miles (64 km) in length, so an additional hail report was only added for every unique town within the swath.

were simply modified to an earlier report time, with preference given to keeping the original time, even if the radar presentation of the storm did not “line up” well with the report (because estimating hailfall times from radar is an imprecise endeavor). A vast majority of reports could be edited with this process, but a small amount had more unique errors that had to be addressed with forensic meteorology techniques, as expanded upon in the following sub-section.

2.1.1 Fixing Report Errors with Forensic Meteorology

Even with this strict refinement method, a handful of reports were ambiguous and required additional steps to correct. For a simple example, Case 79 in southwest Maine on 11 September 2013 had only one sig hail report plotted very obviously too far south. Fortunately, SED had an “event narrative” that stated the street name of where the report occurred, which differed from the coordinates listed by >5 miles (>8 km). The new location better aligned with the radar presentation of the storm, so the report was corrected accordingly. A more complex example was Case 7, which reported hail from the western part of Vestal, NY. This location was roughly 3 miles (5 km) west of the compact core of the storm, which was only 12 km from the radar site (i.e., a very low scan was taken of this storm, so the report should be closer to the core). The associated SED comment for this report stated “One large car dealership had over 500 damaged vehicles.” After researching every car dealership in the Vestal, NY, zipcode, there was only one which even had an inventory >500 vehicles. Thus, the hail must have occurred in this location, which was on the eastern side of the town and now aligned with radar imagery. A third example comes from Case 54. Irwin, PA, had six reports of hail, the first of which occurred at 2215 UTC and the last at 2244 UTC. The town extends much farther west than where the “center” of it is located (i.e., where preliminary reports automatically are set to if the reporter does not specify where in town “X” they are located). So, using the initial time of the report with this slower moving storm, there was enough confidence to move some of the reports to the western part of the zip code to align with Z_H , Z_{DR} , and report time, and keep reports from later times in their original location. There were dozens of other reports that had similar

errors, many of which were corrected by extensive research of the township boundaries/zip codes, local businesses, population density, and other forensic meteorological techniques. There were also two to three times as many reports that had simple errors, where a suburb of a city or neighborhood name is mentioned in the comments, but the report is still in the center of the city/town. These reports were often a few km at most from the correct location.

A final example of forensic meteorology techniques used for data collection was from Case 125. As with a few other cases, a photo of the largest hailstone was found that proved it was much larger than reported in the SED (the hailstone reported as 2.75 in/70 mm was measured to be 4.00 in/102 mm). While reviewing images for this report, two other hailstone images were found from this same storm, in locations not reported in SPC reports or SED. A hailstone at least golf-ball sized was posted on social media from Kennerdell, PA. With no additional information, it was placed in the center of the town. However, the second hailstone image posted from Rockland, PA, had a street address with it. After adding it to the Case's list of reports, it was a staggering 8.2 miles (13.2 km) away from the next closest report in the original databases, filling in a very large gap in the middle of the Case's hail swath. Though specific examples like these are not written in detail, additional Case information can be found in Appendix A and B, and at the following link: <https://sites.psu.edu/northeastsignificantthailcases/all-cases/>.

The duration of each hail report is likely biased slightly toward longer than what was actually observed. This is due to the lack of precision of a majority of reports. If, for example, a report was placed 8 km further east than where the hail actually occurred because this was where the township center is located, but the initial report time was accurate, then that erroneous report would not have been adjusted backward in time. A report cannot be submitted early (because the hail would not have occurred yet!), so without knowing if the location was correct, dual-pol variables were analyzed for the location, and the duration for these reports would have been extended to match what was inferred from the radar signals. Though imperfect, this approach is advantageous over leaving unrealistic one-minute durations for most reports. Also, reports were often submitted late, normally anywhere from the middle of the duration to just after the storm had passed, so these reports would have been adjusted forward for an accurate start time.

Given these uncertainties, the durations of each report should be viewed cautiously, with uncertainties of up to ~5 min or so likely. However, it is doubtful that this largely affects the overall case duration *statistics*, which will be the primary focus of our analysis.

2.2 Storm Mode Classification

The storm mode for each case was determined by scrutinizing PPI scans of Z_H and radial velocity (v_r) at multiple elevation angles, following the methods of Smith et al. (2012). Six categories were used, each having two or three sub-categories following Figure 2 of their paper. A storm was defined as a discrete area of $Z_H \geq 35$ dBZ that generally consisted of a single, dominant updraft. A QLCS was defined as a continuous line of echoes at or above the same Z_H threshold, with horizontal extent ≥ 100 km and a length-to-width ratio of $\geq 3:1$. Supercells, subdivided into cyclonic or right-movers (RM) and anticyclonic or left-movers (LM), consisted of storms with an organized rotating updraft inferred from azimuthal shear in v_r that met the following criteria: a peak rotational velocity ≥ 10 m s⁻¹ (i.e., gate-to-gate shear ≥ 20 m s⁻¹) over a distance of less than ~7 km (3.5 nmi), an updraft duration of at least three radar volume scans (generally at least 15 minutes), and rotation extending through at least one-fourth of the storm's depth. Linear Hybrids consisted of storms that had both linear and supercellular structures simultaneously, but one category or the other could not adequately describe the storm; this category was used only when the storm could not be decisively put in another category. Marginal storms consisted of the Cases that did not meet the criteria for the supercell category (e.g., azimuthal shear was too weak, too short in duration, or too shallow), but still had supercellular characteristics. All other storms that could not reasonably fit into any other category were denoted as “disorganized,” also known as “pulse cells” (e.g., Wilk et al. 1979). After a storm's major category was chosen, the subcategory was determined. For cellular convection, this included discrete cell, cell in cluster (i.e., one storm “connected” to another storm via $Z_H > 35$ dBZ), and cell in line (same as cluster, but oriented linearly in a length-to-width ratio of $\geq 3:1$); for the QLCS category, line (i.e., smaller-scale line segments) and bow-echo (i.e., extensive squall lines); and for linear hybrids, QLCS and cell in line. We adhered to all these definitions *except*

chose to ignore the rotational velocity threshold for the “Supercell (RM and LM)” category, to include “marginal” supercells in this category as well, since we were merely interested in the overall convective storm mode and not the strength of the supercell. These marginal Cases still had to meet the other thresholds to be considered a supercell.

Even with these criteria, a few Cases were difficult to categorize with certainty. Storm mode is a fluid spectrum. The storm mode chosen for each Case was evaluated at and around the time of the largest hail report, but some Cases featured mixed modes or evolution from one mode to another throughout the Case’s full duration. For example, Case 117 began as a discrete supercell, eventually growing upscale with neighboring convection but keeping its supercell structure within the cluster. Though the largest hail occurred both while it was a discrete RM and a cluster RM, the case was more representative of a discrete RM, because a majority of its hail reports and duration occurred in this storm mode compared to the latter.

2.3 Computing Convective Parameters of Interest

Environments for each case were analyzed using the fifth-generation ECMWF reanalysis (ERA5) hourly data on pressure levels (Buontempo 2022). The data were selected from the closest grid point to the location of the largest sig hail report for each case. If there was >1 report of the same size, the earliest report was given preference. A 9-grid point average ($0.5^\circ \times 0.5^\circ$ square) centered on this location was taken to mitigate possible errors in reanalysis data. The hourly reanalysis that fell between 60-119 minutes prior to the time of the largest magnitude hail report for each Case was chosen, following Gensini et al. (2021), to ensure no convective contamination occurred. For example, for a 1959 UTC report, we would use the 1800 UTC reanalysis, but for a 2000 UTC report, we would use the 1900 UTC reanalysis. Five ERA5 variables on pressure levels were used: the zonal and meridional (u and v) wind components, relative humidity, temperature, and geopotential. In addition, surface pressure was downloaded using “single level” data to derive the height

above ground level (AGL) and to ensure the correct surface data were being used³. For cases that had surface pressures >1000 hPa (the lowest level available in the “pressure levels” data), we linearly extrapolated the profiles to the surface pressure value using their slope between 975 and 1000 hPa (Case 37 shows one example of this in Appendix A).

Zero-to-twelve km hodographs were constructed using the u and v wind data. To obtain the u - and v -wind components at standard height levels (i.e., 500 m, 1-km, 3-km, etc., useful for calculating common forecast parameters), geopotential was evaluated at each pressure level, and data were interpolated to a height grid with 5-m resolution. To enable direct comparisons between Case hodographs and allow composite calculations, they were converted into a storm-relative reference frame using the methodologies from Warren et al. (2021). u and v profiles were first transformed by subtracting the mean 0-500 m wind, then the hodograph was rotated to align the 0-6 km shear vector (computed from the mean 0-500 m and mean 5.5-6 km winds) with the positive x direction.

Skew-T log-p diagrams were constructed and convective parameters of interest were calculated using the Python module MetPy (May et al., 2022). The parameters were displayed on the top right of the skew-T plots and both the top right and bottom right of the hodographs and some are displayed in table form, described in detail in Chapter 5. These convective parameters include the surface-based and most unstable convective available potential energy and convective inhibition (SB/MUCAPE and SB/MUCIN), water vapor mixing ratio (w_v), lapse rate (Γ), thickness of the hail growth zone (difference in heights between -10 °C and -30 °C, THK_{HGZ}), storm-relative wind, bulk wind difference, and storm-relative helicity.

³ For example, Case 55 was located in the mountains of western Maryland and had a surface pressure of 938 hPa (Appendix A), so the reanalysis temperature of 92°F at the 1000-hPa level could not be used as the true surface temperature.

Given our focus on significantly severe hail, the significant hail parameter (SHIP) was calculated, using the following formula (SPC 2014),

$$SHIP = \frac{MUCAPE \times w_v \times \Gamma_{700-500mb} \times -T_{500mb} \times BWD_{0-6km}}{42,000,000}$$

where MUCAPE is the CAPE of the most unstable parcel [J kg^{-1}], w_v is the water vapor mixing ratio of the most unstable parcel [g kg^{-1}], $\Gamma_{700-500mb}$ is the temperature lapse rate between 700 and 500 hPa [$^{\circ}\text{C km}^{-1}$], T_{500mb} is the temperature at 500 hPa [$^{\circ}\text{C}$], BWD_{0-6km} is the surface to 6-km BWD [m s^{-1}], and 42,000,000 is a normalizing constant. SHIP values ≥ 1 suggest an environment conducive for sig hail (SPC 2014).

CHAPTER 3

RESULTS AND GENERAL STATISTICS OF CASES AND EVENTS

Between 2011 and 2022, 323 reports of sig hail occurred in the Northeast U.S., composed of 167 Cases across 87 Events. These Cases produced an additional 1000 severe hail reports, for a total of 1323 reports analyzed (Appendix C lists details of all reports). Table 3.1 provides a summary of the spatial and temporal distributions of the reports. Table 3.2 (located at the end of this chapter) shows these data in more detail for each Case.

One hundred and five Cases (62.9%) had only a single sig hail report. Case 4 had the most sig hail reports (21) and Case 8 had the second most (12, Table 3.2). Both Cases had greater numbers of reports in part because of post-storm damage surveys (Scafer and Edwards 1999) (i.e., officials specifically searching for hail damage and providing additional reports) and delayed public reports. Case 82 had the most (9) preliminary sig hail reports (i.e., reported in real-time), five of which occurred within the same town of Amsterdam, NY, which experienced hail up to 4.00 in (102 mm) in maximum dimension. For severe

Table 3.1. Distribution of severe (sev) and sig hail reports for year, month, state, and WFO. Counts are reported in the first two columns and percentages (of the total number of hail reports of that size category) are in the second two columns.

By Year					By Month					By State					By WFO				
	count		percent			count		percent			count		percent			count		percent	
	sev	sig	sev	sig		sev	sig	sev	sig		sev	sig	sev	sig		sev	sig	sev	sig
2011	363	94	36.3	29.1	Mar	64	23	6.4	7.1	CT	20	6	2.0	1.9	AKQ	3	3	0.3	0.9
2012	175	37	17.5	11.5	Apr	37	7	3.7	2.2	DE	6	3	0.6	0.9	ALY	77	41	7.7	12.7
2013	82	20	8.2	6.2	May	453	149	45.3	46.1	MA	83	14	8.3	4.3	BGM	95	30	9.5	9.3
2014	108	25	10.8	7.7	Jun	144	60	14.4	18.6	MD	76	27	7.6	8.4	BOX	87	15	8.7	4.6
2015	102	15	10.2	4.6	Jul	147	47	14.7	14.6	ME	30	14	3.0	4.3	BTW	34	7	3.4	2.2
2016	52	12	5.2	3.7	Aug	118	27	11.8	8.4	NH	21	7	2.1	2.2	BUF	28	13	2.8	4.0
2017	41	13	4.1	4.0	Sept	23	6	2.3	1.9	NJ	33	7	3.3	2.2	CAR	5	3	0.5	0.9
2018	57	15	5.7	4.6	Oct	2	2	0.2	0.6	NY	187	83	18.7	25.7	CLE	155	62	15.5	19.2
2019	135	29	13.5	9.0	Nov	12	2	1.2	0.6	OH	185	71	18.5	22.0	CTP	53	21	5.3	6.5
2020	61	21	6.1	6.5						PA	244	64	24.4	19.8	GYX	46	18	4.6	5.6
2021	11	5	1.1	1.5						RI	7	1	0.7	0.3	LWX	126	35	12.6	10.8
2022	136	37	13.6	11.5						VA	42	9	4.2	2.8	OKX	36	14	3.6	4.3
										VT	40	9	4.0	2.8	PBZ	168	41	16.8	12.7
										WV	26	8	2.6	2.5	PHI	78	18	7.8	5.6
															other	9	2	0.9	0.6
Total	1000	323	100	100	Total	1000	323	100	100	Total	1000	323	100	100	Total	1000	323	100	100

hail reports, Case 4 and Case 8 again had the most, with 61 and 50, respectively. Though a portion of these reports were also not preliminary, they would still be the top two Cases if only preliminary reports were considered. The average sig hail report count per Case was 1.9, and the average associated severe hail report count per Case was 6.0, for a total average hail report count of 7.9 per Case. Because of a few Cases with large outliers (Cases 4 and 8), median values for these quantities give a better representation of a typical Case: 1.0 sig hail and 5.0 total hail reports, respectively.

Eighty-nine Cases (53.3%) had a maximum reported hail size of 2.00 in (51 mm), with 2.50 in (64 mm) being the second-most reported (30 Cases, or 18.0%; Fig. 3.1). There were only five⁴ Cases that had a maximum reported hail size of 2.25 in (57 mm). The unphysical jump in number of reports from maximum dimensions of 2.25 in to 2.50 in (57 to 64 mm) can be attributed to the size of common objects used by the public for comparison, which introduces bias. This bias is exacerbated by, for example, the official size chart from the NWS (e.g., Fig. 3.2, NWS Raleigh 2019): tennis-ball sized hail is 2.50 in (64 mm) and 2.00 in (51 mm) is listed as corresponding to either lime sized, hen-egg sized, or simply “larger

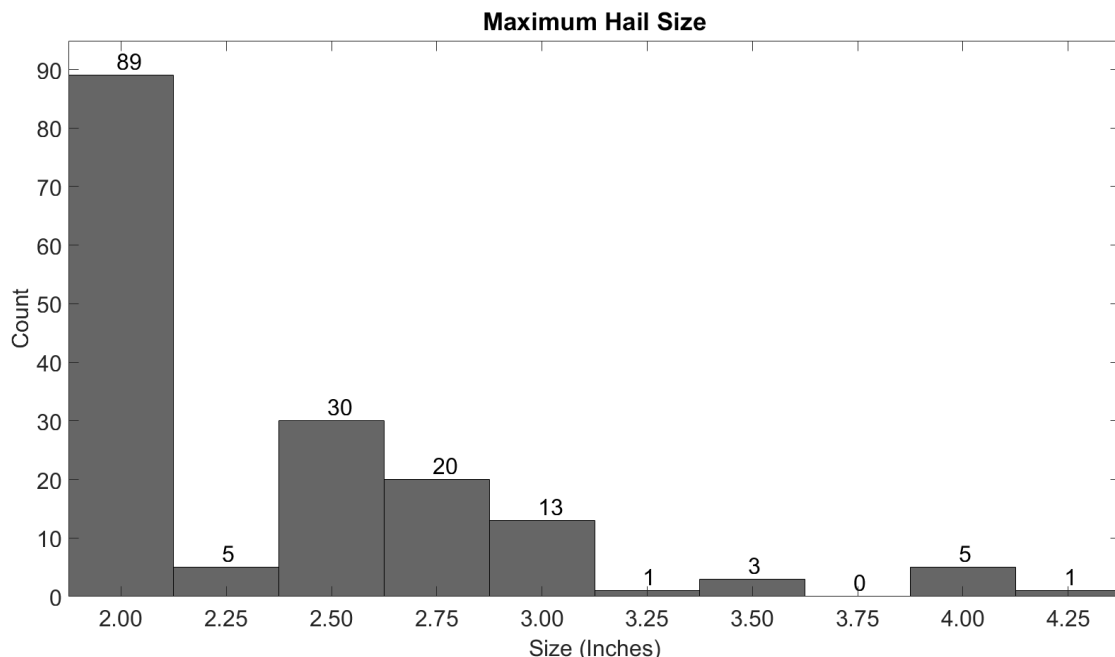


Figure 3.1. Maximum reported hail size for each of 167 Cases.

⁴ One of these (Case 96) in which the maximum reported hail size was increased from 2.00 in (51 mm) to 2.25 in (57 mm) after a photo of the hailstone was found: it showed a hailstone 2.25 in (57 mm) in maximum dimension next to a ruler, despite only being reported as 2.00 in (51 mm). See Appendix B.

than golf ball sized.” In other words, a common standard object of 2.25 in (57 mm) is not on the chart, and thus is arbitrarily reported much less frequently (e.g., Schaefer et al. 2004). Billiard balls are 2.25 in (57 mm) in diameter; although this is probably not commonly thought of as a reference object, a few of the hail reports of 2.25 in (57 mm) were actually reported as billiard-ball sized.

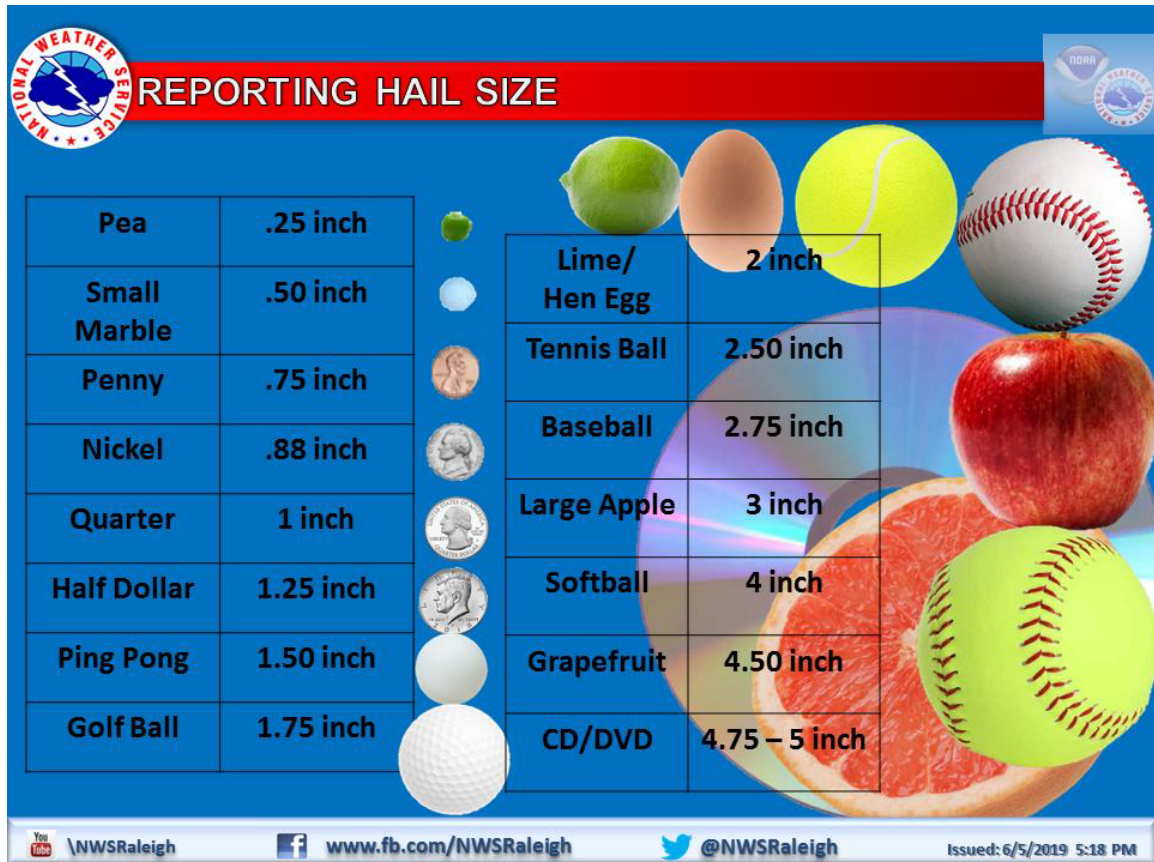


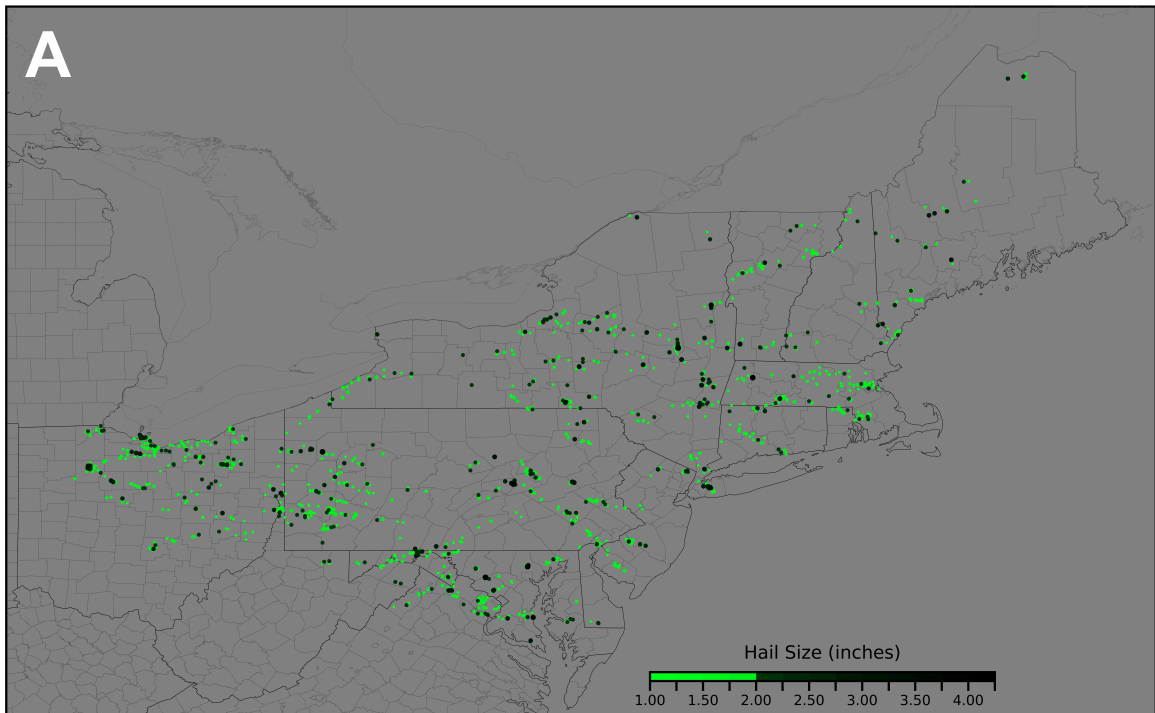
Figure 3.2. Graphic from NWS Raleigh with objects of standard size for hail reporting.

This same pattern of reference objects inducing a bias in the hail reports can also be seen at larger hail sizes, though it is less apparent because of the smaller sample sizes (Fig. 3.1). Hail sizes of 3.25 in (83 mm), 3.50 in (89 mm) and 3.75 in (95 mm) have no common reference objects, and thus are reported less frequently than 3.00 in (76 mm) and 4.00 in (102 mm). The lone 3.25-in (83-mm) report was measured with a ruler, as was one of the three 3.50-in (89-mm) reports. The other two 3.50-in (89-mm) reports (Cases 37 and 150; see Appendix B) were manually changed from 3.00 in (76 mm) after the author identified social media pictures depicting hailstones compared to smaller reference objects, and confirmed the hailstones had maximum dimensions of 3.50 in (89 mm).

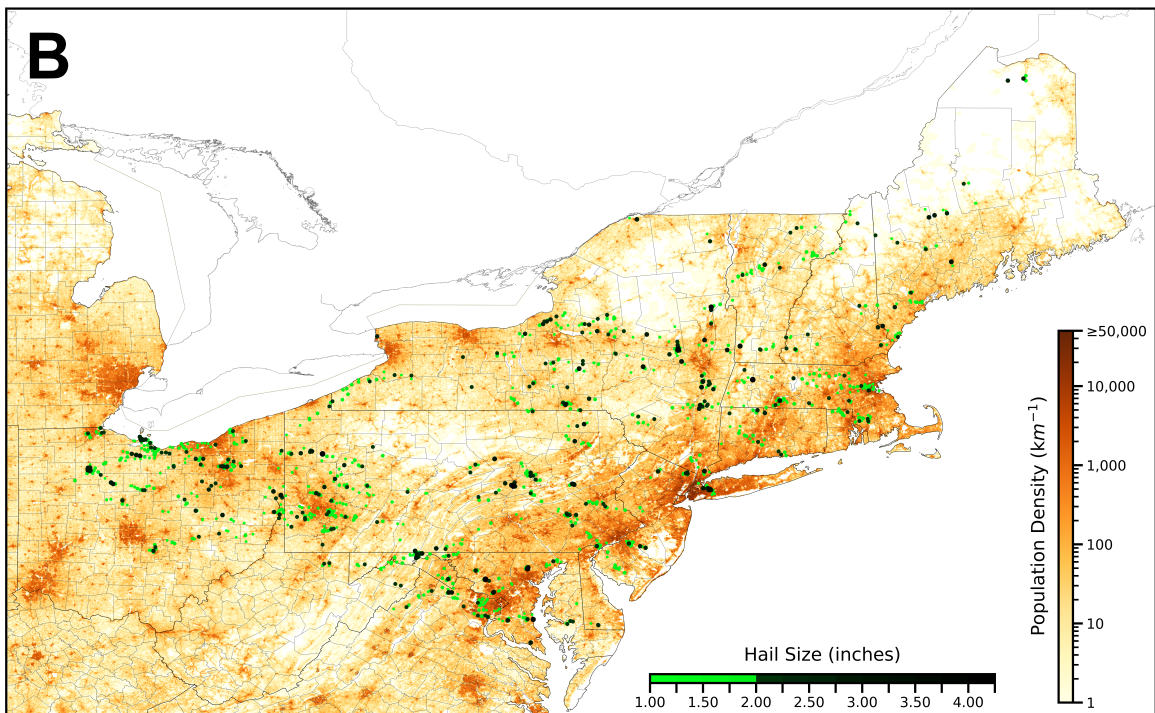
3.1 Spatial Distribution

Pennsylvania, New York, and Ohio accounted for 61.6% of severe hail and 67.5% of sig hail reports (Table 3.1). Only 3.3% of reports occurred in Connecticut, Delaware, and Rhode Island combined. This was likely due to not only their small size but also their proximity to the coast, which was shown to exhibit a reduction in hail reports by 10% compared to interior regions of the Northeast (Lombardo and Colle 2011). The density of hail reports appeared to be at least partially correlated with distance to coastlines: Eastern New Jersey and Connecticut, Long Island, NY, most of Delaware, eastern Maryland, and Rhode Island all have relatively large gaps between reports (Fig. 3.3a), despite having relatively high population densities, except for portions of Delaware/eastern Maryland, and the Pine Barrens of southeastern New Jersey (Fig. 3.3b). Ignoring these possible coastal effects, hail reports are often spatially associated with regions of greater population density, owing to a higher likelihood of hail being reported and/or the maximum-sized hailstones from the case being observed (Allen and Tippet 2015). The Alleghany plateau in north-central Pennsylvania, the Adirondacks of upstate New York, the White Mountains of northern New Hampshire, and the Allagash wilderness region of western and northern Maine have few-to-no reports within the 12-year period analyzed. The few reports that did occur in these areas are mostly due to reporting luck. For example, Case 165 (northern Maine) had one of its only two sig hail reports observed in a zero-population area because a family had been camping there and posted pictures of hail beside a travel-sized toothpaste bottle on social media, which was estimated to be tennis-ball sized (Appendix B). One of the only other regions that did not follow this pattern of more hail reports clustered in regions of higher population density was south of central and western portions of Lake Ontario, between Buffalo and Rochester, NY. In contrast, there are large concentrations of hail reports along almost the entire southern coast of Lake Erie. We speculate that these disparities may be due to the effects of terrain: the western edge of the Appalachians extends into western Pennsylvania and eastern Ohio, which may inhibit richer moisture from reaching western New York in southwest flow regimes. Further, air that passes over the deeper Lake Ontario may be less conducive to deep convection more often than air that passes over the shallower Lake Erie, because Lake Ontario's surface temperatures tend to be lower, especially in spring, but even into summer (Wang et al. 2022).

Sig Hail and Associated Severe Hail Reports 2011-2022



Sig Hail and Associated Severe Hail Reports 2011-2022



Sig Hail and Associated Severe Hail Reports 2011-2022

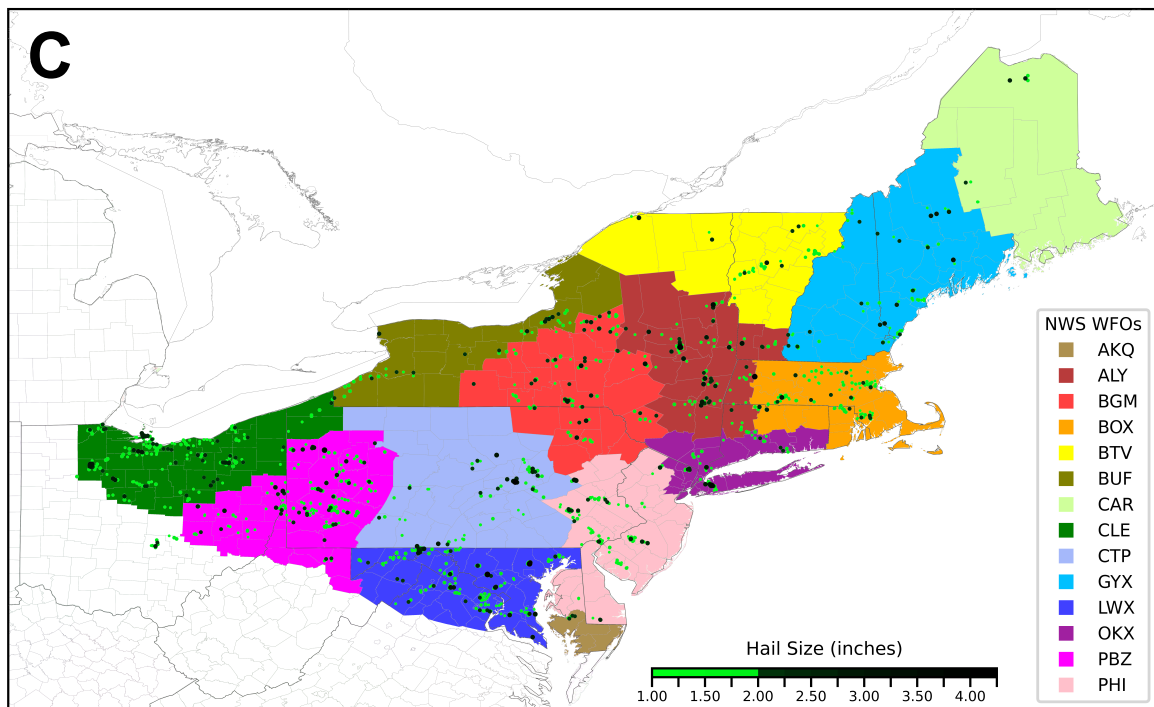


Figure 3.3. (a), (b), and (c) depict the 1,323 hail reports from all 167 cases. (a) has a plain gray background for ease of spatial analysis. (b) plots population density (persons per square kilometer), and (c) plots the boundaries of the 14 WFOs of interest for the study area, two of which (AKQ and LWX) are limited to only northern portions of the WFO (refer to Figure 1).

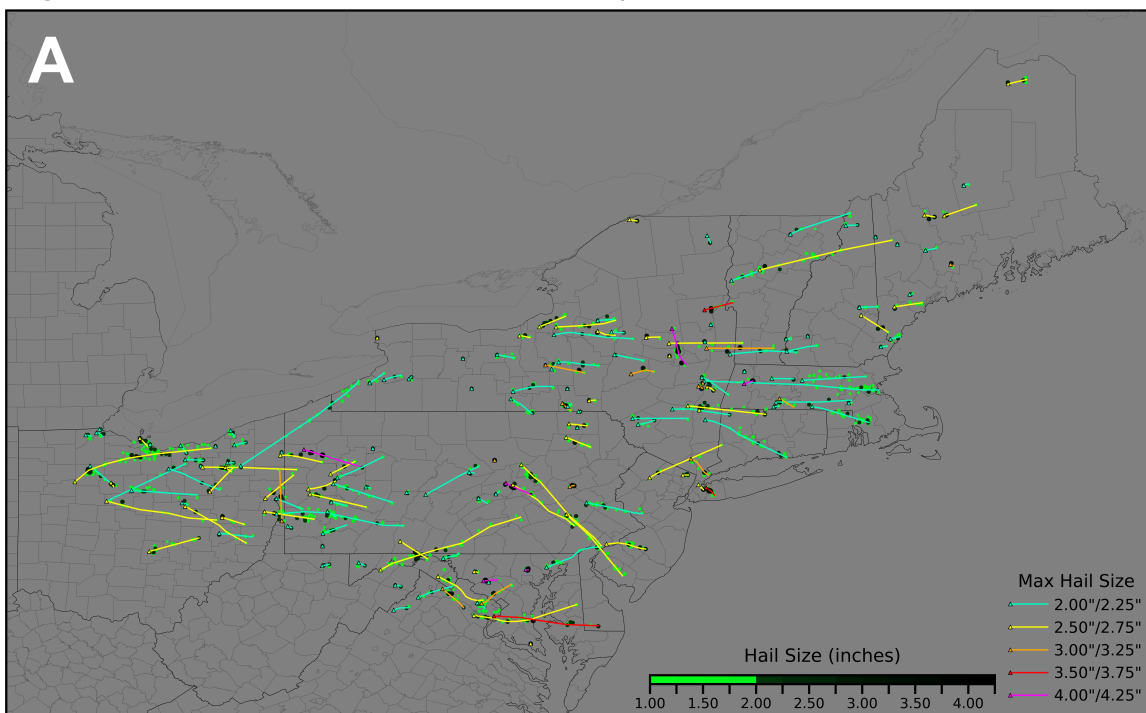
Of all hail reports, 77.7% occurred in the Cleveland (CLE), Pittsburgh (PBZ), Sterling (LWX), Binghamton (BGM), Albany (ALY), Boston (BOX), and Philadelphia (PHI) WFOs (Fig. 3.3c). This accounts for only seven of the 14 WFOs in the region analyzed. However, BOX and PHI are overrepresented in these bulk statistics owing to a few cases with very large report counts (PHI: Cases 84, 132, and 151 had 62 total reports combined, accounting for 64.6% of the WFO's total reports; BOX: Cases 56, 96, and 97 had 77 total reports combined, accounting for 75.5%). Additionally, these two WFOs had fewer sig hail reports than the other five WFOs. If we exclude BOX and PHI, 64.6% of all sig hail reports occurred within CLE, PBZ, LWX, BGM, and ALY alone.

Hail swath lengths were also calculated (Table 3.2). Similar to how tornado paths are constructed, the hail swaths are generated assuming hail fell at all locations between the first and last hail report. For a vast majority of Cases, this is thought to be representative of the storm because most large gaps in reports are attributable to sparse population density

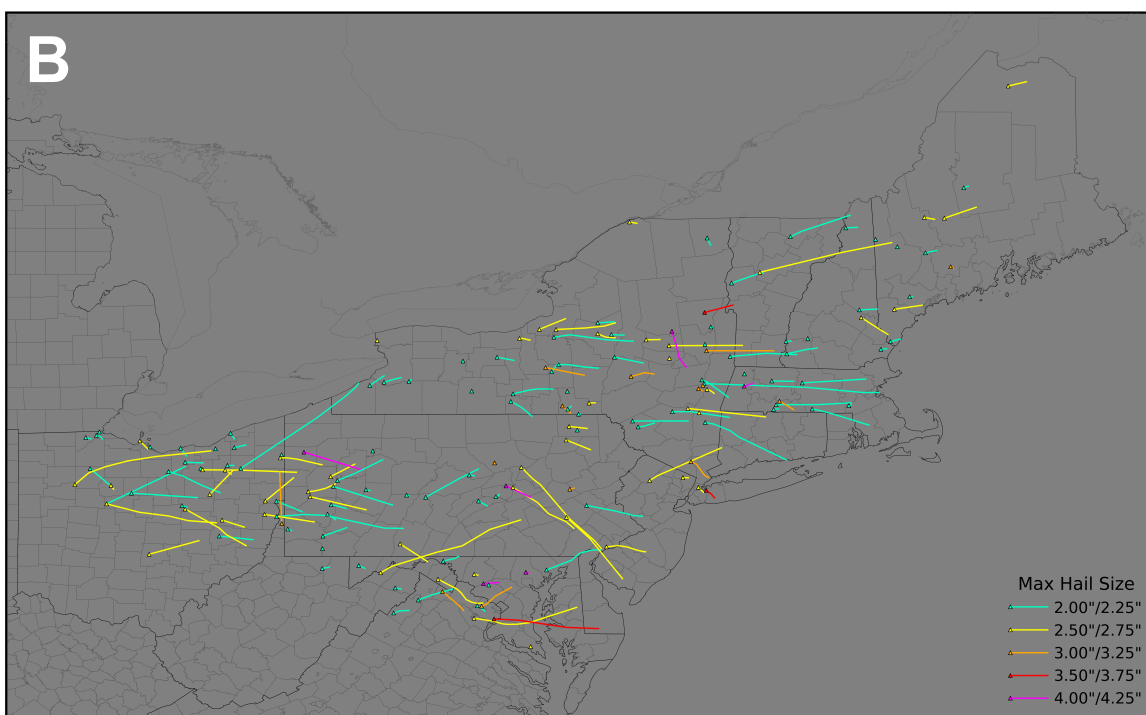
and not weakening of the storm, at least inferred from its radar presentation. However, fluctuations in hail production are known to occur even in mature, long-lived supercells (e.g., Kumjian et al. 2021). The hail swaths are presented in Fig. 3.4, and are color-coded by the largest hail report received for the case. To obtain an accurate swath length and path, the storm motion vector (SMV) was estimated from radar reflectivity animations using the built-in storm motion tool in the GR2Analyst software (Gibson Ridge 2005), and includes any significant deviations in motion during the storm's lifespan. Because hail does not always occur within the center of the hail core, and because many Cases had large or elongated hail cores, simply choosing to use the location of the first and last hail reports for the start and end point of the swath would be an inaccurate visual representation. Instead, preference was given to place the path closer to the center of the hail core to preserve the observed SMVs.

In one example, both the start and end locations of Case 82 had to be adjusted slightly (Fig. 3.4a: the magenta swath in east central NY that is directed towards the south-southeast). The first hail report from this storm was from the eastern edge of the hail core. If the swath start point had been placed here instead of farther west, and the SMV had been preserved, the rest of the swath would have been skewed to the east of the large cluster of reports to the south. At the end of the storm's life, it took a hard left turn. However, the last few hail reports from this storm occurred within its rear flank downdraft region, skewing the hail core location to the west. Thus, the swath had to be placed a little farther east to account for the extreme change in the SMV. For another example, Case 8's swath (Fig. 3.4a: the yellow swath that begins on the border of WV and MD and continues into south-central PA) had to split the difference between reports on the northern and southern edges of its hail core, as seen with the last one-third of its path in PA. For cases where this procedure was necessary, to ensure swath lengths were not arbitrarily increased or decreased, the new location of the start or end point was placed at a 90° angle to the SMV. Figure 3.4b shows a clean version of all swath paths without hail reports plotted.

Sig Hail and Associated Severe Hail Reports with Hail Swaths 2011-2022



Case Hail Swaths 2011-2022



Case Hail Swaths 2011-2022

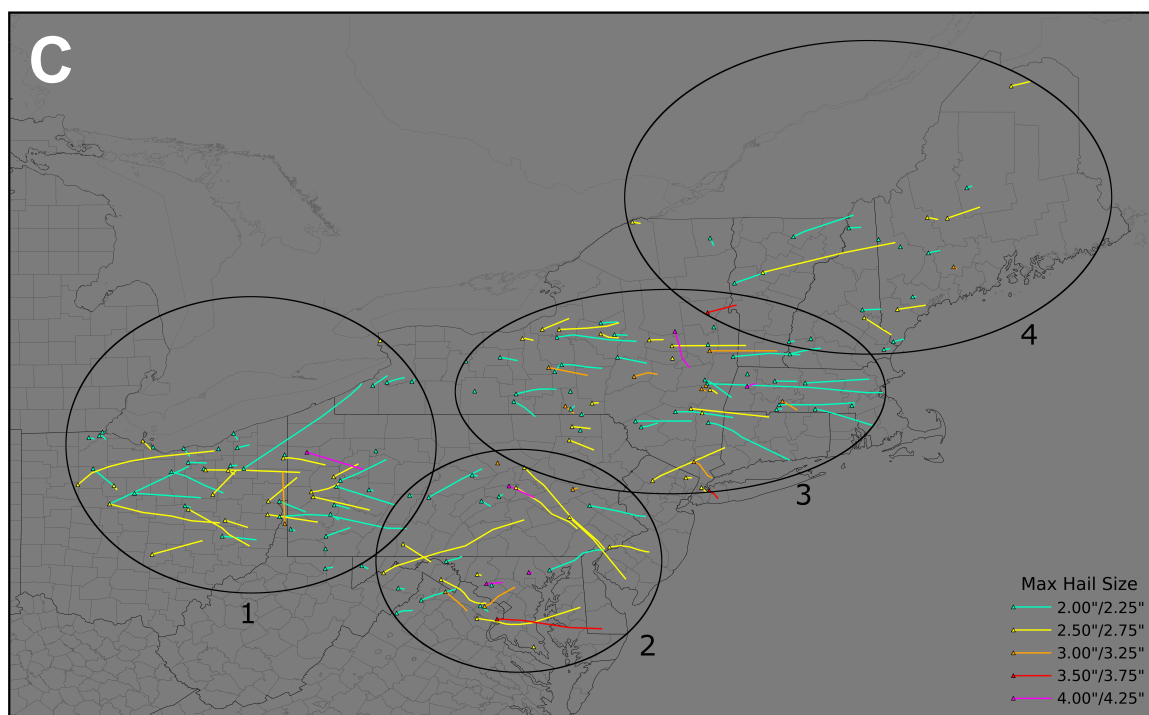


Figure 3.4. Hail swath paths for all 167 cases interpolated from the reports, the SMV, and the location of its hail core. (a) shows both reports and swaths, to illustrate how some of the swaths had to follow a line of best fit rather than the exact location of the reports. (b) shows a clean version without hail reports plotted, and (c) highlights four distinct hail regions.

The average severe hail swath length was 26.7 mi (43.0 km), with a median value of 14.5 mi (23.3 km). Twenty cases (12.0%) had only a single hail report, and thus their swath lengths were considered to be zero, as setting them to any small number greater than zero would be arbitrary. Case 96 had the longest hail swath, beginning about 12 mi (19.3 km) south of Albany, NY, and ending with a marine hail report from Boston Harbor, MA, resulting in a swath 144.1 mi (231.9 km) in length (Table 3.2). Cases 121 and 8 followed closely behind, with swath lengths of 135.0 mi (217.2 km) and 134.4 mi (216.3 km) across NE OH, NW PA, and southwestern NY (Case 121), and eastern WV, western MD, and south-central PA (Case 8). Seven cases (4.2%) had swaths at least 100 mi (161 km) long, and 32 cases (19.2%) had swaths of at least 50 mi (80 km) in length, suggesting that longer hail swaths are not uncommon.

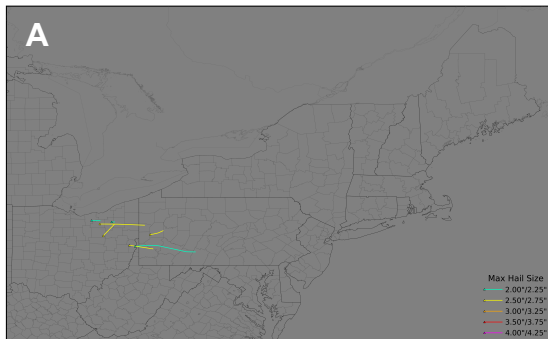
Unsurprisingly, the spatial distribution of hail swaths is similar to that of the hail reports, but additional patterns emerge. For example, the swaths appear to cluster into four distinct regions: (Fig. 3.4c):

1. OH, western PA, and extreme southwest NY
2. Central/eastern PA, eastern WV, MD, VA, DE, and southern/central NJ
3. Central/eastern NY, northern NJ, and southern New England
4. Northern New England

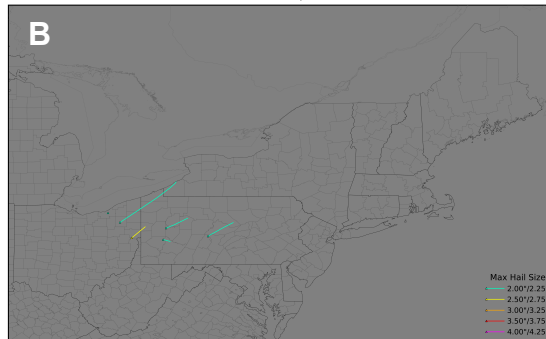
Few sig severe hailstorms traversed between any of these four regions; notably, none crossed the Appalachian spine located just west of central PA. Although short-track (< 10 mi or 16.1 km) and long-track (> 50.0 mi or 80.5 km) cases occurred in every region, Regions 1 and 2 had a higher proportion of longer-track cases, while Regions 3 and 4 had a higher proportion of shorter-track cases. The highest density of shorter-track cases appeared to be along the Hudson Valley of NY and westward into central NY, as well as along the southern shore of Lake Erie. The former pattern is likely due to the sporadic population in central NY, including a lack of population centers just east of the north-to-south sprawling Hudson Valley. The latter pattern is more interesting: northern OH is densely populated compared to the entire region analyzed, so other factors may be at play. For example, we speculate that the locally increased low-level shear and moisture convergence provided by lake breezes (e.g., King et al. 2003) provided environments that were capable of sustaining supercells only briefly. Once the storms moved off the favorable boundary, environments were no longer supportive. Such sea/lake breeze circulations are known to contribute to hail “hot spots” in other parts of the world, like eastern Australia (e.g., Soderholm et al. 2016). In particular, Cases 34, 109, 111, 112, 148, and 152 all appear to be directly influenced by lake-related boundaries, evident on radar scans of Z_H and v_r . Similarly, Case 56 initiated along a west-northwest to east-southeast oriented sea breeze in southeast MA and northern RI, anchoring its inflow notch along the boundary as it strengthened and produced a large area of sig hail reports (see the 0.5° elevation angle Z_H scan from Case 56 featured in Appendix A). Despite the possible lake’s influence on the hailstorms, however, all four regions had at least one case that tracked > 100 mi (161 km), suggesting that conditions in all four regions can be supportive of long-lived, significantly severe hail-producing storms.

To understand any seasonal or annual variability in hail swath spatial distributions, case swaths were also grouped by month and by year. The distributions of swaths by month (Fig. 3.5a-i) show pronounced spatial patterns. March Cases occur only within OH and western PA. In April, Cases occur farther north and east into central PA and southwest NY. By May and June, Cases are spread across the entire Northeast region. July is much the same, although it has a decrease in the number of Cases and a preference for long-track Cases to be farther north and east in regions 3 and 4, and for fewer, more short-track Cases in regions 1 and 2. This pattern continues into August as Case counts again decrease. September exhibits a wide range of Case locations, but only one is long-track. October only has two Cases, one of which is surprisingly far north on the US/Canadian border in northern NY (Case 136). November only has one Case (Case 167), but its location in southwest portions of the study region is much like the early season months of March and April. Figures 3.5j-u separate Cases by year, explored more in the next sub-section.

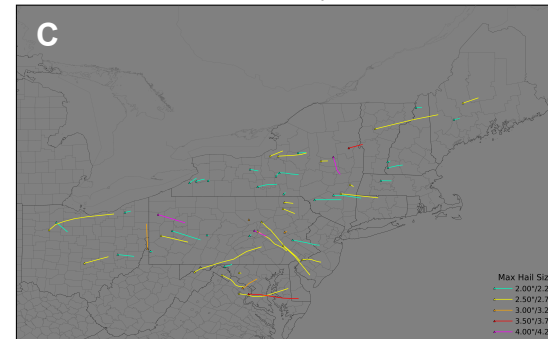
Case Hail Swaths March 2011-2022



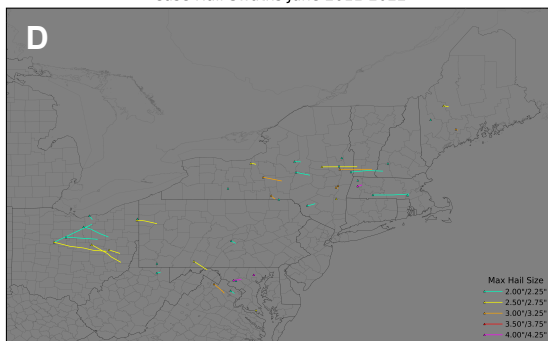
Case Hail Swaths April 2011-2022



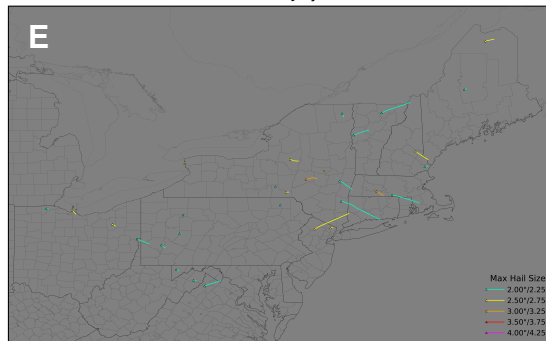
Case Hail Swaths May 2011-2022



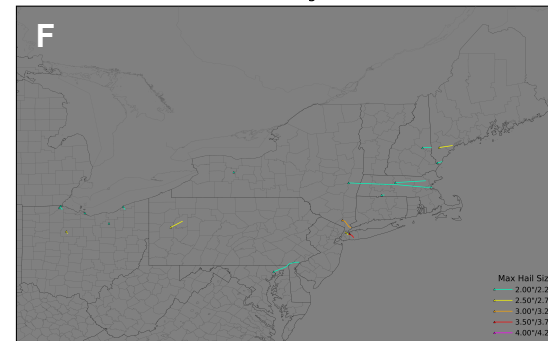
Case Hail Swaths June 2011-2022



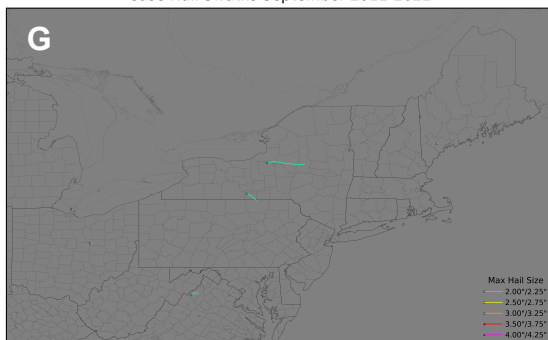
Case Hail Swaths July 2011-2022



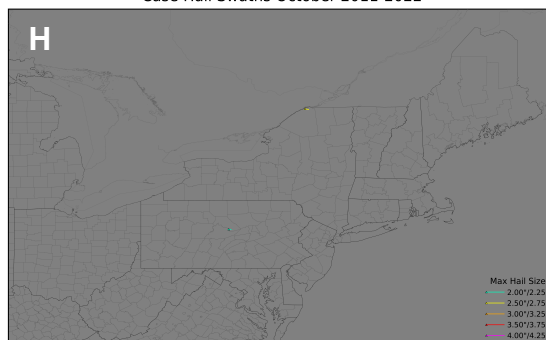
Case Hail Swaths August 2011-2022



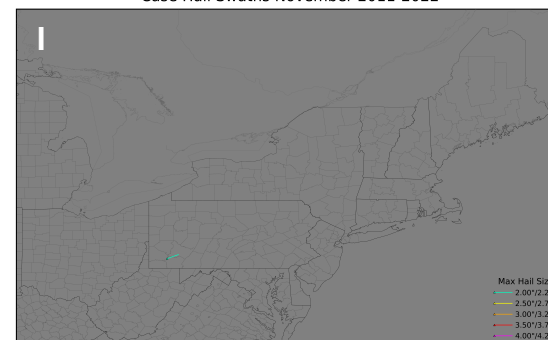
Case Hail Swaths September 2011-2022



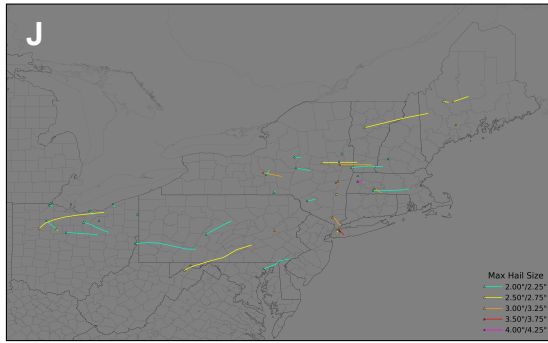
Case Hail Swaths October 2011-2022



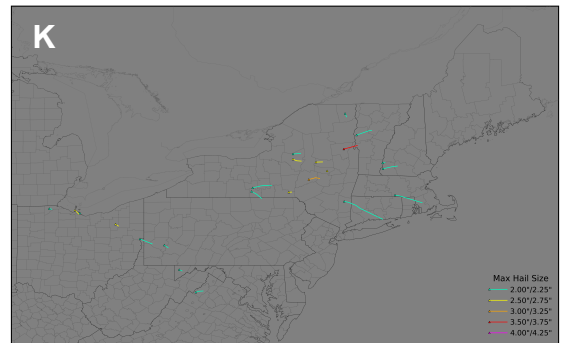
Case Hail Swaths November 2011-2022



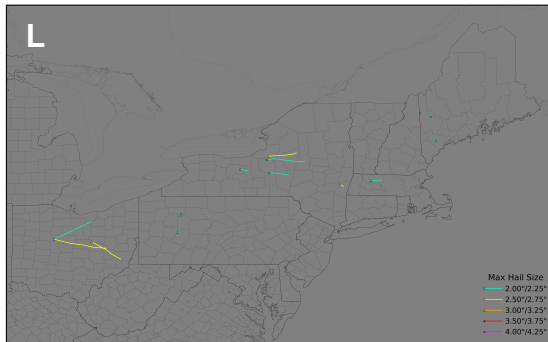
Case Hail Swaths 2011



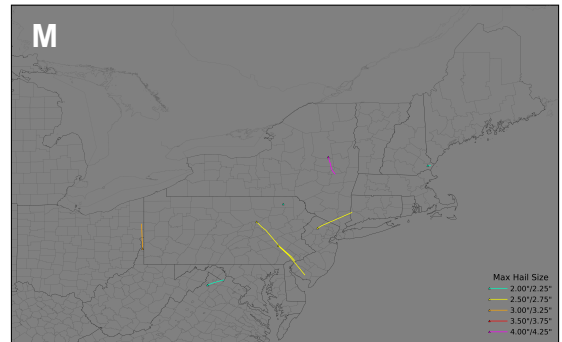
Case Hail Swaths 2012



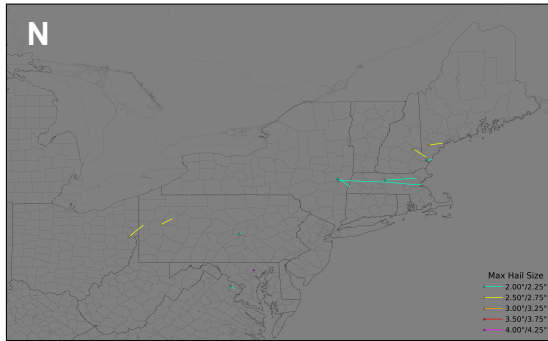
Case Hail Swaths 2013



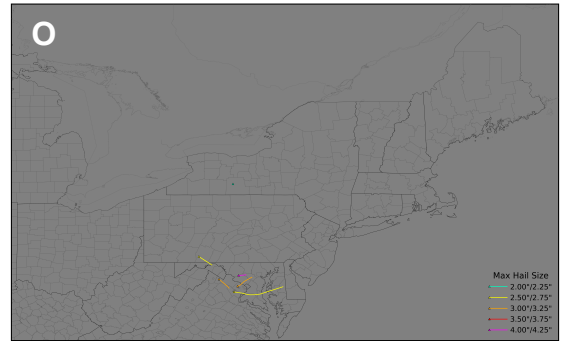
Case Hail Swaths 2014



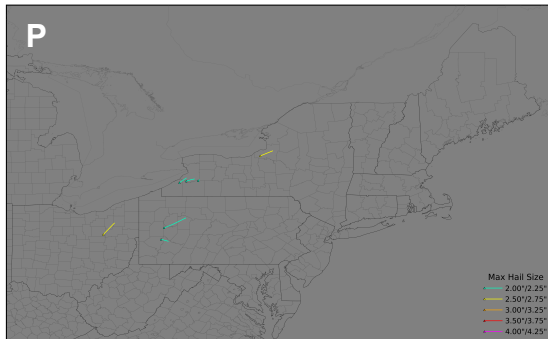
Case Hail Swaths 2015



Case Hail Swaths 2016



Case Hail Swaths 2017



Case Hail Swaths 2018

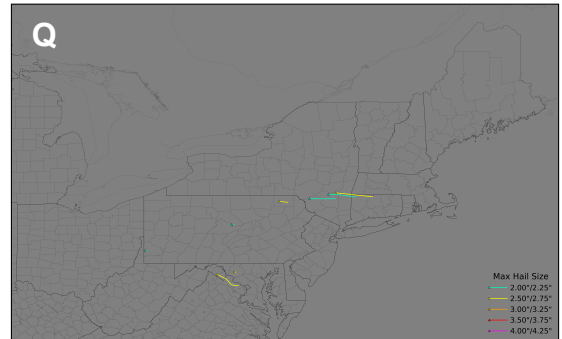


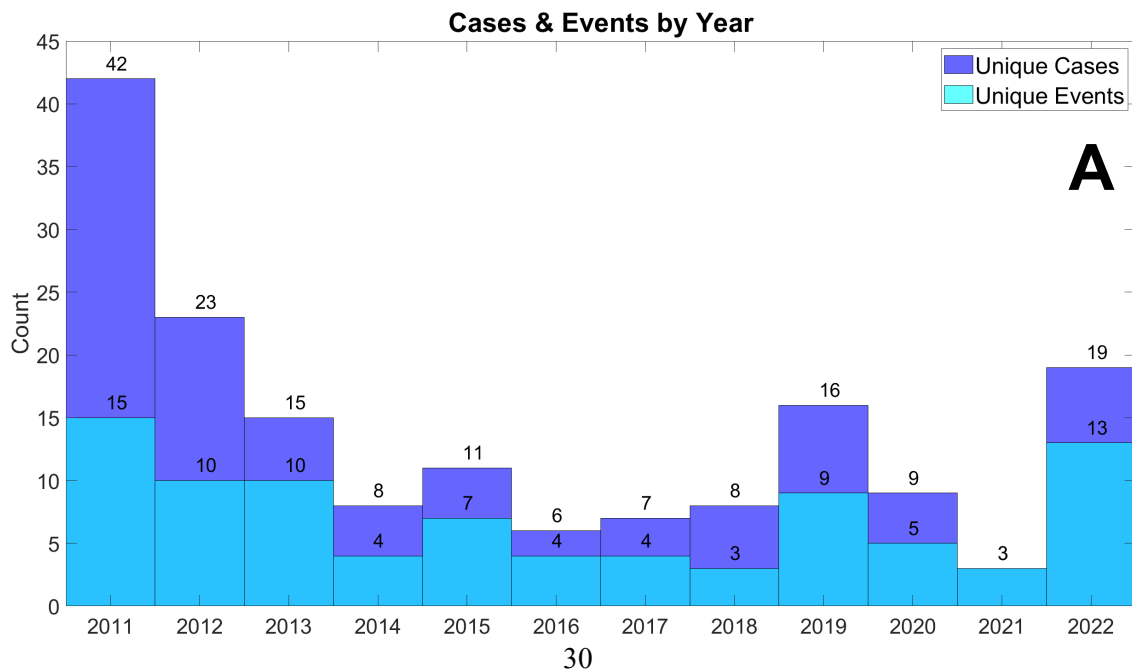


Figure 3.5. Panels of Case swath paths organized by (a) through (i) month and (j) through (u) year.

3.2 Temporal Distribution

The average year produced 26.9 sig hail, 83.3 associated severe hail, and 110.3 total hail reports, distributed amongst 13.9 Cases and 7.3 Events. However, the interannual variability was quite large. For example, the year 2011 was particularly active, both in the traditional severe weather alleys of the U.S. (Simmons and Sutter 2012) as well as in the Northeast. This year saw 42 Cases across 15 Events (Fig. 3.6a), which accounted for 29.1% of sig hail, 26.9% of associated severe hail, 27.4% of total hail reports, as well as 25.1% of Cases in the 12-year period (Table 3.1). It also, on average, produced longer swaths than any other year (Fig. 3.5j-u). Conversely, 2022 produced only three Cases, two of which were single-report Cases, which accounted for 1.5% of sig hail, 0.6% of associated severe hail, 0.8% of total hail reports, and was the only year to have no multi-Case Events.

A predictable pattern occurred when organizing this data by month (Fig. 3.6b). The early season months of March and April, and the late season months of September, October, and November are dominated almost exclusively by single-Case Events. For example, 20 April 2017 and 28 March 2020 are the only two early- or late-season Events with >1 Case, having two and five, respectively. This pattern can most likely be attributed to the lack of widespread conducive conditions for sig hail-producing convection during early and late season months, as will be discussed in Chapter 5.



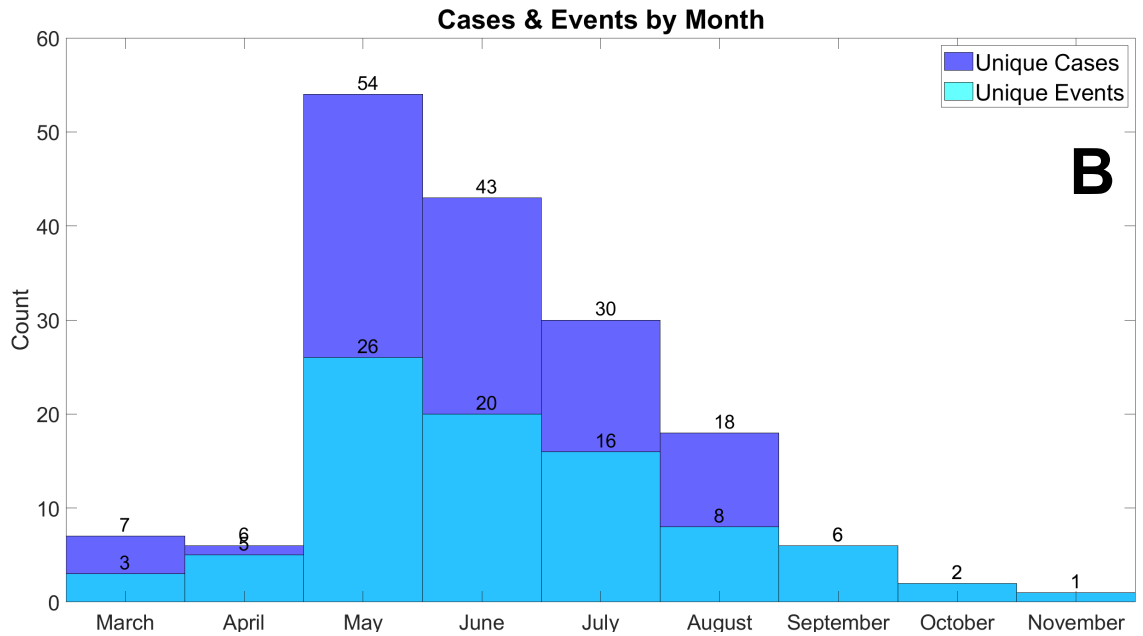


Figure 3.6. Histogram of all cases (167) and events (87) of sig hail occurring between 2011 and 2022 in the Northeast United States, with respect to (a) year and (b) month.

Figure 3.7 shows the distribution of severe and sig hail Case durations. The average severe-hail duration (green dots) was 56.0 min (Table 3.2), with a median of 38.0 min. This means that typical Northeastern sig-severe hailstorms are capable of producing sustained damaging hail (i.e., are not simply transient or “flukes”). Given the low average report count (7.9), the high average case duration can be attributed to 37 cases (22.2%) having at least one gap of 30 min or more between two consecutive hail reports. There were 23 cases (13.8%) that had a 45-min or longer gap, 13 cases (7.8%) that had a 60-min or longer gap, and seven Cases (4.2%) that had a 75-min or longer gap, with Case 100 having the longest gap (109 min) as it slowly trekked across the Chesapeake Bay⁵. This illustrates that even when there is a long gap between reports, it should not necessarily be concluded that the storm had weakened below severe limits. Though 41 Cases (24.6%) had a duration of ≤ 15 min, 35 Cases (21.0%) had a duration > 90 min, 21 Cases (12.6%) > 2 hrs, seven Cases (4.2%) > 3 hrs, and two Cases > 4 hrs. Four Cases were within eight minutes of reaching the 3-hr threshold, and two Cases were within five minutes of the 4-hr threshold. Case 100 had

⁵ Case 100 was only one of two cases to do so, the other being Case 150, which had just a 35-minute gap between reports.

the longest duration (4 hr 14 min), followed closely by Case 72 (4 hr 6 min), Case 8 (3 hr 57 min), and Case 96 (3 hr 55 min).

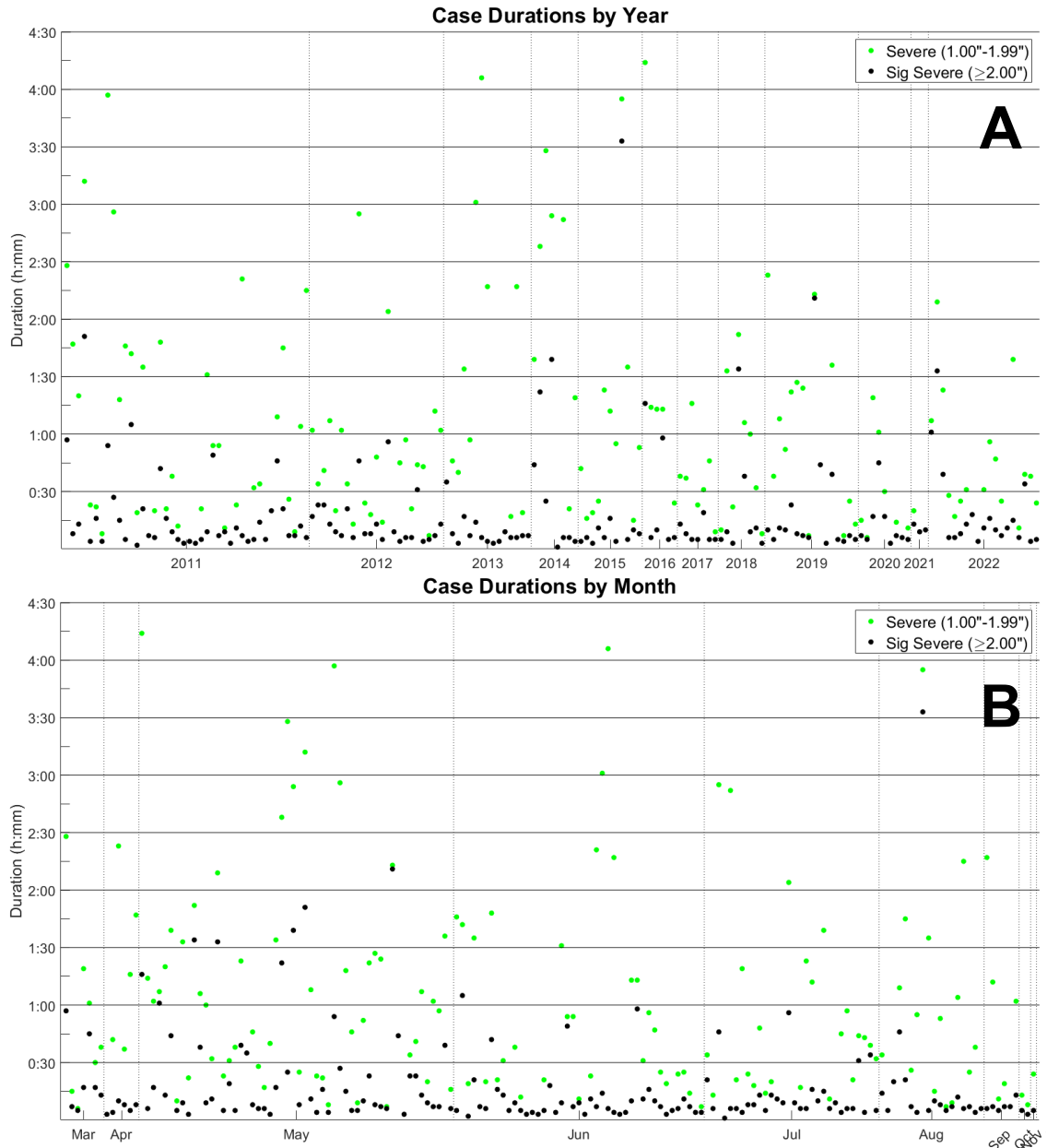


Figure 3.7. Scatter plot of the duration of hail in minutes for each of the 167 sig hail producing cases. The green dots denote severe hail while the black dots denote sig hail. (a) is organized by year, and (b) is in chronological order by date.

In contrast to these sustained periods of severe hail production, sig hail durations were much shorter, averaging only 17.9 min (Fig. 3.7, black dots). This comparatively short duration is consistent with the average Case sig hail count (1.9 reports) because a vast

majority of Cases with ≥ 2 sig hail reports had them occur in close spatial proximity (and thus close in time). The median sig hail duration (8.0 min) may more closely represent the typical Case, which commonly recorded either two closely spaced sig hail reports or one report with a duration of 5-10 min. A majority of Cases (121, 72.5%) had a sig hail duration of ≤ 15 min (large cluster of black points at the bottom of Fig. 3.7). However, Cases with longer durations of sig hail did occur: 27 (16.2%) had a sig hail duration >30 min, 17 (10.2%) >45 min, 10 (6.0 %) >60 minutes, six (3.6 %) >90 min, and two (1.2 %) >120 min. The longest sig hail duration is an extreme outlier with a duration of 3 hr 33 min (Case 96); however, this statistic is heavily skewed by the storm's longevity. The first sig hail report concluded at 1640 UTC south of Albany, NY, and over three hours went by until the next sig hail report occurred west of Boston, MA, at 1955 UTC. Further, only three sig hail reports occurred with this case in total. It is unclear whether the case weakened below sig hail strength for a majority of this gap. However, radar imagery from 0.5° elevation angle scans reveal large Z_H with co-located low Z_{DR} in the supercell while it was impacting central MA between roughly 1830 to 1930 UTC, implying at least severe hail was being produced for this entire time. Although there were four severe hail reports during that period, a majority of the hail core was located over sparsely populated regions. Thus, it is plausible that sig hail was occurring and not observed or reported. Of the ten cases with sig hail durations >60 min, 90% had gaps in sig hail reports lasting >30 min. Even the second-longest sig hail duration (Case 129) had a 115-min gap between its only two sig reports, one that occurred near the start and one near the end of its swath (however, there was a 1.75 in or 44.4 mm report close to the midpoint of its swath). Unlike with the severe hail durations, for which many of the storms appeared to maintain their strength between such large gaps in reports, it is much more ambiguous whether the same is true for the gaps in sig hail reports. This ambiguity arises because S-band dual-polarization and Doppler radar variables alone are not enough to identify hail sizes above roughly 0.8-1.2 in (20-30 mm, i.e., near the severe hail threshold) owing in part to backscattering for which the Rayleigh approximation is not valid (Kumjian 2013c; Kumjian et al. 2024).

3.3 Diurnal and Seasonal Patterns

Figure 3.7b presents Case duration by the date on which they occurred. Although one could argue there is a small correlation between decreased severe hail durations in late-season (i.e., starting in September) Cases, there is a small sample size of such late-season Cases. Additionally, early-season Cases do not seem to follow this pattern of decreased severe hail durations. The earliest case occurred on 23 March (Case 1) and had a duration of 2 hr 28 min, making it the 13th longest-lasting case. Another case from April (Case 121) was the 14th longest-lasting case, and six out of the 13 early-season cases had a severe duration >1 hr. Though there is no evident seasonal pattern in severe hail durations, sig hail durations do show a trend: Sig hail durations increase starting with early-season Cases, peak in May, and taper off directly after May through the rest of the season. Though there are only 11 fewer Cases in June than in May, June only had four Cases with a >30-min sig hail duration, whereas May had 15. Of the ten Cases to have a duration >1 hr, eight occurred in May and one of the two others occurred on 1 June (Case 12; the other was the extreme outlier Case 96 from 4 August). July also had four cases with a duration >30 min, and August only had two. After 4 August, the rest of the season saw no Cases surpassing even a 15-minute duration of sig hail. Unlike early season storms, this implies that late-season storms only have a small window in which they are capable of producing sig hail.

Figure 3.8a depicts the full duration of severe hail (green lines) and sig hail (overlaid black lines) reports for every Case, with respect to the time of day in Eastern Time (ET). Except for five early morning outliers that occurred between 5:50 and 10:28 am ET (four of which occurred in 2011), every Case had its first hail report occur no earlier than 11:58 am. Only nine Cases (5.4%) had a start time after 8:30 pm ET (i.e., roughly sunset during the summer months), two of which occurred after midnight (Case 23 and 104). Between 12 pm and 9 pm ET, it appeared equally likely to have a short-duration (≤ 15 min) or long-duration (≥ 75 min) Case. After 9 pm ET, only five out of 15 cases were long duration⁶. Interestingly, the five early morning cases were of a moderate duration, between 34 and 91

⁶ Three of these five Cases occurred during the same Event on 12 June 2013.

minutes, and all occurred in OH (Case 62 crossed into PA, but only produced sig hail in OH). Only 14 cases (8.4%) had an end time after 9 pm ET. These data suggest that, although sig hail can be produced at nearly any time of day in the Northeast U.S., there is a clear preference for diurnal storms.

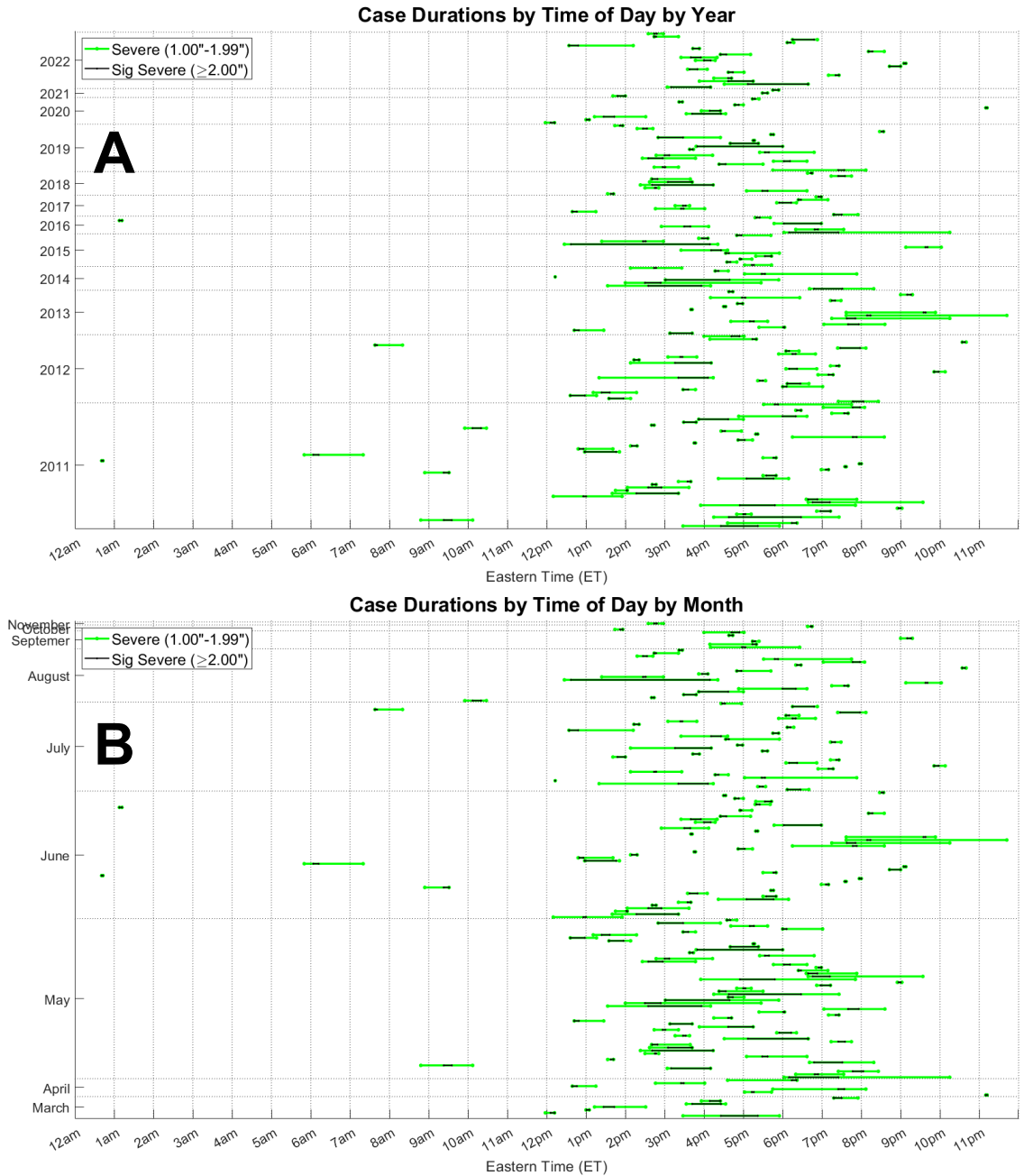


Figure 3.8. Line plot depicting the start and end time in Eastern Time for each of the 167 sig hail producing cases. The green line denotes severe hail duration while the black line denotes sig hail duration. Figure 3.8a is organized by the year in which each case occurred, while 3.8b is organized by the date each case occurred.

Figure 3.8b presents the same hail-duration and time of day data, but plotted chronologically by date. Surprisingly, very little pattern exists between the date and time of day in which the Case occurred. The early- and late-season months all had Cases occur within roughly the same timespans as the peak-season months. Case 137 from March 2020 had the sixth-earliest start time of any Case and the earliest start time excluding the five “early morning outliers.” April 2020 had Case 142 with a start time after 11 pm ET, the third-latest start time of any case. Case 79 from September 2013 occurred after 9 pm ET in southern Maine. Although March only had one Case with a start time after 6 pm ET and September saw no cases start before 4 pm ET, these observations could be due to small sample sizes. In contrast, the Cases that occurred outside of diurnal heating tended to occur during the peak season: All but one Case that had a start time before 11 am ET or an end time after 10 pm ET (14 total) occurred between May and August.

Figure 3.9a is a histogram showing the count of all sig-severe (black) and associated severe hail (green) occurrence as a function of time of day in ET, binned into 1-min intervals. The peak frequency of severe hail was from 4:55 pm to 4:57 pm ET, during which there were 27 concurrent Cases. The peak frequency of sig hail occurred at 3:40 pm and 3:42 pm ET with 15 Cases, which aligns closely with the secondary peak of severe hail frequency (26 Cases from 3:35 pm to 3:38 pm ET). A broader peak in severe hail frequency occurred between 2:35 pm and 7:54 pm ET, where 77.8% of Cases had at least a 1-min duration, and where at least 14 Cases were happening concurrently during any time in this period (Fig. 3.9b; yellow). Within the same time range, 75.4% of Cases had at least a 1-min duration of sig hail. Expanding the filter to only include ≥ 5 concurrent Cases producing severe hail gives a range between 12:39 pm and 10:02 pm ET, which now includes at least a 1-min duration of severe hail from 93.4% of Cases (93.4% for sig hail; shown in blue). However, from 8:36 pm through 9:53 pm ET, there were only three concurrent Cases and they were from the same event (Case 71, 72, and 73 from 12 June 2013), which may have skewed this end time later by as much as 45 min. Three or more concurrent Cases produced sig hail between 12:37 pm and 7:58 pm ET, which includes at least a 1-min duration of sig hail from 86.2% of Cases (88.6% for severe hail, though there were a few gaps with less than three concurrent cases between 12:37 pm and 2:27 pm ET; shown in red). Any of

these time periods (which are annotated in Fig. 3.9b) could be considered the most active period for sig hail producing convection in the Northeast, but the latter most of the groups seems like the best definition, as most Cases that lie outside this time range appear to be statistical outliers.

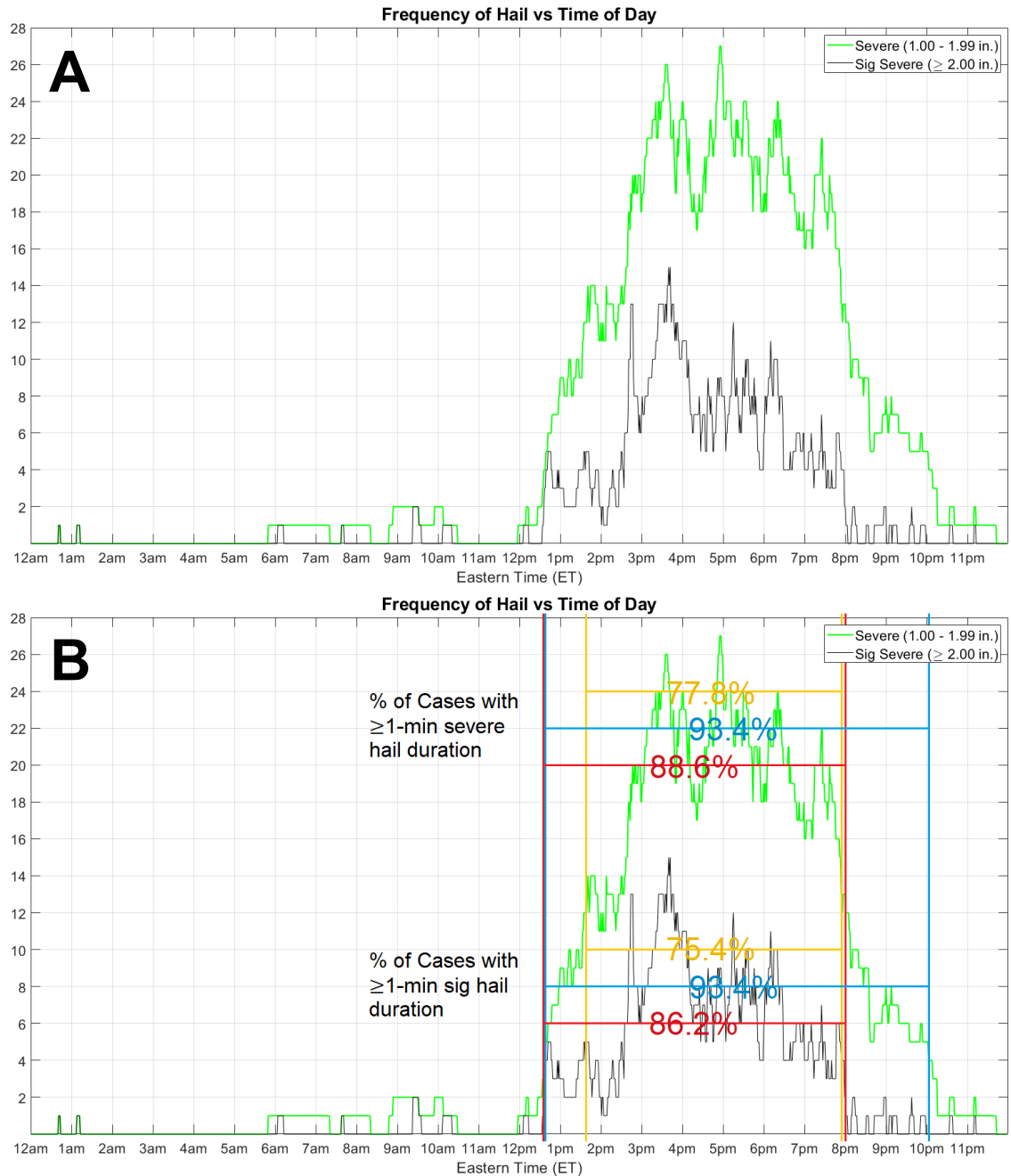


Figure 3.9. Histogram with 1-minute bins of the time of day when severe and sig hail occurred for each of the 167 sig hail producing cases. The green line denotes severe hail while the black line denotes sig hail. (b) Annotations denote three time periods where hail is “most common.”

Cases were then plotted by the day and month in which they occurred (Fig. 3.10a). The earliest Case occurred on 23 March 2011 and the latest Case occurred on 27 November 2022, which, coincidentally, are the first and last cases in this study (Case 1 and 167, respectively). Case 1 occurred only five days before the next observed Case in the period of study, while Case 167 occurred a staggering 56 days after the next-latest case on 2 October 2018 (Case 120). Points that are vertically stacked on the plot denote dates that had more than one case, highlighting multi-Case Events. The Events that produced the most Cases were 1 June 2011 and 28 May 2019, each with eight Cases (Fig. 3.10a). The 9 June 2011 and 1 August 2011 Events both had the second most, with six each. Ten out of 87 Events (11.5%) produced at least five Cases, which accounted for 34.7% of total Cases; 2011 produced five of these ten events. Eighteen out of 87 Events (20.7%) produced at least three Cases, which accounted for 50.1% of total Cases, whereas 56 Events (64.4%) only had a single Case (which accounted for 33.5% of total Cases). The earliest multi-Case Event was 28 March 2020 and the latest was 18 August 2011. Excluding the extreme outlier of 28 March 2020, the other nine events with ≥ 5 Cases occurred between 15 May and 1 August. During this same time period, 74.9% of total Cases were observed. According to Fig. 3.10b, this date range appears to be representative of the “main season” for sig hail producing convection. Expanding this range to 2 May through 18 August includes 85.0% of Cases and nearly every multi-Case Event, except 20 April 2017 and 28 March 2020. Nearly all Events before 2 May and after 18 August were single-Case Events, and are spread out much farther in date.

Overall, sig-severe hail producing storms in the Northeast were more prevalent than expected, with 167 Cases in a twelve-year period. Report dependence on population density suggests it is likely that a handful of Cases were not observed. Though 56.3% of Cases barely reached the 2 in (51mm) sig-severe threshold, large median duration and path lengths prove Cases were almost exclusively produced by strong, organized convection. Even so, a vast majority of Cases only resulted in 1-2 short duration sig reports. Additionally, an average of only 1.92 Cases per Event highlights the semi-isolated nature of conducive environments for Northeast sig hail. Case frequency varied both diurnally and seasonally, though interestingly not diurnally *with respect to* season. Spatial

distribution also followed a seasonal pattern. The likely best representation of the “Northeastern U.S. sig hail season” can be defined between 2 May through 18 August, occurring from 12:37 pm to 7:58 pm ET.

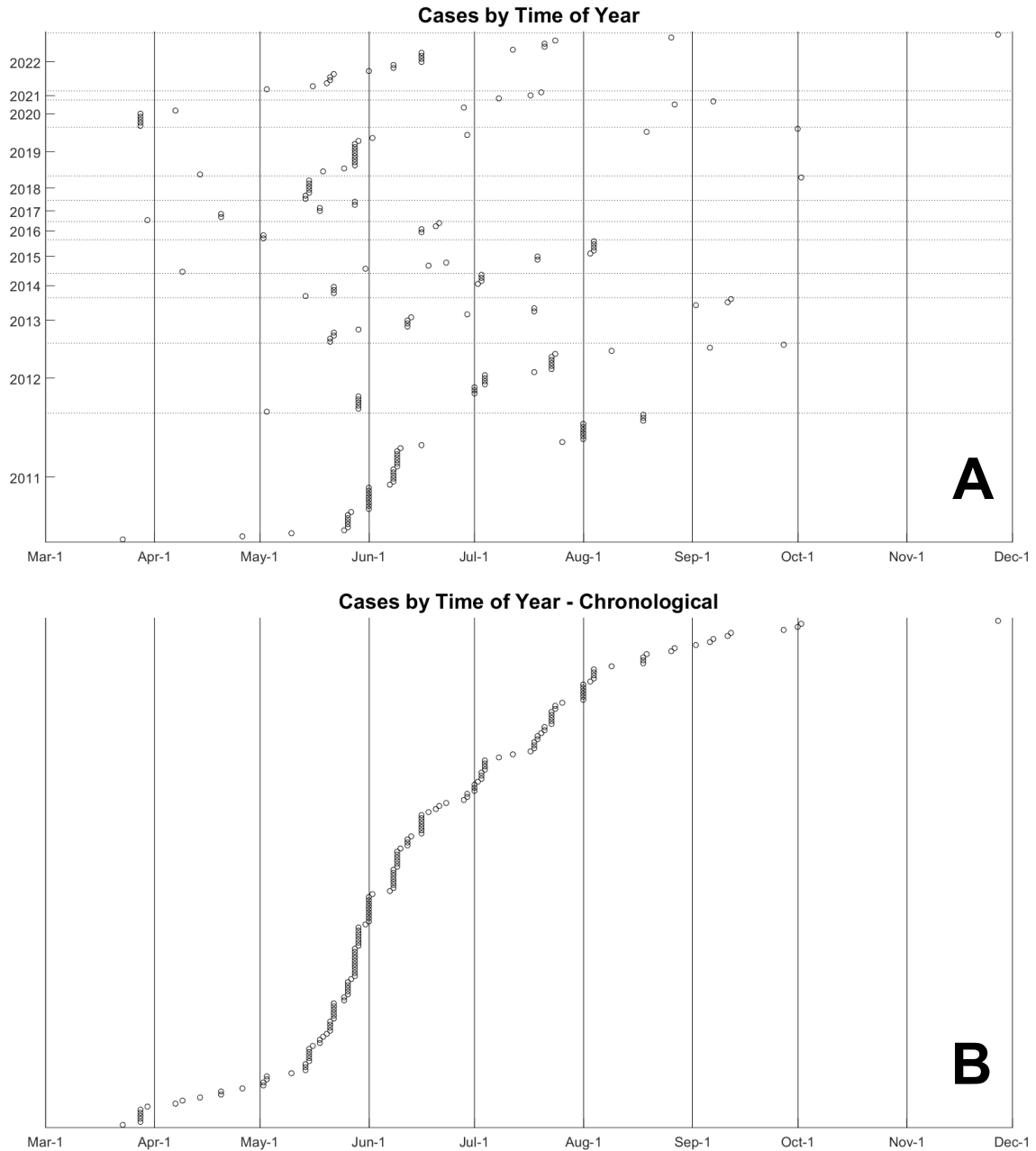


Figure 3.10. Scatter plot depicting the time of year each of the 167 sig hail producing cases occurred. (a) chronological order by year, and (b) chronological order by date.

Table 3.2. Basic statistical information for each of 167 sig hail producing cases. Listed from left to right are the Case ID, year, month, day, start and end time of severe hail (UTC), duration of severe hail (minutes), start and end time of sig hail (UTC), duration of sig hail (minutes), the distance from the first to last severe report (in statute miles and kilometers), number of total (severe plus sig) and sig hail reports, list of states and WFOs that at least one severe or sig hail report occurred within, and the largest reported hail size.

Case ID	Year	Month	Day	Severe Duration (UTC)			Sig Duration (UTC)			Swath Length		Report Count		Report Locations		Max Size (inches)
				Start	End	Time	Start	End	Time	sm	km	Total	Sig	States	WFOs	
1	2011	March	23	1928	2155	148	2026	2122	57	109.52	176.26	29	3	OH,PA	PBZ,CTP	2.00
2	2011	April	26	2036	2222	107	2214	2221	8	54.32	87.43	7	1	PA	CTP	2.00
3	2011	May	10	1248	1407	80	1323	1335	13	28.83	46.40	9	1	OH	CLE	2.00
4	2011	May	25	2015	2326	192	2038	2228	111	122.76	197.56	61	21	OH	IWX,CLE	2.75
5	2011	May	26	2050	2112	23	2055	2058	4	10.85	17.45	4	1	NY	BGM	2.00
6	2011	May	26	2252	2313	22	2258	2313	16	3.75	6.04	4	3	PA	CTP,PHI	3.00
7	2011	May	26	0055	0102	8	0057	0100	4	4.28	6.89	5	1	NY	BGM	2.00
8	2011	May	26	1955	2351	237	2055	2148	54	134.42	216.33	50	12	WV,MD,PA	LWX,CTP	2.75
9	2011	May	26	2239	0134	176	2246	2312	27	109.22	175.77	23	2	VT,NH,ME	BTV,GYX	2.75
10	2011	May	27	2236	2353	78	2239	2253	15	27.39	44.08	5	1	ME	GYX,CAR	2.50
11	2011	June	1	1610	1755	106	1656	1700	5	59.63	95.96	5	1	NY,VT	ALY	2.75
12	2011	June	1	1740	1921	102	1817	1921	65	54.37	87.50	9	3	NY,VT,NH	ALY,GYX	2.00
13	2011	June	1	1745	1803	19	1802	1803	2	14.10	22.68	6	1	NY	BGM	2.00
14	2011	June	1	1803	1937	95	1835	1855	21	54.56	87.80	10	2	NY,VT	ALY	3.25
15	2011	June	1	1841	1847	7	1841	1847	7	---	---	1	1	MA	ALY	2.00
16	2011	June	1	1921	1940	20	1935	1940	6	7.57	12.18	2	1	MA	ALY	4.00
17	2011	June	1	2022	2209	108	2105	2146	42	62.06	99.87	6	2	MA	BOX	2.00
18	2011	June	1	2130	2150	21	2135	2150	16	8.24	13.26	3	2	ME	GYX	2.75
19	2011	June	7	1254	1331	38	1323	1331	9	9.71	15.63	7	1	OH	CLE	2.00
20	2011	June	8	2259	2310	12	2306	2310	5	3.85	6.20	2	1	NY	ALY	3.00
21	2011	June	8	2335	2337	3	2335	2337	3	---	---	1	1	NY	ALY	2.00
22	2011	June	8	2357	0000	4	2357	0000	4	---	---	1	1	NY	ALY	3.00
23	2011	June	8	0441	0443	3	0441	0443	3	---	---	1	1	NY	ALY	2.75
24	2011	June	8	2130	2150	21	2146	2150	5	10.09	16.24	5	1	NY	BGM,ALY	2.00
25	2011	June	9	0950	1120	91	1004	1012	9	55.69	89.62	10	2	OH	CLE	2.00
26	2011	June	9	1658	1751	54	1658	1746	49	32.57	52.42	7	3	NY	BGM	3.00
27	2011	June	9	1648	1741	54	1650	1656	7	24.12	38.81	7	2	NY	BGM,ALY	2.00
28	2011	June	9	1808	1818	11	1810	1818	9	1.23	1.98	2	1	NY	ALY	2.00
29	2011	June	9	1945	1947	3	1945	1947	3	---	---	1	1	NH	GYX	2.00
30	2011	June	9	2052	2114	23	2052	2102	11	2.88	4.63	2	1	ME	GYX	3.00
31	2011	June	10	2215	0035	141	2347	2353	7	49.15	79.10	3	1	OH	CLE	2.00
32	2011	June	16	2119	2122	4	2119	2122	4	---	---	1	1	OH	CLE	2.00

Case ID	Year	Month	Day	Severe Duration (UTC)			Sig Duration (UTC)			Swath Length		Report Count		Report Locations		Max Size (inches)
				Start	End	Time	Start	End	Time	sm	km	Total	Sig	States	WFOs	
33	2011	July	26	2026	2057	32	2028	2032	5	14.89	23.97	10	1	MA	BOX	3.00
34	2011	August	1	1355	1428	34	1407	1420	14	6.97	11.22	11	1	OH	CLE	2.00
35	2011	August	1	1840	1844	5	1840	1844	5	---	---	1	1	OH	CLE	2.00
36	2011	August	1	1929	1948	20	1929	1948	20	4.82	7.75	5	2	OH	CLE	2.75
37	2011	August	1	1952	2100	69	1952	2037	46	11.09	17.84	14	6	NY	OKX	3.50
38	2011	August	1	2053	2237	105	2200	2220	21	23.59	37.96	9	1	NY	OKX	3.00
39	2011	August	1	2315	2340	26	2334	2340	7	6.93	11.16	2	1	NY	OKX	2.75
40	2011	August	18	2220	2228	9	2222	2228	7	1.03	1.66	3	1	OH	CLE	2.00
41	2011	August	18	2302	0005	64	2347	2358	12	6.76	10.88	7	2	OH	CLE	2.00
42	2011	August	18	2131	2345	135	2148	2153	6	52.71	84.83	12	1	MD,PA,DE	LWX,PHI	2.25
43	2012	May	3	2325	0026	62	2347	0003	17	33.57	54.03	10	2	NY	BGM	2.00
44	2012	May	29	1735	1808	34	1735	1757	23	13.09	21.06	6	2	NY	BGM	2.00
45	2012	May	29	1636	1716	41	1636	1658	23	11.15	17.95	3	1	NY	ALY	2.75
46	2012	May	29	1711	1817	67	1724	1736	13	24.14	38.85	7	2	NY,VT	ALY,BTV	3.50
47	2012	May	29	1928	1947	20	1928	1936	9	4.10	6.60	5	1	NY,VT	ALY,GYX	2.00
48	2012	May	29	2200	2301	62	2200	2206	7	25.46	40.97	2	1	NH	GYX	2.00
49	2012	July	1	2207	2240	34	2207	2227	21	11.22	18.06	14	6	OH	CLE	2.50
50	2012	July	1	2122	2134	13	2125	2130	6	4.44	7.15	6	1	OH	CLE	2.00
51	2012	July	1	1720	2014	175	1921	2006	46	79.17	127.42	18	3	NY,CT	ALY,OKX	2.00
52	2012	July	4	2254	2317	24	2310	2317	8	7.74	12.46	3	1	NY	BTV	2.25
53	2012	July	4	0151	0208	18	0151	0158	8	6.76	10.88	7	1	OH	CLE	2.50
54	2012	July	4	2205	2252	48	2210	2222	13	9.25	14.88	18	1	PA	PBZ	2.00
55	2012	July	4	2313	2327	15	2327	2327	1	6.08	9.79	3	1	MD	PBZ	2.00
56	2012	July	18	1808	2011	124	1916	2011	56	50.31	80.97	26	4	MA,RI	BOX	2.00
57	2012	July	23	1813	1821	9	1813	1821	9	---	---	1	1	NY	ALY	2.50
58	2012	July	23	1905	1949	45	1924	1927	4	19.52	31.42	4	1	NY	BGM,ALY	3.00
59	2012	July	23	2154	2250	57	2215	2220	6	27.37	44.05	13	1	VT	BTV	2.00
60	2012	July	23	2205	2225	21	2205	2210	6	4.98	8.02	2	1	NY	BGM	2.50
61	2012	July	23	2324	0007	44	2328	2358	31	15.12	24.34	6	2	NY	BGM	2.50
62	2012	July	24	1138	1220	43	1138	1141	4	24.56	39.53	3	1	OH,PA	PBZ	2.00
63	2012	August	9	0234	0240	7	0234	0238	5	0.92	1.48	2	1	OH	CLE,LEZ144	2.00
64	2012	September	6	2009	2120	72	2114	2120	7	23.78	38.28	13	1	NY,PA	BGM	2.00
65	2012	September	27	2000	2101	62	2042	2054	13	13.83	22.26	3	1	VA	LWX	2.00
66	2013	May	21	1908	1942	35	1908	1942	35	7.21	11.61	9	3	NY	ALY	2.50
67	2013	May	21	1642	1727	46	1642	1649	8	14.10	22.70	5	1	NY	BUF,BGM	2.00
68	2013	May	22	2124	2203	40	2201	2203	3	17.83	28.69	2	1	MA	BOX	2.25
69	2013	May	22	2303	0036	94	2340	2356	17	48.76	78.48	12	2	NY	BUF,BGM	2.50

Case ID	Year	Month	Day	Severe Duration (UTC)			Sig Duration (UTC)			Swath Length		Report Count		Report Locations		Max Size (inches)
				Start	End	Time	Start	End	Time	sm	km	Total	Sig	States	WFOs	
70	2013	May	29	2041	2137	57	2110	2116	7	32.79	52.78	7	2	NY	BGM	2.00
71	2013	June	12	2315	0215	181	2338	2351	14	66.18	106.50	8	1	OH	CLE,PBZ	2.50
72	2013	June	12	2337	0342	246	0009	0014	6	95.67	153.96	11	1	OH	CLE,PBZ	2.50
73	2013	June	12	2337	0153	137	0135	0138	4	77.83	125.26	10	2	OH	CLE	2.00
74	2013	June	13	1940	1942	3	1940	1942	3	---	---	1	1	MD	LWX	2.75
75	2013	June	29	2030	2033	4	2030	2033	4	---	---	1	1	ME	GYX	2.00
76	2013	July	18	2051	2059	9	2051	2059	9	---	---	1	1	PA	PBZ	2.00
77	2013	July	18	2313	2329	17	2315	2320	6	3.46	5.57	6	1	PA	PBZ	2.00
78	2013	September	2	2010	2226	137	2058	2103	6	64.82	104.32	5	1	NY	BGM,ALY	2.00
79	2013	September	11	0100	0118	19	0110	0116	7	2.30	3.70	3	1	ME	GYX	2.00
80	2013	September	12	2038	2044	7	2038	2044	7	---	---	1	1	ME	GYX	2.00
81	2014	May	14	2241	0019	99	2248	2331	44	56.96	91.67	13	3	WV,OH,PA	PBZ,CLE	3.00
82	2014	May	22	1733	2010	158	1835	1956	82	40.35	64.94	24	9	NY	ALY	4.00
83	2014	May	22	1800	2127	208	1830	1854	25	113.05	181.94	25	4	PA	CTP,PHI	2.50
84	2014	May	22	1901	2154	174	1901	2039	99	83.92	135.05	27	5	PA,DE,NJ	PHI	2.50
85	2014	July	2	1613	1613	1	1613	1613	1	---	---	1	1	PA	BGM	2.00
86	2014	July	3	2102	2353	172	2128	2133	6	70.06	112.75	7	1	NJ,NY,CT	PHI,OKX	2.50
87	2014	July	3	2017	2037	21	2017	2022	6	4.76	7.66	4	1	NH	GYX	2.00
88	2014	July	3	1808	1926	79	1844	1847	4	32.07	51.61	7	1	VA	LWX	2.00
89	2015	April	9	2102	2143	42	2113	2116	4	34.95	56.24	4	1	OH,PA	PBZ	2.75
90	2015	May	31	2035	2050	16	2035	2040	6	3.72	5.99	2	1	PA	CTP	2.00
91	2015	June	18	2055	2113	19	2055	2057	3	8.94	14.38	10	1	VA	LWX	2.00
92	2015	June	23	2119	2143	25	2133	2143	11	2.13	3.43	7	2	MD	LWX	4.00
93	2015	July	19	2033	2155	83	2033	2038	6	28.80	46.34	3	1	NY,MA	ALY	2.00
94	2015	July	19	1925	2035	71	2011	2026	16	28.09	45.21	4	2	NH,ME	GYX	2.75
95	2015	August	3	0108	0202	55	0138	0141	4	24.56	39.52	5	1	PA	PBZ	2.50
96	2015	August	4	1627	2021	235	1637	2009	213	144.08	231.87	34	3	NY,MA	ALY,BOX,ANZ230	2.25
97	2015	August	4	1724	1858	95	1827	1831	5	52.11	83.86	17	1	MA	BOX	2.00
98	2015	August	4	1952	2006	15	1957	2006	10	8.41	13.53	6	1	ME	GYX	2.00
99	2015	August	4	2050	2142	53	2050	2057	8	22.72	36.57	10	1	ME	GYX	2.50
100	2016	May	2	2202	0215	254	2210	2325	76	93.70	150.79	19	4	VA,MD	LWX,PHI	2.75
101	2016	May	2	2220	2333	74	2249	2254	6	33.83	54.44	13	2	VA,MD	LWX	3.00
102	2016	June	16	1855	2007	73	1930	1939	10	30.57	49.20	4	1	PA,MD,WV	CTP,LWX	2.75
103	2016	June	16	2147	2259	73	2202	2259	58	28.19	45.37	10	3	VA	LWX	3.00
104	2016	June	20	0508	0512	5	0508	0512	5	---	---	1	1	NY	BGM	2.00
105	2016	June	21	2118	2141	24	2120	2125	6	13.44	21.63	5	1	MD	LWX	4.25
106	2017	March	30	2318	2355	38	2318	2330	13	32.97	53.07	5	3	OH	CLE	2.50

Case ID	Year	Month	Day	Severe Duration (UTC)			Sig Duration (UTC)			Swath Length		Report Count		Report Locations		Max Size (inches)
				Start	End	Time	Start	End	Time	sm	km	Total	Sig	States	WFOs	
107	2017	April	20	1639	1715	37	1639	1646	8	13.29	21.38	10	1	PA	PBZ	2.00
108	2017	April	20	1846	2001	76	1925	1929	5	44.36	71.39	6	1	PA	PBZ	2.00
109	2017	May	18	1916	1938	23	1928	1932	5	14.86	23.91	3	1	NY	BUF	2.00
110	2017	May	18	2151	2221	31	2155	2213	19	23.94	38.52	11	5	NY	BUF	2.50
111	2017	May	28	2224	2309	46	2224	2228	5	15.64	25.17	4	1	NY	BUF	2.00
112	2017	May	28	2251	2259	9	2255	2259	5	2.88	4.64	2	1	NY	BUF	2.00
113	2018	May	14	1733	1742	10	1738	1742	5	3.70	5.96	2	1	PA	PBZ	2.00
114	2018	May	14	2105	2237	93	2129	2137	9	49.46	79.60	11	1	WV,VA	LWX	2.50
115	2018	May	15	1830	1851	22	1845	1847	3	15.07	24.25	3	1	PA	BGM	2.75
116	2018	May	15	1823	2014	112	1841	2014	94	64.73	104.17	19	7	NY,CT,MA	ALY,BOX	2.75
117	2018	May	15	1837	1942	66	1905	1942	38	47.82	76.97	8	2	NY,CT	ALY	2.00
118	2018	May	15	1840	1939	60	1841	1849	9	45.90	73.87	5	1	NY	BGM,ALY	2.00
119	2018	May	15	2314	2345	32	2325	2335	11	3.30	5.31	7	1	MD	LWX	2.50
120	2018	October	2	2238	2245	8	2243	2245	3	4.14	6.66	2	1	PA	CTP	2.00
121	2019	April	14	2145	0007	143	2325	2334	10	134.95	217.17	16	2	OH,PA,NY	CLE,BUF	2.00
122	2019	May	19	1844	1921	38	1857	1901	5	14.14	22.75	7	1	MD,PA	LWX,CTP	2.00
123	2019	May	25	2023	2130	68	2023	2033	11	28.83	46.40	4	1	OH	PBZ	2.00
124	2019	May	28	2146	2237	52	2202	2211	10	22.72	36.56	10	1	PA	BGM	2.75
125	2019	May	28	1826	1947	82	1835	1857	23	50.47	81.23	14	4	PA	PBZ	4.00
126	2019	May	28	1847	2013	87	1900	1907	8	53.97	86.85	14	1	PA	PBZ,CTP	2.00
127	2019	May	28	2125	2248	84	2133	2139	7	49.40	79.51	11	2	PA	PBZ	2.50
128	2019	May	28	1938	1944	7	1938	1943	6	2.10	3.38	2	1	PA	CTP	2.00
129	2019	May	28	1948	2200	133	1950	2200	131	69.29	111.50	20	2	PA	CTP,PHI	2.75
130	2019	May	28	2040	2123	44	2040	2123	44	24.39	39.25	9	6	PA	CTP	4.00
131	2019	May	28	2115	2117	3	2115	2117	3	---	---	1	1	PA	CTP	3.00
132	2019	May	29	1850	2025	96	1850	1928	39	48.90	78.69	17	3	PA	PHI	2.00
133	2019	June	2	2142	2146	5	2142	2146	5	0.43	0.69	2	1	MD	LWX	2.00
134	2019	June	29	0028	0034	7	0031	0034	4	1.54	2.48	3	1	NY	BGM	2.00
135	2019	August	19	1818	1842	25	1827	1833	7	4.24	6.82	3	1	MA	BOX	2.00
136	2019	October	1	1744	1756	13	1752	1756	5	6.03	9.70	2	1	NY	BTB	2.75
137	2020	March	28	1558	1612	15	1606	1612	7	15.08	24.28	8	2	OH	CLE	2.25
138	2020	March	28	1700	1705	6	1701	1705	5	5.20	8.37	4	2	OH	CLE	2.00
139	2020	March	28	1713	1831	79	1727	1743	17	78.68	126.62	14	5	OH,PA	CLE,PBZ	2.50
140	2020	March	28	1933	2033	61	1942	2026	45	42.87	68.99	22	6	OH,WV,PA	PBZ	2.50
141	2020	March	28	1956	2025	30	2009	2025	17	24.75	39.83	5	2	PA	PBZ	2.50
142	2020	April	7	0310	0312	3	0310	0312	3	---	---	1	1	OH	CLE	2.00
143	2020	June	28	2047	2100	14	2047	2053	7	2.06	3.31	2	1	MA	BOX	2.00

Case ID	Year	Month	Day	Severe Duration (UTC)			Sig Duration (UTC)			Swath Length		Report Count		Report Locations		Max Size (inches)
				Start	End	Time	Start	End	Time	sm	km	Total	Sig	States	WFOs	
144	2020	August	27	1922	1927	6	1922	1927	6	---	---	1	1	NY	BUF	2.00
145	2020	September	7	2114	2124	11	2114	2118	5	4.70	7.57	4	1	OH	CLE	2.00
146	2021	July	8	1741	1800	20	1748	1800	13	4.43	7.13	9	3	NJ	OKX	2.50
147	2021	July	17	2129	2137	9	2129	2137	9	---	---	1	1	NY	BGM	2.00
148	2021	July	20	2145	2154	10	2145	2154	10	---	---	1	1	NY	BUF	2.50
149	2022	May	3	1904	2010	67	1910	2010	61	45.06	72.52	14	3	OH	ILN,RLX,PBZ	2.50
150	2022	May	16	2031	2239	129	2107	2239	93	91.57	147.36	22	7	VA,MD,DE	LWX,AKQ,PHI	3.50
151	2022	May	20	1953	2115	83	2037	2115	39	34.63	55.73	18	3	PA, NJ	PHI	2.50
152	2022	May	21	2015	2042	28	2037	2042	6	10.01	16.10	6	1	OH	CLE	2.00
153	2022	May	21	2310	2326	17	2321	2326	6	9.30	14.96	2	1	NH	GYX	2.00
154	2022	May	22	2037	2101	25	2037	2044	8	9.10	14.64	4	1	ME	GYX	2.00
155	2022	June	1	1935	2005	31	1938	1950	13	10.16	16.35	12	3	NY	BGM	3.00
156	2022	June	8	0043	0100	18	0043	0100	18	6.31	10.15	4	2	WV	PBZ	2.00
157	2022	June	8	0105	0108	4	0105	0108	4	---	---	1	1	PA	PBZ	2.00
158	2022	June	16	1947	2017	31	2000	2010	11	8.65	13.92	4	1	NY	BUF	2.50
159	2022	June	16	1925	2020	56	1940	1955	16	35.81	57.64	9	2	OH,PA	CLE,PBZ	2.50
160	2022	June	16	2025	2111	47	2025	2034	10	20.36	32.76	4	1	OH	PBZ	2.75
161	2022	June	16	0011	0035	25	0011	0017	7	9.26	14.90	3	1	PA	CTP	2.00
162	2022	July	12	1943	1953	11	1943	1953	11	5.03	8.10	3	2	WV	LWX	2.00
163	2022	July	21	1634	1812	99	1634	1648	15	52.02	83.72	7	2	VT,NH	BTV,GYX	2.00
164	2022	July	21	2207	2217	11	2207	2212	6	4.07	6.55	2	1	ME	CAR	2.00
165	2022	July	24	2215	2253	39	2215	2248	34	14.46	23.28	4	2	ME	CAR	2.50
166	2022	August	26	1844	1921	38	1844	1847	4	14.52	23.37	3	1	NH	GYX	2.00
167	2022	November	27	1935	1958	24	1944	1948	5	22.30	35.89	14	2	PA	PBZ	2.00
mean						56.0			17.9	26.73	43.03	7.9	1.9			
median						38.0			8.0	14.46	23.28	5.0	1.0			
mode						3			5 & 6			1	1			

CHAPTER 4

CONVECTIVE CHARACTERISTICS

In this Chapter, we explore characteristics of the convective storms that produced significantly severe hail in the northeastern United States. These characteristics encompass convective mode and storm behaviors, including storm motion vectors and tornado production. It is well known that across the United States, supercell storms produce the vast majority (>90%) of sig hail (e.g., Thompson et al. 2003), >99% of giant (>4 in or 102 mm) hail (Blair et al. 2011), and 100% of gargantuan (>6 in or 152 mm) hail (Gutierrez and Kumjian 2021). We explore how the Northeastern U.S. sig hail storm modes compare. Further, storm motion can play an important role in modulating the low-level storm-relative inflow, which is thought to affect updraft properties (e.g., Peters et al. 2019) important for hail production (Kumjian and Lombardo 2020; Lin and Kumjian 2022). We examine how storm motion directions deviate from the predicted supercell motion (Bunkers et al. 2000) to identify any systematic differences that may be important for hail production. Finally, given the widespread anecdote that storms that produce tornadoes are less likely to be prolific hail producers (e.g., Nixon et al. 2023), which has recent theoretical support (Lin and Kumjian 2026), we explore the frequency of tornado occurrence across Cases.

4.1 Storm Mode Classification

Recall from Chapter 2 that we apply a version of the Smith et al. (2012) storm classification system, categorizing storms into 1 of 5 possible classes: QLCS, right-moving supercell, left-moving supercell, linear hybrid, and disorganized. Out of the 167 Cases, only eight (4.8%) did not fall within one of the supercell classifications (Fig. 4.1). That >95% of sig hail-producing storms in the Northeast U.S. are supercells aligns with our understanding that storms capable of producing sig hail are nearly exclusively supercells (Rasmussen and Blanchard 1998; Thompson et al. 2003; Blair et al. 2011; Gutierrez and Kumjian 2021). Of the supercell Cases, 133 of 159 (83.6%) were cyclonic, or so-called “right movers” (RMs) and 26 Cases (16.4%) were anticyclonic or “left-movers” (LMs). The terms cyclonic/anticyclonic supercell and right-/left- mover are used interchangeably hereafter.

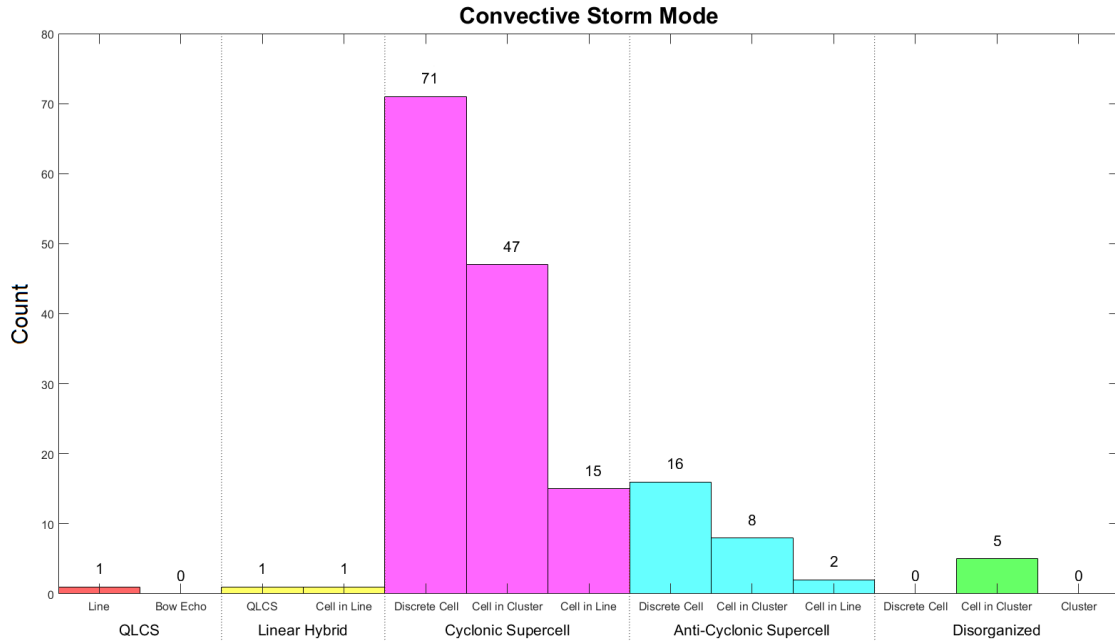


Figure 4.1. Storm-mode classification following the methods of Smith et al. 2012 for each of the 167 sig hail producing cases.

There were more discrete cyclonic and anticyclonic supercells than their cluster and linear counterparts and both appeared to have a proportionally similar distribution of the three subclasses: 53.4% of RMs, 61.5% of LMs, and 54.7% of all supercells were discrete. These were the most common storm modes observed and displayed some of the most impressive radar signatures, including “classic” cyclonic supercell structures (e.g., Markowski and Richardson 2010) with well-defined hook echoes (e.g., Cases 18 and 70), and classic hail signatures like prominent three-body scattering signatures (TBSS; Zrnić 1987) like Cases 69, 94, 116, and 132. The anticyclonic discrete counterparts also depicted these impressive signatures, like Case 5 (which had a large TBSS and an elongated core of low-level Z_H values >70 dBz), and Case 134 (which, incredibly, had a hook echo and took the shape of a classic Southern Hemisphere supercell). See Appendix A for these and other examples listed throughout this paper.

Further, 35.3% of RMs, 30.8% of LMs, and 34.6% of all supercells were in the cluster subclass. These cases displayed a large range of structures, from closely spaced but well-defined supercells (Case 16), to supercells interacting with each other (Case 92), to supercells embedded within large areas of disorganized convection (Case 89). Sometimes

it was difficult to distinguish between discrete and cluster. Roughly a dozen or so Cases were placed into this cluster subclass because there was a significant storm merger or the storm was interacting with other convection at the time of sig hail production, even when a majority of the Case was discrete before and after this period. Nixon et al. (2024) found storm interactions/mergers are common for sig hail-producing storms: upwards of 40% of the ≥ 3 -in (7.5-cm) hail-producing storms (as well as the null cases) they investigated were reported to have experienced an interaction of some sort in the 15 min prior to the hail reports. In contrast, we find that a majority of the Northeastern U.S. sig hail-producing supercells were discrete (i.e., did not have apparent mergers or interactions at the time of sig hail production). Part of this discrepancy may be related to differing definitions: Nixon et al. (2024) defined “discrete” as having no other precipitation feature with 30-dBz Z_H within 25 km distance from the storm of interest, whereas this study defines discrete as only having a non-continuous $Z_H \geq 35$ dBZ contour (i.e., if separated by even a few kilometers, the two storms are considered discrete). This also included a few cases of small, closely spaced supercells that may have fit better into the discrete category (e.g., Case 147), but they were joined by $Z_H \geq 35$ dBZ at the time of sig hail production and thus placed in this category to adhere to the definition set by Smith et al. (2012). Cases that were undergoing a storm split at the time of storm mode classification were considered discrete instead of clustered, as long as both the parent and split storm were not interacting with other convection (e.g., Case 13). Cluster supercells more often than not were fairly well-defined within their cluster.

Linear modes (including cell in line RMs and LMs, linear hybrids, and QLCSSs) made up 12.0% of all Cases. Similarly, only 11.3% of RMs, 7.7% of LMs, and 10.7% of all supercells were embedded in a line (Fig. 4.1). For example, Case 19 was a “tail-end Charley” (Branick 1996) cyclonic supercell embedded within a morning MCS moving southeast off Lake Erie. Case 121 was a long-lived cyclonic supercell embedded within a powerful early-season QLCSS. Case 43 was a left-split from a cluster of convection and quickly oriented itself as the northern cell of a small bowing segment. Case 7 split off a discrete cyclonic supercell, merged into the leading edge of a bow echo, and produced sig hail immediately thereafter. Case 162 was a linear hybrid that produced wind-driven sig

hail with a measured wind gust of 89 knots (45.8 m s^{-1}). Case 167 was an extremely late-season, fast-moving linear hybrid that had at least five separate mesovortices embedded within a north-to-south oriented high-reflectivity core. And finally, Case 4 began as a cluster RM that transitioned into a small line segment, which was extremely similar in structure to the efficient hail producing “multicellular-supercellular” hybrid storms described in Nelson (1987), as it had one of the largest swaths with the most hail reports. These linear mode Cases generally occurred sporadically during Events, including many with other convective modes ongoing concurrently. An exception is the Event on 8 June 2011, which had four total Cases, three of which were linear. This proportion of linear Cases is similar to that found by Gallus et al. (2008) for sig hail amongst their nine storm mode classifications, except for one of the five linear modes (parallel stratiform), which saw the highest proportion of sig hail. This structure resembles a line with the classic tail-end Charlie, which interestingly was not found to have a higher tornado tendency (Beveridge et al. 2018), but was not tested for other severe hazard tendencies, like hail.

Of the linear convective mode categories, QLCSs were the least common to produce sig hail. Only a single case (Case 29) produced one report of sig hail (and no additional hail reports), even though the storm traveled hundreds of km across New England. Although it did travel through many areas of low population density, it is unlikely that the lack of reports for this Case is an under-sampling issue. None of the Cases were categorized as the QLCS bow echo subclass; however, Case 114 was in the process of transitioning to a bow echo, producing reports of wind damage (“many large, uprooted trees” and “homes with roof damage,” per the SED) very close to where 2.50 in (63.5 mm) hail was reported. The storm eventually produced one final hail report (1.75 in or 44.5 mm) after fully transitioning to a bow echo.⁷

Finally, all five “Disorganized” Cases (Case 40, 54, 76, 77, and 143) were generally “pulse cells” (Wilk et al. 1979) that briefly strengthened to produce sig hail within a conglomerate or cluster of convection. Except for Case 54, all had a severe hail duration of <18 min and

⁷ The case’s odd swath path can be attributed to this storm mode transition, and is seen in Fig 3.4b as the yellow swath in northern VA that makes a sharp turn from southeast to east.

produced between one and six reports; Case 54 had a duration of 48 min and produced 18 severe hail reports (but only one sig hail report). The relatively long duration of this Case is surprising; based on analysis of the radar imagery for this Case, we speculate the storm could have been maintained by repeated collisions of outflow boundaries from neighboring decaying pulse cells. However, note that its severe hail duration still falls within the 30-60 min life cycle of a standard thunderstorm updraft in light shear (Byers, 1949). Additionally, its report count was boosted due to its proximity to the highly populated suburbs east-southeast of Pittsburgh, PA. Such disorganized cells are not generally thought of being capable of producing sig hail, and any hail growth pathways that do exist are unknown.

There was little relationship between any storm mode classification and the average reported maximum hail size for the Case. The mean hail size for all Cases was 2.37 in (60.2 mm). For all RM supercells (133 cases), the mean was 2.40" (61.0 mm), and for all LM supercells (26 Cases) it was 2.35 in (59.7 mm). Thus, either supercellular mode was capable of sig hail, which is consistent with the findings of Blair et al. (2017) for Great Plains supercell storms. Dividing the supercell storm mode into sub-classes yielded similar results: the averages were 2.36 in (59.9 mm) for all discrete modes (87 Cases), 2.40 in (61.0 mm) for cluster modes (60 Cases), and 2.33 in (59.2 mm) for linear modes (20 Cases). All eight non-supercellular cases recorded exactly 2.00 in (50.8 mm) hail for the maximum size. Thus, although supercell storm modes were capable of hail much larger than 2.00 in (50.8 mm), the differences in mean reported maximum sizes between storm modes are insignificant, especially when considering the numerous biases in hail reporting discussed in Chapter 2.

As mentioned in Chapter 2, there were six cases that had two distinct storm modes while producing sig hail. Cases 17, 116, 117, and 129 began as discrete RM supercells and later transitioned into cluster right movers. Cases 4 and 130 both began as cluster right movers, then transitioned to a cell in line right mover and discrete right-mover, respectively. For consistency in our analysis, the storm mode during which the largest hail was reported was recorded as the primary convective mode, though both modes were reported in the subclass column of Table 4.1 (the one in bold being the primary mode). However, Cases 4, 17, and

117 produced their largest hail reports during *both* distinct storm modes, so preference was given to the mode during which the storm produced more total hail reports.

4.2 Storm Motion Vectors

As mentioned in the introduction to this Chapter, storm motion plays an important role in determining the storm-relative wind profile and storm-relative inflow into the storm. Here, we calculate the observed storm motion vector (SMV) direction and compare it to that predicted by the Bunkers et al. (2000) empirical method.

The mean observed SMV angle across all Cases was 276° , and the median was 277° (Fig. 4.2). The most common SMV angle is the bin centered on 280° (containing Cases with SMV angles from 277.5° to 282.5°), with 18 Cases. Despite the inherent uncertainties in determining storm motion vectors, we do see some broad patterns in the results. There is a distinct drop off in frequency of occurrence for SMV angles more southerly than 245° and more northerly than 310° ; this range encompasses 87.4% of all Cases, with every 5° bin containing at least six Cases. Further, all but two Cases had a SMV between 219° and 334° . There was a small tendency for Cases to move slightly south of due eastward: 55.1% of Cases had SMV angles $<270^\circ$, whereas only 35.3% had angles $>270^\circ$. The results likely reflect the predominant westerly component to the mean wind for environments conducive to sig-severe hail production; we will examine these environments in detail in Chapter 5.

Compared to the Bunkers et al. (2000) method's prediction for supercell storm motion⁸, the observed cases tended to have motion vectors directed 10.9° (or 9.5° when removing the five disorganized Cases) counter-clockwise of the Bunkers prediction (Fig. 4.3) and a Pearson's correlation coefficient of 0.89. In most cases, this corresponds to storm motion to the left (or less rightward) than the Bunkers prediction. According to data presented in Bunkers (2017), this could indicate environments with relatively weaker deep-layer shear,

⁸ Left-moving supercell environmental wind profiles were adjusted so as to facilitate comparison with the right-moving supercells. See Chapter 5 for details.

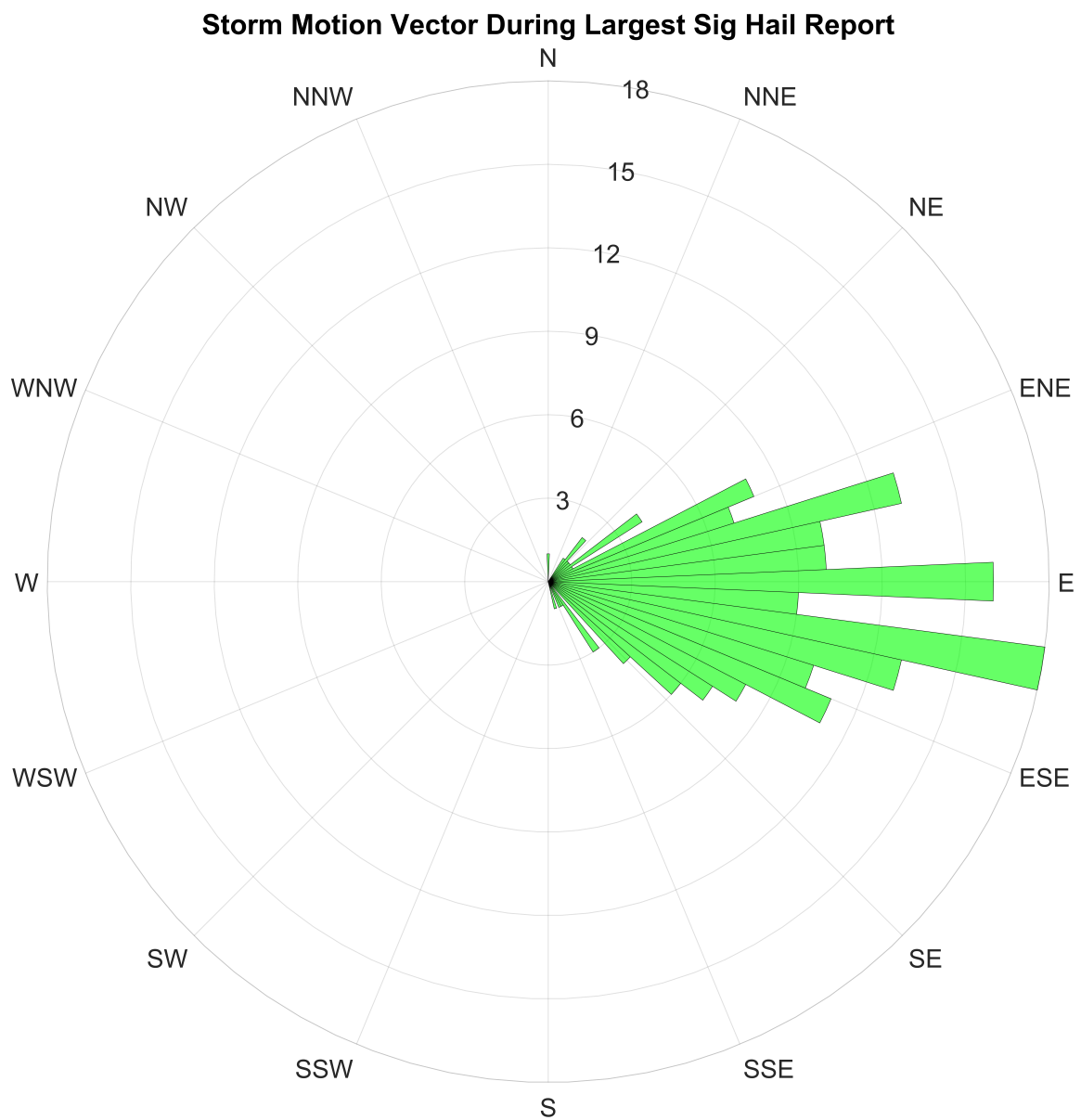


Figure 4.2. Frequency of storm motion for all 167 sig hail producing cases, binned in 5-degree intervals centered on East (i.e., the East bin contains storm motion vectors for 268 through 272 degrees).

weaker 4-5-km storm-relative flow, and/or weaker 0-3-km SRH. Further, the discrepancy for these northeastern U.S. sig-severe hailstorms is of the opposite direction to those found in Gutierrez and Kumjian (2021) for gargantuan hail, which makes sense given that gargantuan hail-producing storms form in more extreme environments that are uncommon in the northeastern U.S. (i.e., there are no gargantuan hail reports in our analysis period). The outlier SMV angles were Case 81 (178°) and Case 82 (347°). The former was a cluster left-mover over the panhandle of WV, which traveled slightly *west* of due north and was, oddly, the only storm in the region to deviate left during its lifetime. The latter case was a RM supercell that occurred only eight days later in east-central NY. This Case was notable in that it produced some of the most extreme hazards anywhere within the Northeast in the last decade (4.00 in or 102 mm hail and an EF-3 tornado) and is discussed in great detail in Tang et al. (2016). Interestingly, this case deviated 11° further right from the predicted Bunker's SMV of 336° , which would have aligned with the bin containing the most southward-moving storms for the rest of the Cases. In addition, it also had a storm motion 5 kts (2.6 m s^{-1}) slower than predicted. This slower and more rightward movement is consistent with Gutierrez and Kumjian (2021), who found a similar (albeit stronger) deviation from the Bunkers predicted motion for gargantuan hail-producing storms. Bunkers (2017) found that such a deviation from the predicted storm motion tends to occur in environments with greater low-level vertical wind shear and/or large low-level SRH. Tang et al. (2016) did find increased 0-1-km vertical wind shear ($> 10 \text{ m s}^{-1}$) after the storm crossed a remnant outflow boundary snaking through the Mohawk valley of east-central NY, although the reported 0-1-km SRH ($50\text{-}100 \text{ m}^2 \text{ s}^{-2}$) is not particularly large.

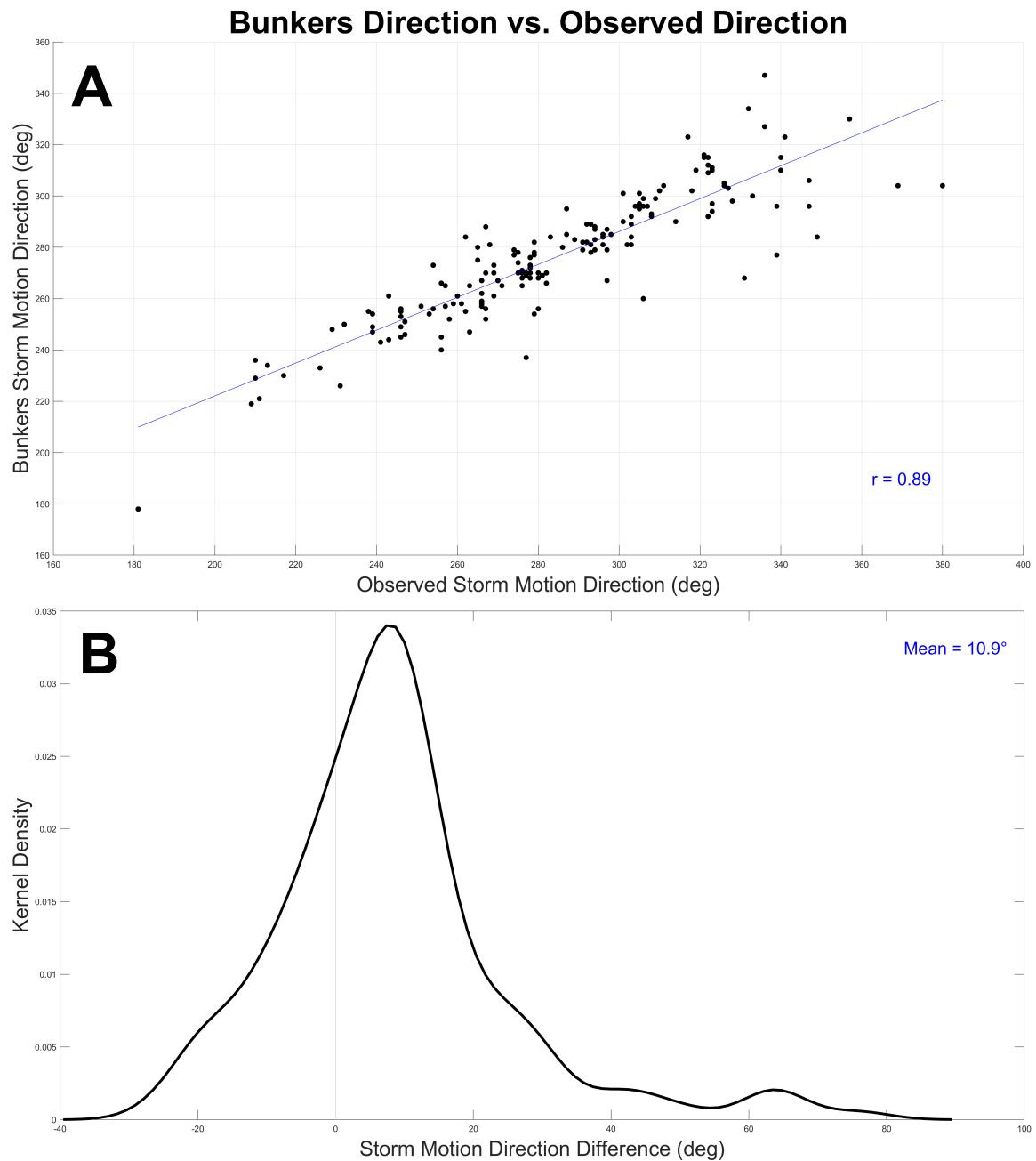


Figure 4.3. (a) Scatterplot of observed storm motion direction vs. the Bunkers method prediction, and (b) kernel density estimate of the difference in storm motion direction (Bunkers minus observed). Relevant statistics are included in the panels.

4.3 Tornado Frequency

Only 16 Cases (9.6%) produced at least one tornado of any strength (Table 4.1), four of which produced significant (EF-2+) tornadoes: Case 1 on 23 March 2011 in Hempfield, PA (EF-2); Case 17 on 1 June 2011 in Springfield, MA (EF-3); Case 82 on 22 May 2014 in Duaneburg, NY (EF-3); and Case 129 on 28 May 2019 in Morgantown, PA (EF-2). Five Cases produced >1 tornado; two produced three tornadoes. Cases produced tornadoes in each month from March through July, but not from August through November. The lack of late summer to late-season tornadoes may be related to weaker low-level shear expected in the late summer months and too little CAPE for high-shear environments in the late-season months in the Northeast U.S. (e.g., Hurlbut and Cohen 2014).

This surprisingly small proportion of sig hail Cases that produced tornadoes closely matches results from Warren et al. (2021), who found that only 10% of tornado reports were accompanied by either sig hail or significantly severe wind reports, in their analysis of the environments of >10,000 RM supercells in the United States. However, they also mentioned a possible reporting bias, considering it is less likely for hail to be reported when a tornado is present. The low fraction of tornadic sig hail Cases is also consistent with recent findings that the thermodynamic and kinematic parameter space for environments conducive for large hail and tornadoes do not fully overlap (Nixon and Allen 2022). Those authors found that the most important difference between tornadic and large-hail environments was the shape of the hodograph. Larger ground-relative wind speeds in the lower and mid-levels (i.e., roughly 0-6-km) have been shown to distinguish between tornadic and non-tornadic supercells (Markowski et al. 2003) and large curvative/vertical wind shear, particularly in the lowest 1 km or even the lowest 500 m, is most favorable for significant tornadoes (Coffer et al. 2019, 2023). However, this environment is not as conducive for large hail-producing supercells, where large low-level (0-1 or 0-2 km) shear is found to disfavor hail production (e.g., Kumjian and Lombardo 2020), as is large 0-1-km hodograph curvature (Lin and Kumjian 2026). We explore the environments for sig hail Cases in more detail in Chapter 5.

Because of the apparent rarity of storms being simultaneously favorable for both significant tornadoes and hail, the four Cases that produced both hazards are worth briefly examining. Case 82 generated the Duanesburgh, NY EF-3 and 4.00 in (102 mm) hail has already been discussed in Section 4.2. Case 1 was the earliest Case of sig hail in the study period as well as the only March case to produce a tornado. Case 1 produced the Hempfield, PA, EF-2 tornado that was accompanied by a swath of accumulating large hail that left the eastern suburbs of Pittsburgh, PA, coated in what looked like snow after only 5-7 min, in addition to damaging the hundreds of roofs in this area. The tornado itself only impacted a 7-mile (11-km) stretch near the center of the 110-mile (176-km) long hail swath, suggesting that, despite the storm's longevity and maintained hail production, conditions were only favorable for tornadoes during a relatively short period of its lifecycle. The severe weather Event that day was mostly localized to this isolated supercell, much like the Duanesburgh, NY EF-3 tornado (Case 82); two other Cases (83 and 84) occurred during this Event, but were nearly 200 mi (321 km) away in southeastern PA.

Case 17 was an extremely high-impact storm, producing the high-end EF-3 Springfield tornado that tracked 39 mi (63 km) through southern MA, which was only the 12th killer tornado to strike New England since 1950 (Banacos et al. 2012). Because of the tornado's significant impacts, we speculate this may be an example of a hail underreporting bias when more life-threatening hazards are observed (e.g., Warren et al. 2021 and references therein). For example, despite the large distance from the first to the last hail report (62 mi or 100 km), there were only 6 total hail reports, even though the storm traveled through highly populated Springfield, MA, and its eastern suburbs (where only two severe hail reports were made). The 1 June 2011 Event included five other tornadoes, though only one was associated with any of the other seven sig hail Cases (Case 18 in south-central ME). Thus, the conditions across New England seemingly were favorable for both sig hazards simultaneously.

The 28 May 2019 Event is the last in the study period to have produced a significant tornado, and was the most significant hail day for the Northeast during the study period. Over 100 preliminary reports of severe hail occurred across the state of PA alone, 81 of

which were associated with the 8 sig hail Cases from the Event. Though multiple reports of 4.00 in (102 mm) hail were the main topic of local news headlines that day, six tornadoes also occurred across the Northeast. Four of these tornadoes occurred in only 3 (of 8) sig hail Cases. However, all six tornadoes, including the Morgantown, PA EF-2, were short-lived, traveling no more than 3.2 mi (5.1 km). Thus, although the environment from this day had some similarities to the 1 June 2011 Event, large 0-1-km hodograph curvature and SRH was lacking in across the region (see section 5.2), which likely led to shorter-lived tornadoes (Coffer et al. 2019). The lack of large low-level SRH also may have contributed to greater sig hail production on this day for reasons elucidated by Lin and Kumjian (2026).

Storm modes varied for the 16 total tornadic Cases: 7 were discrete right-movers, 6 were cluster right-movers, 3 were cell in line right-movers, and 1 was a linear hybrid (there are 17 total storm modes listed because Case 116 produced separate tornadoes in both the discrete RM and cluster RM storm modes). All four of these storm modes were responsible for the 5 Cases that produced >1 tornado. Of the four significantly tornadic (EF2+) Cases, three were cluster RMs and one was a discrete RM that became a cluster RM shortly after producing the tornado. That the significant tornado cases generally occurred in storms with other convection nearby seems consistent with the findings of Nixon et al. (2024), who report that storm interactions and mergers are extremely common in significant tornado cases.

Finally, there is some indication that, although few in number, the tornadic Cases produce larger mean reported hail sizes and feature longer severe- and sig hail durations. The average reported maximum hail size for tornadic cases was 2.50 in (63.5 mm), slightly larger than the average for all non-tornadic Cases (2.36 in or 59.9 mm). The mean severe- and sig hail durations were 101.9 and 42.8 min, respectively, substantially longer than the non-tornadic Case means of 51.2 and 15.3 min, respectively. This suggests that longer-lived sig hail Cases have a higher likelihood of producing a tornado, perhaps reflecting the fact that tornado formation requires a somewhat fortuitous confluence of factors (e.g., Markowski 2024; Fischer et al. 2024 and references therein) that may be more achievable given longer storm lifetimes. This general trend continues when considering maximum

tornado strength: for significantly tornadic Cases, the average reported maximum hail size rises to 2.69 in (68.3 mm), and severe and sig hail duration increased to 136.8 and 78.0 min, respectively. This is suggestive that “high-end” days in the Northeastern U.S. should be considered favorable for all significant severe hazards. However, considering the small sample size (only four Cases), this result requires further validation with an expanded dataset.

Table 4.1. A table containing convective characteristics of interest for each of the 167 sig hail producing cases. Listed are storm mode classification (Smith et al. 2012), predicted Bunkers right/left SMV angle (based on ERA5), observed SMV angle during sig hail production, difference (Bunkers minus Observed) and associated tornadoes and their EF-rating (if applicable).

Case ID	Storm Mode		SMV [degrees]			Associated Tornadoes
	Classification	Subclass	Bunk	Obs	Diff	
1	Supercell - right	cluster	279	282	-3	EF2
2	Supercell - right	cluster	241	243	-2	
3	Supercell - right	cluster	340	310	30	
4	Supercell - right	cluster→line	243	261	-18	EF1
5	Supercell - left	discrete	209	219	10	
6	Supercell - right	discrete	254	256	-2	
7	Supercell - left	line	210	229	19	
8	Supercell - right	cluster	246	253	-7	EF1
9	Supercell - right	cluster	251	257	-6	
10	Supercell - right	discrete	267	252	15	
11	Supercell - right	discrete	278	270	8	
12	Supercell - right	discrete	278	273	5	
13	Supercell - left	discrete	239	254	15	
14	Supercell - right	discrete	277	270	7	
15	Supercell - left	discrete	238	255	17	
16	Supercell - right	cluster	279	254	25	
17	Supercell - right	discrete→cluster	280	270	10	EF3
18	Supercell - right	discrete	268	281	-13	EF1
19	Supercell - right	line	317	323	-6	
20	Supercell - right	cluster	328	298	30	
21	Supercell - right	line	314	290	24	
22	Supercell - right	line	326	305	21	
23	Supercell - right	line	323	311	12	
24	Supercell - left	discrete	269	273	4	
25	Supercell - right	cluster	275	274	1	
26	Supercell - right	discrete	291	282	9	
27	Supercell - right	cluster	292	282	10	
28	Supercell - right	line	296	285	11	
29	QLCS	line	303	281	22	
30	Supercell - right	cluster	310	302	8	
31	Supercell - right	discrete	304	296	8	
32	Supercell - right	line	257	265	-8	
33	Supercell - right	line	301	301	0	
34	Supercell - right	discrete	336	327	9	
35	Supercell - right	discrete	347	296	51	
36	Supercell - right	discrete	357	330	27	
37	Supercell - right	discrete	347	306	41	
38	Supercell - right	cluster	341	323	18	
39	Supercell - right	discrete	340	315	25	
40	Disorganized	cluster	339	277	62	
41	Supercell - right	cluster	326	304	22	
42	Supercell - left	cluster	239	249	10	
43	Supercell - left	line	246	256	10	
44	Supercell - right	discrete	270	267	3	
45	Supercell - right	cluster	277	269	8	
46	Supercell - right	discrete	280	256	24	
47	Supercell - right	discrete	282	266	16	

Case ID	Storm Mode		SMV [degrees]			Associated Tornadoes
	Classification	Subclass	Bunk	Obs	Diff	
48	Supercell - right	cluster	266	258	8	
49	Supercell - right	discrete	321	316	5	
50	Supercell - left	cluster	262	284	22	
51	Supercell - right	discrete	306	296	10	
52	Supercell - right	cluster	332	334	-2	
53	Supercell - right	line	20	304	76	
54	Disorganized	cluster	9	304	65	
55	Supercell - left	discrete	287	295	8	
56	Supercell - right	cluster	294	287	7	
57	Supercell - right	discrete	333	300	33	
58	Supercell - left	cluster	262	255	-7	
59	Supercell - left	discrete	247	251	4	
60	Supercell - right	discrete	331	268	63	
61	Supercell - right	discrete	323	294	29	
62	Supercell - right	discrete	322	292	30	
63	Supercell - right	discrete	293	289	4	
64	Supercell - right	discrete	319	310	9	
65	Supercell - right	discrete	281	269	12	
66	Supercell - right	discrete	322	309	13	
67	Supercell - right	discrete	302	281	21	
68	Supercell - right	discrete	282	270	12	
69	Supercell - right	discrete	276	265	11	
70	Supercell - right	discrete	291	279	12	EF1
71	Supercell - right	discrete	309	299	10	
72	Supercell - right	discrete	298	285	13	
73	Supercell - left	discrete	256	245	-11	
74	Supercell - right	line	269	261	8	EF0,EF0,EF0
75	Supercell - right	discrete	239	247	-8	
76	Disorganized	cluster	339	296	43	
77	Disorganized	cluster	349	284	65	
78	Supercell - right	cluster	279	278	1	
79	Supercell - right	cluster	280	268	12	
80	Supercell - right	discrete	263	265	-2	
81	Supercell - left	cluster	181	178	-3	
82	Supercell - right	cluster	336	347	-11	EF3
83	Supercell - right	cluster	322	315	7	
84	Supercell - right	discrete	322	312	10	
85	Supercell - right	cluster	260	261	-1	
86	Supercell - right	discrete	256	240	16	
87	Supercell - right	discrete	271	265	6	
88	Supercell - right	cluster	253	254	-1	
89	Supercell - left	cluster	217	230	13	
90	Supercell - right	cluster	277	237	40	
91	Supercell - right	cluster	311	304	7	
92	Supercell - right	cluster	294	279	15	
93	Supercell - right	discrete	308	293	15	
94	Supercell - right	discrete	318	302	16	
95	Supercell - left	discrete	241	243	2	
96	Supercell - right	cluster	265	275	-10	
97	Supercell - right	discrete	266	267	-1	
98	Supercell - right	discrete	266	257	9	
99	Supercell - right	discrete	266	262	4	
100	Supercell - right	discrete	287	285	2	

Case ID	Storm Mode		SMV [degrees]			Associated Tornadoes
	Classification	Subclass	Bunk	Obs	Diff	
101	Supercell - left	discrete	231	226	-5	
102	Supercell - right	discrete	327	303	24	EF0
103	Supercell - right	discrete	323	310	13	
104	Supercell - left	cluster	254	273	19	
105	Supercell - left	discrete	256	266	10	
106	Supercell - left	cluster	211	221	10	
107	Supercell - right	cluster	296	281	15	
108	Supercell - left	discrete	243	244	1	
109	Supercell - right	discrete	259	258	1	
110	Supercell - left	discrete	229	248	19	
111	Supercell - left	discrete	210	236	26	
112	Supercell - left	discrete	213	234	21	
113	Supercell - right	cluster	308	292	16	
114	Supercell - right	line	323	297	26	
115	Supercell - right	line	274	277	-3	
116	Supercell - right	discrete →cluster	278	276	2	EF1,EF1,EFU
117	Supercell - right	discrete →cluster	275	278	-3	
118	Supercell - right	discrete	275	270	5	
119	Supercell - right	line	296	284	12	
120	Supercell - right	discrete	293	278	15	
121	Supercell - right	line	226	233	-7	EF0,EF0
122	Supercell - right	discrete	267	256	11	
123	Supercell - right	discrete	279	277	2	
124	Supercell - right	cluster	303	292	11	EF0,EF1
125	Supercell - right	discrete	297	287	10	
126	Supercell - right	discrete	297	287	10	EF0
127	Supercell - right	cluster	294	283	11	
128	Supercell - right	discrete	303	289	14	
129	Supercell - right	discrete →cluster	305	301	4	EF2
130	Supercell - right	cluster →discrete	305	295	10	
131	Supercell - right	cluster	303	284	19	
132	Supercell - right	discrete	293	281	12	EF0
133	Supercell - right	discrete	307	296	11	
134	Supercell - left	discrete	269	270	1	
135	Supercell - right	cluster	297	267	30	
136	Supercell - left	discrete	265	280	15	
137	Supercell - right	discrete	278	272	6	
138	Supercell - right	discrete	276	270	6	
139	Supercell - right	discrete	276	271	5	
140	Supercell - right	cluster	279	278	1	
141	Supercell - left	cluster	247	246	-1	
142	Supercell - right	cluster	297	279	18	
143	Disorganized	cluster	306	260	46	
144	Supercell - right	cluster	305	297	8	
145	Supercell - right	cluster	292	289	3	
146	Supercell - right	discrete	267	270	-3	
147	Supercell - right	cluster	263	247	16	
148	Supercell - right	cluster	301	290	11	
149	Supercell - right	cluster	246	255	-9	
150	Supercell - right	discrete	274	279	-5	
151	Supercell - right	discrete	267	288	-21	
152	Supercell - right	discrete	261	258	3	
153	Supercell - right	line	278	268	10	

Case ID	Storm Mode		SMV [degrees]			Associated Tornadoes
	Classification	Subclass	Bunk	Obs	Diff	
154	Supercell - right	cluster	266	259	7	
155	Supercell - right	cluster	321	315	6	
156	Supercell - right	discrete	266	259	7	
157	Supercell - right	cluster	258	252	6	
158	Supercell - right	discrete	283	284	-1	
159	Supercell - right	cluster	289	283	6	
160	Supercell - right	cluster	294	288	6	
161	Supercell - right	cluster	306	299	7	
162	Linear hybrid	line right	286	280	6	EF0,EF0
163	Supercell - right	discrete	246	245	1	
164	Supercell - right	discrete	246	249	-3	
165	Supercell - right	discrete	257	257	0	
166	Supercell - right	cluster	276	268	8	
167	Linear hybrid	QLCS	232	250	-18	

CHAPTER 5

ERA5 ENVIRONMENTS

In this chapter, we examine the environments associated with significantly severe hailstorms in the northeastern United States. We first examine the vertical wind profiles of these storms through composite hodographs of varying categories of interest, and then examine the thermodynamic environments using skew-Ts. Finally, we compare reanalysis calculations of a well-known composite index for large hail, the significant hail parameter.

5.1 Composite Hodographs

ERA5 pressure- and single-level data were compiled for each Case and composited into categories of statistical interest. Firstly, Figure 5.1 shows a composite of all 167 cases in a Bunker’s right-moving storm-relative frame of reference (the exact rotation scheme explained in section 2.3). Even though 26 of the 167 cases were left movers, all were rotated in this manner since it is a commonly used standard (e.g., Homeyer et al. 2023) to evaluate the storm-relative wind profile. In the top left, the composite category of interest is listed, along with the sample size of the composite and the breakdown of each Case’s convective storm mode. The top right portion plots the composite’s storm-relative winds in kts (multiply value by 0.5144 to convert to m s^{-1}), and the bottom right portion plots the BWD from the surface to levels of interest, the storm-relative helicity from the surface to levels of interest, and the storm motion vector. Each Case has its own figure in Appendix A, and all variables are also listed in Table 5.1. All composite figures were constructed in this exact format, with the presented values averaged, to facilitate comparison.

Full Composite

Figure 5.1 depicts a composite hodograph with moderate curvature from the surface to 1 km and a relatively straight, “elongated” shape from 1-12 km. This shape is consistent with other recent studies, some of which have successfully differentiated between hodographs that are more likely to produce sig hail versus sig tornadoes, which often have extreme low-level curvature (e.g., Coffey et al. 2019; Nixon and Allen 2022). Too much curvature

in the lowest few kilometers appears to have an adverse effect on large hail production (Lin and Kumjian 2026). Further, greater low-level shear (especially that with a meridionally oriented component) is detrimental to hail production because the resulting stronger southerly storm-relative flow shifts the midlevel optimal embryo source regions farther from the updraft to regions where hydrometeors are less likely (Dennis and Kumjian 2017), and greater storm-relative flow leads to stronger in-updraft horizontal winds, which decrease hailstone residence time by advecting particles through the hail growth zone more rapidly (Kumjian and Lombardo 2020; Lin and Kumjian 2022).

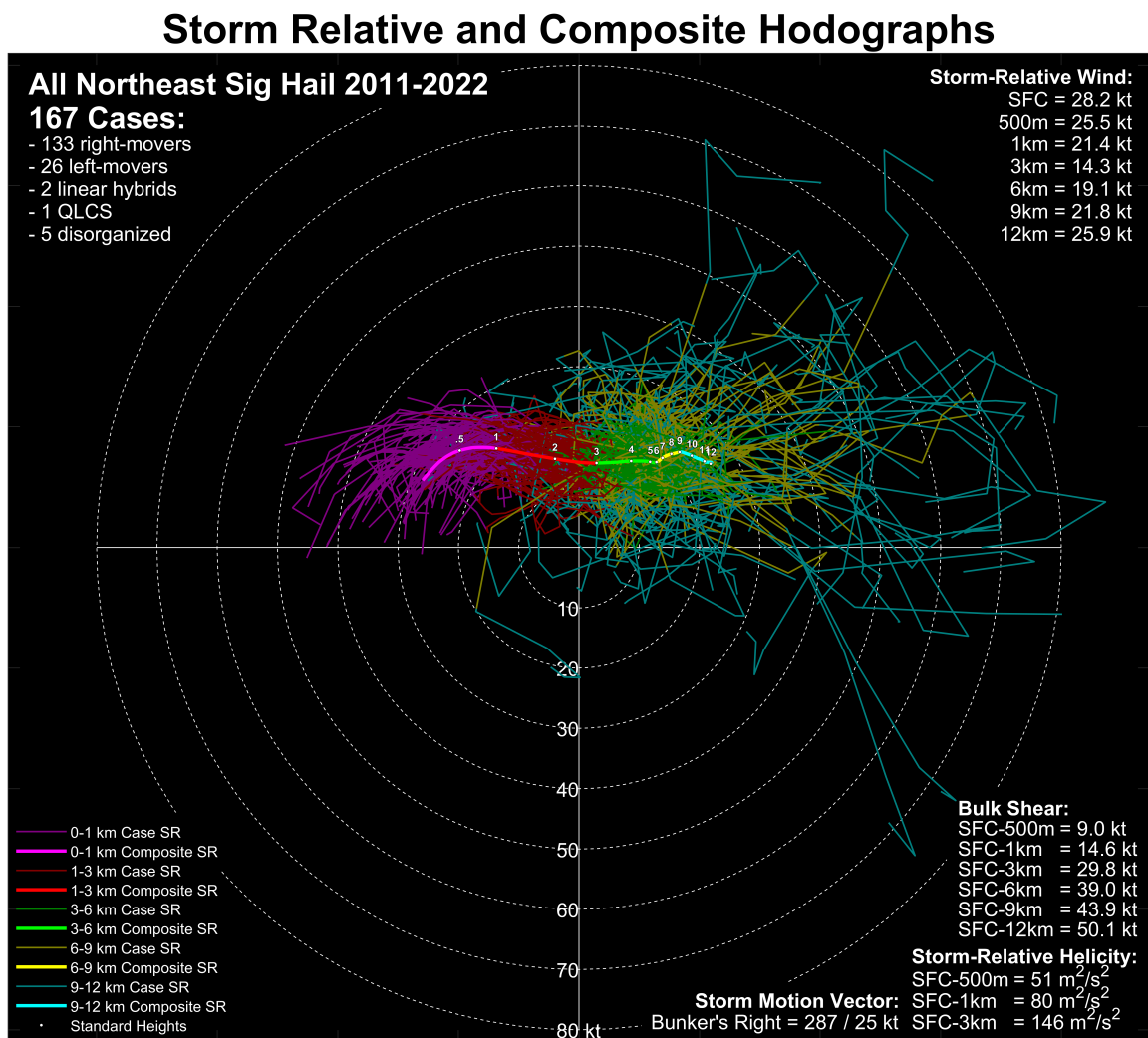


Figure 5.1. A composite hodograph of all 167 sig hail producing cases in the right-mover storm-relative frame of reference. Individual case hodographs are plotted in thinner, duller colors to express variance. The above ground elevation is marked at every kilometer and parameters of interest are noted in the corners of the figure.

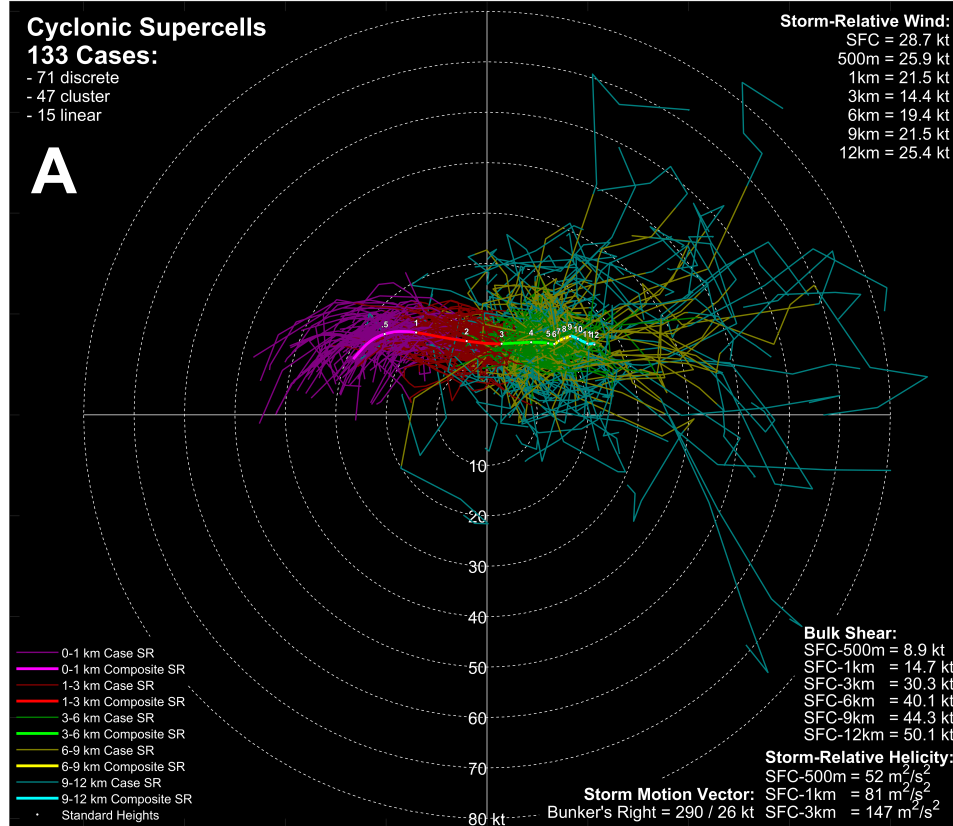
Large bulk wind differences (BWD) can be seen in the composite, particularly within the 1-2-km layer (and to a lesser extent in the 2-4-km layer). Above that, though BWD between each subsequent km is much less, the rather straight shape of the hodograph continues the whole way through the 12-km layer. It begins to deviate from the straight shape slightly starting at the 6-km layer, but this is due to the wide variability of the upper-level winds from case to case, as seen with the individual case plots (duller colors). For example, some cases had similar windspeeds in the 6-12-km layer as in the 3-6-km layer, whereas others had winds that continued to increase with height. That additional shear present above 6 km seemingly is conducive to sig hail production (Johnson and Sugden 2014; Warren et al. 2017). One last detail to note for the shape of the composite hodograph is how much it reveals winds that “back” in 1-7 km layer. In this composite, there is a slight bend back towards the origin within the 1-4 km layer, centered at roughly 2.5 km, but it is only a few kts in magnitude (and likely within the variance of the distribution of winds at this altitude). This “veer-back” pattern has, in the past, been anecdotally associated with negative impacts on supercell longevity and tornadogenesis, though now is suggested to effect supercells far less than other factors like SRH and along-line flow (Parker, 2017). However, for the applications of large hail, backing aloft can provide weaker storm-relative flow through that layer, which may lead to slower hailstone advection speeds across the updraft and thus greater potential residence times and growth (e.g., Kumjian and Lombardo 2020). This pattern is also consistent with the weaker mid-level storm-relative flow that Bunkers (2017) found for supercells whose motion vectors were to the left of that predicted by the Bunkers et al. (2000) method, and thus may explain the $\sim 10^\circ$ discrepancy in observed storm motion direction we found in the previous chapter.

Cyclonic and Anticyclonic Supercell Composites

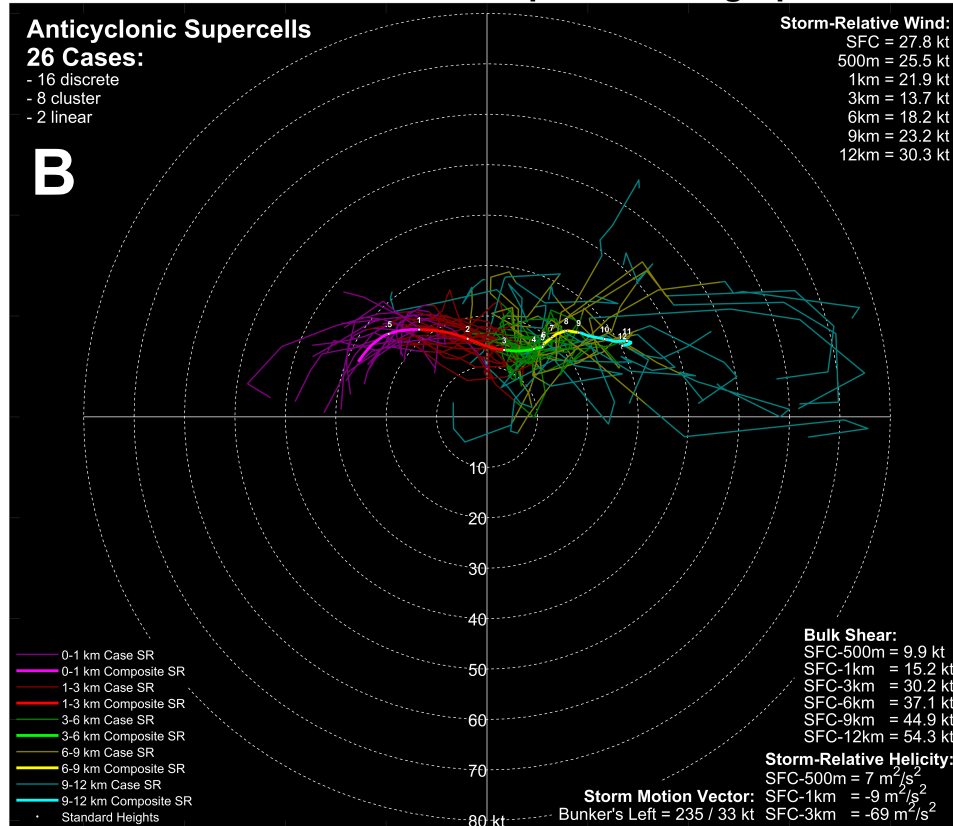
Different groupings of Cases were composited to compare and contrast the shape with the total and with each other in an effort to elucidate any details that may be lost in the overall composite. First, we select right-movers (133 Cases) and left-movers (26 Cases) for compositing (Figure 5.2a and 5.2b, respectively). Separating the 26 left-movers and 8 non-supercellular cases from the total (Figure 5.1) hardly impacted the shape of the resulting composite right-moving hodograph, given that it was dominated by right-moving

supercells. The largest difference between the total composite and the cyclonic supercell composite is a slight shift towards stronger low-level storm-relative wind, with the surface magnitude increasing by 0.5 kts and the 12-km magnitude decreasing by 0.5 kts. There is also a slight elongation in the 0-2-km layer and a slight shortening in the 6-12-km layer. A much more notable contrast is seen between the cyclonic and anticyclonic composites. Figure 5.2c combines these and zooms in for added detail. The anticyclonic composite displays much stronger backing in the 1.5-8-km layer, centered at about 3.5 km. At this level, storm-relative winds are 15.5 kts for the cyclonic composite and 14.7 for the anticyclonic composite. Although this is only a 0.8-knot difference in *storm-relative wind*, the 3.5-km level translated roughly 1.3 kts parallel to storm motion as compared to the same level in the cyclonic composite, while the 1.5-km and 8-km levels translated roughly 1.5 kts and 1.9 kts antiparallel to storm motion; thus, this veer-back-veer shift is not arbitrary and shifts the overall distribution of shear and likely affects storm structure and hail potential (e.g., Fischer et al. 2025). Previous works by Bunkers (2002) and Nixon & Allen (2022) both show a similar contrast in general composite shapes between cyclonic and anticyclonic supercells. Though the anticyclonic hodograph would still be recognized as favorable for cyclonic sig hail producers (57.7% of anticyclonic Cases had cyclonic Cases occur within the same Event), even subtle backing in the mid-levels can enhance the likelihood of a left-mover strengthening to sig-severe levels. Note that many LM Cases were shorter lived. Only 23.1% of left-movers had a hail duration >1 hour, compared to 41.4% of right-movers. This is likely in part because of unfavorable low-level storm-relative helicity. Right-movers on average had $84 \text{ m}^2 \text{ s}^{-2}$ greater 0-3-km SRH than left-movers ($150 \text{ m}^2 \text{ s}^{-2}$ vs $-66 \text{ m}^2 \text{ s}^{-2}$). Considering that many left-movers were likely elevated (some because of near-surface temperature inversions; see section 5.2), we can modify the 0-3-km SRH by removing the positive contribution to the total SRH (which was almost entirely in the lowest 500-m for all 26 Cases). Doing so results in a decrease in SRH to $-91 \text{ m}^2 \text{ s}^{-2}$. Thus, the right-mover composite still features greater low-level SRH magnitude than the left-mover composite, even if accounting for potential differences in the inflow layer.

Storm Relative and Composite Hodographs



Storm Relative and Composite Hodographs



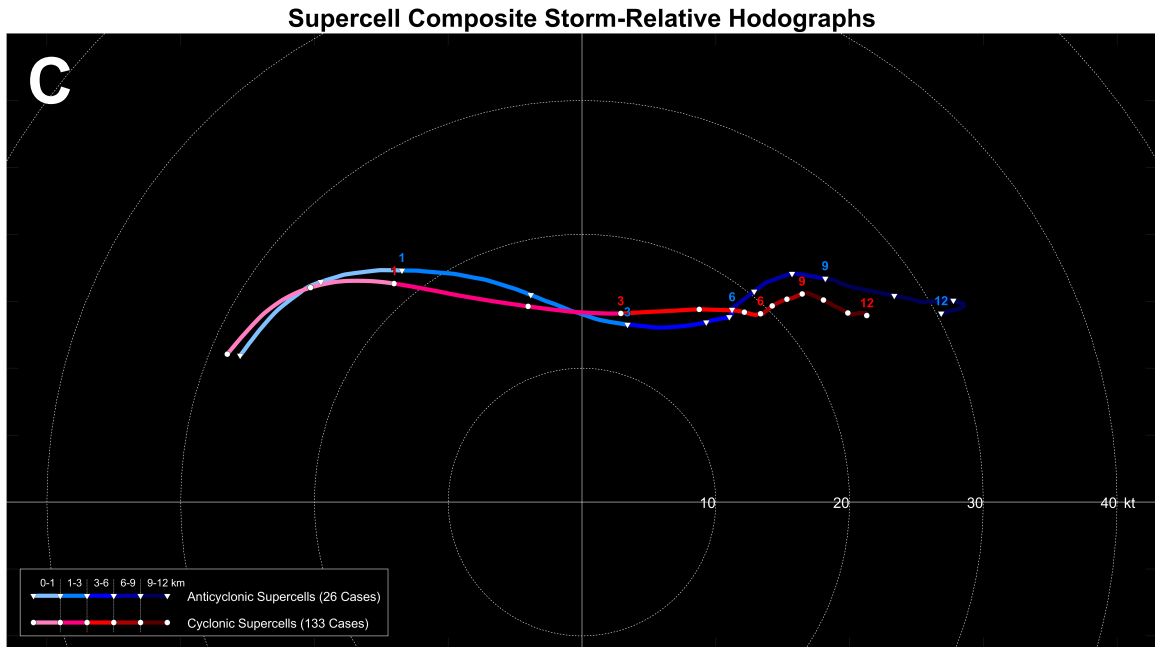


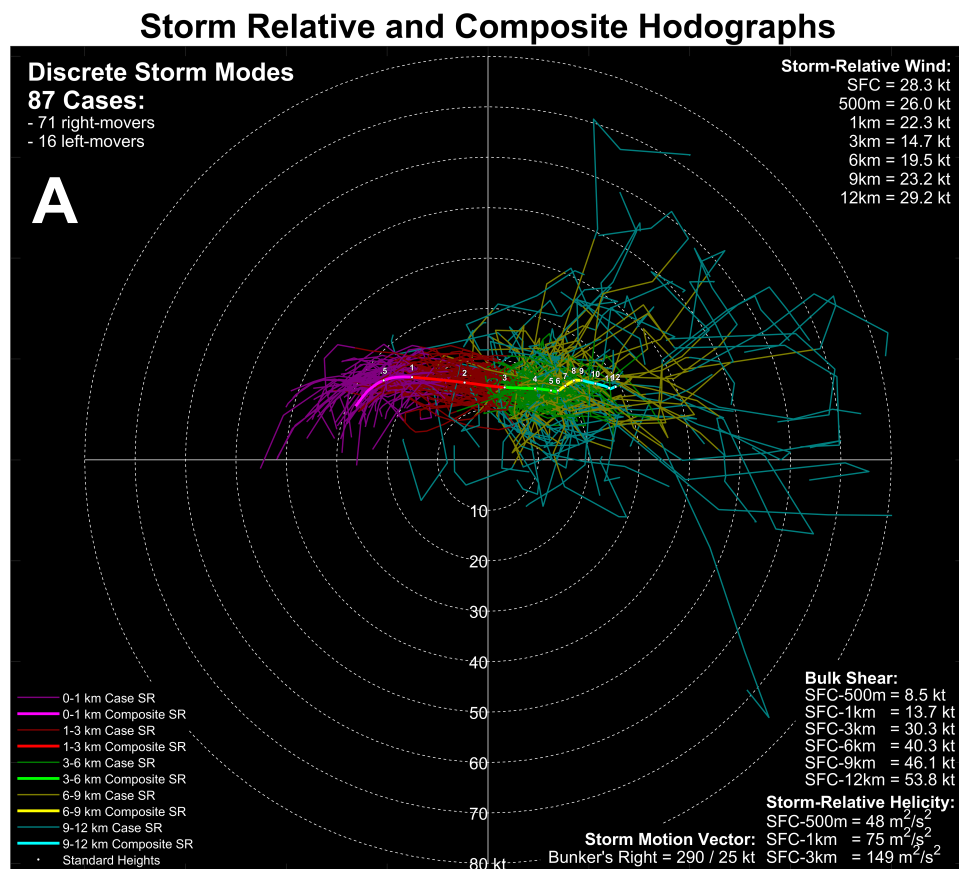
Figure 5.2. Composite hodographs of (a) cyclonic (right-moving) supercells and (b) anticyclonic (left-moving) supercells in a right-mover storm-relative frame of reference. Individual case hodographs are plotted in thinner, duller colors to express variance. The above ground elevation is marked at every kilometer and parameters of interest are noted in the corners of the figure. (c) Composites are zoomed in for greater detail.

Additional Storm Mode Composites

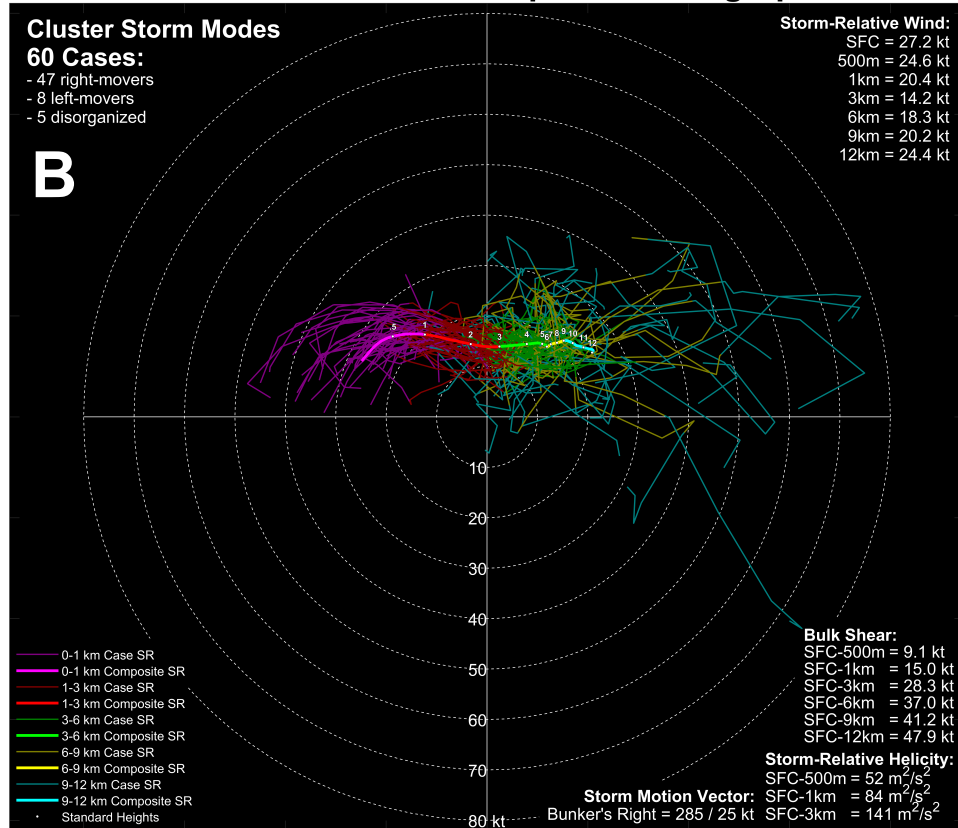
The next set of composites also focused on storm modes. Discrete (87 Cases), Cluster (60 Cases), and Linear (20 Cases) modes were separated (Figures 5.3a, 5.3b, and 5.3c). The two linear hybrid Cases and one QLCS case were grouped with the 17 “cell in line” supercells, and the five disorganized cases were grouped with the 55 “cell in cluster” supercells (cf. Fig. 4.1). An interesting pattern is seen when comparing these three. As one goes from the discrete composite to the cluster composite and then the linear composite, mid-level backing of the storm-relative winds becomes more pronounced (Figure 5.3d). In the discrete composite, the 1-6-km layer features a hodograph that is essentially perfectly straight, and the 2.5-km level has a SR wind magnitude of 14.8 kts. This same layer in the cluster composite has a weaker component of SR wind perpendicular to Bunker’s motion (e.g., backing) of 14.0 kts, and in the linear composite, it is 12.1 kts. In the lowest 1 km, the discrete composite hodograph is slightly more curved than the cluster composite hodograph, and both of which are more curved than the linear composite hodograph. However, the linear composite has larger SR winds at the surface (30.9 kts), compared to

27.2 kts for clusters and 28.3 kts for discrete. This increased SR wind is what contributes to the linear composite's 10-14 $\text{m}^2 \text{s}^{-2}$ larger values of 0-500-m SRH and 9-18 $\text{m}^2 \text{s}^{-2}$ larger values of 0-1-km SRH, not hodograph curvature.

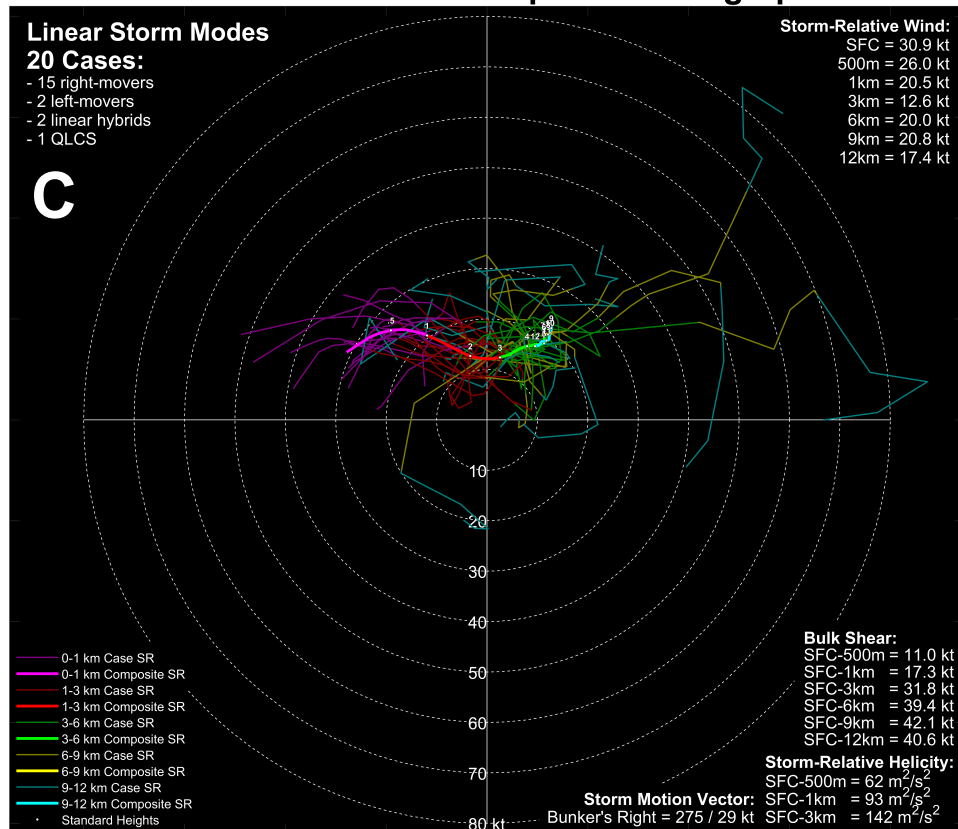
By the 1-km level, though, the discrete composite has nearly 2.0 kts greater of SR wind compared to the other two and 7-8 $\text{m}^2 \text{s}^{-2}$ larger values of 0-3-km SRH, highlighting how much more elongated its hodograph is in the lower and mid-levels. Lastly, while the discrete and cluster composites both have roughly 10 kts of BWD in the 6-12-km layer, the linear composite has only half of that, with a far more curvy shape. Because of the small sample size of 20 cases, and the large variability of upper-level winds from cases to case, it is hard to say how impactful this difference is. But, as seen in Figure 5.3c, only three out of the 20 Cases (15%) had > 50 kts of SR wind at any level above 6 km, though two of the three outliers had the two largest values of SR wind of any other Case (Case 167 - 84.5 kts at 12 km, and Case 121 - 87.7 kts at 10.8 km).



Storm Relative and Composite Hodographs



Storm Relative and Composite Hodographs



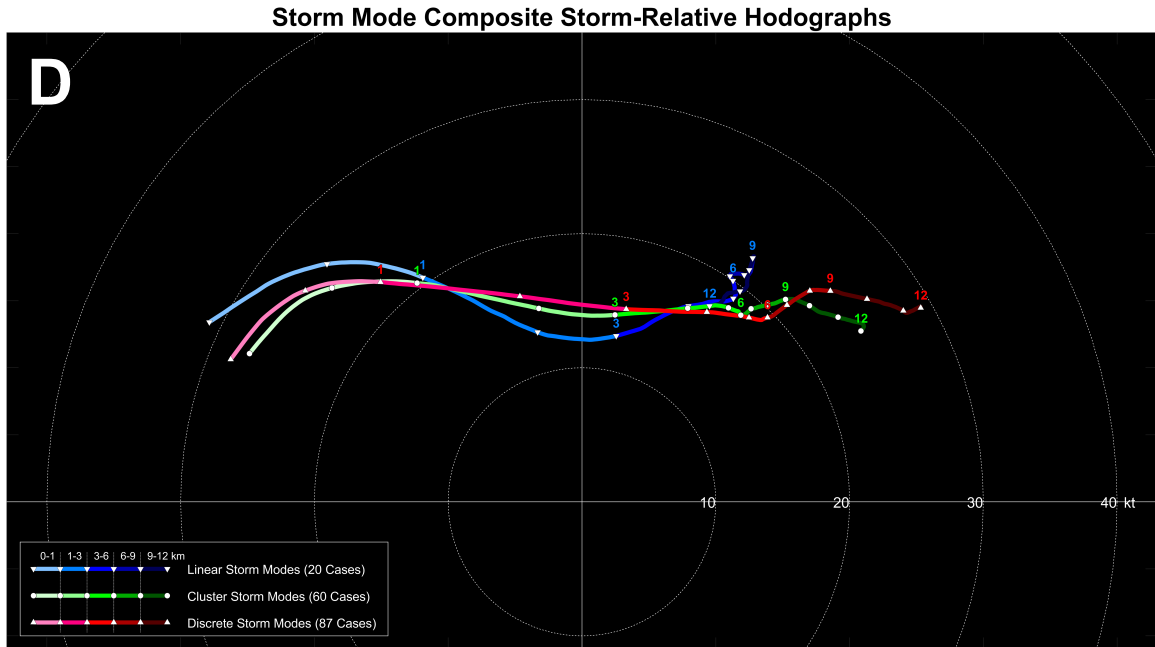
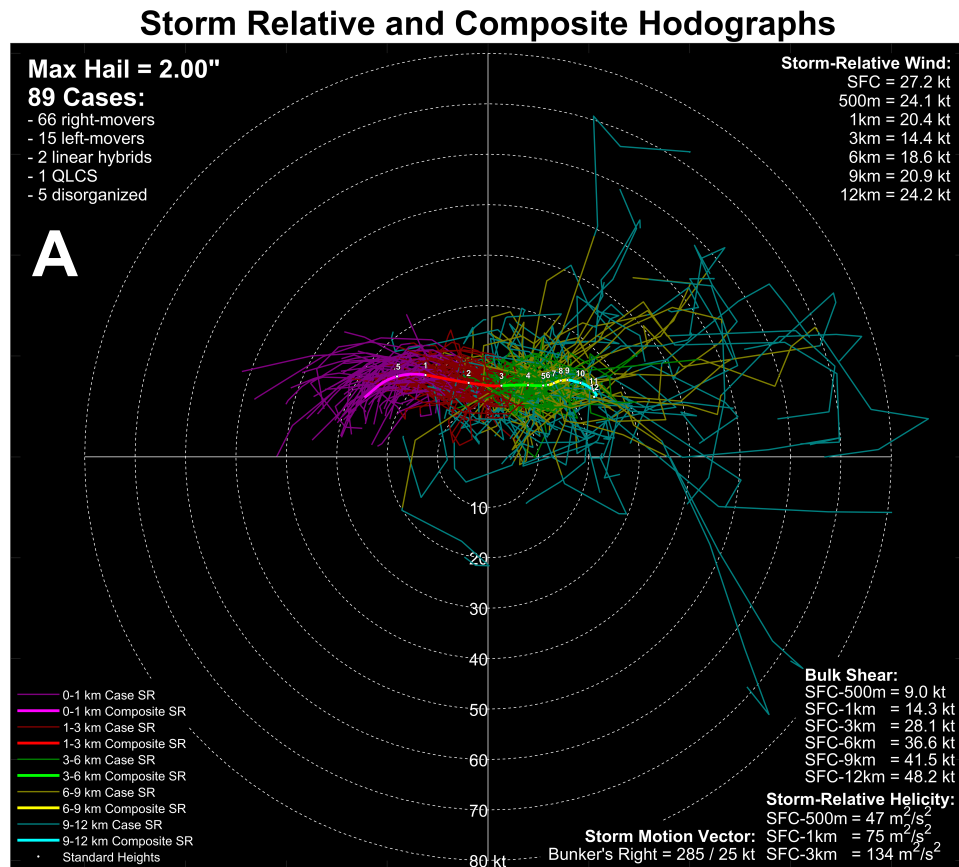


Figure 5.3. Composite hodographs of (a) discrete, (b) cluster, and (c) linear Cases in a right-mover storm-relative frame of reference. Individual case hodographs are plotted in thinner, duller colors to express variance. The above ground elevation is marked at every kilometer and parameters of interest are noted in the corners of the figure. (d) Composites are zoomed in for greater detail.

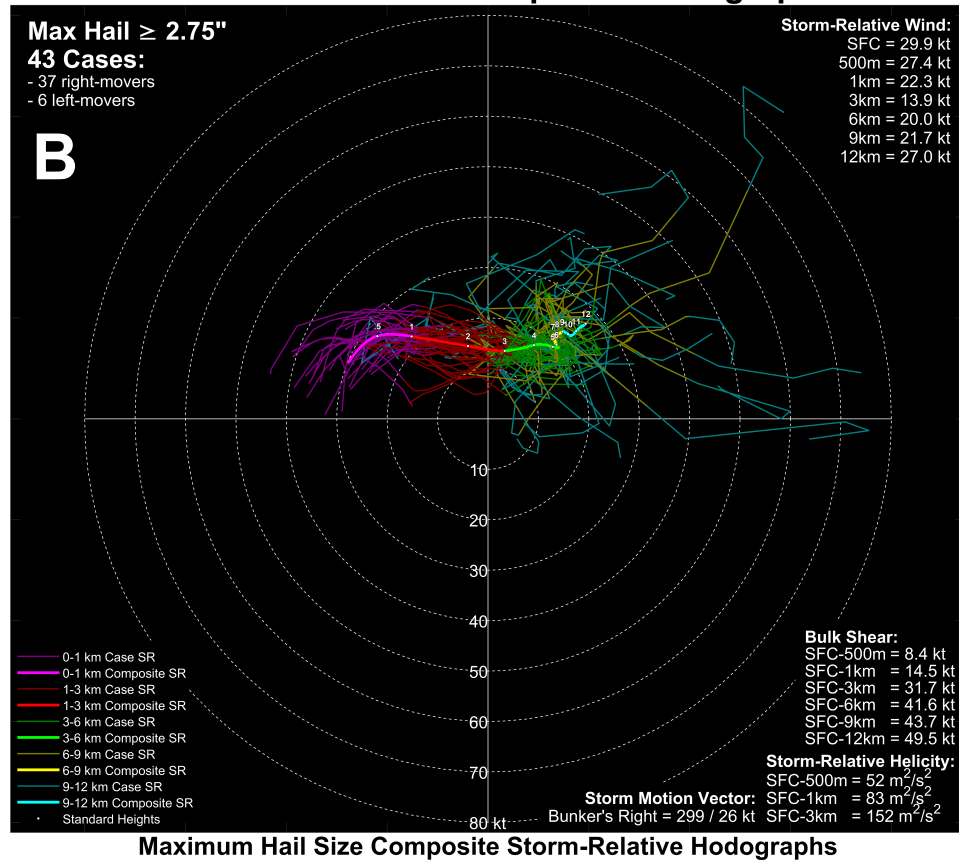
Maximum Hail Size Composites

The maximum hail size reported for each case fell between 2.00" and 4.25" (51 mm and 108 mm). Cases were separated into two size categories: exactly 2.00" and ≥ 2.75 " (70 mm) which equates to baseball-sized or larger (Figures 5.4a and 5.4b). Cases with a maximum hail size of 2.25" or 2.50" (57 mm or 64 mm) were filtered out from these two groups to provide a larger separation between the size categories, in part to account for reporting biases described earlier. There is a large increase in SR winds at the surface, 500 m, and 1-km levels in the $\geq$ baseball-sized composite (Figure 5.4c), the largest of which is a 3.3-kt increase from 24.1 kts to 27.4 kts at 500 m. Additionally, there is moderately more enhanced curvature in the hodograph in this layer, which is supported by an increase of $5 \text{ m}^2 \text{ s}^{-2}$ and $8 \text{ m}^2 \text{ s}^{-2}$ SRH at the 0-500-m and 0-1-km layers, respectively, even though bulk shear in the 0-500-m layer actually *decreased* by 0.6 kts for the $\geq$ baseball-sized composite. An increase of $18 \text{ m}^2 \text{ s}^{-2}$ of SRH was noted in the 0-3-km layer, which, unlike the lower layers, is entirely due to an increased bulk shear of 3.6 kts, a majority of which is within the 1-2-km layer. Farther aloft, both the 3-4-km and 4-5-km layers are more elongated in the $\geq$ baseball-sized composite, and, though the 6-12-km bulk shear for both composites is

similar, the last few kilometers of the $\geq$ baseball-sized hodograph bend further away from the origin, increasing the 12-km SR wind by 2.8 kts, which is consistent with findings made in Homeyer et al. (2023). Though the $\geq$ baseball-sized composite has only half as many samples as the exactly 2.00" composite, this observation does suggest that larger upper-level SR wind is important for sig hail production. Further, recent modeling work by Lombardo and Kumjian (2025) showed that greater shear concentrated in the 2-4 km layer leads to enhanced hail sizes owing to storms having greater off-hodograph motion and thus greater low-level SR winds; the hail size composites seem to be consistent with this finding.



Storm Relative and Composite Hodographs



Maximum Hail Size Composite Storm-Relative Hodographs

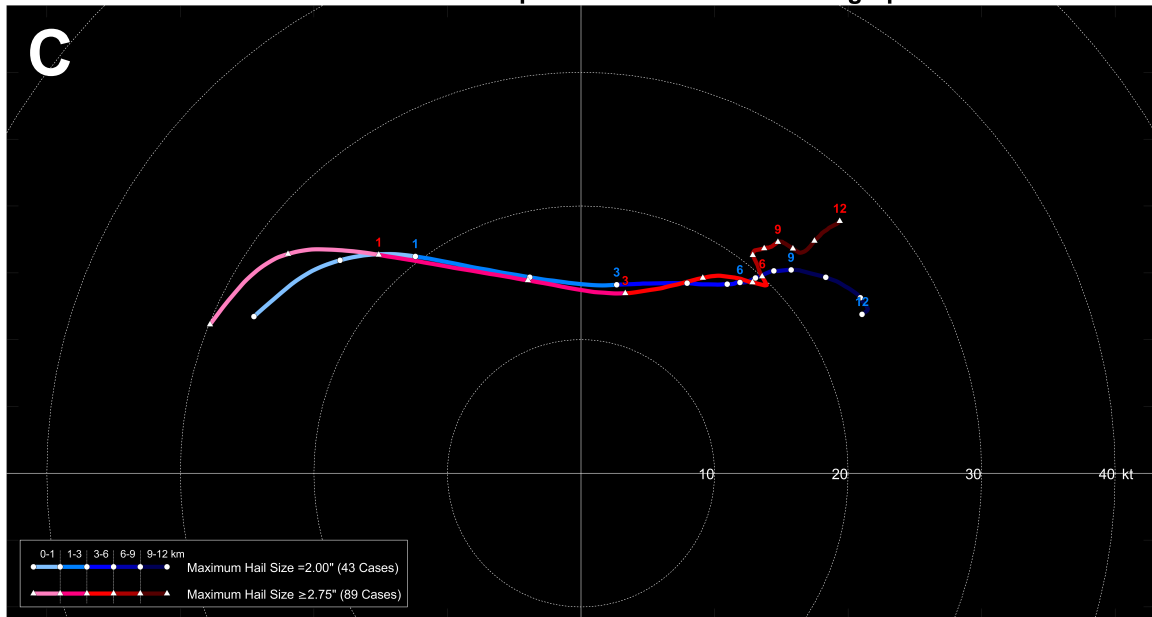
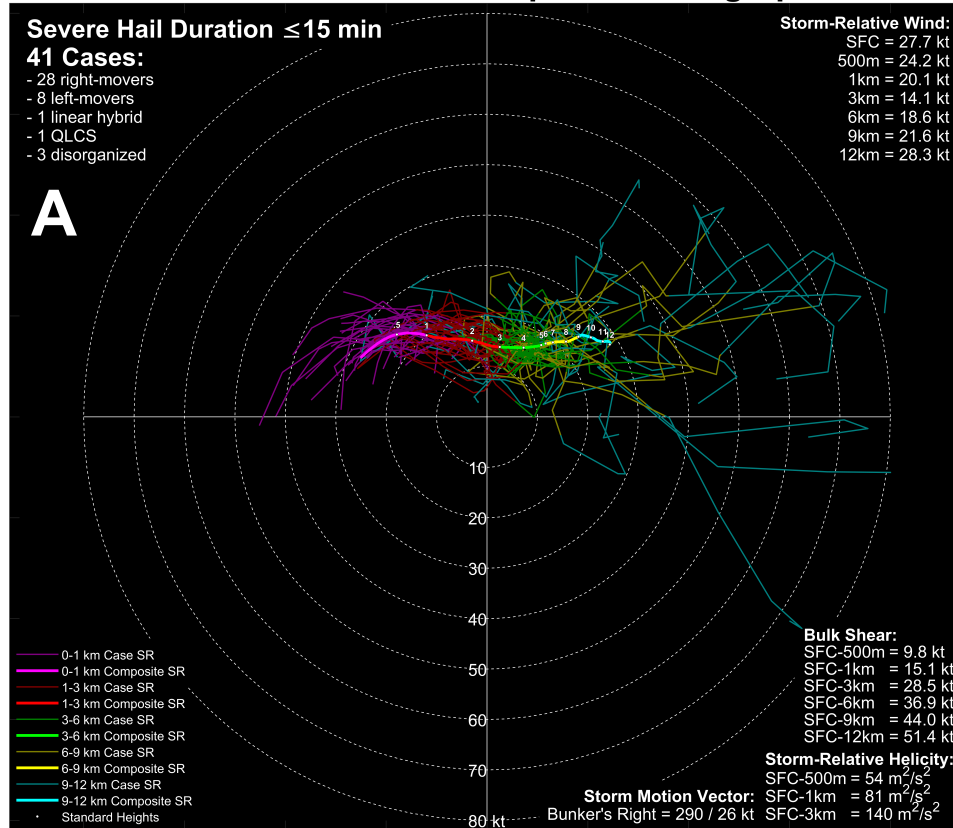


Figure 5.4. Composite hodographs of cases that produced (a) exactly 2.00" hail and (b) 2.75" or larger hail in a right-mover storm-relative frame of reference. Individual case hodographs are plotted in thinner, duller colors to express variance. The above ground elevation is marked at every kilometer and parameters of interest are noted in the corners of the figure. (c) Composites are zoomed in for greater detail.

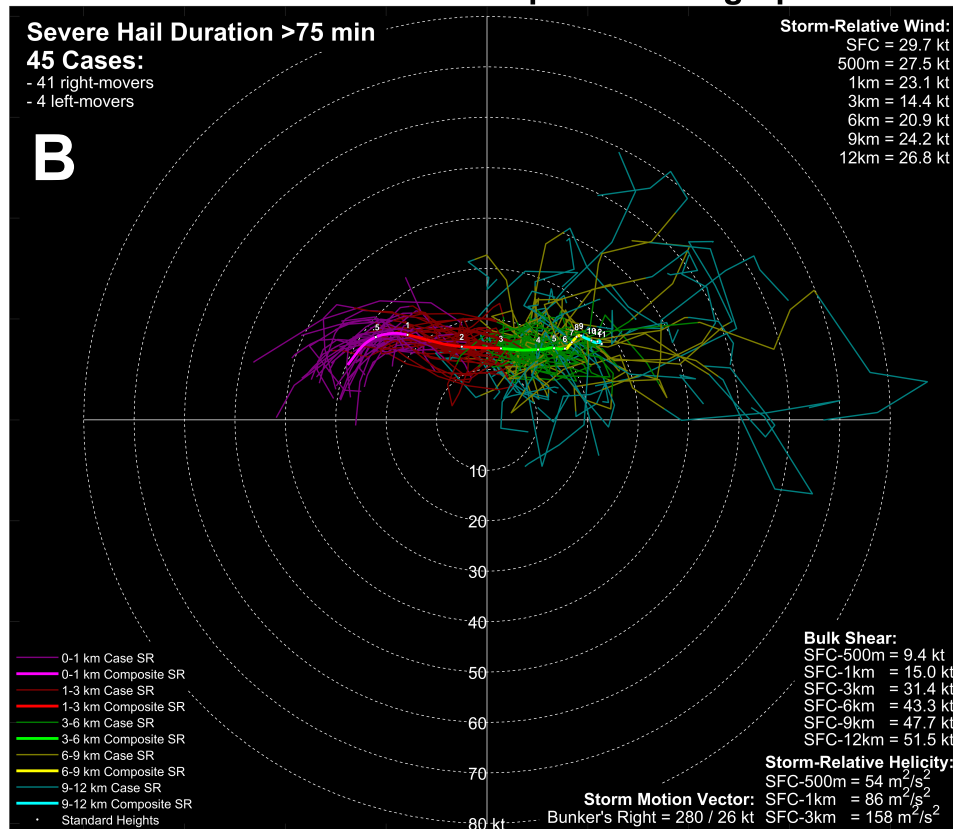
Hail Duration Composites

The duration of severe hail associated with each sig hail Case was divided into two groups: Cases with a duration of ≤ 15 min were considered short-lived and Cases with a duration of > 75 minutes were considered long-lived (Figures 5.5a and 5.5b). These values were chosen yet again to separate the two groups from Cases with closer to average durations, so two distinct groups could be analyzed. These cut-offs also led to each group having roughly the same sample size: the short-lived composite has 41 Cases and the long-lived composite has 45 Cases. Interestingly, a fairly similar contrast was observed between these two composites and the maximum hail size composites (Figure 5.5c). There is again a sharp increase in SR winds in the lowest 1-km, and a larger curvature in the hodograph for the long-lived composite. The SR wind difference is slightly less than in the previous composites (3.0 kts) and the largest difference is now at the 1-km level. Though there is no difference in 0-500-m SRH values between the short- and long-lived composites, the 0-1-km SRH is $7 \text{ m}^2 \text{ s}^{-2}$ larger and the 0-3-km SRH is $18 \text{ m}^2 \text{ s}^{-2}$ larger for the long-lived composite owing to the increased low-level curvature and elongation of the hodograph. Above these levels, every 1-km section from 1-6-km is much more elongated in the long-lived composite, and by 6-km, there is a 6.4-kt increase in 0-6-km BWD. Unlike the last set of composites, there is a decrease of upper-level SR wind in the long-lived composite, but only in the last few kilometers, as the 12-km level decreased by 1.5 kts, yet the 9-km level increased by 2.6 kts.

Storm Relative and Composite Hodographs



Storm Relative and Composite Hodographs



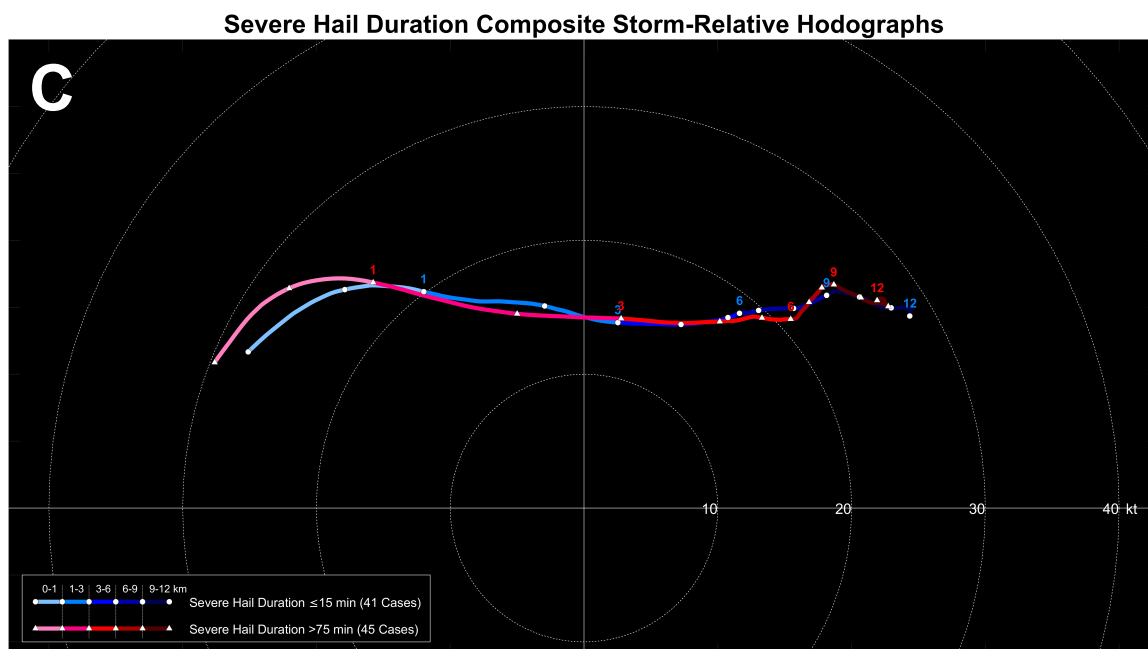


Figure 5.5. Composite hodographs of cases with durations of (a) 15 minutes or less and (b) durations greater than 75 minutes in a right-mover storm-relative frame of reference. Individual case hodographs are plotted in thinner, duller colors to express variance. The above ground elevation is marked at every kilometer and parameters of interest are noted in the corners of the figure. (c) Composites are zoomed in for greater detail.

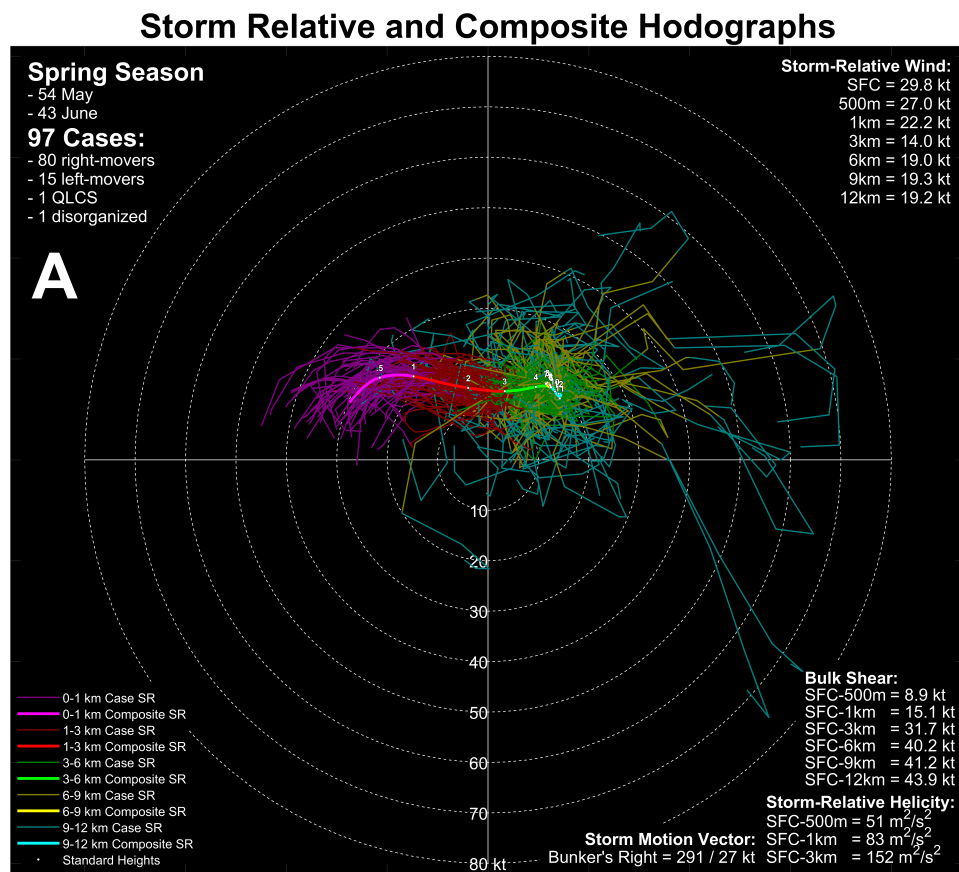
Seasonal Composites

All but one Case occurred between 23 March and 2 October in their respective years (Case 167 being an extreme outlier on 27 November). The Cases were divided into three “Seasons”: Spring consisted of May and June; Summer, July and August; and Early/Late Season was March and April plus September, October, and November (Figures 5.6a, 5.6b, and 5.6c). The Early/Late Season composite featured extreme BWD over the entire depth of the troposphere considered. Almost every layer had nearly equal or larger BWD than the Spring and Summer composites, except for the 1-2-km and 2-3-km layers (Figure 5.6d). Though a 22-Case composite is a smaller sample size, this signal is robust. The Early/Late Season composite includes months that typically are not associated with severe weather in the Northeast US, owing mostly to a lack of instability (e.g., Hurlbut and Cohen 2014). However, there are indications that, when considering CAPE and shear, if one is lacking, the other can “make up for it” by having larger quantities than what is normally necessary to meet the threshold for severe weather; this is particularly common in the southeastern U.S. in so-called “high-shear, low-CAPE environments” (e.g., Wade and Parker 2021). As

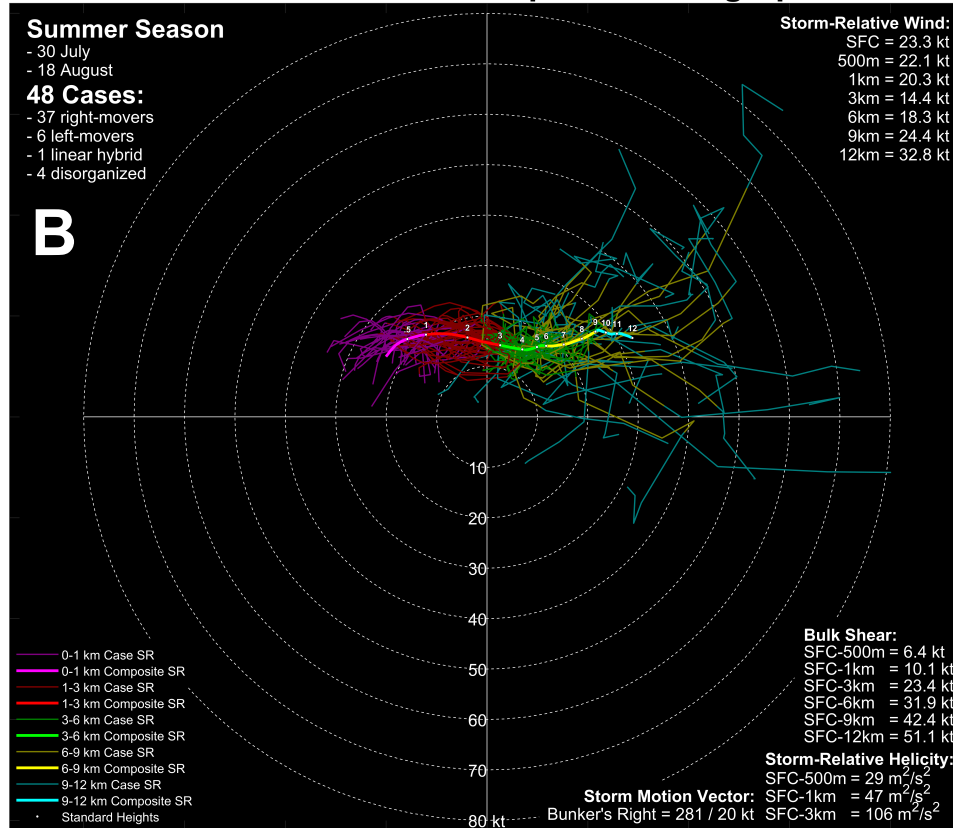
will be discussed more in the next section, Early/Late Season Cases were almost entirely dominated by such high-shear, low-CAPE environments. The extreme shear is particularly striking below 3-km and above 9-km in Figure 5.7d. From 0-500 m, the BWD for the Early/Late Season composite was 6.2 kts greater than the Spring composite, and 8.7 kts greater than the Summer composite. From 0-1-km, the magnitude is even larger, a 7.3-kt and 12.3-kt increase, respectively. This contrast lessens a bit from 0-3-km, with a 3.6-kt and 11.9-kt increase. Though low-level SR wind is within a few kts for all three composites from 1-3-km, there are large disparities below 1-km. The 500-m and surface SR wind for Summer are shifted roughly 5-6 kts closer to the origin than Spring. This weaker SR wind could lead to narrower updrafts and less potential updraft velocity (e.g., Peters et al. 2019). Spring shares a similar low-level hodograph shape to Early/Late Season, with the 500-m level having roughly equal SR wind, yet the surface to 500-m layer is much shorter. Though this only equates to a 3.2-kt decrease in surface SR wind, SRH aids in highlighting how dissimilar the lower-level wind fields are between all three seasons: 0-500-m SRH almost doubles from Summer to Spring to Early/Late Season from $29 \text{ m}^2 \text{ s}^{-2}$ to $51 \text{ m}^2 \text{ s}^{-2}$ to $97 \text{ m}^2 \text{ s}^{-2}$, respectively. A similar pattern is seen with 0-1-km and 0-3-km SRH, for which the Early/Late Season produced the largest values of any other composite in this study.

The upper levels tell an interesting story. The Early/Late season has an elongated shape with the 12-km SR wind surpassing both of the other composites by 10-20 kts. However, the Spring composite has surprisingly small magnitudes of SR wind and BWD in the entire 6-12-km layer, while the Summer composite depicts the more classic elongated upper-level hodograph shape. This result is even more striking when considering Figures 5.7b and 5.7c. The individual Case hodograph plots for Spring are extremely clustered between 10 and 25 kts in the northeast quadrant of the plot. In fact, only 16.5% of Cases had SR winds greater than 40 kts at any level above 4-km, while Summer had 43.8% of cases surpassing this threshold. Spring had 97 Cases, so compared to many other composites with a smaller sample size, this sample may be relatively representative of the population. This suggests that some environments in the Northeast U.S. may be more unique to the region for hail production. One possibility is that the lack of upper-level SR winds may have been counteracted by enhanced low-level shear. Both the Spring and Summer composites had

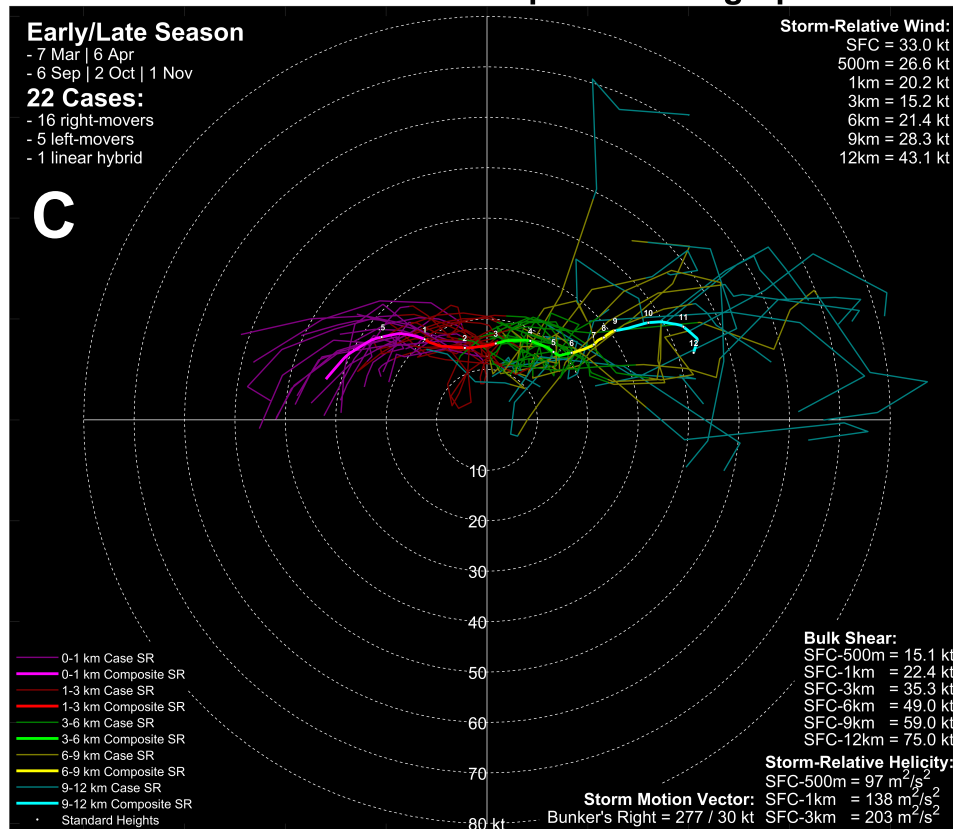
larger BWD in the 2-3-km layer, at 7.3 kts and 6.7 kts compared to 6.2 kts respectively, but more striking was the 1-2-km layer. As with many other composite comparisons in this study, a large difference was found in the 1-2-km layer. Early/Late Season and Summer composites displayed similar BWD at 8.2 and 8.3 kts respectively, but the Spring composite had nearly three kts greater, at 11.1 kts.



Storm Relative and Composite Hodographs



Storm Relative and Composite Hodographs



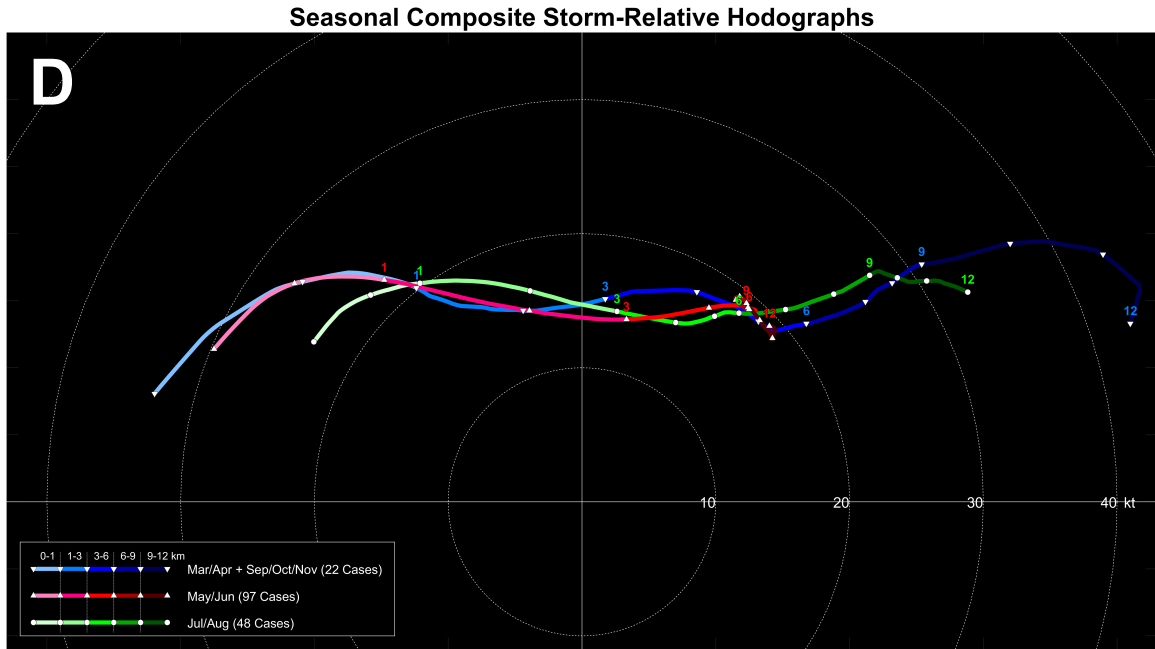
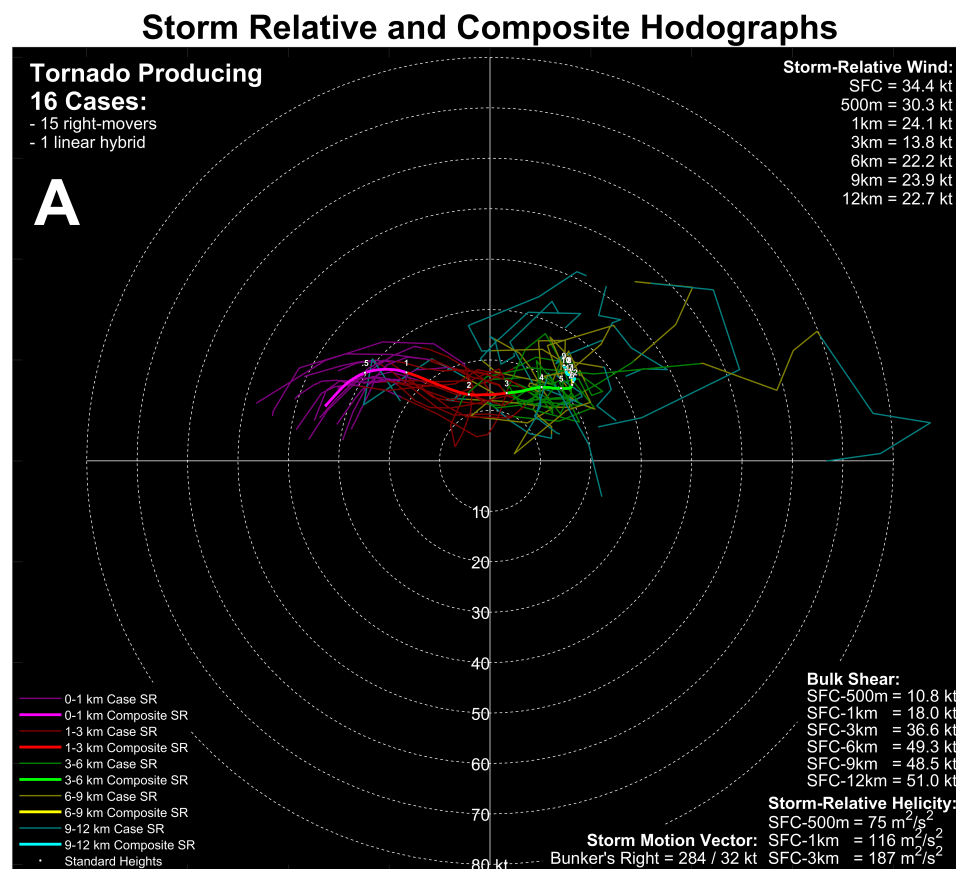


Figure 5.6. Composite hodographs of (a) Spring (May/June), (b) Summer (July/August), and (c) Early/Late Season (March/April/September/October/November) cases in a right-mover storm-relative frame of reference. Individual case hodographs are plotted in thinner, duller colors to express variance. The above ground elevation is marked at every kilometer and parameters of interest are noted in the corners of the figure. (d) Composites are zoomed in for greater detail.

Tornadic vs. Nontornadic Composites

Finally, composites were taken for Cases that produced a tornado and Cases that did not (Figures 5.7a and 5.7b). Though only 16 Cases (9.6%) across 13 Events produced at least one tornado, making this the smallest sample size of any composite, the hodograph *very* closely follows those presented in Nixon and Allen (2022) and Warren et al. (2021). There is an extreme increase in near-surface SR winds, BWD, and SRH for the tornadic composite (Figure 5.7c). The magnitude of SR wind increased by 6.8 kts at the surface, 5.3 kts at 500 m, and 3.0 kts at 1 km for the tornadic composite. It also had significantly more curvature than the nontornadic composite, leading to SRH values increasing by a staggering $27 \text{ m}^2 \text{ s}^{-2}$ from 0-500 m ($48 \text{ m}^2 \text{ s}^{-2}$ to $75 \text{ m}^2 \text{ s}^{-2}$) and $40 \text{ m}^2 \text{ s}^{-2}$ from 0-1 km ($76 \text{ m}^2 \text{ s}^{-2}$ to $116 \text{ m}^2 \text{ s}^{-2}$). The lowest 1 km (especially the 0-500 m level) has been shown to be the most important for tornadogenesis, often depicting extreme values of SRH (e.g., Coffey et al. 2019; Nixon and Allen 2022). Coffey et al. (2019) found a proportionally similar difference in mean 0-500 m and 0-1 km SRH between nontor and weak tor RM supercells; and increases of $63 \text{ m}^2 \text{ s}^{-2}$ ($64 \text{ m}^2 \text{ s}^{-2}$ to $127 \text{ m}^2 \text{ s}^{-2}$) and $82 \text{ m}^2 \text{ s}^{-2}$ ($108 \text{ m}^2 \text{ s}^{-2}$ to $190 \text{ m}^2 \text{ s}^{-2}$)

²). However, as established previously, efficient hail-producing supercells often favor only marginal curvature at the surface and a straighter, longer hodographs with larger SR winds in the upper levels (i.e., above 6 km; Dennis and Kumjian 2017; Warren et al. 2017; Kumjian and Lombardo 2020; Homeyer et al. 2023). These hail-favorable hodographs overlap most closely with the non-tornadic supercell mean hodographs presented in Markowski et al. (2003). This is likely a major factor that contributed to the small percentage of tornadic Cases in our dataset: by selecting for significantly severe hail events, we likely favored non-tornadic hodographs. From about 1-4-km AGL, there is moderate backing of SR wind centered at 2 km. Owing to the small sample size, it is unknown if this artifact would appear in larger composites and the effects of backing aloft have been shown to affect supercell processes far less than other variables, like BWD and SRH (Parker, 2017). Above 6 km, there is surprisingly little increase in SR wind; however, strong upper-level SR winds may not be necessary for tornadogenesis, which is an inherently low-level phenomenon (e.g., Fischer et al. 2024 and references therein).



Storm Relative and Composite Hodographs

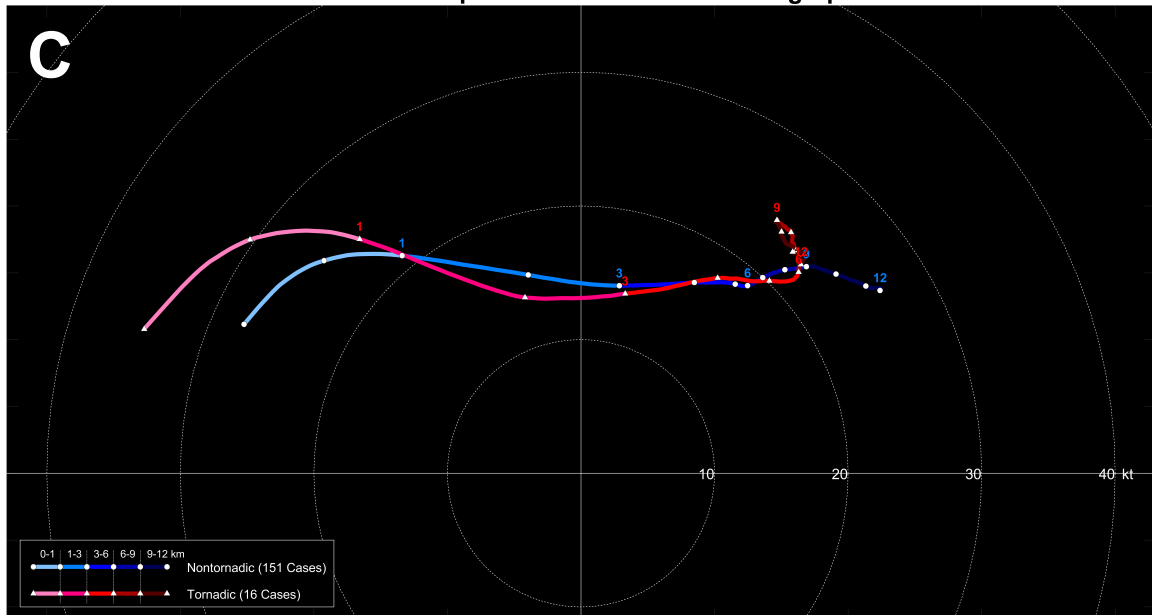
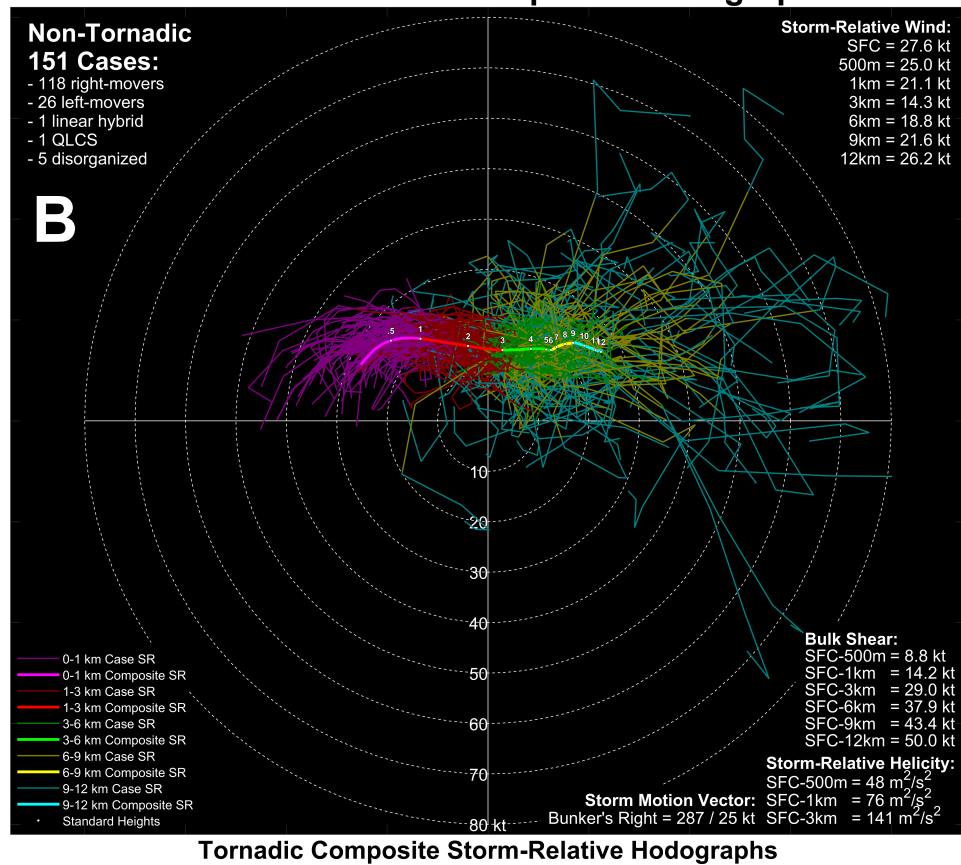


Figure 5.7. Composite hodographs of cases that produced (a) at least one tornado and (b) no tornadoes in a right-mover storm-relative frame of reference. Individual case hodographs are plotted in thinner, duller colors to express variance. The above ground elevation is marked at every kilometer and parameters of interest are noted in the corners of the figure. (c) Composites are zoomed in for greater detail.

5.2 Composite Thermodynamic Environments

While the focus of this Chapter so far was on the characteristics of environmental wind with height, Case skew-Ts were also generated and analyzed to calculate simple thermodynamic parameters. Figures 5.8a and 5.8b show two example Case Skew-Ts (every case has its own in Appendix A). Common forecasting convective parameters (outlined in section 2.4) are plotted in the top right (and listed in Table 5.1). Within the skew-T plots, the lifting condensation level (LCL), level of free convection (LFC), equilibrium level (EL), and the top and bottom of the HGZ are listed, with their exact heights denoted in meters. In the top left corner, the Case ID and latitude/longitude of the central ERA5 grid point are noted. The small map shows the full 9-grid-point box of ERA5 data selected, the location of the sig hail report that the box was centered around, and the Case's hail swath path, marked in the same color scheme as in Figs. 3.4 and 3.5. Both a surface parcel's trajectory (solid black line) and the most unstable parcel's trajectory (dotted black line) were plotted (Figure 5.8b shows an example of an elevated parcel). The date and time in UTC are located in the top right above the parameters in yyyy-dd-mm tttt format.

Though 73 Cases had a most-unstable parcel origination height above the surface per ERA5 calculations, only 11 Cases were deemed to likely have been elevated based on analyzing the thermodynamic profile (Case 3, 19, 25, 73, 104, 106, 136, 137, 138, 139, and 141). Six of these Cases occurred in the Early/Late Season and the other five either occurred in the late evening or early morning hours. The 28 March 2020 Event was the most prolific, having four of its five total Cases being elevated. Cases 137, 138, and 139 were dominated by abnormally spikey hailstones produced by fast-moving “mini” supercells in northern Ohio. Very similarly spikey hailstones were also documented in another northern Ohio elevated supercell from March, Case 106 (images from both can be found in Appendix B).

The mean Case surface temperature and dew point analyzed by ERA5 were 77.4°F (25.2°C) and 64.7°F (18.2°C) respectively. The median value for temperature was similar at 77.6°F (25.3°C) while the median for dewpoint was much higher at 65.8°F (18.8°C), owing to fairly low surface dewpoints in most elevated Cases. There was a 16.2°F (9.0°C) difference between the 90th and 10th percentile temperatures, which ranged from 85.4°F

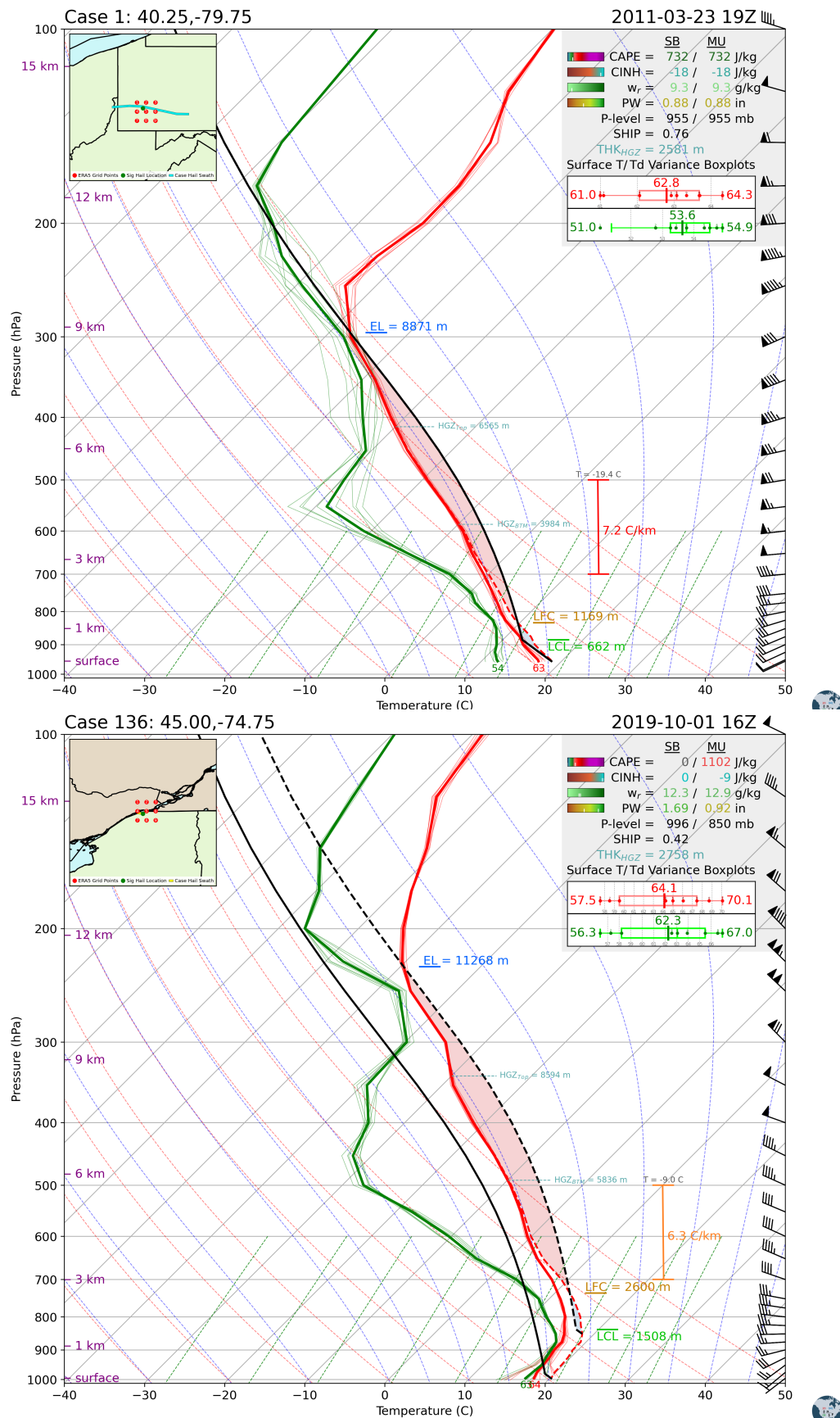


Figure 5.8. Example skew-Ts from Case 1 and 136. All skew-Ts can be found in Appendix A.

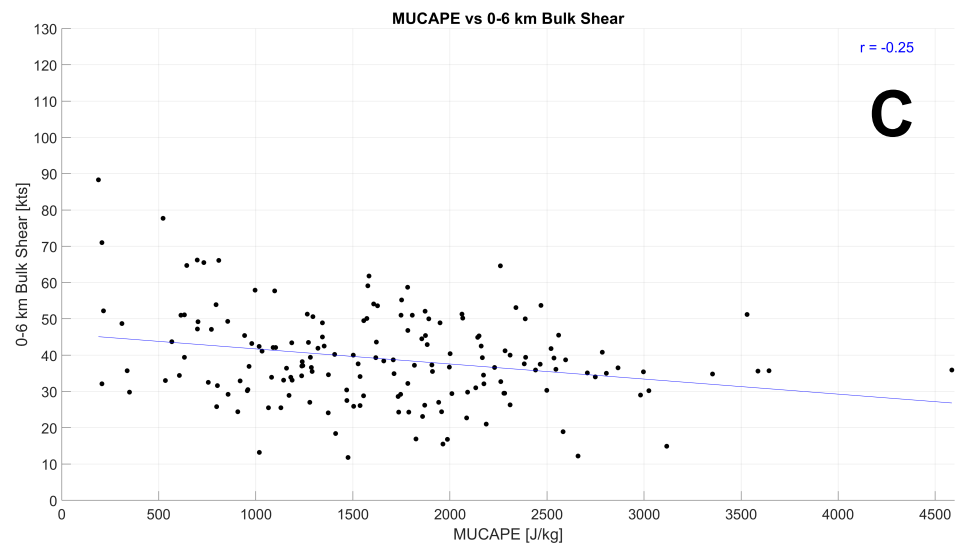
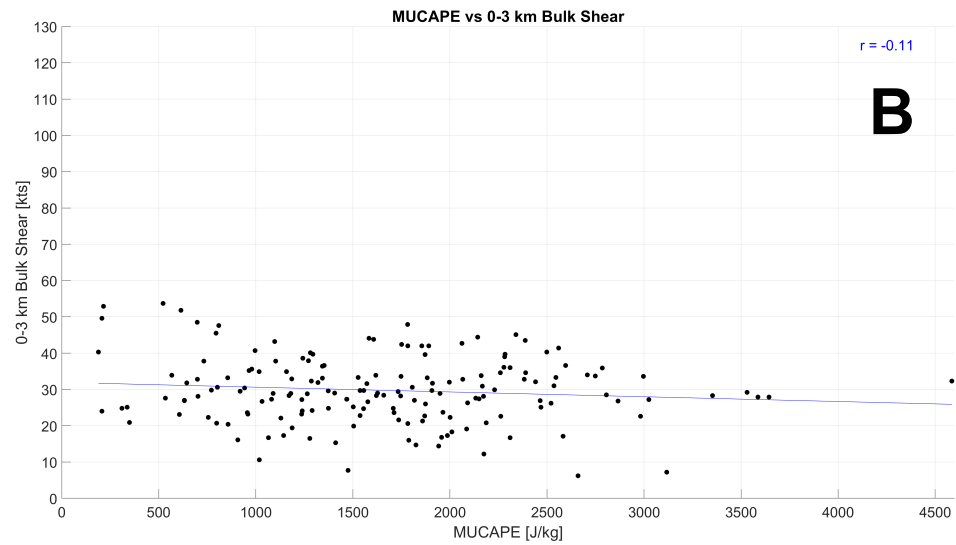
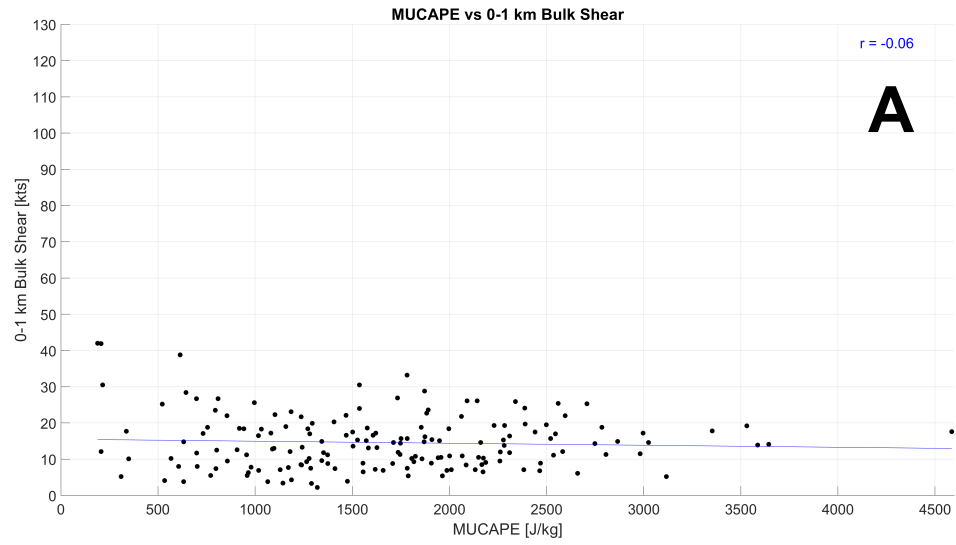
(29.7°C) to 69.2°F (20.7°C). Warmer Cases normally occurred in the summer season (e.g., the 1 August 2011 Event had three of its six Cases within a few degrees of the 90th percentile temperature). Surface temperatures close to the 10th percentile had a bias towards early and late season, but also occurred in Cases in the spring and summer months (Cases 82, 32, and 95 being examples). Dew points had a lower variance than temperature of 11.5°F (6.4°C) at these percentiles, with a range of 69.1°F (20.6°C) to 57.6°F (14.2°C). A majority of Cases that had a dewpoint near or below the 10th percentile were elevated; the others either had large dewpoint depressions with “inverted-V” shaped soundings or were Cases that had relatively cooler temperatures through the entire depth of the atmosphere (e.g., Cases 1 and 82, for example). The mean and median dewpoint depressions were 12.7°F (7.1°C) and 12.4°F (6.9°C). The more extreme Cases in the 90th percentile had a dewpoint depression $\geq 20.9^\circ\text{F}$ (11.6°C) and included Cases like Case 8, 51, 50, and 54, which had the maximum dewpoint depression of 31.1°F (17.3°C). Case 162 is a perfect example of a thunderstorm with the inverted-V environmental profile, which favors downbursts: the storm produced a measured wind gust of 89 kts coincident with one of its sig hail reports.

The mean and median most unstable (MU) mixing ratios were 13.60 g kg⁻¹ and 13.95 g kg⁻¹, respectively, and the 90th and 10th percentile range was from 15.85 g kg⁻¹ to 10.79 g kg⁻¹. Lapse rates in the 700-500-hPa layer were surprisingly marginal for most Cases, with a mean of 6.33°C km⁻¹ and a median of 6.30°C km⁻¹. Even the 90th percentile was only 6.94°C km⁻¹, and the 10th percentile was 5.66 C°km⁻¹. These relatively weak lapse rates suggest elevated mixed layers were not common in the dataset. The mean and median 500-hPa temperatures were -10.9°C and -10.8°C, respectively. The 90th to 10th percentile range was -8.2°C to -13.4°C, but there was a much larger outlier in the minimum, which was 6.0°C colder than the 10th percentile, while the maximum was only 0.9°C warmer than the 90th percentile. A majority of the lowest 500-hPa temperatures occurred with early season Cases (not as much with late season Cases), but it was not exclusive to these months. Cases 82, 83, and 84 from the 22 May 2014 Event had 500-hPa temperatures ranging from -15.4°C to -19.3°C, and a few other Cases outside of March, April, or November had values near the 10th percentile.

CAPE in Northeast U.S. severe weather events is often much smaller than in other regions, like the central Great Plains (Lombardo and Colle 2011). CAPE was calculated using the “virtual temperature adjustment” as this has been proven to be a more accurate representation of the potential thermodynamics that an updraft has access to, especially in lower CAPE environments (Doswell and Rasmussen, 1994)⁹. When using this method, values of CAPE increased by roughly 15-17% for most categories of interest presented in this chapter. The mean SBCAPE and MUCAPE were 1586 J kg⁻¹ and 1655 J kg⁻¹, respectively. These values decrease slightly to 1577 J kg⁻¹ and 1618 J kg⁻¹ when considering the median. Five outlier Cases had >3300 J kg⁻¹ of SBCAPE, four of which occurred during the same event (Cases 20-23 on 8 June 2011; the 6th largest SBCAPE also occurred during that event). These values are far below the “typical” values for sig hail reported in climatologies heavily weighted by the U.S. Great Plains. While they are within the range seen in the Lombardo and Colle (2011) study of Northeast coastal convection (MUCAPE ≈ 1200 J kg⁻¹), Johnson and Sugden (2014) evaluated ERA5 MUCAPE of 137 Cases of hail ranging from 2.00-3.25 in (predominantly from the Great Plains) and found a mean of 2671 J kg⁻¹. Even the 25th percentile (1909 J kg⁻¹) was larger than the mean of Northeast sig hail environments. Interestingly, CAPE distributions appear relatively similar to that of Spain. Calvo-Sancho et al. (2022) found a median SB and MUCAPE of 1231 J kg⁻¹ using ERA5 data for 43 Cases of sig hail occurring between 2011-2020.

MUCAPE varied largely between seasons. The Spring Season saw a mean of 1822 J kg⁻¹ and median of 1788 J kg⁻¹; the Summer Season, 1662 J kg⁻¹ and 1632 J kg⁻¹; and the Early/Late Season, 900 J kg⁻¹ and 832 J kg⁻¹. The Early/Late season Cases had, on average, significantly less CAPE than the other two seasons, which lends further credence to the concept of overcoming smaller CAPE with stronger shear as mentioned above. Figures 5.9a through 5.9e are scatterplots showing MUCAPE versus BWD over five different layers of the atmosphere. There is little association in the 0-1 km layer (Pearson’s correlation coefficient $r = -0.06$), but as the layer depth is increased, negative correlation increases in magnitude. By 0-6 km, $r = -0.25$, signifying a weak association, and by 0-12

⁹ The most extreme increase was for Case 167. The original SBCAPE value analyzed was only 64 J kg⁻¹, but this increased to 201 J kg⁻¹ using the virtual temperature adjustment.



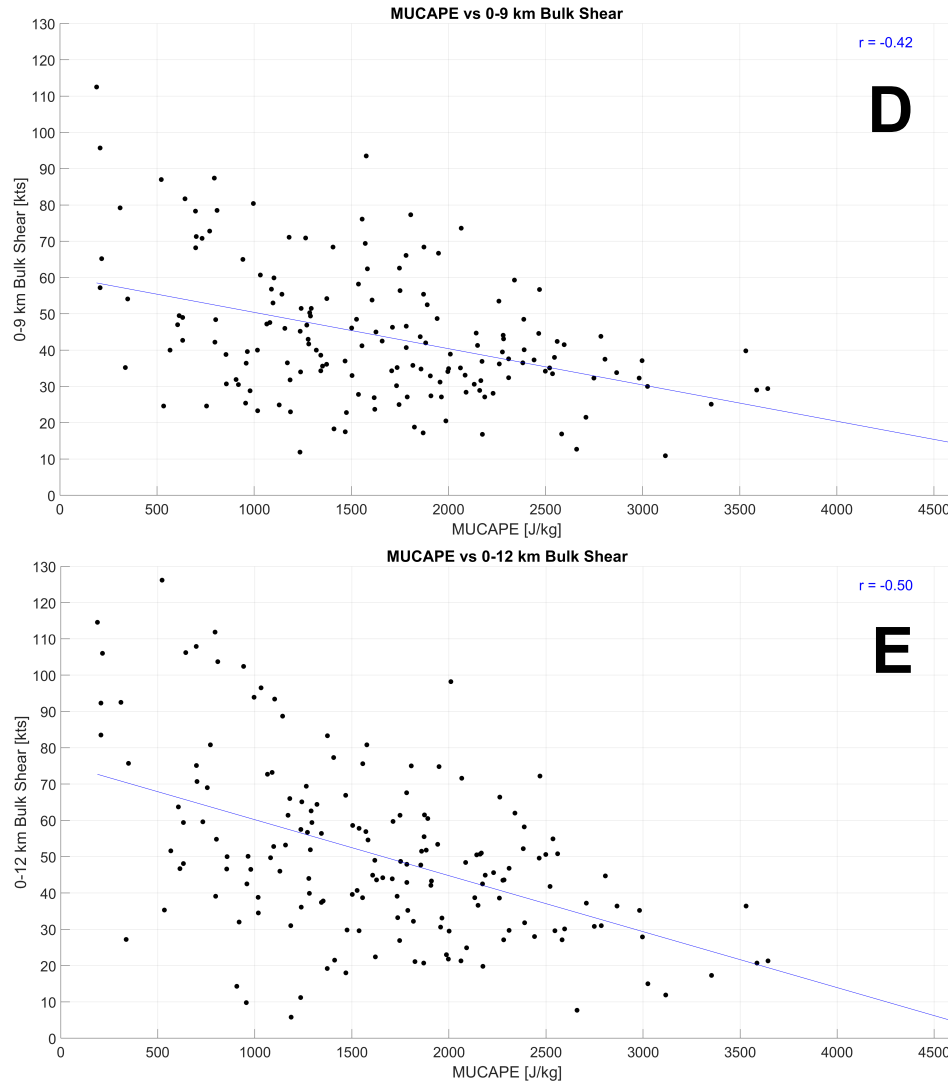


Figure 5.9. Scatter plot of case MUCAPE vs BWD from (a) 0-1 km, (b) 0-3 km, (c) 0-6 km, (d) 0-9 km, and (e) 0-12 km, with Pearson's correlation coefficient r plotted.

km, $r = -0.50$ reaches the level of moderate association. The variability between individual Cases is large, yet a definite relationship between the variables exists. Lastly, the mean and median MUCAPE of elevated Cases was 1051 J kg^{-1} and 809 J kg^{-1} , respectively. Though the sample size is small, it is reasonable to state that elevated Cases on average had much less MUCAPE than non-elevated Cases.

SBCIN and MUCIN were also calculated from the composite profiles. The SBCIN of elevated Cases was excluded from the averages. SBCIN had a mean and median of -19 and -12 J kg^{-1} , respectively, while MUCIN had a mean and median of -13 and -5 J kg^{-1} . The

10th percentile of SBCIN and MUCIN was -46 J kg^{-1} and -32 J kg^{-1} , respectively. There were a handful of outliers well below this, however, with minimum values of -212 J kg^{-1} and -148 J kg^{-1} . Some of these extreme outliers may be unrealistic, though. For example, Case 121 occurred in NW PA and SW NY very close to Lake Erie on 14 April. Lake temperatures were still in the upper 30s °F (roughly 3-4°C) while land temperatures were in the upper 60s °F (roughly 20°C). Five of the nine ERA5 grid points were likely not representative of the inflow environment to the south that the storm was ingesting, so there is a large negative CIN bias. Still, in the individual Case skew-T (Appendix A), every grid point profile depicts a warm nose near 750 hPa, so CIN was likely still large; however, it appears to have been counteracted by the largest BWD of any case in the study. There are likely other thermodynamic biases like this in the ERA5 data analysis method, but it is impossible to account for every Case's potential environmental biases.

On average, Case LCLs were under 1 km, with a mean of 993 m and a median of 954 m. The 90th percentile LCL was 1552 m, which included Cases that had dry but well-mixed boundary layers and elevated Cases, and the 10th percentile LCL was 459 m. The LFC was considerably higher on average, with a mean of 1614 m and median of 1555 m. The separation of these two levels was mostly due to low-level CIN that could have eroded more by the time sig hail was produced or was overcome by forcing for ascent. The EL varied quite a bit between Cases. The mean and median were 11196 m and 11427 m, but the 90th and 10th percentiles ranged from 13046 m to 9196 m. Some of the lower-EL Cases were shallower convection setups, often in the Early/Late season (Case 1, 82, and 167 for example), but sometimes due to “skinny” CAPE (Case 10, 33, and 111 for example).

The mean HGZ thickness was 2950 m with a 25th and 75th percentile thickness of 2811 m and 3068 m. This is shallower than the same statistical range found by Johnson and Sugden (2014) of 2832 m to 3169 m for 2.00-3.25” hail. Interestingly, this finding aligns closer with the ≥ 3.50 ” hail range of 2725 m to 3062 m, even though only 9 cases (5.4%) produced hail of this size. Though the HGZs in Northeast environments were only marginally shallower, it is compelling to report, because Johnson and Sugden (2014) noted a negative

correlation between HGZ thickness and hail size in their study. This highlights how there can be substantial regional differences in environments conducive to large hail.

5.3 Significant Hail Parameter

The significant hail parameter (SPC 2014) was designed to be an accurate predictor of favorable sig hail environments. However, certain biases have been shown to greatly affect this simple predictive parameter, like large MUCAPE “bullseyes” which may align with regions of weaker shear that over-predict sig hail, and “high-shear, low-CAPE” regimes that likely under-predict sig hail or even show it to be impossible (i.e., SHIP = 0), even though these environments have been proven to generate hail through modeling (e.g., Wade and Parker 2021). There are other versions of this equation, but the original form was used in this study both for simplicity and it was found to predict sig hail the best for the particular Cases in this study. Still, the predictive ability of SHIP was lacking with this dataset. Figure 5.10 displays each Case’s maximum hail size versus the calculated SHIP. Though the r -value between the two variables suggests moderate association, only 39 Cases (23.4%) had a SHIP ≥ 1.00 . Theoretically, 100% of Cases should have SHIP ≥ 1.00 if it were a reliable indicator of sig hail in the Northeastern U.S. Instead, the mean and median values of SHIP were 0.73 and 0.62, respectively. A few Cases with particularly large MUCAPE were biased towards much larger values of SHIP, like Case 23 and 72. SHIP also performed particularly poorly for a majority of the larger hail Cases. Case 82 produced widespread sig hail reports up to softball sized while only having a SHIP value of 0.59. Case 37 produced baseball to 3.50” (89 mm) diameter hail close to Queens, NY, and had a SHIP value of 0.57. Case 155 impacted the western suburbs of Binghamton, NY, and had densely packed severe and sig hail reports up to 3.00” (76 mm), but only had a SHIP value of 0.23. SHIP underperformed for elevated Cases and Early/Late Season Cases as well, due to them more commonly occurring within high-shear low-CAPE environments. Of the eleven elevated Cases, the largest value of SHIP analyzed was only 0.79. Thus, perhaps mainly owing to the weaker MUCAPE values in Northeastern U.S. sig hail environments, SHIP is not reliable.

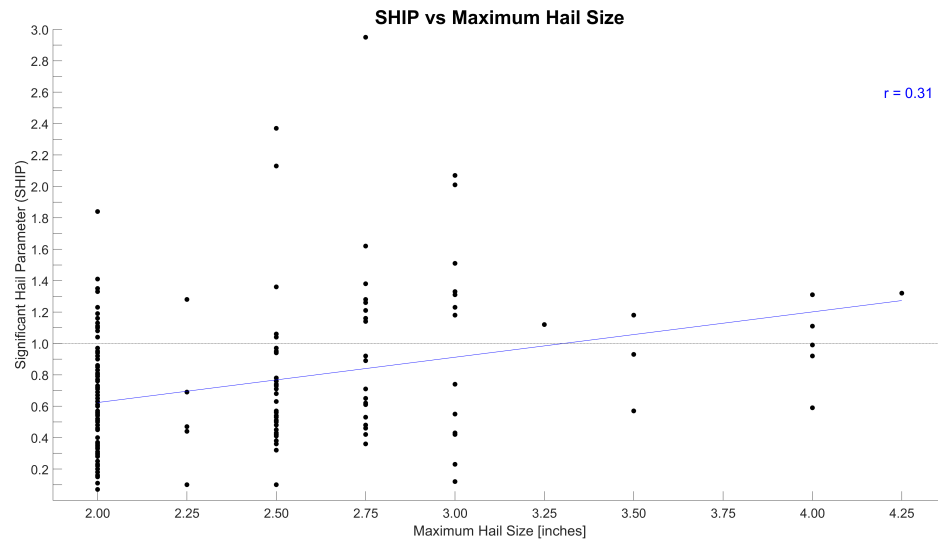


Figure 5.10. Scatter plot of case maximum hail size vs predicted SHIP values, with Pearson's correlation coefficient r plotted.

Table 5.1. A table containing convective characteristics of interest for each of the 167 sig hail producing cases. Listed are storm mode classification (Smith et al. 2012), storm motion during sig hail production, change in storm motion between before hail production and during sig hail production (if applicable), storm splitting tendency and frequency, and tornadogenesis frequency and strength.

Case ID	Bulk Wind Shear [kts]						CAPE [J/kg]		CIN [J/kg]		SRH [m ² /s ²]			LCL	LFC	EL	HGZ	SFC T	SFC Td	SFC P [hPa]	MU P [hPa]	SHIP
	0-500m	0-1km	0-3km	0-6km	0-9km	0-12km	SB	MU	SB	MU	0-500m	0-1km	0-3km									
1	10.8	17.1	37.8	65.5	70.8	59.6	732	732	-18	-18	71	105	153	662	1169	8871	2581	62.8	53.6	954.9	sfc	0.76
2	16.3	23.1	32.9	43.4	31.8	31.0	1185	1185	-12	-12	111	162	218	954	1259	11045	2821	73.9	60.7	960.7	sfc	0.54
3	13.2	14.8	27.0	51.1	42.7	48.1	0	632	---	-6	93	162	216	2068	2553	9894	2563	56.3	43.3	984.4	800	0.33
4	11.5	17.2	28.3	43.6	23.7	22.4	1621	1621	-3	-3	78	118	156	481	900	11299	3234	73.5	67.2	979.4	sfc	0.92
5	10.8	14.9	36.4	45.0	34.3	37.4	1343	1343	-12	-12	3	2	-109	1292	1555	10792	2921	79.1	61.1	966.4	sfc	0.76
6	8.2	11.1	31.0	39.2	33.5	54.9	2536	2536	0	0	62	84	165	1137	1446	12066	2941	81.4	65.4	973.5	sfc	1.51
7	13.3	19.5	40.3	30.3	34.2	50.6	2499	2499	0	0	-50	-66	-130	261	613	12152	2845	71.9	68.5	962.0	sfc	0.86
8	6.0	7.8	35.6	43.2	28.8	46.5	979	979	0	0	41	49	100	1886	2254	10239	3029	83.8	57.1	970.1	sfc	0.53
9	11.9	18.4	37.9	43.5	46.9	56.7	1271	1271	-13	-13	101	163	246	1104	1772	10737	2812	77.5	62.1	965.8	sfc	0.61
10	2.4	10.2	33.9	43.7	40.0	51.6	567	567	-9	-9	18	66	199	486	1589	8815	3012	69.2	62.7	984.0	sfc	0.32
11	8.7	18.8	35.9	40.8	43.8	31.0	2736	2785	-9	-2	63	99	165	636	1220	12528	2673	77.0	68.5	986.6	975	1.62
12	11.1	19.7	34.6	39.4	40.1	31.8	2390	2390	-17	-17	78	128	203	895	1510	12419	2683	78.6	66.2	976.0	sfc	1.19
13	11.0	18.4	32.0	36.7	34.1	21.8	1997	1997	-29	-29	-8	-21	-78	976	1553	12211	2813	77.8	64.3	964.0	sfc	0.90
14	10.2	17.5	32.1	35.9	37.3	28.0	2387	2441	-26	-5	65	101	170	713	1363	12334	2664	76.3	66.4	970.1	925	1.12
15	8.9	17.2	33.6	35.4	37.1	27.9	2936	2997	-18	0	8	-34	-87	724	1265	12613	2659	77.4	67.4	969.2	950	1.41
16	11.5	17.0	33.3	36.1	38.0	29.6	2546	2546	-17	-17	70	102	189	517	1305	12660	2635	74.9	67.8	970.1	sfc	1.11
17	14.1	22.0	36.6	38.7	41.5	30.1	2571	2596	-35	-22	101	161	251	586	1693	12610	2634	76.7	68.9	991.3	925	1.33
18	19.6	28.8	39.6	52.1	55.4	55.5	1872	1872	-14	-14	150	217	289	502	1298	11857	2678	72.6	65.7	967.0	sfc	1.21
19	15.0	26.1	26.3	29.8	28.4	24.9	659	2091	-194	-4	67	116	110	1773	2107	13558	3026	73.3	65.3	985.3	825	0.73
20	9.4	14.1	27.9	35.7	29.4	21.3	3644	3644	-28	-28	63	90	157	1249	1662	13380	3019	86.2	69.1	981.3	sfc	2.07
21	12.7	17.8	28.3	34.8	25.1	17.3	3353	3353	-24	-24	75	101	157	1309	1699	13259	3121	86.2	68.3	982.1	sfc	1.84
22	9.3	13.9	27.9	35.6	29.0	20.7	3587	3587	-28	-28	62	87	156	1284	1674	13356	3024	86.4	68.9	981.9	sfc	2.01
23	9.7	17.6	32.3	35.9	28.9	20.8	4586	4586	-19	-19	32	54	120	480	1376	13422	2942	79.7	73.5	985.0	sfc	2.95
24	7.6	14.6	27.2	30.2	30.0	15.0	3025	3025	0	0	8	1	-47	1061	1492	12860	2771	82.1	67.4	964.1	sfc	1.13
25	15.4	24.0	22.8	26.1	27.8	29.6	1431	1537	-149	-27	8	16	23	1681	2243	11127	2810	73.7	66.9	977.2	875	0.45
26	4.7	14.9	26.8	36.5	33.8	36.4	2865	2866	-8	0	28	63	103	922	1413	12740	3023	80.4	67.7	963.1	950	1.33
27	6.5	14.3	33.7	34.0	32.3	30.8	2728	2749	-25	-17	20	35	112	589	1642	12215	2993	76.6	68.6	964.3	950	1.35
28	4.2	6.5	28.1	34.5	36.9	42.5	2173	2173	-12	-12	31	34	102	959	1777	12582	3069	80.5	67.2	977.1	sfc	0.85
29	4.7	7.1	27.6	31.0	30.6	38.7	1845	2133	-6	0	31	40	119	1556	1911	12118	3108	85.5	63.6	970.8	950	0.71
30	4.3	6.9	28.4	38.4	42.5	44.2	1598	1659	-26	-4	32	43	90	1452	2201	12207	3211	85.2	65.1	994.6	975	0.74
31	4.6	12.5	30.6	31.6	48.4	54.8	802	802	-28	-28	28	92	222	895	1642	9608	3017	77.4	64.9	975.3	sfc	0.20

Case ID	Bulk Wind Shear [kts]						CAPE [J/kg]		CIN [J/kg]		SRH [m ² /s ²]			LCL	LFC	EL	HGZ	SFC T	SFC Td	SFC P [hPa]	MU P [hPa]	SHIP
	0-500m	0-1km	0-3km	0-6km	0-9km	0-12km	SB	MU	SB	MU	0-500m	0-1km	0-3km									
32	9.2	12.6	16.1	24.4	31.9	14.3	907	907	-19	-19	14	27	44	605	1135	9416	2777	69.1	60.7	970.2	sfc	0.25
33	3.8	5.2	24.8	48.7	79.2	92.5	291	310	-11	0	27	36	63	1618	2385	7305	3020	79.6	57.3	982.9	975	0.12
34	7.1	12.0	22.6	32.7	36.2	66.4	2226	2262	-20	-5	27	45	108	621	1568	11335	2774	77.2	68.9	988.4	975	1.04
35	4.5	7.1	18.3	29.4	38.9	98.2	1930	2010	0	0	21	32	90	1320	1631	10849	2908	84.2	65.9	981.7	975	0.67
36	2.7	3.4	17.3	33.1	55.4	88.7	1064	1143	-1	0	13	17	82	1776	2248	9786	3187	87.7	62.9	984.1	975	0.36
37	5.4	8.9	24.7	28.8	41.2	38.7	1555	1555	-26	-26	20	35	109	1618	2135	11024	2826	86.1	63.2	1007.8	sfc	0.57
38	7.0	11.5	22.6	29.0	32.3	35.2	2982	2982	0	0	29	47	92	467	1260	12230	2805	77.6	71.1	1001.2	sfc	1.18
39	6.6	10.5	16.8	24.4	31.2	30.6	1957	1957	-73	-73	32	50	78	950	1875	11989	3022	81.3	68.1	1004.4	sfc	0.62
40	2.7	3.9	7.7	11.8	22.8	29.8	1463	1475	-4	0	9	12	31	1483	1744	10459	2675	82.1	61.5	990.1	975	0.20
41	4.2	6.9	10.6	13.2	23.3	34.5	968	1018	-89	-71	14	23	39	1131	2326	9829	2902	77.5	61.9	990.0	975	0.16
42	5.9	6.9	17.3	16.8	20.5	23.0	1987	1987	-17	-17	27	19	-11	987	1436	11513	2803	80.1	66.3	1004.1	sfc	0.44
43	4.8	11.2	29.6	24.1	36.1	19.2	1373	1373	-24	-24	-5	-21	-64	1263	1617	11427	3176	78.7	61.0	970.2	sfc	0.46
44	4.5	11.8	36.0	40.0	37.6	46.8	2300	2310	0	0	28	26	104	750	1090	11572	2981	78.1	67.7	967.5	950	1.16
45	5.3	14.6	33.8	42.5	28.9	50.7	2161	2161	-9	-9	18	1	61	614	1232	11264	2975	75.6	67.2	957.3	sfc	1.14
46	4.8	8.5	30.9	39.3	31.6	51.0	2164	2167	-4	0	29	21	72	778	1497	11354	3063	78.2	67.4	971.7	sfc	1.18
47	4.3	7.1	32.8	37.6	36.5	52.2	2299	2383	0	0	27	48	127	1053	1380	11667	2984	81.3	66.7	965.7	950	1.08
48	13.7	19.3	29.9	36.6	28.1	45.6	2230	2230	-10	-10	72	102	159	534	1189	11958	2956	76.3	69.0	967.5	sfc	0.92
49	7.1	12.8	28.9	42.1	56.8	73.2	1089	1089	-71	-71	42	75	131	1756	2925	10637	2956	85.7	61.2	991.2	sfc	0.56
50	2.5	3.3	24.2	35.5	49.4	62.6	1192	1290	-20	0	-1	-3	-126	1998	2929	10684	3021	88.3	60.3	989.6	975	0.57
51	5.1	7.7	28.3	28.9	36.5	61.4	1018	1171	-2	0	31	41	111	1912	2159	10731	2774	87.2	60.3	995.5	975	0.30
52	8.8	16.2	26.0	45.4	68.4	61.5	1874	1874	-14	-14	36	71	120	967	1361	11588	2597	79.2	65.7	970.2	sfc	0.69
53	8.8	12.1	17.1	18.9	16.9	27.1	2583	2583	-16	-16	30	50	107	1677	2005	12801	2788	90.7	67.1	973.3	sfc	0.45
54	6.3	7.4	15.3	18.4	18.3	21.5	1260	1411	-20	0	14	18	72	2209	2460	11519	2782	91.5	60.3	970.2	950	0.20
55	7.8	10.8	14.7	16.9	18.8	21.1	1825	1825	-48	-48	16	21	-20	1368	1872	11893	2836	83.1	64.0	938.4	sfc	0.25
56	4.8	8.4	24.1	38.2	34.0	36.1	1172	1239	-71	-36	17	34	97	1878	2464	11880	2940	91.3	65.0	997.6	975	0.34
57	4.5	10.1	21.3	23.1	34.8	51.5	1792	1859	0	0	22	58	124	939	1251	11483	2876	78.8	65.6	972.5	950	0.48
58	4.8	9.1	20.8	21.0	27.1	44.9	2095	2187	0	0	14	8	-41	993	1312	11796	3008	79.7	65.9	960.7	950	0.55
59	5.7	7.1	22.1	25.5	24.9	46.0	1096	1129	0	0	28	31	-39	1482	1758	11239	3125	83.5	62.5	975.2	950	0.28
60	6.3	8.4	19.1	22.7	33.1	48.4	2032	2086	0	0	20	33	110	1080	1402	11473	2939	81.3	66.3	960.4	950	0.50
61	8.9	16.4	16.7	26.3	32.4	29.7	2310	2310	-13	-13	45	80	89	893	1414	11956	3164	81.1	68.7	971.2	sfc	0.74
62	17.4	15.3	33.3	37.6	48.5	40.7	1527	1527	-103	-103	96	84	160	555	2367	11318	2931	77.3	69.6	972.3	sfc	0.57
63	2.9	12.1	28.9	33.9	71.1	66.0	1180	1180	0	0	21	73	165	440	795	9537	3024	72.3	66.6	985.8	sfc	0.51
64	2.8	3.8	16.7	25.5	47.2	72.7	1014	1065	-11	0	14	19	68	1549	1795	9445	2654	81.0	59.2	962.9	950	0.22
65	2.2	4.1	27.6	33.0	24.6	35.3	491	534	-20	0	12	24	123	1474	1755	7330	3265	77.5	56.6	971.3	950	0.16
66	2.6	4.3	19.4	33.1	23.0	5.8	1153	1187	-8	0	15	24	93	1384	1879	10918	2991	80.5	61.3	982.3	950	0.43

Case ID	Bulk Wind Shear [kts]						CAPE [J/kg]		CIN [J/kg]		SRH [m ² /s ²]			LCL	LFC	EL	HGZ	SFC T	SFC Td	SFC P [hPa]	MU P [hPa]	SHIP
	0-500m	0-1km	0-3km	0-6km	0-9km	0-12km	SB	MU	SB	MU	0-500m	0-1km	0-3km									
67	4.0	8.5	23.2	34.3	11.9	11.2	1080	1236	-44	-16	18	32	101	899	1795	10430	3008	75.9	63.7	984.4	950	0.50
68	3.6	17.7	25.1	35.7	35.2	27.2	244	337	-76	-47	23	94	139	575	2327	6916	2994	71.0	63.3	983.3	900	0.10
69	10.2	15.3	36.1	29.5	39.5	43.5	2278	2278	-24	-24	63	90	173	645	1206	12913	3037	76.6	67.7	971.5	sfc	0.71
70	7.4	11.8	36.6	42.5	35.6	37.8	1352	1352	0	0	53	83	176	998	1283	11565	2917	77.2	63.3	969.4	sfc	0.56
71	8.1	9.5	34.6	64.6	53.5	38.6	2260	2260	-12	-12	52	76	221	1088	1530	11671	3140	82.2	67.0	973.8	sfc	2.13
72	14.4	19.2	29.2	51.2	39.8	36.4	3531	3531	-12	-12	90	126	186	759	1274	12631	2995	82.2	71.6	973.5	sfc	2.37
73	10.1	13.2	29.0	53.6	45.0	43.6	1323	1627	-33	0	67	72	-6	1400	1706	12015	3091	74.0	68.9	976.2	850	0.79
74	11.9	21.8	42.7	51.3	35.1	21.3	2062	2062	-32	-32	102	141	166	1116	2180	12299	3264	85.2	69.7	998.9	sfc	1.26
75	8.6	18.6	26.6	59.1	93.5	80.8	1577	1577	0	0	55	91	119	431	753	9442	2991	71.8	66.0	956.2	sfc	0.92
76	3.4	5.2	7.2	14.9	10.9	11.9	2989	3117	0	0	14	22	31	1068	1432	13334	2935	84.4	69.5	961.7	950	0.40
77	5.0	6.1	6.2	12.2	12.7	7.7	2660	2660	-19	-19	16	19	18	784	1368	13408	3174	81.7	70.9	967.5	sfc	0.35
78	5.3	10.4	14.4	27.0	48.7	53.4	1942	1942	0	0	26	52	67	675	1005	10780	2919	76.5	67.1	972.4	sfc	0.69
79	19.1	26.9	29.4	28.6	30.2	39.1	1733	1733	-148	-148	70	93	107	759	2636	13172	3374	81.0	70.5	1002.4	sfc	0.72
80	13.0	19.0	34.9	36.4	46.0	53.2	1158	1158	0	0	65	82	135	234	569	11378	3135	69.9	66.7	947.0	sfc	0.40
81	10.3	11.3	28.5	35.0	37.5	44.7	2806	2806	0	0	15	3	-81	831	1167	12988	3073	79.3	67.7	974.3	sfc	1.23
82	4.4	10.2	16.5	27.0	43.0	44.0	1278	1278	0	0	27	58	78	445	674	8895	2647	63.6	57.4	971.2	sfc	0.59
83	3.2	8.0	28.1	49.2	71.3	70.7	702	702	-4	-4	15	22	59	1230	1621	8738	2987	72.2	54.8	972.9	sfc	0.41
84	2.8	5.5	29.8	47.1	72.8	80.8	755	771	-12	0	16	24	48	1254	1692	9187	2900	74.2	56.9	987.6	975	0.42
85	4.1	8.8	24.8	38.7	34.3	43.9	1551	1708	0	0	21	39	108	647	1000	11857	3142	77.5	68.7	963.6	950	0.65
86	4.0	6.8	26.9	37.5	44.6	49.6	2411	2465	0	0	26	40	113	1065	1429	13395	3133	84.8	70.2	990.2	975	0.97
87	4.0	7.5	20.6	32.2	40.7	47.9	1783	1783	-32	-32	21	30	66	585	1446	12681	3043	80.0	71.9	1006.1	sfc	0.51
88	3.3	3.8	26.9	39.4	49.0	59.4	594	632	-25	-12	20	25	99	1507	2224	9097	3057	84.2	63.2	982.9	950	0.18
89	18.8	22.0	33.2	49.3	38.8	46.6	843	855	-15	0	53	21	-25	501	1338	11598	3122	69.2	62.2	972.8	875	0.48
90	1.8	7.4	20.7	25.8	42.2	39.1	753	798	-15	0	8	40	119	1383	1707	10209	2896	80.1	60.9	983.8	975	0.18
91	3.8	6.3	35.2	36.9	39.6	50.1	965	965	0	0	27	39	118	1310	1630	10257	3290	85.7	67.2	1001.8	sfc	0.30
92	7.7	10.9	22.3	40.4	34.9	29.5	2001	2001	-6	-6	45	64	110	1422	1765	13357	3245	88.7	68.9	996.6	sfc	0.92
93	6.0	8.8	24.8	34.6	54.2	83.3	1376	1374	-30	-19	30	48	125	1455	2229	11203	2875	85.3	65.3	980.8	975	0.45
94	6.9	13.3	38.6	37.1	51.5	65.1	1179	1242	-68	-37	54	103	273	1082	1841	11115	3010	81.8	66.9	996.6	975	0.46
95	8.8	14.4	33.6	51.0	62.6	61.4	1748	1748	-1	-1	-28	-47	-119	312	802	11080	2836	69.9	65.8	961.3	sfc	1.04
96	8.4	10.9	32.8	50.2	73.6	71.6	2066	2066	0	0	45	55	131	1452	1731	11388	2806	84.2	63.7	1003.5	sfc	1.28
97	5.2	6.5	29.7	49.5	76.1	75.6	1402	1556	-1	0	29	35	104	1522	1773	10793	2689	81.9	60.6	994.9	975	0.83
98	5.3	10.2	30.6	51.0	77.3	75.0	1806	1806	-30	-30	27	29	75	735	1356	10962	2623	76.1	65.8	1004.8	sfc	1.11
99	6.6	9.3	28.8	51.3	70.9	69.4	1265	1265	-44	-44	47	47	106	1007	1630	10370	2661	75.9	61.9	995.9	sfc	0.76
100	9.0	15.1	28.9	48.9	66.7	74.8	1886	1949	-36	0	56	95	137	391	1281	11958	2924	73.0	67.6	1004.7	925	1.28
101	6.4	11.7	32.8	47.2	68.2	75.1	699	699	-16	-16	-4	-28	-134	1366	1681	9202	2998	77.6	58.4	997.8	sfc	0.42

Case ID	Bulk Wind Shear [kts]						CAPE [J/kg]		CIN [J/kg]		SRH [m ² /s ²]			LCL	LFC	EL	HGZ	SFC T	SFC Td	SFC P [hPa]	MU P [hPa]	SHIP
	0-500m	0-1km	0-3km	0-6km	0-9km	0-12km	SB	MU	SB	MU	0-500m	0-1km	0-3km									
102	1.3	7.2	33.9	39.3	26.9	49.0	1618	1618	-10	-10	8	28	94	387	1258	10929	3012	73.2	68.0	965.6	sfc	0.65
103	1.5	2.2	31.9	41.9	40.0	64.4	1264	1320	0	0	3	14	135	1373	1769	10921	2951	83.9	65.2	982.1	975	0.43
104	21.1	30.5	29.7	34.1	58.2	57.8	1109	1537	-93	0	-52	-88	-88	1467	1732	10986	2796	74.8	62.6	955.2	825	0.52
105	5.1	8.9	25.1	53.7	56.7	72.2	2389	2469	-12	0	-8	-13	-67	1114	1440	12079	2696	82.7	67.4	992.1	975	1.32
106	13.7	30.5	52.9	52.2	65.2	106.0	0	215	---	-4	107	90	-12	2015	2309	6158	3130	56.6	51.2	968.5	800	0.10
107	7.0	18.8	22.3	32.5	24.6	69.0	755	755	-14	-13	39	90	98	466	1300	9430	2946	67.4	60.8	975.7	sfc	0.31
108	8.3	22.1	27.3	30.4	37.0	66.9	1390	1468	0	0	18	-32	-51	534	808	11167	2964	69.2	61.9	962.4	950	0.60
109	13.4	17.0	40.1	39.4	41.7	39.9	1211	1281	-21	0	59	79	162	1331	2101	10994	2658	78.1	59.5	965.0	950	0.55
110	11.5	15.7	42.0	46.8	46.6	42.9	1783	1783	-18	-18	-28	-30	-140	1343	1666	11581	2675	81.5	63.1	990.0	sfc	0.94
111	6.7	12.1	24.0	32.1	57.2	83.5	207	207	-57	-57	15	14	-41	967	2026	6881	3121	70.3	56.8	967.0	sfc	0.07
112	8.0	10.1	20.9	29.8	54.1	75.7	349	349	-21	-21	28	22	-44	893	1458	7244	3081	69.6	57.2	957.0	sfc	0.11
113	8.6	14.8	22.7	26.2	17.2	20.7	1870	1870	0	0	43	57	77	254	1253	12721	3115	71.2	67.7	976.7	sfc	0.77
114	4.4	11.3	28.2	29.2	25.0	26.9	1746	1746	-23	-23	21	44	82	646	1751	12564	3096	76.3	67.6	990.8	sfc	0.73
115	7.4	15.7	42.4	55.2	56.4	48.7	1686	1751	0	0	51	74	139	1023	1423	12016	3299	77.5	63.3	958.7	950	1.38
116	6.1	13.0	43.2	57.7	53.0	52.8	1097	1097	-14	-14	49	76	182	958	1744	10793	3267	76.7	63.7	980.7	sfc	0.89
117	6.5	13.1	44.1	61.8	62.4	54.6	1583	1583	-9	-9	57	94	193	1000	1403	12169	3265	78.3	64.7	979.5	sfc	1.35
118	7.6	16.6	43.8	54.1	53.8	44.9	1607	1607	-3	-3	51	88	167	869	1279	11915	3301	75.4	63.1	951.0	sfc	1.23
119	10.2	13.8	39.0	29.5	44.1	27.1	2282	2282	-52	-52	88	117	166	557	1650	13913	3211	77.4	70.1	989.4	sfc	0.95
120	15.0	21.7	27.2	37.0	45.2	57.5	1237	1237	0	0	95	128	150	167	490	11019	3067	68.6	66.3	969.7	sfc	0.61
121	28.5	42.0	40.3	88.3	112.5	114.6	84	189	-212	-93	235	321	326	554	3831	5707	3372	64.2	56.4	951.7	900	0.23
122	4.8	16.6	27.3	27.5	17.5	18.0	1424	1469	-27	-12	28	76	98	1182	1851	11286	2798	80.7	64.5	986.2	975	0.36
123	6.4	8.9	29.7	37.3	32.9	42.1	1892	1907	0	0	42	56	112	1053	1376	11890	2759	81.4	66.9	981.4	975	0.55
124	17.8	33.2	47.9	58.7	66.1	67.6	1782	1782	-5	-5	177	274	345	386	1046	12425	2847	71.7	66.4	955.4	sfc	1.16
125	12.2	24.1	43.5	50.0	48.5	58.2	2388	2388	0	0	93	160	252	593	927	12660	2751	75.2	67.1	959.0	sfc	1.31
126	12.9	18.8	42.0	44.5	43.7	47.7	1855	1855	-17	-17	98	140	260	657	1166	12386	2823	75.5	66.5	962.0	sfc	0.80
127	16.5	25.4	41.4	45.5	42.4	50.8	2560	2560	0	0	118	178	258	420	818	13133	2922	75.0	69.3	966.1	sfc	1.36
128	15.2	26.1	44.4	44.9	44.7	50.5	2143	2143	0	0	113	175	275	662	984	12590	2724	75.0	65.8	948.4	sfc	0.94
129	9.7	19.9	39.7	50.6	51.5	59.4	1294	1294	-5	-5	84	136	228	682	1237	11598	2796	74.9	65.5	976.5	sfc	0.71
130	10.3	23.6	42.0	50.0	52.5	60.5	1891	1891	-9	-9	86	167	262	801	1212	12459	2713	77.3	66.2	975.7	sfc	0.99
131	9.0	25.9	45.1	53.1	59.3	62.0	2340	2340	0	0	85	200	300	715	1044	12815	2778	76.4	66.6	959.4	sfc	1.31
132	4.7	9.6	33.1	48.9	38.6	56.4	1343	1343	-6	-6	30	51	149	893	1376	11273	3161	78.3	66.3	984.4	sfc	0.81
133	4.2	5.5	23.2	30.5	36.4	42.5	905	959	-5	0	23	30	109	1724	1939	10623	2775	80.4	56.5	989.0	975	0.30
134	13.2	14.6	23.6	34.9	46.3	59.7	1712	1712	0	0	-53	-57	-98	563	923	12019	2949	74.0	66.3	963.8	sfc	0.72
135	3.7	5.4	23.7	15.5	27.1	33.1	1876	1964	0	0	21	26	98	1122	1462	12190	3028	84.0	68.6	992.9	975	0.28
136	19.5	22.3	37.8	42.1	59.9	93.4	0	1102	---	-9	112	82	25	1508	2600	11268	2758	64.4	62.5	996.0	850	0.42

Case ID	Bulk Wind Shear [kts]						CAPE [J/kg]		CIN [J/kg]		SRH [m ² /s ²]			LCL	LFC	EL	HGZ	SFC T	SFC Td	SFC P [hPa]	MU P [hPa]	SHIP
	0-500m	0-1km	0-3km	0-6km	0-9km	0-12km	SB	MU	SB	MU	0-500m	0-1km	0-3km									
137	23.8	25.2	53.7	77.7	87.0	126.2	0	522	---	0	211	211	365	1163	2290	9239	3067	57.6	54.0	975.1	850	0.47
138	21.5	26.7	48.5	66.2	78.3	107.9	0	698	---	-4	168	197	340	1457	2167	9642	2959	60.9	56.0	971.0	825	0.50
139	22.5	26.7	47.6	66.1	78.5	103.7	0	809	---	-3	171	193	317	1493	2062	10178	2919	61.8	56.9	970.3	825	0.57
140	16.2	25.6	40.7	57.9	80.4	93.9	283	996	-101	-10	122	164	223	292	2909	8267	2848	65.9	62.0	968.6	875	0.68
141	12.4	23.5	45.5	53.9	87.4	111.9	526	795	-54	-11	47	9	-70	1374	2227	9789	2980	67.7	62.0	965.6	850	0.51
142	19.8	28.4	31.8	64.7	81.7	106.2	644	644	-78	-78	123	171	203	426	1608	8633	2574	63.7	57.7	973.1	sfc	0.77
143	4.1	5.4	16.0	24.3	27.1	35.2	1675	1788	-14	0	19	28	65	1194	1520	11339	2757	81.1	64.7	995.1	975	0.48
144	14.0	22.7	33.2	42.9	42.0	51.8	1726	1883	-21	-1	95	143	189	923	1570	11604	2755	80.6	67.8	969.3	950	0.65
145	8.3	11.2	23.6	30.2	25.4	9.8	849	956	-34	-18	46	65	141	1194	2846	11051	3071	80.4	63.6	973.8	950	0.33
146	3.6	13.6	19.9	25.9	33.0	58.6	1504	1504	-12	-12	24	77	115	584	1494	12084	3007	78.2	70.1	1001.9	sfc	0.38
147	4.9	15.4	31.7	35.5	27.4	43.3	1910	1910	0	0	34	101	192	674	1037	12502	2979	78.7	69.4	965.8	sfc	0.52
148	8.0	11.9	21.6	24.3	35.2	33.2	1736	1736	-10	-10	35	52	80	449	1147	11511	3074	74.8	68.7	995.8	sfc	0.53
149	21.8	38.8	51.8	51.0	49.5	46.7	609	614	-40	-37	228	337	374	855	1779	7887	3257	72.7	60.8	976.8	975	0.36
150	9.1	15.1	31.6	50.1	69.4	56.9	1550	1572	-23	0	46	48	77	796	1236	11277	2747	75.8	64.6	1001.4	975	0.93
151	13.7	16.5	34.9	42.4	40.0	38.8	1017	1017	-51	-51	95	150	283	901	2150	11508	3149	78.8	66.1	1007.8	sfc	0.54
152	7.1	10.3	12.2	32.1	16.8	19.8	2175	2175	0	0	29	44	29	1218	1521	12947	2838	82.1	65.3	981.7	sfc	0.95
153	18.2	25.3	34.0	35.1	21.5	37.2	2708	2708	-10	-10	119	163	204	907	1233	13534	2754	78.9	66.2	950.2	sfc	0.97
154	11.3	18.5	29.5	32.9	30.5	32.0	741	919	-83	-24	82	134	188	886	2181	10010	3042	77.3	65.3	988.5	900	0.29
155	5.3	9.5	20.4	29.2	30.7	50.0	857	857	-27	-27	28	51	105	817	1470	10344	2920	75.0	63.7	964.0	sfc	0.23
156	10.7	18.3	26.7	41.1	60.7	96.5	1032	1032	-6	-6	66	107	136	572	1024	10773	2983	73.2	65.1	950.0	sfc	0.36
157	9.0	18.4	30.4	45.4	65.0	102.4	942	942	-12	-12	65	108	156	622	1173	10397	2936	73.5	65.0	958.8	sfc	0.37
158	12.4	15.7	26.2	41.8	35.1	41.8	2521	2521	-23	-23	81	108	171	782	1298	13254	2949	82.2	71.6	992.6	sfc	1.06
159	8.6	10.5	27.4	45.3	41.3	36.6	2144	2150	0	0	53	64	136	1375	1707	13307	2985	86.6	67.4	970.9	950	0.78
160	7.7	9.3	27.0	37.2	35.8	32.2	1798	1817	0	0	41	49	107	1525	1845	13187	2893	87.9	66.6	978.6	975	0.53
161	12.6	19.3	39.7	41.2	43.1	43.6	2284	2284	-20	-20	116	186	280	421	1657	13472	3123	77.6	71.9	977.7	sfc	1.10
162	5.6	7.5	32.3	36.6	50.3	51.9	1184	1286	0	0	28	36	86	1639	2079	11181	2900	85.8	62.8	958.6	950	0.40
163	10.7	17.5	25.2	40.0	46.1	39.6	1502	1502	0	0	61	81	120	953	1293	9923	3323	79.9	66.8	958.4	sfc	0.63
164	14.4	17.2	27.3	33.9	47.6	49.7	1081	1081	-21	-21	89	119	156	1002	1948	9643	3290	80.1	66.3	962.9	sfc	0.35
165	14.3	20.3	29.0	40.2	68.4	77.3	1406	1406	-19	-19	71	100	170	930	1379	11745	3366	79.6	66.6	975.3	sfc	0.63
166	3.2	8.0	23.1	34.4	47.0	63.7	564	606	-16	-4	19	47	131	1137	1742	8730	2944	76.4	60.7	982.5	975	0.18
167	26.3	41.9	49.6	71.0	95.7	92.3	201	207	-3	-1	172	230	258	183	1455	5914	2921	59.6	57.1	950.5	850	0.15

CHAPTER 6

SUMMARY AND CONCLUSIONS

Cases of significantly severe hail that impacted the Northeast U.S. between 2011 and 2022 were analyzed to account for a lack of studies which focused solely on Northeast hail environments. Quality-controlled hail reports along with ERA5 reanalysis data were collected, and case studies, which included radar imagery, skew-Ts, and hodographs, were compiled for all Cases observed. A suite of statistical composites were performed across variables of interest and compared to other studies on environments that produced large hail. The results yielded a surprisingly large sample size of 167 Cases with a mean duration of nearly one hour and swath length of roughly 27 mi (43 km), suggesting these Cases were well organized rather than short lived, isolated occurrences.

While many similar patterns emerged between the environments and evolutions of sig hail in the Northeast compared to other regions of the U.S., there were a few distinct differences. Firstly, the greatest similarities were displayed by the composite hodographs. It was shown that as Cases produced larger maximum hail sizes, were longer in duration, or went from linear to cluster to the discrete supercell storm mode, the length of the hodograph increased, particularly between the 1 to 5 km levels. Additionally, the curvature in the lowest 1 to 1.5 km decreased, leading to less low-level SRH. The only exception to this were the 16 Cases that produced tornadoes; their hodographs' low level curvature increased dramatically from the total Case composite, mirroring findings from recent studies that have been able to differentiate between environments that are more favorable for sig hail versus sigtors. Diurnal patterns were observed, with roughly 85% of Cases occurring between 12:39 pm and 7:58 pm ET and only a handful of Cases either continuing or initiating after daylight hours, which matches other regions, though with a smaller proportion of after dark Cases. Nearly all Cases fell within the supercellular storm mode, with 16% of them being anticyclonic. Finally, hail report sampling was heavily biased by population density, as seen throughout all severe hazards reporting across the U.S.

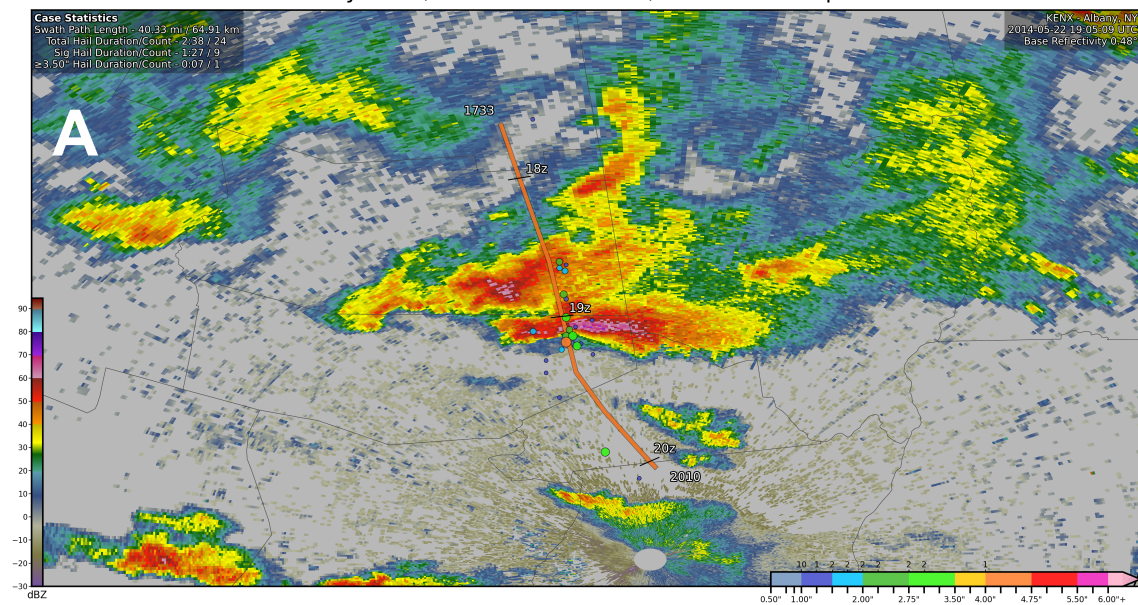
Similarities aside, some key differences, ranging from subtle to more significant, were noted. There were far less early season (March and April) Cases in the Northeast compared to the traditional sig hail producing regions. Though CAPE matched that of other Northeast severe weather environment studies, it was much lower than averages found amongst sig hail events across the rest of the U.S. Roughly two-thirds of Cases with <1000 CAPE counteracted this with a larger-than-average BWD across all levels. This was fairly prevalent in the seasonal hodographs in which the early/late season composite had the largest increase in shear in any level in any composite comparison, as well as in the MUCAPE versus 0-12km BWD plot, which displayed negative correlation. 700-500 mb lapse rates were also much lower than expected, and only the most prolific events (i.e., 1 June 2011) displayed distinct EMLs. Thicker HGZs were also observed, which more closely aligned with ≥ 3.25 in (83 mm) composites from other studies, even though all but 10 Cases had smaller maximum hail than this. SMV angles also differed dramatically from predicted Bunkers motion for both RMs and LMs, deviating nearly 10° opposite of expected (i.e., 10° left for RMs and 10° right for LMs). Finally, although other studies have proven SHIP not to be the most accurate indicator of a sig hail environment, Northeast sig hail performed even worse, with only 39 Cases reaching the 1.0 threshold on the index and 19 Cases only reaching 0.25 or lower.

6.1 Future Work

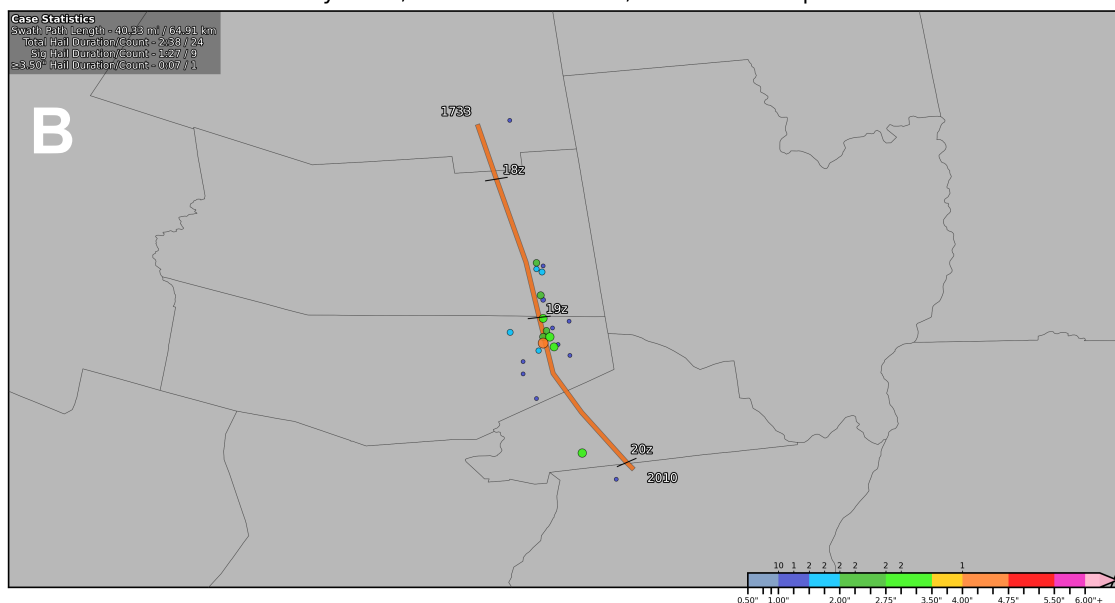
Plans for future work include expanding the study time period for Northeast sig hail to boost the sample size for some of the smaller environmental composites. Since it has been shown that these environments differ non-trivially from sig hail environments across other U.S. regions, operational meteorologists forecasting severe weather events in the Northeast could highly benefit from the results of this study. Additionally, compiling these Cases in greater detail has not only led to finding unique case studies that otherwise may have never been discovered, but also proved the importance of collecting data in this manner. No large hail study has used manual case selection and quality control (likely due to the extensive time required to do so) to analyze composite hail environments. To account for this, a related study has been started to compile all Cases of ≥ 3.50 in (88.9 mm) that have occurred

across the entire U.S. from 1998 to present. Roughly 900 to 1000 Cases have been identified, spanning from New England, to Florida, to Montana, to even Hawaii. Figures 6.1a and 6.1b show Case 82 from this study in the new format for the future study, while Figures 6.1c and 6.1d are an example of a long track Case from Colorado/Nebraska. The goal of this work is not only to add value to other large hail studies using higher quality observed data, but also to explore any novel patterns that may only arise through an analysis like this. A secondary goal will be to maintain a public database of these Cases, much like the Purdue Tornado Tracks archive.

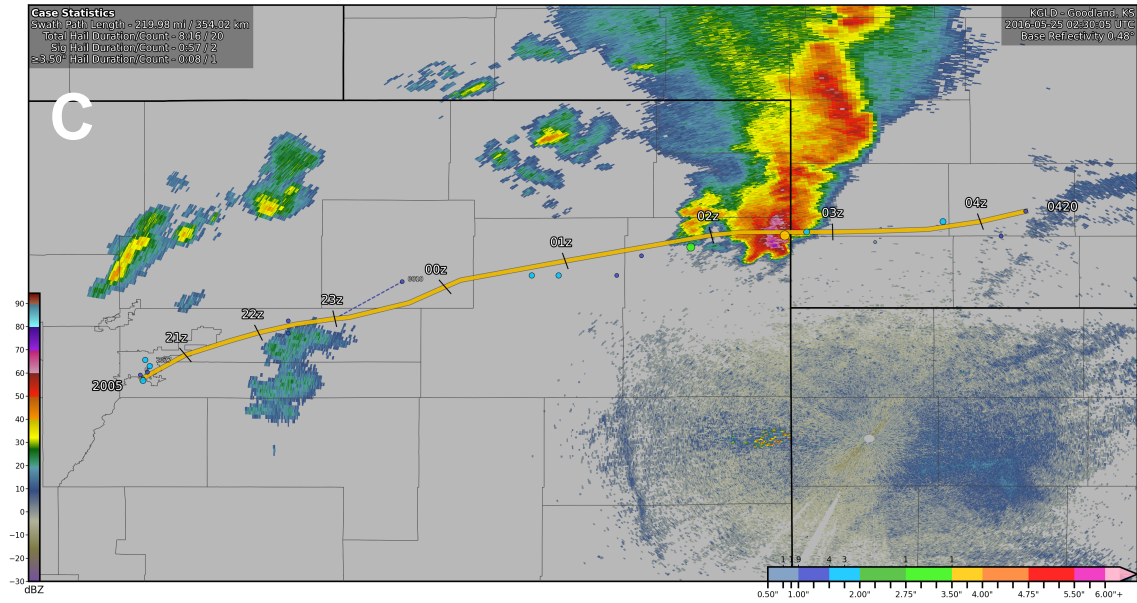
May 22nd, 2014 - Amsterdam, NY Case Example



May 22nd, 2014 - Amsterdam, NY Case Example



May 24th, 2016 - Alvin, CO Case Example



May 24th, 2016 - Alvin, CO Case Example

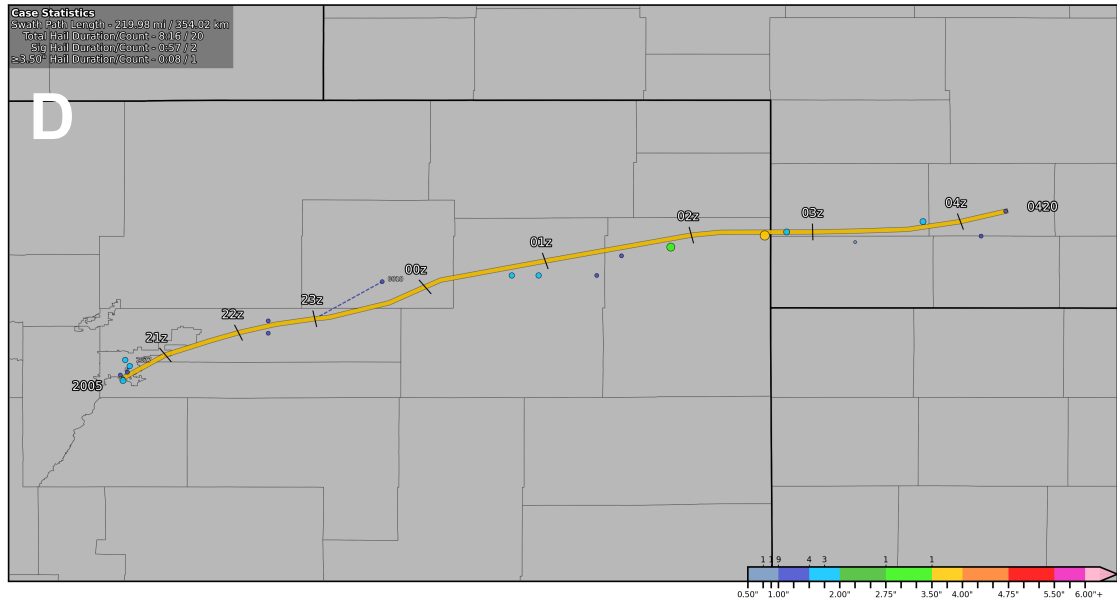


Figure 6.1. Two examples of preliminary figures for the future ≥ 3.50 in (88.9 mm) full U.S. hail study. (a) and (b) show Case 82 from the Northeast sig hail study while (c) and (d) show a new long-track Case from Colorado/Nebraska.

BIBLIOGRAPHY

- Allen, J. T., and M. K. Tippett, 2015: The characteristics of United States hail reports: 1955-2014. *Electronic J. Severe Storms Meteor.*, **10** (3), 1-31, <https://doi.org/10.55599/ejssm.v10i3.60>.
- Allen, J. T., M. K. Tippett, Y. Kaheil, A. H. Sobel, C. Lepore, S. Nong, and A. Muehlbauer, 2017: An Extreme Value Model for U.S. Hail Size. *Mon. Wea. Rev.*, **145**, 4501-4519, <https://doi.org/10.1175/MWR-D-17-0119.1>.
- Allen, J. T., I. M. Giammanco, M. R. Kumjian, H. J. Punge, Q. Zhang, P. Groenemeijer, M. Kunz, and K. Ortega, 2020: Understanding hail in the Earth system. *Reviews of Geophysics*, **58**, e2019RG000665, <https://doi.org/10.1029/2019RG000665>.
- Allen, J. T., and Coauthors (2024, personal communication from an ongoing study).
- Banacos, P. C., M. L. Ekster, J. W. Dellicarpini, and E. J. Lyons, 2012: A multiscale analysis of the 1 June 2011 Northeast U.S. severe weather outbreak and associated Springfield, Massachusetts tornado. *Electronic J. Severe Storms Meteor.*, **7** (7), 1-40, <https://doi.org/10.55599/ejssm.v7i7.43>.
- Benjamin, S. G., and Coauthors, 2004: An Hourly Assimilation-Forecast Cycle: The RUC. *Mon. Wea. Rev.*, **132**, 495-518, [https://doi.org/10.1175/1520-0493\(2004\)132<0495:AHACTR>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<0495:AHACTR>2.0.CO;2).
- Beveridge, S. L., J. L. Houser, and S. R. Marzola, 2018: A statistical evaluation of tornado-production tendencies of southernmost supercells compared to adjacent supercells in a north-south-oriented line. *Electronic J. Severe Storms Meteor.*, **14** (1), 1-33, <https://doi.org/10.55599/ejssm.v14i1.71>.
- Blair, S. F., D. R. Deroche, J. M. Boustead, J. W. Leighton, B. L. Barjenbruch, and W. P. Gargan, 2011: A radar-based assessment of the detectability of giant hail. *Electronic J. Severe Storms Meteor.*, **6** (7), 1-30, <https://doi.org/10.55599/ejssm.v6i7.34>.

- Blair, S. F., and Coauthors, 2017: High-Resolution Hail Observations: Implications for NWS Warning Operations. *Wea. Forecasting*, **32**, 1101-1119, <https://doi.org/10.1175/WAF-D-16-0203.1>.
- Bowen, S., B. Kerschner, J. Zheng Ng, 2024: Natural Catastrophe and Climate Report: 2023. *Gallagher Re*, <https://www.ajg.com/gallagherre/news-and-insights/2023-natural-catastrophe-and-climate-report/>.
- Branick, M., 1996: NOAA Technical Memorandum NWS SR-145: A comprehensive glossary of weather terms for storm spotters (2nd Edition). *NOAA/NWS, Norman, OK*, <https://www.la.utexas.edu/users/kimmel/nws-sr145.pdf>.
- Bryan, G. H., and J. M. Fritsch, 2002: A Benchmark Simulation for Moist Nonhydrostatic Numerical Models. *Mon. Wea. Rev.*, **130**, 2917-2928, [https://doi.org/10.1175/1520-0493\(2002\)130<2917:ABSFMN>2.0.CO;2](https://doi.org/10.1175/1520-0493(2002)130<2917:ABSFMN>2.0.CO;2).
- Bunkers, M. J., B. A. Klimowski, J. W. Zeitler, R. L. Thompson, and M. L. Weisman, 2000: Predicting Supercell Motion Using a New Hodograph Technique. *Wea. Forecasting*, **15**, 61-79, [https://doi.org/10.1175/1520-0434\(2000\)015<0061:PSMUAN>2.0.CO;2](https://doi.org/10.1175/1520-0434(2000)015<0061:PSMUAN>2.0.CO;2).
- Bunkers, M. J., 2002: Vertical Wind Shear Associated with Left-Moving Supercells. *Wea. Forecasting*, **17**, 845-855, [https://doi.org/10.1175/1520-0434\(2002\)017<0845:VWSAWL>2.0.CO;2](https://doi.org/10.1175/1520-0434(2002)017<0845:VWSAWL>2.0.CO;2).
- Bunkers, M. J., J. S. Johnson, L. J. Czepyha, J. M. Grzywacz, B. A. Klimowski, and M. R. Hjelmfelt, 2006: An Observational Examination of Long-Lived Supercells. Part II: Environmental Conditions and Forecasting. *Wea. Forecasting*, **21**, 689-714, <https://doi.org/10.1175/WAF952.1>.
- Bunkers, M. J., 2017: Observations of Right-Moving Supercell Motion Forecast Errors. *Wea. Forecasting*, **33**, 145-159, <https://doi.org/10.1175/WAF-D-17-0133.1>.
- Buontempo, C., and Coauthors, 2022: The Copernicus Climate Change Service: Climate Science in Action. *Bull. Amer. Meteor. Soc.*, **103**, E2669-E2687, <https://doi.org/10.1175/BAMS-D-21-0315.1>.

- Byers, H.R., 1949: Principal Results of a Comprehensive Investigation of the Structure and Dynamics of the Thunderstorm. *Tellus*, **1**, 6-17, <https://doi.org/10.1111/j.2153-3490.1949.tb01269.x>.
- Calvo-Sancho, C., J. Díaz-Fernández, Y. Martín, P. Bolgiani, M. Sastre, J. J. González-Alemán, D. Santos-Muñoz, J. I. Farrán, and M. L. Martín, 2022: Supercell convective environments in Spain based on ERA5: hail and non-hail differences. *Weather Clim. Dynam.*, **3**, 1021-1036, <https://doi.org/10.5194/wcd-3-1021-2022>.
- Cerniglia, C. S., and W. R. Snyder, 2002: Development of warning criteria for severe pulse thunderstorms in the Northeastern United States using the WSR-88D. *NOAA/NWS Albany, NY*, <https://repository.library.noaa.gov/view/noaa/6664>.
- Changnon, S. A., 1999: Data and Approaches for Determining Hail Risk in the Contiguous United States. *J. Appl. Meteor. Climatol.*, **38**, 1730-1739, [https://doi.org/10.1175/1520-0450\(1999\)038<1730:DAAFDH>2.0.CO;2](https://doi.org/10.1175/1520-0450(1999)038<1730:DAAFDH>2.0.CO;2).
- Cintineo, J. L., T. M. Smith, V. Lakshmanan, H. E. Brooks, and K. L. Ortega, 2012: An Objective High-Resolution Hail Climatology of the Contiguous United States. *Wea. Forecasting*, **27**, 1235-1248, <https://doi.org/10.1175/WAF-D-11-00151.1>.
- Coffer, B. E., M. D. Parker, R. L. Thompson, B. T. Smith, and R. E. Jewell, 2019: Using Near-Ground Storm Relative Helicity in Supercell Tornado Forecasting. *Wea. Forecasting*, **34**, 1417-1435, <https://doi.org/10.1175/WAF-D-19-0115.1>.
- Coffer, B. E., M. D. Parker, J. M. Peters, and A. R. Wade, 2023: Supercell Low-Level Mesocyclones: Origins of Inflow and Vorticity. *Mon. Wea. Rev.*, **151**, 2205-2232, <https://doi.org/10.1175/MWR-D-22-0269.1>.
- Dennis, E. J., and M. R. Kumjian, 2017: The Impact of Vertical Wind Shear on Hail Growth in Simulated Supercells. *J. Atmos. Sci.*, **74**, 641-663, <https://doi.org/10.1175/JAS-D-16-0066.1>.
- Doswell, C. A., and E. N. Rasmussen, 1994: The Effect of Neglecting the Virtual Temperature Correction on CAPE Calculations. *Wea. Forecasting*, **9**, 625-629, [https://doi.org/10.1175/1520-0434\(1994\)009<0625:TEONTV>2.0.CO;2](https://doi.org/10.1175/1520-0434(1994)009<0625:TEONTV>2.0.CO;2).

- Eisenbach, S., 2023: Hail Record Broken Again - 19cm Hailstone Confirmed in Italy, *European Severe Storms Laboratory*, <https://www.essl.org/cms/hail-record-broken-again-19cm-hailstone-confirmed-in-italy/>.
- Fischer, J., J. M. L. Dahl, B. E. Coffey, J. L. Houser, P. M. Markowski, M. D. Parker, C. C. Weiss, and A. Schueth, 2024: Supercell Tornadogenesis: Recent Progress in Our State of Understanding. *Bull. Amer. Meteor. Soc.*, **105**, E1084-E1097, <https://doi.org/10.1175/BAMS-D-23-0031.1>.
- Fischer, J., M. Kunz, K. Lombardo, and M. R. Kumjian, 2025: Hail Trajectories in a Wide Spectrum of Supercell-Like Updrafts. *J. Atmos. Sci.*, **82**, 1403-1422, <https://doi.org/10.1175/JAS-D-24-0222.1>.
- Gallus, W. A., N. A. Snook, and E. V. Johnson, 2008: Spring and Summer Severe Weather Reports over the Midwest as a Function of Convective Mode: A Preliminary Study. *Wea. Forecasting*, **23**, 101-113, <https://doi.org/10.1175/2007WAF2006120.1>.
- Gensini, V. A., C. Converse, W. S. Ashley, and M. Taszarek, 2021: Machine Learning Classification of Significant Tornadoes and Hail in the United States Using ERA5 Proximity Soundings. *Wea. Forecasting*, **36**, 2143-2160, <https://doi.org/10.1175/WAF-D-21-0056.1>.
- Gutierrez, R. E., and M. R. Kumjian, 2021: Environmental and Radar Characteristics of Gargantuan Hail-Producing Storms. *Mon. Wea. Rev.*, **149**, 2523-2538, <https://doi.org/10.1175/MWR-D-20-0298.1>.
- Hersbach H., B. Bell, P. Berrisford, et al., 2020: The ERA5 global reanalysis. *Q J R Meteorol Soc.*, **146**, 1999-2049, <https://doi.org/10.1002/qj.3803>.
- Homeyer, C. R., and K. P. Bowman, 2022. Algorithm Description Document for Version 4.2 of the Three-Dimensional Gridded NEXRAD WSR-88D Radar (GridRad) Dataset, Technical Report, <https://gridrad.org/pdf/GridRad-v4.2-Algorithm-Description.pdf>.

- Homeyer, C. R., E. M. Murillo, and M. R. Kumjian, 2023: Relationships between 10 Years of Radar-Observed Supercell Characteristics and Hail Potential. *Mon. Wea. Rev.*, **151**, 2609-2632, <https://doi.org/10.1175/MWR-D-23-0019.1>.
- Hurlbut, M. M., and A. E. Cohen, 2014: Environments of Northeast U.S. Severe Thunderstorm Events from 1999 to 2009. *Wea. Forecasting*, **29**, 3-22, <https://doi.org/10.1175/WAF-D-12-00042.1>.
- Johnson, A. W. and K. E. Sugden, 2014: Evaluation of sounding-derived thermodynamic and wind-related parameters associated with large hail events. *Electronic J. Severe Storms Meteor.*, **9** (5), 1-42, <https://doi.org/10.55599/ejssm.v9i5.57>.
- Keegan, J., 2022: Designing for the Impacts of Very Severe Hail. CE Center. <https://continuingeducation.bnppmedia.com/architect/courses/gaf/designing-for-the-impacts-of-very-severe-hail/1/>.
- King, P. W. S., M. J. Leduc, D. M. L. Sills, N. R. Donaldson, D. R. Hudak, P. Joe, and B. P. Murphy, 2003: Lake Breezes in Southern Ontario and Their Relation to Tornado Climatology. *Wea. Forecasting*, **18**, 795-807, [https://doi.org/10.1175/1520-0434\(2003\)018<0795:LBISOA>2.0.CO;2](https://doi.org/10.1175/1520-0434(2003)018<0795:LBISOA>2.0.CO;2).
- Kumjian, M. R., 2013a: Principles and applications of dual-polarization weather radar. Part I: Description of the polarimetric radar variables. *J. Operational Meteor.*, **1** (19), 226-242, <http://dx.doi.org/10.15191/nwajom.2013.0119>.
- Kumjian, M. R., 2013b: Principles and applications of dual-polarization weather radar. Part II: Warm- and cold-season applications. *J. Operational Meteor.*, **1** (20), 243-264, <http://dx.doi.org/10.15191/nwajom.2013.0120>.
- Kumjian, M. R., 2013c: Principles and applications of dual-polarization weather radar. Part III: Artifacts. *J. Operational Meteor.*, **1** (21), 265-274, <http://dx.doi.org/10.15191/nwajom.2013.0121>.
- Kumjian, M. R., and K. Lombardo, 2020: A Hail Growth Trajectory Model for Exploring the Environmental Controls on Hail Size: Model Physics and Idealized Tests. *J. Atmos. Sci.*, **77**, 2765-2791, <https://doi.org/10.1175/JAS-D-20-0016.1>.

- Kumjian, M. R., K. Lombardo, and S. Loeffler, 2021: The Evolution of Hail Production in Simulated Supercell Storms. *J. Atmos. Sci.*, **78**, 3417-3440, <https://doi.org/10.1175/JAS-D-21-0034.1>.
- Kumjian, M. R., R. S. Schrom, J. S. Soderholm, and I. M. Giammanco, 2024, Radar and hail: advances in scattering, detection, and sizing, *Advances in Weather Radar. Volume 2: Precipitation science, scattering and processing algorithms*, V.N. Bringi, K. V. Mishra, and M. Thurai, The Institute of Engineering and Technology, 143-207, https://doi.org/10.1049/SBRA557G_ch4.
- Lin, Y., and M. R. Kumjian, 2022: Influences of CAPE on Hail Production in Simulated Supercell Storms. *J. Atmos. Sci.*, **79**, 179-204, <https://doi.org/10.1175/JAS-D-21-0054.1>.
- Lin, Y., and M. R. Kumjian (2026, unpublished manuscript).
- Lombardo, K. A., and B. A. Colle, 2011: Convective Storm Structures and Ambient Conditions Associated with Severe Weather over the Northeast United States. *Wea. Forecasting*, **26**, 940-956, <https://doi.org/10.1175/WAF-D-11-00002.1>.
- Lombardo, K. and M. R. Kumjian, 2025: The Sensitivity of Hail Production in Supercell Storms to the Distribution of Vertical Wind Shear, 12th European Conference on Severe Storms, Utrecht, The Netherlands, 17–21 Nov 2025, ECSS2025-187, <https://doi.org/10.5194/ecss2025-187>.
- Markowski, P., C. Hannon, J. Frame, E. Lancaster, A. Pietrycha, R. Edwards, and R. L. Thompson, 2003: Characteristics of Vertical Wind Profiles near Supercells Obtained from the Rapid Update Cycle. *Wea. Forecasting*, **18**, 1262-1272, [https://doi.org/10.1175/1520-0434\(2003\)018<1262:COVWPN>2.0.CO;2](https://doi.org/10.1175/1520-0434(2003)018<1262:COVWPN>2.0.CO;2).
- Markowski, P., and Y. Richardson, 2010, Organization of Isolated Convection, *Mesoscale Meteorology in Midlatitudes*, John Wiley & Sons, Ltd, 201-244, <https://doi.org/10.1002/9780470682104.ch8>

- Markowski, P. M., 2024: A New Pathway for Tornadogenesis Exposed by Numerical Simulations of Supercells in Turbulent Environments. *J. Atmos. Sci.*, **81**, 481-518, <https://doi.org/10.1175/JAS-D-23-0161.1>.
- May, R. M., and Coauthors, 2022: MetPy: A Meteorological Python Library for Data Analysis and Visualization. *Bull. Amer. Meteor. Soc.*, **103**, E2273-E2284, <https://doi.org/10.1175/BAMS-D-21-0125.1>.
- Mesinger, F., and Coauthors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.*, **87**, 343-360, <https://doi.org/10.1175/BAMS-87-3-343>.
- Murillo, E. M., C. R. Homeyer, and J. T. Allen, 2021: A 23-Year Severe Hail Climatology Using GridRad MESH Observations. *Mon. Wea. Rev.*, **149**, 945-958, <https://doi.org/10.1175/MWR-D-20-0178.1>.
- Nelson, S. P., 1987: The Hybrid Multicellular-Supercellular Storm—an Efficient Hail Producer. Part II. General Characteristics and Implications for Hail Growth. *J. Atmos. Sci.*, **44**, 2060-2073, [https://doi.org/10.1175/1520-0469\(1987\)044<2060:THMSEH>2.0.CO;2](https://doi.org/10.1175/1520-0469(1987)044<2060:THMSEH>2.0.CO;2).
- Nixon, C. J., and J. T. Allen, 2022: Distinguishing between Hodographs of Severe Hail and Tornadoes. *Wea. Forecasting*, **37**, 1761-1782, <https://doi.org/10.1175/WAF-D-21-0136.1>.
- Nixon, C. J., J. T. Allen, and M. Taszarek, 2023: Hodographs and Skew Ts of Hail-Producing Storms. *Wea. Forecasting*, **38**, 2217-2236, <https://doi.org/10.1175/WAF-D-23-0031.1>.
- Nixon, C. J., J. T. Allen, M. B. Wilson, M. J. Bunkers, and M. Taszarek, 2024: Cell Mergers, Boundary Interactions, and Convective Systems in Cases of Significant Tornadoes and Hail. *Wea. Forecasting*, **39**, 1435-1458, <https://doi.org/10.1175/WAF-D-23-0117.1>.
- Parker, M. D., 2017: How Much Does “Backing Aloft” Actually Impact a Supercell?. *Wea. Forecasting*, **32**, 1937-1957, <https://doi.org/10.1175/WAF-D-17-0064.1>.

- Peters, J. M., C. J. Nowotarski, and H. Morrison, 2019: The Role of Vertical Wind Shear in Modulating Maximum Supercell Updraft Velocities. *J. Atmos. Sci.*, **76**, 3169-3189, <https://doi.org/10.1175/JAS-D-19-0096.1>.
- Porter, K., 2024: Top 10 states most vulnerable to hail damage in 2024. Insurify. <https://insurify.com/car-insurance/insights/states-most-vulnerable-to-hail-damage/>.
- Prein, A. F., and G. J. Holland, 2018: Global estimates of damaging hail hazard. *Weather and Climate Extremes*, **22**, 10-23, <https://doi.org/10.1016/j.wace.2018.10.004>.
- Rasmussen, E. N., and D. O. Blanchard, 1998: A Baseline Climatology of Sounding-Derived Supercell and Tornado Forecast Parameters. *Wea. Forecasting*, **13**, 1148-1164, [https://doi.org/10.1175/1520-0434\(1998\)013<1148:ABCOSED>2.0.CO;2](https://doi.org/10.1175/1520-0434(1998)013<1148:ABCOSED>2.0.CO;2).
- Schaefer, J. T., and R. Edwards, 1999: The SPC tornado/severe thunderstorm database. Preprints, *11th Conf. on Applied Climatology*, Dallas, TX, Amer. Meteor. Soc., 603-606, <https://ams.confex.com/ams/99annual/abstracts/1360.htm>.
- Schaefer, J. T., J. J. Levit, S. J. Weiss, and D. W. McCarthy, 2004: The frequency of large hail over the contiguous United States. *NOAA/NWS/NCEP/SPC, Norman, OK*, https://ams.confex.com/ams/84Annual/techprogram/paper_69834.htm.
- Simmons, K. M., and D. Sutter, 2012: The 2011 Tornadoes and the Future of Tornado Research. *Bull. Amer. Meteor. Soc.*, **93**, 959-961, <https://doi.org/10.1175/BAMS-D-11-00126.1>.
- Smith, B. T., R. L. Thompson, J. S. Grams, C. Broyles, and H. E. Brooks, 2012: Convective Modes for Significant Severe Thunderstorms in the Contiguous United States. Part I: Storm Classification and Climatology. *Wea. Forecasting*, **27**, 1114-1135, <https://doi.org/10.1175/WAF-D-11-00115.1>.
- Smith, T. M., and Coauthors, 2016: Multi-Radar Multi-Sensor (MRMS) Severe Weather and Aviation Products: Initial Operating Capabilities. *Bull. Amer. Meteor. Soc.*, **97**, 1617-1630, <https://doi.org/10.1175/BAMS-D-14-00173.1>.

- Soderholm, J., H. McGowan, H. Richter, K. Walsh, T. Weckwerth, and M. Coleman, 2016: The Coastal Convective Interactions Experiment (CCIE): Understanding the Role of Sea Breezes for Hailstorm Hotspots in Eastern Australia. *Bull. Amer. Meteor. Soc.*, **97**, 1687-1698, <https://doi.org/10.1175/BAMS-D-14-00212.1>.
- SPC, 2014: Significant hail parameter (SHIP): [Parameter description available at https://www.spc.noaa.gov/exper/mesoanalysis/help/help_sigh.html.]
- Tang, B., M. Vaughan, R. Lazear, K. Corbosiero, L. Bosart, T. Wasula, I. Lee, and K. Lipton, 2016: Topographic and Boundary Influences on the 22 May 2014 Duquesburg, New York, Tornadic Supercell. *Wea. Forecasting*, **31**, 107-127, <https://doi.org/10.1175/WAF-D-15-0101.1>.
- Taszarek, M., H. E. Brooks, and B. Czernecki, 2017: Sounding-Derived Parameters Associated with Convective Hazards in Europe. *Mon. Wea. Rev.*, **145**, 1511-1528, <https://doi.org/10.1175/MWR-D-16-0384.1>.
- Taszarek, M., N. Pilgus, J. T. Allen, V. Gensini, H. E. Brooks, and P. Szuster, 2021: Comparison of Convective Parameters Derived from ERA5 and MERRA-2 with Rawinsonde Data over Europe and North America. *J. Climate*, **34**, 3211-3237, <https://doi.org/10.1175/JCLI-D-20-0484.1>.
- Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski, 2003: Close Proximity Soundings within Supercell Environments Obtained from the Rapid Update Cycle. *Wea. Forecasting*, **18**, 1243-1261, [https://doi.org/10.1175/1520-0434\(2003\)018<1243:CPSWSE>2.0.CO;2](https://doi.org/10.1175/1520-0434(2003)018<1243:CPSWSE>2.0.CO;2).
- Wade, A. R., and M. D. Parker, 2021: Dynamics of Simulated High-Shear, Low-CAPE Supercells. *J. Atmos. Sci.*, **78**, 1389-1410, <https://doi.org/10.1175/JAS-D-20-0117.1>.
- Wang, J., Xue, P., Pringle, W., Yang, Z., & Qian, Y. (2022). Impacts of lake surface temperature on the summer climate over the Great Lakes Region. *Journal of Geophysical Research: Atmospheres*, 127, e2021JD036231, <https://doi.org/10.1029/2021JD036231>.

- Warren, R. A., H. Richter, H. A. Ramsay, S. T. Siems, and M. J. Manton, 2017: Impact of Variations in Upper-Level Shear on Simulated Supercells. *Mon. Wea. Rev.*, **145**, 2659-2681, <https://doi.org/10.1175/MWR-D-16-0412.1>.
- Warren, R. A., H. Richter, and R. L. Thompson, 2021: Spectrum of Near-Storm Environments for Significant Severe Right-Moving Supercells in the Contiguous United States. *Mon. Wea. Rev.*, **149**, 3299-3323, <https://doi.org/10.1175/MWR-D-21-0006.1>.
- Wendt, N. A., and I. L. Jirak, 2021: An Hourly Climatology of Operational MRMS MESH-Diagnosed Severe and Significant Hail with Comparisons to Storm Data Hail Reports. *Wea. Forecasting*, **36**, 645-659, <https://doi.org/10.1175/WAF-D-20-0158.1>.
- Wilk, K. E., L. R. Lemon, and D. W. Burgess, 1979: Interpretation of radar echoes from severe thunderstorms: A series of illustrations with extended captions. Prepared for training of FAA ARTCC Coordinators, National Severe Storms Laboratory, 55 pp.
- Witt, A., M. D. Eilts, G. J. Stumpf, J. T. Johnson, E. D. W. Mitchell, and K. W. Thomas, 1998: An Enhanced Hail Detection Algorithm for the WSR-88D. *Wea. Forecasting*, **13**, 286-303, [https://doi.org/10.1175/1520-0434\(1998\)013<0286:AEHDAF>2.0.CO;2](https://doi.org/10.1175/1520-0434(1998)013<0286:AEHDAF>2.0.CO;2).
- Zrnić, D. S., 1987: Three-body scattering produces precipitation signature of special diagnostic value. *Radio Science*, **22**, 76-86, <https://doi.org/10.1029/RS022i001p00076>.