Using GOES-16 to characterize thunderstorms: hail scar producing storms vs. non-hail scar producing storms

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USING GOES-16 TO CHARACTERIZE THUNDERSTORMS: HAIL SCAR PRODUCING STORMS VS. NON-HAIL SCAR PRODUCING STORMS

by

ABIGAIL ELIZABETH WHITESIDE

A THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in The Department of Atmospheric and Earth Science to The School of Graduate Studies of The University of Alabama in Huntsville

HUNTSVILLE, ALABAMA

2021
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We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate of the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements for the degree of Master of Science in Atmospheric and Earth Science.

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Every year in North America, severe thunderstorms produce copious amounts of damage to agriculture, infrastructure, and lives. The United States relies heavily on the Next Generation Weather Radar for weather information. The U.S.’s reliance on radar has led to one of the most extensive radar networks in the world. However, this network has gaps in coverage that could put many at risk. Multiple studies have shown that satellite data provides valuable storm information to forecasters. The GOES-R series offers high resolution imagery of cloud tops. An important variable to examine is the overshooting top (OT). One variable that stems from an OT is the Above Anvil Cirrus Plume (AACP). Both elements have been shown to be indicators of severe storms. Another aspect to examine is Flash Extent Density (FED). The Geostationary Lightning Mapper (GLM) is a valuable tool for tracking lightning in severe storms. It has been shown that increases in lightning correlates to increases in storm intensity.

This project aims to bridge the gap between radar data and satellite data. OT and AACP frequency and duration will be examined in both hail scar producing
storms and non-hail scar producing storms. Maximum Expected Size Hail (MESH) values will be used to compare minimum cloud top temperatures (CTT) and maximum FED between hail scar producing storms and non-hail scar producing storms. Finally, a probability will be computed of a hail scar occurring, a severe storm occurring, and a non-severe storm occurring given specific CTT and FED. Within hail scars, OT appeared 100% of the time and AACP appeared 80% of the time. Severe storms that did not produce a hail scar had OT appear 70.8% and AACP form 27% of the time. Non-severe storms also saw OT (10.1%) and AACP (15.8%). There was not a high distinction between hail scar storms, severe storms, and non-severe storms CTT and FED values. Many of these values overlapped with each other and their distributions were close. Maximum MESH showed the highest distinction between the storm types. Hail scar producing storms had a mean MESH value of 49 mm and non-hail scar storms had a mean MESH value of 10 mm.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Severe thunderstorms have the ability to produce damage to agriculture, communities, and infrastructure through the severe weather they produce. Thunderstorms that are severe have the potential to produce any mode of hazardous weather, which includes large hail, lightning, damaging winds, flash floods, and tornadoes. The National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) considers a thunderstorm severe only if it produces one or more of the following: damaging wind gusts (58 miles per hour or higher), large hail (1 inch or greater), or tornadoes. Between 2008 and 2013, the United States has experienced over $80 billion in insured losses from thunderstorm related dangers [Waters, 2017]. In 2017, North America experienced $25 billion in loss from severe thunderstorms [Löw, 2018]. That same year, 70% of loss from severe thunderstorms came from hail, with 20% and 10% coming from tornadoes and straight-line wind damage, respectively [Waters, 2017].

Up to softball size hail ($\leq 4$ inches), fell in Colorado Springs, Colorado in August 2018. Damage was seen to vehicles, roofs, siding, windows, and other structural
areas. At the Cheyenne Mountain Zoo, buildings were extensively damaged and five animals were killed as a result of the hail storm. The Rocky Mountain Insurance Information Association reported that 21,000 claims on vehicles and 6,000 claims on homes were filed after the storm totaling $172.8 million worth of damage [Heilman, 2018]. A less considered consequence of hail damage is the impact on crops. This was studied extensively in 1936 by Iowa State University. They found that the annual hail damage to Iowa crops ran about $4.5M, or about $84M in 2020. It was estimated that 1 in 6 farmers experienced crop damage due to hail in Iowa. [Eldridge, 1936].

Today, farmers still suffer serious devastation to their crops due to hail. Between 1949 and 2006, the national average annual crop loss due to hail valued around $581M, or about $709M in 2020 [Changnon, 2009]. Changnon [2009] discovered that crops east of the Rockies and west of Illinois are more prone to hail damage (Fig. 1.1). There are certain factors that lead to a crop’s survival from a hail storm. Things like crop type, crop row density, stage of crop growth, and field location all affect the outcome of the crop. However, there seems to be a connection between weather and crop survivability. Factors like hail size, wind driven hail, and hail fall intensity play a part in crop survivability.
Figure 1.1: Adapted from Changnon et al. [2009]. This figure shows the crop-hail intensities determined for peak months (June and July) of wheat and corn damages. Areas east of the Rockies and west of Illinois experienced the highest amount of crop damage due to hail.

The hail damage to acres of fields can be seen from space. The damage swath seen from aerial views has been coined hail scars. Hail scars can easily be identified with visible satellite channels. Most of the time, they are characterized by browning areas in a sea of green hues. Figure 1.2 shows a hail scar that totaled 129 km in
length and travelled from southeast Wyoming into northwest Nebraska. This storm caused extensive damage to both crop and structural properties.

Figure 1.2: A hail scar from a severe thunderstorm that formed over Wyoming and travelled into Nebraska on August 15, 2019. Damage areas are seen from eastern Wyoming to north of Scottsbluff, Nebraska.

The United States relies heavily on the National Weather Service (NWS) Next Generation Weather Radar (NEXRAD) for weather information. The U.S.’s reliance on radar has led to one of the most extensive radar networks in the world. Many areas of the world don’t receive the spatial coverage that the U.S. does. Whether it be terrain or economic reasons, it is not feasible to put more radars to provide adequate coverage of the atmosphere across the globe. Comparing satellite data to already known radar and hail relationships will allow better forecasting in regions of the world where access to ground truth data is severely limited.
Numerous studies have shown that satellites provide a useful tool pertaining to severe weather hazards [Reynolds, 1980, McCann, 1983, Adler et al., 1985, Bedka et al., 2010]. Recent advancements have been made in satellite technology with the launches of the Geostationary Operational Environmental Satellite (GOES) 16 and 17, formerly known as the GOES-R series. GOES-R provides some of the highest resolution imagery ever offered on a satellite. It significantly improves the detection of weather phenomena. The GOES-R series has the Advanced Baseline Imager (ABI) which offers 16 spectral bands compared to five bands on previous GOES series. ABI includes two visible wavelength channels, four near-infrared channels, and 10 infrared channels. Satellites use various combinations of channels to look at different phenomena in the atmosphere and on the Earth’s surface. The GOES-R series is the first satellite group to be outfitted with a lightning sensor, the Geostationary Lightning Mapper (GLM). GLM is a single-channel, near-infrared sensor that detects minute changes in the optical scene. Both GOES-16 and GOES-17 make a field of view that spans the Americas with a near-uniform spatial resolution of 10 km. Innumerable correlations between distinct satellite features and reported severe weather events have been shown in studies.

One feature that is useful for severe weather prediction is the Overshooting Top (OT). OT have been shown to exist in storms with hazardous weather such as heavy rainfall [Negri, A. J. and Adler, R. F., ], damaging winds [Heymsfield and Spinhirne, 1991], damaging hail [Reynolds, 1980, Bedka et al., 2018], and tornadoes [Fujita, 1989,Heymsfield, G. M. and Blackmer , R. H., 1988]. Another useful characteristic for determining potential severe weather hazard is the above anvil cirrus plume (AACP).
AACP form from severe thunderstorms with strong updrafts. GLM has provided critical total lightning data that can be used to help forecasters focus on storms that are strengthening. Schultz et al. [2011] showed that total lightning trends are good indicators of storms strengthening.

The overall goal of this project is to use atmospheric variables derived from GOES-R series to determine characteristics associated with hail scar producing thunderstorms within the GOES-R domain. It is hypothesized that hail scar producing thunderstorms will exhibit a colder cloud top temperatures (CTT), higher flash extent density (FED) rates, and a higher number of OT and AACP than non-hail scar producing storms. If not, the hypothesis is rejected. Based on the results, the aim is to improve detection of hail producing thunderstorms using satellite data. A more in depth approach to the characterization of hail scar producing thunderstorms will be discussed in the following chapters of this work. Chapter 2 explains the background information about OT, AACP, CTT, FED, and the relationship between lightning and hail. Chapter 3 explores the methodology and instrumentation used in this study. Chapter 4 will provide in depth example cases of hail scar producing thunderstorms and non-hail scar producing thunderstorms. Chapters 5 and 6 will contain discussions and conclusions about this study.
2.1 Thunderstorm Processes

Thunderstorms are usually composed of cumulonimbus clouds and are composed of single or groups of individual convective storms. Thunderstorms are capable of producing all modes of severe weather including heavy rainfall, lightning, straight-line winds, tornadoes, and hail. This paper will focus on the last mode of severe weather, hail.

The most important ingredients for thunderstorm formation are moisture, instability, and lift. When these ingredients are all present, fair weather cumulus clouds can grow into towering cumulonimbus clouds. A cell begins when relatively warm, moist air becomes more buoyant or less dense than the surrounding air. The parcel of air then accelerates upward. The mathematical expression that can represent the relationship between updraft and buoyancy can be given by the vertical component of the momentum equation

\[
\frac{Dw}{Dt} = -\frac{1}{\rho_o} \frac{\partial p^*}{\partial z} + B
\]  

(2.1)
where \( w \) is the vertical velocity, \( \rho_o \) is the reference state density, \( p^* \) is the pressure perturbation relative to a reference state, and \( B \) is buoyancy.

Another important ingredient to buoyancy and thunderstorm development is Convective Available Potential Energy (CAPE). CAPE is defined as the maximum energy available to an ascending particle. It is expressed as

\[
CAPE = \int_{LFC}^{EL} \frac{T_{v_{\text{parcel}}} - T_{v_{\text{environment}}}}{g} \frac{dz}{T_{v_{\text{environment}}}}
\]

where LFC is the level of free convection, and EL is the equilibrium level. The LFC is the height at which a saturated particle becomes warmer than the environment, EL is the equilibrium level where the temperature starts warming with height as the parcel enters the stratosphere. The remaining constants and variables are the gravitational acceleration constant \((g)\), the virtual temperature of the specific parcel \((T_{v_{\text{parcel}}})\), and the virtual temperature of the environment \((T_{v_{\text{environment}}})\) \cite{Vasquez2006}. Mixing due to entrainment and turbulence make pressure perturbations, water loading, and friction can be ignored and it is assumed that the available potential energy is converted to kinetic energy. CAPE can be used to estimate the maximum updraft velocity. The equation to represent a vertically rising particle parcel can be expressed as

\[
w_{\text{max}} = \sqrt{2 \times CAPE}
\]

\(W_{\text{max}}\) can be considered the upper estimate of the actual vertical velocity that can occur within convection and may be much larger than the actual updraft.
Even when an environment is conducive to support thunderstorm development, a trigger is required to lift the parcels to the LFC. This trigger is usually in the form of a frontal boundary, dry line, convective outflows, sea breezes, surface heating, and orographic lifting. The opposite of CAPE is Convective inhibition (CIN). CIN is where a parcel of air is lifted colder than the surrounding environment (negative buoyancy). The lifting mechanisms mentioned above need to be strong enough to overcome CIN. If CIN is greater than CAPE, then capping will take place and thunderstorms will not grow. If CAPE is greater than CIN, then there is the potential for thunderstorms. The type of convection and severity of the thunderstorms depend on the different dynamic and thermodynamic factors such as CAPE, and the vertical profile of wind, water vapor, and buoyancy.

While thermodynamics play a large role in thunderstorm dynamics, strong convection is also greatly influenced by vertical wind shear. Vertical wind shear can lead to larger and stronger thunderstorm development by allowing precipitation particles to fall outside of the updraft [Dennis and Kumjian, 2017]. It can also move new convection along the gust front which will allow warm, moist air to infiltrate into the cloud. An increase of the wind speed with height will tilt a thunderstorm’s updraft. This causes the updraft and downdraft to occur within separate areas of the storm, and can reduce the amount of water loading in the updraft. The downdraft will not cut off the air flowing up into the storm and will thus strengthen the updraft due to them being in separate locations. Horizontal vorticity tubes are tilted vertically by the updraft which can lead to rotation. This enhances the vertical pressure gradients along the flanks of the updraft [Lemon, L. R. and Doswell, C. A., 1979]. This
increases the updraft strength and causes the cell to deviate from the mean wind which increases the relative inflow and updraft rotation [Rotunno and Klemp, 1985]. A change in wind direction with height can help remove extra mass from the top of the thunderstorm which reduces the effect of precipitation loading on the updraft, allowing it to strengthen. However, too much vertical shear can tear the updraft apart. Therefore, storm types and strength depend on the thermodynamics and vertical wind shear available to the storm.

Now, it is time to discuss the specific environmental set up of hail storms. There are several ingredients that need to come together for hail storm formation. It is well known from sounding data that there is a strong correlation between CAPE, wind shear, and severe thunderstorms [Rasmussen and Blanchard, 1998, Craven, JP and Brooks, 2004, Brooks, 2009, Brooks, 2013]. As discussed in previous sections, hail storms thrive on stronger updrafts and higher levels of wind shear. However, there are many more environmental ingredients that thunderstorms require to produce hail. Taszarek, Allen, Púčik, Hoogewind, and Brooks [2020] studied severe convective storms across the United States and Europe. They found that the United States is characterized by higher moisture values, CAPE, CIN, wind shear, and mid-tropospheric lapse rates. Consistent with previous studies, hail severity increases with increasing CAPE. In the US, hail storms form between 500 J/kg to 2000 J/kg CAPE. Specifically, CAPE is notably higher for hail ≥ 5 cm. On average, the lifting condensation level (LCL), the level at which a parcel becomes saturated, occurs between 500 m and 1500 m for hail storms in the United States. Values for the LFC range from 1500 m to 2750 m. For CIN, values that promote hail growth include -25 J/kg to
-125 J/kg. It is noted that higher levels of CIN may delay convective initiation until the CAPE is maximized and allow for discrete convective modes to form supercells, and thus larger hail. Also, increasing moisture content generally increases the hail size. For large hail events, effective shear has the best skill in discriminating between nonsevere thunderstorms and hail storms that produce hail $\geq 5$ cm.

2.2 Hailstorm Processes

There are several contributing factors to hail stone formation. Knight and Knight [1970] found that a small particle is needed to serve as a core for larger hail growth ($\geq 2.5$ cm). This particle usually ranges from 0.5 cm to 1 cm and is known as an embryo. Normally, embryos form from aggregates, snow crystals, ice particles, or ice fragments. They can also form through liquid drop coalescence. Dust and other aerosols may be responsible for a small percentage of hail storm embryos. In order for large hail to form, the concentration of hail embryos has to be quite low [List, R., Charlton, R. B. and Buttuls, 1968]. Smaller cells to the side of a main thunderstorm cell can act as a feeder cell of particles into the main thunderstorm. Strong relative winds aid in transporting the particles into the main updraft [Heymsfield and Frank, 1980]. This schematic can be viewed in Figure 2.1. While it is important to have a strong updraft for hail growth, an updraft that is too strong can prevent the embryos to grow to an adequate size [Knight, 1981].

Once an embryo is formed, it will need an abundance of supercooled liquid water, when water particles are below the freezing point but in liquid form. Hail formation occurs when supercooled liquid water is gathered on the embryo and ei-
Figure 2.1: A schematic of a feeder cell and a main cell that shows the ideal relationship between the two for favorable feeding of particles into the main hail storm. Adapted from Heymsfield, Jameson, and Frank [1980].

ther freezes or stays a liquid. Rimming is the process in which liquid water freezes immediately on contact with the ice particle. Accretion is the process in which liquid water contacts an ice particle and stays in liquid form. The majority of supercooled liquid water comes from the convective storm’s updraft. These water particles lack a nucleus so they are unable to freeze until they hit an ice particle. Growth occurs through condensation, coalescence, and through the recycling of melting ice particles [Allen et al., 2020]. Hail requires the presence of liquid water to grow into an appreciable size. Therefore, research suggests that most hail forms between -10° C and -25° C where there is abundant liquid water and ice crystals [Foote, 1984, Nelson, 1983, Ziegler, C. L., Ray, P. S. and Knight, 1983].
Another necessary process for hail storms is a very unstable atmosphere. The more unstable the atmosphere, the more likely that thunderstorms will form with an updraft strength capable of supporting large hailstones. As mentioned previously, the updraft velocity plays an important role for hail to grow into sizable stones. The biggest hailstones do not come from the biggest updrafts. If an updraft is too big, then the growing hailstones will not stay in the updraft. If an updraft is too weak, then larger hailstones fall out of the growth area. The ideal updraft is one that balances hail terminal velocities and high updraft speeds [List, R., Charlton, R. B. and Buttuls, 1968]. Nelson [1983] found that the ideal updraft is a broad region of moderate velocity (20-40 ms$^{-1}$). As well as a moderate updraft, storms tend to need copious amounts of time for large hail stone growth. This can be accomplished by strong wind shear. Wind shear aids in the formation of hailstones by sustaining the updraft/downdraft couplet leading towards the largest hail growth. The wind shear from the environment causes the updraft to tilt and allows the precipitation to fall into the lower atmosphere. Here, it hardly affects the recycling. The diverging winds aloft cause smaller amounts of precipitation to make the radar overhang, also known as the “embryo curtain” shown in Figure 2.2 [Browning, K.A. and Foote, 1976]. Dennis and Kumijan [2017] found that the embryo curtain wraps around the rear of the storm with altitude. Some studies show that larger hailstones may exist in the growth region of storms for as long as 10 -15 minutes [Nelson, 1983].

Dennis and Kumijan [2017] discussed how hailstones can take several different trajectories through the storm. Trajectories are key to critical hail growth. Several studies have shown that the path a hail stone takes through a storm can be just as
Figure 2.2: A vertical cross section of a hail storm in Fleming, Colorado superimposed with the radar echoes. Bold arrows on the side of the plane show the environmental wind speeds measured by a nearby sounding. Thin arrows leading into the storm show the streamlines of air into the storm. It is important to note the location of the embryo curtain as indicated by the larger radar reflectivity values. Adapted from Browning and Foote [1976].

important as the storm’s updraft [Dennis and Kumjian, 2017, Nelson, 1983, Ziegler, C. L., Ray, P. S. and Knight, 1983]. Browning and Foote [1976] proposed three different trajectories that occur in hail producing supercells. The first trajectory allows hail embryos to enter a strong updraft and are immediately ejected through the forward anvil before having time to grow. The second trajectory calls for hail embryos to enter into an area with a weaker updraft along the perimeter of the main updraft and cycle in the reflectivity overhang. This trajectory allows them to grow at moderate rates. The third trajectory takes hail stones from the second trajectory and cycles them up into the main updraft where a balance is achieved between updraft velocity and hailstone fall velocity. In this suspended state, hailstones have the opportunity to grow into large, dangerous stones. The hailstone trajectories can be viewed in Figure 2.3.
Figure 2.3: A schematic model of a hail producing thunderstorm showing the trajectories of a hail stone within the supercell based upon an airflow model. This vertical cross section shows the trajectory based on the direction of travel. Trajectories 1, 2, and 3 represent the three stages in the growth of large hailstones. The transition of 2 into 3 represents the re-entry of a hail stone into the main updraft. The 0 trajectory represents hail embryos that enter the main updraft too rapidly and are soon ejected into the anvil. Adapted from Browning and Foote [1976].

To summarize, hail formation and growth are reasonably well understood. The first step is embryo generation during ascent in an updraft. They may also be formed in feeder cells, or flanking lines of convection. If the embryo source is occurring in a singular storm, then growth will take place primarily in the outer brim of the main updraft. Wider updrafts are ideal for hail growth. Particles in the strongest part of the updraft, the center, will be lofted too quickly for substantial growth [Heymsfield and Musil, 1982]. The next step takes the newly formed embryos and ejects them into the updraft via the storm’s inflow. The radar overhang, or embryo curtain, is the best location for embryo formation. Kumjian et al. [2010] discovered that the embryo curtain is visible on radar. At mid levels, a differential reflectivity ($Z_{DR}$) ring occurs around the updraft and values are 0 when graupel is present. The correlation
coefficient between the backscattered returns at horizontal and vertical polarizations at zero lag time ($\rho_{HV}$) values are large (>0.98). Both of these variables indicate ice hydrometers present. The next stage takes the embryos into the updraft full of abundant supercooled liquid water where they begin to experience growth. Here, this can be marked on radar by an abrupt shift in $Z_{DR}$ and $\rho_{HV}$. $Z_{DR}$ increases dramatically and $\rho_{HV}$ decreases, both indicating that the ice is gone. It has been shown that hail does not “circulate” in the updraft like previously thought [Dennis and Kumjian, 2017, Foote, 1984, Nelson, 1983, Ziegler, C. L., Ray, P. S. and Knight, 1983]. Optimizing hail growth requires balance between hail stone fall speed and the updraft feed. If the updraft speed is too large, then the particle is lifted out of the growth region. If the particle fall speed is greater than the updraft speed, then the particle will fall from the updraft. When a balance is reached, the particle will remain suspended around a constant altitude.

2.3 Hailstorm Frequency

Hail storms occur all over the globe but there are certain places that hail occurs more frequently. They occur in areas where the ingredients for hail storms come together. Bang and Cecil [2019] used a space based passive microwave radar, the Global Precipitation Measurement (GPM), to make a global climatology of hail storms. Figure 2.4 shows the GPM normalized hail occurrence density per year. They found the highest hail frequencies over northern Argentina through Paraguay, Uruguay, and southern Brazil; the central United States; and a swath through subsaharan Africa.
Figure 2.4: Climatology of hail in the GPM domain from April 2014 to March 2018. The climatology has been subjected to snow and ice filters, normalized for overpasses and area, and averaged into $2^\circ \times 2^\circ$ boxes for smoothness. Adapted from Bang and Cecil [2019].

Allen and Tippett [2015] studied hail reports dating from the 1950s to the 2010s in the United States. The results showed a bias towards hail reports occurring closer to cities. They found that early on hail reports were sparse and as cities grew and more people moved out west hail reports increased. When normalized, the greatest hail occurrence happened in the central Plains, from South Dakota to the panhandle of Texas. Figure 2.5 shows the mean number of hail days where there are greater than 1 inch hail stones from 1995 to 2014.

2.4 Thunderstorm Electrification

The kinematics, microphysics, and environment of hail storms discussed in previous sections lay the foundation for exploring the thunderstorm charging process that leads to the initiation of lightning and why it is an important tool for identifying
The majority of thunderstorm electrification theories are based on two primary concepts: 1) an inductive process by which preexisting electric field induces charges on polarized particles which are then segregated through collision and separation, and 2) a non-inductive process by which electrochemical or thermoelectric properties of colliding solid and liquid hydrometers lead to charge separation in thunderstorms [Kuettner, J. P., Sartor, J. D. and Levin, 1981].

### 2.4.1 Inductive Charging Theory

Inductive charge theory requires two polarized hydrometers to rebound and collide between each other [Sator, 1981]. It is hypothesized that when a precipitation particle and a cloud droplet or small ice particle collide and rebound, the larger parti-
cle becomes negatively charged and the smaller one becomes positively charged. The larger, heavier particle falls lower in the cloud and the lighter, smaller particle gets caught in the updraft and rises within the cloud. This process leads to polarization in the cloud with a positive area in the top of the cloud and a negative charge residing in the lower precipitation area of the cloud. However, Illingworth and Latham [1977] concluded that liquid-liquid induction charge is not capable of thunderstorm electrification. Ice-ice charging mechanisms are far more likely to play a major importance in thunderstorm electrification. The induction mechanism needs a high frequency of collision and rebound between cloud particles. Brooks and Saunders [1994] suggested that the inductive charging mechanism can be utilized in the later stages of thunderstorm lifespan. This is because researchers detected small graupel particles with charges that are much larger than what can be produced by inductive charging [Marshall and Winn, 1982]. It is more likely that it acts as a contributing mechanism in the later stages of thunderstorm electrification.

2.4.2 Non-Inductive Charging Theory

Non-inductive charging (NIC) theory includes any charging mechanism that does not require the presence of an existing electric field. There have been many studies to show how specific thunderstorm cloud conditions can change the charge transferred between colliding graupel and ice particles. Dye et al. [1989] proved the development of an ice phase within the thunderstorm leads to electrification. Reynolds et al. [1957] showed in laboratory experiments that riming graupel pellets gained more charge per collision when they collide with ice crystals. This is adequate
to account for summertime thunderstorms but it does not account for many other types. In a cold room laboratory experiment, Takahashi [1978] showed that the sign of the charge within the cloud is dependent on the temperature and cloud water content. Takahashi simulated thunderstorm conditions by using ice and supercooled water droplets in a chamber with electric probes measuring the electric field. It was found during this experiment that to produce high enough electric fields both ice and supercooled water need to be present in the chamber. Saunders et al. [1991] found results that were similar to the results from Takahashi [1978]. However, there were minor differences in the magnitude of the charge transferred at different cloud water content and temperature. Saunders et al. [2006] found that the presence of supercooled liquid water in the cloud affected the rime temperature through accretional heating, but is also indicative of water supersaturation conditions that is conductive to ice growth on particles leading to charge transfer. Baker et al. [1987] found that the background thermodynamics, temperature and water content, change the diffusional growth rates of colliding ice surfaces. This determines the charge structure of the particle. Saunders et al. [1991] quantified the charge transfer in terms of ice crystal size, graupel/crystal velocity, and effective liquid water content (EW), where E is the riming particle’s collection efficiency and W is the liquid water content within the cloud. Jayarantne et al. [1983] observed that the amount of charge transferred depended on temperature, liquid water content, graupel/crystal relative velocity, and ice crystal size. Saunders et al. [2006] compiled the results of multiple similar studies [Saunders and Peck, 1998, Pereyra et al., 2000, Takahashi, 1978]. It is important to
note that there is a reversal of polarity in the range from -10 °C to -18 °C that could be absent in high water content clouds.

![Figure 2.6](image)

**Figure 2.6**: Adapted from Saunders et al. [2006]. A figure showing the boundaries found between positive and negative polarities for rimers post-collision for various laboratory studies. The solid line is Saunders et al. [2006]. The dashed is Saunders and Peck [1998]. The solid line broken by dots is Pereyra et al. [2000]. The dotted line is Takahashi [1978].

Saunders and Peck [1998] confirmed that the charge transfer is dependent on all the previously discussed variables. During ice crystal collision, the charging of riming graupel pellets is influenced by the amount of liquid water collected on the rime. It was theorized that the faster growing particle would become the positively charged particle. Accretion rate is highly dependent on the size distribution of supercooled
liquid cloud droplets. Smaller particles are more likely to miss the graupel pellets, as opposed to colliding with them [Saunders and Peck, 1998].

Figure 2.8 exemplifies the NIC process as it pertains to the development of a thunderstorm’s tripole electrical structure. This image is a very simplified version of what is actually happening within a storm. The leading hypothesis pertaining to a storm’s charge structure is determined by gravitational sedimentation caused by the storm’s updraft and differing particle vertical motions. Ice crystals, graupel, and small hail have differing sizes and densities and thus differing terminal fall speeds. A positive charge region develops in the upper portion of the cloud. Then a negative charge region forms in the mid-levels of the cloud and another region of positive charge develops in the lower portions of the cloud. The upper positive portion of the cloud and the negative portion of the cloud are similar in charge magnitude, while the lower positive region is a quarter of the magnitude of the main charge regions [MacGorman and Rust, 1998]. As a result of gravitational sedimentation, smaller size ice particles will be pushed higher in the thunderstorm updraft and larger size particles will descend through the updraft or downdraft to lower levels, depending on their size. In a real-life storm, latent heat drives thunderstorm convection by creating an upward movement of air. This column of air also creates shear-stress in the horizontal gradient of vertical motion. This produces numerous turbulent eddies. These eddies can be responsible for differing vertical velocities between hydrometers. Bruining and MacGorman [2013] found that pockets of negatively and positively charged particles exist within the turbulent areas. The eddies can be thought of as a means to redistribute electrical charges within the cloud. In smaller areas of positively
charged and negatively charged particles, there would be larger flash initiation rates. As the particles collide in the cloud, NIC charge transfer takes place. As a cloud grows, it reaches the threshold where lightning is usually initiated, -10 °C. At this stage in the thunderstorm process, cloud particles in the form of graupel, supercooled liquid water, and ice crystals mix and collide. This collision causes charge transfer between the individual particles as a particle either gains or loses an electron (Fig. 2.7). This phenomenon is due to mass exchange between the particles. The heavier particles gain electrons and thus become negatively charged. The lighter particles lose electrons and thus are positively charged and get carried higher within the updraft. This charge separation is the mechanism that is thought to form lightning. This leads to a charge structure similar to the structure shown in Figure 2.8.

Figure 2.7: Mass and charge transfer from the corner of a crystal to the underside of a sublimating graupel particle. This image shows the mass transfer between the two particles. ∆ Q is the charge value. When it collides with another particle it leaves the original particle. The particle that loses mass becomes positively charged and the particle that gains mass becomes negatively charged. Adapted from Nelson and Baker [2003].
Figure 2.8: Adapted from Saunders [1993]. This figure shows the development of a tripole electrical structure within a thunderstorm. Smaller upward moving ice crystals obtain a positive charge as they collide with negatively charged graupel near the -10 °C.

2.5 Lightning’s Relation to Severe Weather

Early observations indicate that total lightning correlates well with severe weather. Williams et al. [1999] were one of the first groups to observe the relationship between total lightning and severe weather. They found peak flash rates precede severe weather anywhere from 5 to 20 minutes. This study coined the term “lightning jump” and defined it as “abrupt increases in flash rate in advance of the maximum flash rate of the storm.” They believed this was due to the increase in updraft speeds that stimulate the ice microphysics causing increases in charge activity. Deierling et al. [2008] characterized the relationship between total lightning rate and thunderstorm updraft characteristics using multi-Doppler radars. They found that there is a strong correlation (r=0.93) between total lightning rate and updraft volume. They also
found that there was a slight, positive correlation ($r=0.69$) between maximum updraft velocity and total lightning rate. This corresponds well to NIC theory. Larger and wider storm updraft volumes produce more hydrometers in the charging zone, which leads to more collisions between graupel and ice crystals. Lightning performs best when there is an area of broad updraft rather than a faster updraft. It is shown that the updraft volume above the $-5 \, ^{\circ}C$ level with vertical velocities greater than $5 \, m \, s^{-1}$ and $10 \, m \, s^{-1}$ is well correlated to mean total lightning activity ($r = 0.93$ and $r = 0.92$ respectively). This has also been shown to be true for hail formation. It has been thought that larger updraft volumes provide opportunities for large precipitation growth like graupel and hail. This makes large amounts of cloud ice concentrations that allow collisions and charge transfer between rimed graupel pellets and ice crystals [Deierling and Petersen, 2008]. A faster, but narrower updraft would have less particle collisions inside and so any hydrometer within the updraft would be expelled from the cloud before it had a chance to grow. Several studies have shown that there is a high correlation between total flash rates and graupel mass and updrafts greater than or equal to $10 \, m \, s^{-1}$ in the $-10 \, ^{\circ}C$ and $-40 \, ^{\circ}C$ range [Carey et al., 2019, Carey and Rutledge, 1996, Carey, L. D. and Rutledge, 2000, Schultz, C. J., Carey, L. D., Schultz, E. V. and Blakeslee, 2015, Schultz, C. J., Carey, L. D., Schultz, E. V. and Blakeslee, 2017]. Carey et al. [2019] found a positive correlation between the kinematic (updraft volume $> 5 \, m^{-1}$, updraft volume $> 10 \, m^{-1}$, and maximum updraft velocity) and microphysical (graupel echo volume, graupel mass, and $35 \, dBZ$ echo volume) properties and flash rates. Maximum updraft velocity had the lowest correlation between it and flash rate ($\rho = 0.60$) and graupel mass had the highest correlation
(\(\rho = 0.76\)). Schultz et al. [2015] shows this relationship between total flash rate and various kinematic and microphysical processes of a thunderstorm in south-central Tennessee in June 2012 (Fig. 2.9). It is important to note the 5 - 10 minutes lead time of graupel mass and updraft speeds before the total lightning rate increases. An increase in graupel mass indicates the storm the updraft is broad and letting in more supercooled liquid water. Because graupel is important in the electrification process, it is reasonable to expect an increase in lightning following the increase in graupel collisions. Graupel also acts as an embryo for hail formation so you would also have more hail stones forming.
Figure 2.9: A figure from Schultz et al. [2015] showing a time series of total lightning with updraft volume, graupel volume, and updraft speeds for a storm in central Tennessee on 11 June 2012.
One study found two separate increases in lightning flash rates 6-10 minutes before hail occurred in a storm using a phased array radar and the ground based Lightning Mapping Array (LMA) [Emersic, C., Heinselman, P. L., MacGorman, D. R. and Bruning, 2011]. The flash rates coincided with two updraft pulses inferred from the reflectivity and radial velocity measurements.

Schultz, Petersen, and Carey [2011] found similar results in North Alabama using the LMA. The researchers based their study on the notion that lightning production and severe weather are both closely tied to thunderstorm updraft, a key characteristic in thunderstorm intensity. A hail producing supercell developed in Marshall County, Alabama at 2035 UTC. At first, the storm had the appearance of an ordinary thunderstorm for the first hour. The total flash rate during this time was below 10 fl min-1 (Fig. 2.10). At 2140 UTC, the thunderstorm underwent rapid vertical growth as determined by radar. Between 2146 UTC and 2148 UTC, the total flash rate increased from 10 fl min-1 to 18 fl min-1 and a lightning jump was triggered. At 2215 UTC, a 2.54 cm hail report was received by the National Weather Service Forecasting Office in Huntsville, Alabama. The storm continued to grow in intensity. At 2218, another total lightning jump occurred, increasing from 18 fl min-1 to 28 fl min-1. 3.81 cm hail was reported in Boaz, Alabama 26 minutes later at 2244 UTC. Two additional lightning jumps occurred in this storm at 2256 UTC and 2346 UTC with four more large hail reports occurring at 2313 UTC, 2326 UTC, 2342 UTC, and 0008 UTC. The timeline of this storm can be viewed in Figure 2.10. Overall, they found an average of 27 minutes lead time for severe thunderstorms.
Figure 2.10: A figure from Schultz et al [2015]. Time-height plots of maximum reflectivity (dBZ) on top, lightning rates (fl min$^{-1}$) in the middle, and total lightning DFDRT values (fl min$^{-2}$) in a hail producing thunderstorm in eastern Alabama on 18 April 2006. All four total lightning jumps were verified by severe weather occurrences. In the middle plot, total flash counts are represented by the purple bars (scale on left), while CG flash counts are represented by red bars (scale on right). In the bottom plot, red bars represent total lightning jump times. Hail reports are located on the bottom of the graph by green asterisks.

2.6 Cloud-Top Features in Hail Storms

While lightning is an important indicator of severe weather, there are several other indicators that can come from satellite imagery. With better satellite technology, we are able to receive higher resolution images of the Earth and its storms.
These images reveal OT and AACP, both of which are thought to be early indicators of severe weather. The cloud top properties are important to hail identification because they can potentially be used in place of radar data, especially in areas where radar coverage is lacking.

2.6.1 Overshooting Tops

Severe weather can trigger unique phenomena at the top of the storm. Identification of storm top features has been studied since the launch of the first weather satellites. Specifically, OT are associated with intense updrafts which result from deep convection. As its name suggests, OT are cauliflower-like domes at the top of a thunderstorm anvil. This protrusion extends from the upper troposphere into the warmer, lower stratosphere. They have been linked to severe weather events like flash floods, large hail, tornadoes, and strong winds [Marion et al., 2019, Bedka et al., 2010, Dworak et al., 2012, Negri, A. J. and Adler, R. F., Reynolds, 1980]. In a study from Dworak et al. [2012], 75% of OT detection occurred before severe weather events. Because the overshoots on top of convective clouds are thought to be the manifestation of strong updrafts, it is expected that storms with OT are capable of producing hail of large size. Studies over Europe have shown a positive correlation between OT and hail storms. Bedka [2010] showed that the OT-severe weather relationship is strong for large hail (53%) and severe wind (52%). Another study conducted by Mikuš and Mahović [2013] showed that hail is observed in the vicinity of OT 38% of the cases. They hypothesize their smaller correlation occurred due to the smaller spatial region and shorter time period of observation. Figure 2.11 shows
a hail producing storm over Argentina that produced an OT (white arrows) and an AACP (white dashed outline), discussed more in the next section.

2.6.2 Above Anvil Cirrus Plumes

Stemming from OT are AACP. AACP exhibit unique temperature and reflectance patterns in satellite imagery. They are thought to be the result of OT ejecting cloud particles into the stratosphere that then get carried in storm-relative wind environments which leads to the formation of cirrus plumes above the anvil [Bedka et al., 2018]. The lofting of cloud particles during a perturbation event is consistent with the early research done by Fujita [1982]. He observed the cloud-top evolution during plume formation and called it a “jumping cirrus”. AACP are found best in the visible window of the satellite channels. They have a unique texture when viewed in visible satellite channels due to the difference in ice microphysics between the AACP and anvil. IR imagery can be used to help verify where an AACP is located. Bedka et al. [2018] showed that AACP preceded severe weather by an average of 31 minutes. From this study, significant hail was most likely to be produced by an AACP producing storm. A specific case from Bedka et al. [2018] showed that a storm generating an OT and an AACP over Argentina produced hailstones exceeding 18 cm (7 in) in diameter. This storm was viewed by the GOES-16 ABI. Compared with OT, AACP are more likely to be indicators of severe thunderstorms from visible and IR imagery. OT with no AACP are known to still produce severe weather hazards. However, OT are a pervasive sign of deep convective storms throughout the world but severe weather is quite infrequent compared to the total number of
OT generating storms. Only a small amount of OT producing storms penetrate the tropopause > 1km within storm-relative wind conditions can generate AACP.

**Figure 2.11:** (a) GOES-16 0.64-μm visible, (b) 10.3-μm IR+visible sandwich composite, (c) 1.61-μm near-IR, and (d) daytime convection RGB composite imagery of convective storms over Argentina at 2030 UTC 8 Feb 2018. Locations of two AACPs are outlined by dashed lines, and overshooting cloud tops responsible for triggering the AACP are identified by white arrows. The northern AACP storm generated hailstones exceeding 18 cm (7 in.) in diameter in Córdoba, Argentina, near the time of these images. Adapted from Bedka et al. [2018].
2.7 Importance of Background to Characterizing Hail Scar Producing Storms

Hail scars are the result of damaging hail storms moving over an area, usually over crops. Hail can damage urban areas but it is a lot harder to detect via satellites. Hail damage can cost farmers multiple fields which can result in complete crop loss. Crop loss due to hail storms can cause loss of billions of dollars. Using hail scars as a known damage area, we can characterize the thunderstorm associated with the hail scar. This will give us a better idea of when a thunderstorm is potentially doing large amounts of damage.

Using high resolution ABI and GLM observations from the GOES-R series, a proper characterization can be made of these hail scar producing thunderstorms. This study can answer the following questions:

1. What is the frequency and duration of OT and AACP within hail scar and non-hail scar producing storms?
2. What is the difference between hail scar and non-hail scar producing storms with minimum CTT and maximum FED?
3. What is the likelihood of a hail scar occurring solely based on the cloud top characteristics?
CHAPTER 3

METHODOLOGY

Characterizing hail scar producing thunderstorms requires the following steps. First, hail scar producing thunderstorms had to be discovered using NASA satellites. The hail scar storms must be separated from non-hail scar producing thunderstorms. Further, each non-hail scar producing storms were sorted into severe storms and non-severe storms. Secondly, satellite data had to be processed to view OTs and AACPs. Next, GLM data had to be processed to examine FED. Then, the storms had to be tracked. Coordinates taken from the tracked list were used to pull CTT, FED, and maximum expected size hail (MESH). Finally, each storm was visually examined for OT and AACP duration.

3.1 Case Selection

3.1.1 Hail Scar Cases

Hail storms were selected over the United States domain from the SPC’s storm report archive webpage (https://www.spc.noaa.gov/archive/). The time period for this study began in July 2018 and ended July 2020. Cases were selected based on the following criteria: a storm report had hail reported, hail damage could be seen from
NASA Worldview (https://worldview.earthdata.nasa.gov/), satellite and radar data were available. NASA Worldview provides images from a host of NASA satellites. NASA’s MODIS imagery was taken from the Terra satellite and used to inspect hail damage to land. MODIS has a spatial resolution of 250 m and a temporal resolution of 24 hours. Hail scars appear several hours to several days after an event occurs so one can compare the days pre-hail storm and the days post-hail storm. Hail scars are damage to the crops and structures below the storm cell. The vegetation browns as it dies and leaves behind a hail scar that MODIS can view. Once damage was discovered, we used SPC storm reports to confirm that damage was caused by hail. We looked for latitudes and longitudes from hail reports that converged within a damage swath. Hail reports are not very reliable. Hail that falls in less populated areas is less likely to be reported. This means that hail reports are more likely to occur near populated areas. Eleven cases were taken from the plains, two in southern Montana, one in the Southwest, and one in the Southeast. Table 3.1 shows the cases with dates. Storm types range from squall lines to supercells. All but two hail scars occurred during the Summer months, June, July, and August. One Plains storm occurred in early May and the lone Southeast storm occurred in April. Hail scar producing storms were isolated from the overall case domains. Storms were tracked using a combination of hand tracking and a storm tracking technique that will be discussed later.
<table>
<thead>
<tr>
<th>Region</th>
<th>Date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plains</td>
<td>2018, July 27</td>
<td>Eastern NE</td>
</tr>
<tr>
<td></td>
<td>2018, July 28</td>
<td>CO/KS/NE Border</td>
</tr>
<tr>
<td></td>
<td>2019, July 4</td>
<td>Cherry Co, NE</td>
</tr>
<tr>
<td></td>
<td>2019, July 9</td>
<td>Eastern WY</td>
</tr>
<tr>
<td></td>
<td>2019, August 8</td>
<td>SD/NE Border</td>
</tr>
<tr>
<td></td>
<td>2019, August 13</td>
<td>KS/NE/CO Border</td>
</tr>
<tr>
<td></td>
<td>2019, August 15</td>
<td>Western NE</td>
</tr>
<tr>
<td></td>
<td>2019, August 25</td>
<td>WY/SD/NE Border</td>
</tr>
<tr>
<td></td>
<td>2020, May 7</td>
<td>Northeastern TX</td>
</tr>
<tr>
<td></td>
<td>2020, June 4</td>
<td>Northwestern SD</td>
</tr>
<tr>
<td></td>
<td>2020, July 5</td>
<td>Southern SD</td>
</tr>
<tr>
<td>Southern Montana</td>
<td>2019, August 11</td>
<td>Billings, MT</td>
</tr>
<tr>
<td></td>
<td>2020, July 6</td>
<td>Forsyth, MT</td>
</tr>
<tr>
<td>Southwest</td>
<td>2018, August 7</td>
<td>North Central NM</td>
</tr>
<tr>
<td>Southeast</td>
<td>2020, April 19</td>
<td>Eastern AL</td>
</tr>
</tbody>
</table>

Table 3.1: A table showing where and when the hail scars occurred.

3.1.2 Non-Hail Scar Cases

The entire domain has been divided into 9 sub-domains that are defined in Fig 3.1. Each domain includes separate case days that include individual storms. Each storm is tracked and logged individually using tracking algorithms. Case days were selected based on hail reports and non-hail reports. These days included storms that produced hail scars but the data were removed from consideration in this section. Individual cases were separated based on storms that met the criteria for being classified as severe (MESH $\geq 25.4$ mm) and those that were non-severe (MESH $< 25.4$ mm).
3.2 Radar

Level II NEXRAD WSR-88D Radar data are used for both cell tracking and comparison to top of cloud characteristics from radar sites across the country. The data will be downloaded from the National Center for Environmental Information (NCEI) radar archive. Radar data are combined into a multi-radar mosaic and will be used for both tracking and comparison. This study utilized three radar products: base reflectivity, MESH, and vertically integrated liquid (VIL). On a reflectivity plot, the colors represent the strength of returned energy to the radar in terms of decibels (dBZ). As rainfall increases, the strength of returned power increases. Values of 20
dBZ usually indicate light rain is falling. 60 to 65 dBZ indicates that severe weather may be occurring. MESH is a commonly used metric to measure hail intensity. MESH was developed by Witt et al. [1998]. It is based on the severe hail index (SHI), which is based on the following equation:

\[
\dot{E} \quad W(Z)
\]

\[
W(Z) = \begin{cases} 
0 & \text{for } Z \leq Z_L \\
\frac{Z-Z_L}{Z_U-Z_L} & \text{for } Z_L < Z < Z_U \\
1 & \text{for } Z \geq Z_U
\end{cases}
\]  

(3.2)

Here Z is in dBZ, \( \dot{E} \) is the flux values of hail kinetic energy in Joules per square meter per second, and the weighting function W(Z) is the transition zone between rain and hail reflectivities. \( \dot{E} \) is closely related to the damage potential of hail at the ground. \( Z_L \) is 40 dBZ and \( Z_U \) is 50 dBZ. Then a temperature based vertical integration must be considered. This occurs in the next equation.

\[
W_T(H) = \begin{cases} 
0 & \text{for } H \leq H_L \\
\frac{H-H_0}{H_{m20}-H_0} & \text{for } H_0 < H < H_{m20} \\
1 & \text{for } H \geq H_{m20}
\end{cases}
\]  

(3.3)

This equation is based on the fact that hail growth mainly occurs in areas of the cloud \(< 0 \, ^{\circ}C \) and severe hail growth occurs at temperatures \(-20 \, ^{\circ}C \) or colder. Here
H is height above the radar (ARL), $H_0$ is the height of the melting level (ARL), and $H_{m20}$ is the height of the -20 °C environmental temperature. All of these equations go into the SHI (Eqn. 3.3).

$$SHI = 0.1 \int_{H_0}^{H_T} W_T(H) EdH$$  \hspace{1cm} (3.4)

where $H_T$ is the height of the cloud tops and $H_0$ is the height of the cloud bottoms. A simple power-law relationship was developed to fit MESH and SHI.

$$MESH = 2.54(SHI)^{0.5}$$  \hspace{1cm} (3.5)

VIL is based on an equation from Amburn and Wolf [1997]:

$$VIL = 3.44 \times 10^{-6} \int_{H_0}^{H_T} Z^{4/7} dH$$  \hspace{1cm} (3.6)

VIL is used mainly as a tracking variable. Maximum reflectivity and maximum MESH will be used for tracking and radar-satellite comparisons. Data points that have a corresponding MESH value greater than or equal to 25.4 mm will be classified as severe while points less than 25.4 mm are considered non-severe. Picca and Ryzhkov [2012] found that MESH overestimates hail size in a cloud. Providing reliable estimates of hail sizes continues to be a challenge.
3.3 Environmental Data

The Rapid Refresh (RAP) model is used to define the environment for each storm case. RAP data are updated every hour on the hour on a 3 km grid and were acquired from the NCEI. These data are calculated using soundings from nearby locations. RAP data will be ingested into the tracking software. This will aid in MESH and VIL calculations as well as many other outputs within the tracking software. Environmental variables will be pulled for hail scar analysis. Variables will be pulled from areas closest to the hail scar and during the occurrence of the hail scar. The variables pulled will be Most Unstable CAPE (MUCAPE), Precipitable Water (PW), the height when wet bulb is equal to 0 (WB), mean bulk shear from 0-6 km (BS), and mean wind speed from 0-6 km (WS). Variables were selected based on a modified version of Kumjian et al. [2019]. Variables are summarized in the table below (Table 3.2).
<table>
<thead>
<tr>
<th>Environment Name</th>
<th>Short-hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most Unstable Convective Available Potential Energy</td>
<td>MUCAPE</td>
</tr>
<tr>
<td>Precipitable Water</td>
<td>PW</td>
</tr>
<tr>
<td>Height Where Wet-Bulb is 0</td>
<td>WB0</td>
</tr>
<tr>
<td>Bulk Wind Shear 0-6km</td>
<td>BS</td>
</tr>
<tr>
<td>Mean Wind Speed 0-6km</td>
<td>WS</td>
</tr>
</tbody>
</table>

**Table 3.2:** A table summarizing the environmental variables that were used in this study.

### 3.4 WDSS-II

In order to compare individual storm characteristics, a method of tracking individual storms was required. We used the Warning Decision Support System - Integrated Information (WDSS-II) to track storms [Lakshmanan et al., 2003]. WDSS-II integrates NEXRAD radar data from up to eight radars, environmental data from RAP, and lightning data from GLM for a multi-radar and multi-sensor analysis for each case study. WDSS-II generates tracked thunderstorm features, including latitude, longitude, thunderstorm size, VIL, MESH, and GLM Flash Count. The thunderstorm’s coordinates are used to pull satellite values from the tops of the thunderstorm.
3.4.1 Gridding

GLM data are gridded in 0.08 °x 0.08 °. NEXRAD radar data are gridded into 0.01 °x 0.01 °x 1 kilometer grid boxes. All RAP environmental data are gridded into 0.01 °x 0.01 °x 1 kilometer grid boxes.

3.4.2 GLM Lightning

GLM lightning data first was converted into a format that WDSS-II can use. The 20 second Level 2 GLM files are combined into one minute GLM netcdf files. The data was gridded onto one minute grids using the dimensions mentioned above. A 2-D histogram of all flash locations was created on the grid. Next, five minute flash grids were created using WDSS-II’s w2accumulator algorithm This creates a five minute sum of flashes to be used for cell tracking.

3.4.3 VILFRD (Cell Tracking)

An automated cell tracking algorithm called Vertically Integrated Liquid Flash Rate Density (VILFRD) was created by Schultz et al. [2016] and is used alongside WDSS-II’s w2segmotionll algorithm. VILFRD uses a combination of VIL and five minute GLM Flash Rate Densities (FLCT5) to assign values and track individual storms. VILFRD helps track portions of the storm where ice and lightning production are occurring. The equation can be seen in Equation 3.7.

\[
VILFRD = 100 \times \left[ \left( \frac{VIL}{45} \leq 1 \right) + \left( \sqrt{\frac{FLCT5}{45}} \leq 1 \right) \right]
\]  

(3.7)
The algorithm tracks based more on reflectivity when flash rate is low and more on flash rate when reflectivity is low. WDSS-II’s w2segmotionll is used to track VILFRD where values are greater than 20. Schultz et al. [2016] used six scales to track storms based on the VILFRD value. Scale 1 tracks storms with an area around 32 km$^2$ and Scale 6 tracks storms with an area around 243 km$^2$. Scale 2 (65 km$^2$) was determined to be best for this study and was used for all tracking within this study. Statistics are generated within a text file that include latitude and longitude of the center of the cell, cell size, flash count, max VIL, and max MESH. The latitude and longitude were pulled for GOES-R IR BT (CTT) and GLM FED tracking purposes. The points were also pulled for gathering environmental data surrounding the storms. Maximum MESH were used as a comparison of a known radar variable to unknown satellite variables.

3.5 Satellite Data

GOES-16 imagery was retrieved from NOAA Comprehensive Large Array-Data Stewardship System (CLASS). GOES-16 was launched in November 2016 and was declared operational in December 2017. GOES-16 carries the Advanced Baseline Imager (ABI), a 16-channel radiometer containing visible, near-IR, and other IR portions of the electromagnetic spectrum. The ABI offers more advanced spatial, temporal, and spectral resolution compared to the older generation of GOES satellites. The ABI allows for more rapid scans over the continental U.S. [Schmit, T. J., Griffith, P., Gunshor, M. M., Daniels, J. M., Goodman, S. J., and Lebair, 2017]. Scans are available every 30-s, 1-min, 5-min, and 15-min. This study utilized data provided at
1-min and 5-min intervals. Channel 2 (0.64 µm visible) and Channel 13 (10.3 µm near-IR) were downloaded from NOAA CLASS for the study. The spatial resolution of Channel 2 is 0.5 km and the spatial resolution for Channel 13 is 2.0 km. Using the GOES data, images were visualized in Python. Images were examined for OT and AACP using brightness temperatures (BT). Conventional IR imagery records thermal emission from the surface and tops of clouds. It is convenient to express IR radiance observations as BT. The equation for BT can be expressed as:

\[ B_T = B_\lambda^{-1} [\varepsilon B_\lambda(T)] \]  

(3.8)

Emissivity (\(\varepsilon\)) is about 1 over land, water, most clouds, and snow covered land surfaces. This simplifies the above equation to \(T\) approximately equals \(T_B\) making BT a reasonably good measure of actual temperature [Petty, 2006]. Coldest BT are associated with high cirrus clouds or deep thunderstorm clouds. In visible imagery, OT are associated with cauliflower-like protrusions at the top of anvil clouds. In IR imagery, OT are recognized by circular areas of very cold BT compared to the surrounding region (of the same cloud). AACP are made from lofted cloud particles above the anvil. The difference in the ice microphysical structure between the AACP and the anvil create a unique texture that can be identified easily in visible imagery. AACP appear to be smooth streaks above the anvil. In IR imagery, AACP usually appear warmer than the surrounding anvil, however, they have been observed as colder than the surrounding anvil [Bedka et al., 2018]. These features will be used to identify OT and AACP for characterizing hail scar producing storms. The center
of the storms found by the WDSS-II algorithms will be used to make a box of BT for every satellite image. The minimum BT from every box will be saved and used for characterizing the storms. The NWS defines severe storms as storms with hail size greater than or equal to 25.4 mm and this value will be used to separate data that occurred within a severe storm and a non-severe storm. Finally, data will be collected by visually locating OT and AACP from visual and IR imagery. This data will be used to determine the amount of OT and AACP that occur in this study, as well as the duration of OT and AACP. Storms will be separated based on hail scars and non-hail scar storms. Non-hail scar storms will be further subdivided into severe and non-severe storms. A frequency plot will be created to show the occurrence of the OT and AACP.

3.6 Lightning

3.6.1 GLM FED

The lightning data used in this study comes from Lockheed Martin’s GOES-16 GLM instrument. This instrument is the first of its kind orbit based lightning mapper. It provides lightning data in real time by taking hundreds of images every second and mapping it to locations across the country. GLM allows forecasters across the United States to track intensifying storms and aids in decision support services. The Level 2 data in this study is processed using glmtools [Bruning et al., 2019]. Glmtools utilizes the 20-second netCDF outputs from GLM and resamples them to a final 2 km grid. It then combines the flashes for a single 1-minute frame. The
main GLM product used in this study was FED. FED is defined as the count of all flashes through a single grid box during a defined period of time [Lojou, J.U. and Cummins, 2006]. A box was drawn around the center coordinates provided by the tracking system. The maximum FED was pulled from the box for each minute during a storm’s lifetime. Data was separated from hail scars and non-hail scars. Each of those categories were further separated based on the criteria for a severe storm.

3.6.2 Lightning Mapping Array

This study uses Very High Frequency (VHF) lightning data from the Oklahoma Lightning Mapping Array (OKLMA) alongside GLM data for the northern TX hail scar case that occurred on 7 May 2020. This data source was used to compare lightning activity between OKLMA and GLM.

3.7 OT and AACP Counts and Duration

This study uses the presence of OT and AACP as a way of characterizing hail scar producing thunderstorms and non-hail scar producing thunderstorms. For this section of the study, non-hail scar producing thunderstorms were separated into severe thunderstorms and non-severe thunderstorms. If a non-hail scar producing thunderstorm reached a MESH value of 25.4 mm or higher, then it was classified as a severe storm. If it never reached MESH values of 25.4 mm, then it was classified as non-severe. OT and AACP were identified using a combination of IR and visible satellite images. OT were defined as an area of colder CTT (IR images) or a cauliflower-like dome (visible images) that lasted longer than 10 minutes. AACP were defined as a
pool of warmer CTT values near the OT (IR imagery) and smooth textures above the anvil (visible imagery). Both features were documented for presence and duration.

3.8 Probability

3.8.1 Multivariate Normal Distribution

In order to properly characterize the hail scar producing thunderstorms, we must create a probability of the observed characteristics. The easiest way to do this is to use a multivariate normal (MVN) distribution. It is the natural generalization of the Gaussian distribution to multivariate data. The MVN describes the joint distribution of probability density collectively for K-variables in vector x. The univariate Gaussian probability density function (PDF) is visualized as a bell curve. The MVN PDF is defined on the K-dimensional space whose coordinates correspond to the elements of x.

\[
f(x) = \frac{1}{(2\pi)^{K/2}\sqrt{\text{det}|\Sigma|}} \exp\left[-\frac{1}{2} (x - \mu)^T \Sigma^{-1} (x - \mu) \right] \quad (3.9)
\]

Where \( \mu \) is the mean, \( \sigma \) is the covariance matrix, and \( K \) is the dimension of the space where \( x \) takes value. The PDF gives the probability of both CTT and FED occurring simultaneously.
CHAPTER 4

RESULTS

These case studies will be used to examine hail scar producing storms in more detail. The three storms were chosen based on their location within the United States. Also, their storm types were taken into consideration.

4.1 Individual Case Studies

4.1.1 7 May 2020

On 7 May 2020, the Storm Prediction Center (SPC) put the Southern Oklahoma and Northern Texas areas in a slight risk for severe weather. They also put this area at a higher risk for large hail. In fact, the SPC hatched an area around Burkburnett, Tx with a 10% chance or greater of hail larger than 50.8 mm or larger within 40 km of any point in the area. The environment in this area was conducive for supercell storms. A dryline across west TX was the trigger point for these storms to form. Deep layer shear was in place to be supportive of strong supercells. Within the hatched area, convection initialized southeast of Amarillo, Tx around 2120 UTC. This supercell thunderstorm produced a hail scar near the Red River, starting east of Memphis, TX before ending southeast of Seymour, TX (Fig. 4.1). Table 4.1 shows
the numerous hail reports along its path. According to reports, this storm produced hail that reached sizes around 76 mm. This size was recorded at several locations along its trajectory.

<table>
<thead>
<tr>
<th>Date and Time (UTC)</th>
<th>Hail Size</th>
<th>Lat</th>
<th>Lon</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020/05/07 2244</td>
<td>83mm</td>
<td>34.66</td>
<td>-100.18</td>
</tr>
<tr>
<td>2020/05/07 2303</td>
<td>76mm</td>
<td>34.64</td>
<td>-99.98</td>
</tr>
<tr>
<td>2020/05/07 2324</td>
<td>76mm</td>
<td>34.41</td>
<td>-99.72</td>
</tr>
<tr>
<td>2020/05/08 0012</td>
<td>76mm</td>
<td>34.08</td>
<td>-99.38</td>
</tr>
<tr>
<td>2020/05/08 0036</td>
<td>76mm</td>
<td>34.05</td>
<td>-99.41</td>
</tr>
<tr>
<td>2020/05/08 0105</td>
<td>76mm</td>
<td>33.71</td>
<td>-99.03</td>
</tr>
</tbody>
</table>

Table 4.1: A table showing where and when the hail scars occurred.
Figure 4.1: A long hail scar caused by a supercell thunderstorm on 7 May 2020. This image is provided by the Terra MODIS satellite.

Visible imagery from GOES-16 ABI Channel 13 (10.35 µm) was used to diagnose cloud top temperature variability throughout the lifetime of the storm. Early imagery shows that this storm formed from a small field of cumulus clouds. At 2120 UTC, the cloud tops quickly blossomed into cauliflower-like domes. As they grew in size, cloud top temperatures dropped from 240 K to 200 K as indicated by Figure 4.2.
Figure 4.2: Minimum cloud top temperatures taken from the areas surrounding the OT. Cloud top temperatures quickly decreased following the explosive growth of the storm. The OT occurred at 2141 UTC.

NEXRAD radar captured the storm’s explosive growth (Fig. 4.3). Within 30 minutes of the storm’s genesis, 60 dBZ values were measured within the 3-11 km layer. This growth was associated with lightning intensification. The GLM detected lightning activity around 2133 UTC as the storm showed early signs of growth by increasing from 0 fl min-1 to 5 fl min-1 over 2130 UTC to 2200 UTC (Fig. 4.5). The OKLMA observed the same increase in lightning rate as GLM. This lightning activity indicates the storm’s updraft intensified. By 2141 UTC, IR and visible imagery shows that the storm’s updraft punctured the anvil and the beginning of an OT formed. At this time the coldest BT were around 208 K. As the storm intensified, the OT grew and the anvil spread out at a rapid pace. At 2156 UTC, an AACP developed over
the anvil. IR imagery indicates that a warm anomaly developed from the offshoot of the OT with temperatures in the AACP averaging around 223 K (Fig. 4.5).

![Time-Height of Maximum Reflectivity May 07, 2020](image)

**Figure 4.3:** A time-height graph showing the maximum reflectivity of the supercell thunderstorm that left a hail scar in the Red River Valley on 7 May 2020. The storm quickly became severe within 30 minutes of its beginning.
**Figure 4.4**: A time series graph showing the FED, which is the number of flashes per minute, from the GLM. Lightning activity increased rapidly towards the end of the storm.

**Figure 4.5**: GOES-16 ABI visible channel (top) and IR channel (bottom) showing an OT and the early stages of an AACP on 7 May 2020 2156 UTC. Visible imagery shows a cauliflower-like dome (OT) in the upper-left portions of the storm and visible texture anomalies (AACP) extending from the OT. The OT corresponds to a pocket of cooler temperatures hovering around 208 K and the AACP corresponds to an area of warmer temperatures sitting around 223 K.
According to storm reports received by the SPC, 25 mm hail first reached the ground around 2229 UTC over Loco, TX. This corresponded to a maximum reflectivity value of 70 dBZ within the 3-7 km layer. MESH values were around 40 mm. MESH overestimated the size of observed hail most likely due to high Z values (> 65 dBZ) in very cold regions of the storm (< -10 °C). This area would not be conducive to hail growth. GLM measured an increase in FED from 3 fl min\(^{-1}\) at 2213 UTC to 7 fl min\(^{-1}\) at 2217 UTC. The OKLMA confirmed this measurement (Fig. 4.6). Minimum CTT decreased from 208 K to 198 K as the hail fell but returned to around 208 K in 5 minutes.

Figure 4.6: Lightning activity recorded from the OKLMA, a ground based sensor scattered over the Oklahoma and north TX region.

The first severe hail stone was reported at 2244 UTC and estimated 83 mm. Maximum reflectivity diminished from 70 dBZ to 60 dBZ from 2250 UTC to 2320 UTC. During this 30 minute time frame, GLM indicated that lightning activity spiked...
from an 2 fl min\(^{-1}\) to 10 fl min\(^{-1}\) but diminished to 2 fl min\(^{-1}\) shortly after the initial spike. The OKLMA indicated that lightning activity dropped from 6 fl min\(^{-1}\) to 4 fl min\(^{-1}\) then increased to 12 fl min\(^{-1}\) as the storm intensified at 2320 UTC. GLM and OKLMA both show elevated lightning activity from 2330 UTC onwards. GLM measured lower flash rates for the storm compared to OKLMA. It is worth noting that the average GLM flash rate once the sun set at 0030 UTC. OT temperatures hovered around 204 K. Visible imagery shows the OT and AACP becoming more pronounced between 2250 UTC and 2320 UTC.

One of the most prominent areas of the hail scar occurred northeast of Seymour, TX around 0105 UTC. In this area, hail was reported to be 76 mm in diameter. MESH reported values around 80 mm. Visible imagery captured a large OT area and a very prominent AACP (Fig. 4.7). However, this time was close to sunset and the imagery was very dark. IR imagery can be used to better discern the cloud top features. The coldest OT temperatures value at 197 K and AACP temperatures range from 222 K to 224 K. For a brief time, maximum reflectivity reaches 80 dBZ between 4-6 km. GLM indicates a drop in lightning activity (7 fl min\(^{-1}\)) at 0046 UTC before picking up briefly (12 fl min\(^{-1}\)) at 0051UTC. Lightning activity decreased again (7 fl min\(^{-1}\)) from 0052 UTC to 0105 UTC before increasing (15 fl min\(^{-1}\)). OKLMA indicates higher rates of lightning flashes from 0100 UTC to 0130 UTC. These values reach a maximum of 21 fl min\(^{-1}\).
**Figure 4.7:** GOES-16 ABI visible channel (left) and IR channel (right) showing an OT and the early stages of an AACP on 8 May 2020 0106 UTC. Visible imagery shows a cauliflower-like dome (OT) in the upper-left portions of the storm and visible texture anomalies (AACP) extending from the OT. The OT corresponds to a pocket of cooler temperatures hovering around 200 K and the AACP corresponds to an area of warmer temperatures sitting around 223 K.

From this time on, the storm decreased in size and intensity. However, it still produced hail for several more hours. Based on IR imagery, the OT lasted until 0419 UTC. The AACP lasted until 0447 UTC before disappearing. Reflectivity depicts the storm weakening and decreasing in altitude at 0250 UTC. The storm briefly pulses at 0330 UTC where maximum reflectivity is 40 dBZ and occurs in the 5-11 km layer. GLM indicates a rapid increase in lightning activity at 0330 UTC corresponding to the storm’s updraft intensifying. Data for OKLMA drops out as the storm moves out of range. MESH values peaked one last time at 70 mm before gradually reducing to 0. As the storm collapsed, smaller hail dropped from the updraft. At 0430 UTC, the storm became non-severe.
In summary, an OT developed at 2141 UTC, 48 minutes before the first hail report occurred. The average temperature for the OT was 202 K. At 2156 UTC, an AACP formed from the OT, 33 minutes before the first observed hail. It was warmer than the surrounding areas, having an average temperature of 223 K. The OT dissipated at 0419 UTC, lasting for approximately 398 minutes. The AACP lasted approximately 411 minutes. From this case, OT and AACP can indicate that severe weather is probable.

Lightning activity was small during the early portion of the storm. However, GLM showed increases in lightning activity as the storm peaked at different times. OKLMA also shows these peaks but they tend to be slightly lower in value. OKLMA and GLM differ towards the end of the storm’s life span. GLM shows a drastic increase of lightning activity starting at 0315 UTC. The GLM shows FED from 15 fl min\(^{-1}\) at 0315 UTC to 40 fl min\(^{-1}\) at 0400 UTC. Reflectivity indicates that maximum values increased from 20 dBZ to 40 dBZ between 0315 UTC and 0400 UTC. FED drops at 0410 UTC to 8 fl min\(^{-1}\). The average GLM FED value for the duration of this storm was 9.9 fl min\(^{-1}\). OKLMA drastically differs from GLM during the end of the storm due to the storm moving out of LMA’s study area so LMA records a value of 0 fl min\(^{-1}\) from 0305 UTC until the end of the storm.

4.1.2 13 August 2019

During the afternoon of 13 August 2019, an environment conducive to hail storms set up over the Central High Plains. Dew points were around 15.5\(^\circ\) C -18\(^\circ\)C, which was ample enough to support CAPE that had values of 2000 J/kg -3000 J/Kg.
Lapse rates in the mid-levels were steep indicating higher CAPE values. Around 1615 UTC, the first sign of a discrete supercell developed. This storm quickly blossomed into a hail producing thunderstorm. As time went on the thunderstorm evolved into a mesoscale convective system. It left several areas of wind and hail damage in its wake. Some of this hail damage can be seen from space. The MODIS satellite observed several areas of damage in Nebraska, Colorado, and Kansas. These areas corresponded with the SPC’s storm archive. The first supercell developed a hail scar that was 134 km in length and 14.5 km in width in southwest Nebraska. The SPC storm reports indicate that hail fell in this area from 1750 UTC to 2120 UTC. The smallest hail stone was measured at 25.4 mm. The largest hail stone from this initial storm measured in at 64 mm. A smaller area of hail damage occurred on the Nebraska/Kansas border. Hail in this area was estimated to be 51 mm. A final area of damage occurred near Wakeeney, KS. The hail report occurred 2341 UTC and it was measured at 44.5 mm. Figure 4.8A shows the hail reports in the SPC archive. Figure 4.8B shows the long hail scar that was produced by the initial supercell. Figure 4.8C shows the hail scar that occurred near the Nebraska/Kansas border. Figure 4.8D shows the hail damage that occurred near Wakeeney, KS. This component of the paper will be separated into different sections based on the different hail scars and then the final section will examine the characteristics of the storm that did not produce hail.
Figure 4.8: (A) Hail reports that occurred on 13 August 2019 in Nebraska and Kansas. The red outline corresponds to hail damage in 4.8B. The yellow circle corresponds to hail damage in 4.8C. The blue circle corresponds to hail damage in 4.8D. (B) The first area of hail damage that occurred between 17:31 UTC and 21:17 UTC taken from MODIS. (C) An area of hail damage associated with a different OT at 21:49 UTC taken from MODIS. (D) An area of hail damage associated with a separate OT at 23:51 UTC taken from MODIS.

4.1.2.1 Long Hail Scar Nebraska

The storm that caused this damage began on 13 August 2019. Around 1615 UTC, instability was great enough to trigger a supercell thunderstorm. Cloud temperatures initially dropped 20 K in the span of 20 minutes. This was the fastest temperature drop observed in this storm. Between 1631 UTC and 1647 UTC, FED
increased from 0 fl min$^{-1}$ to 8 fl min$^{-1}$ before dropping back to 1 fl min$^{-1}$. Reflectivity increased from 61 dBZ to 65 dBZ at this time. MESH increased from 25.1 mm to 38.6 mm. There were noticeable changes at the cloud top indicating that the storm was becoming severe. The first OT was detected at 1711 UTC, 20 minutes before the first hail report and reflectivity was 67.5 dBZ. Visible imagery indicated that 10 minutes after the OT became apparent, an AACP formed at 1721 UTC. At 1722 UTC, a smaller increase in lightning occurred. Lightning averaged 2 fl min$^{-1}$ before increasing to 5 fl min$^{-1}$. At 1728 UTC, reflectivity measured 71.5 dBZ indicating the storm had strengthened during this time period. MESH had also increased to 90.4 mm. The first recorded hail stone was reported at 1731 UTC. The first recorded, severe hail stone occurred at 1820 UTC. It measured at 63.5 mm. Lightning increased from 3 fl min$^{-1}$ at 1810 UTC to 10 fl min$^{-1}$ at 1816. Fig. 4.9 shows GOES-16 imagery of the storm at 1831 UTC. The colder OT and warmer AACP were both observed in Channel 2 (4.9 Left) and Channel 13 (4.9 Right) images.
Hail was not reported between 1848 UTC and 1929 UTC. However, radar indicates a high MESH values during this time. At 1924 UTC, the MESH value was 109 mm and reflectivity reached 69.5 dBZ. This is a 40 mm and 5.5 dBZ increase in 9 minutes. At 1844 UTC, FED dropped to 2 fl min$^{-1}$. At 1920 UTC, lightning activity peaked at 20 fl min$^{-1}$. Figure 4.10 indicates that the convective core had reflectivity values matching large hail (73 dBZ) and MESH measures 109 mm.

The storm reached its maximum strength at 1949 UTC when reflectivity measured 79.5 dBZ and MESH was 254 mm. At this time CTT were around 203K. Lightning increased from 8 fl min$^{-1}$ to 12 fl min$^{-1}$. During the length of the hail scar, cloud top temperatures oscillated between 208 K and 199 K. A second OT developed adjacent to the initial OT. This second one occurred at 2046 UTC. It quickly overtook the initial OT and caused it to dissipate at 2131 UTC. GLM detected another apex
in FED at 2037 UTC with 11 fl min$^{-1}$. This occurred 9 minutes before the second OT.

4.1.2.2 Hail Scar on the Nebraska/Kansas Border

Only one hail report was associated with this hail scar. A significant hail report occurred in Traer, Kansas on the Nebraska/Kansas border at 2149 UTC. Hail was estimated at 51 mm. This hail damage was associated with the second OT that initialized at 2046 UTC. Another AACP developed at 2151 UTC. At 2131 UTC, FED measured at 14 fl min$^{-1}$ and reflectivity was 67 dBZ. At 2139 UTC, reflectivity increased to 74.5 dBZ and MESH was 103 mm. This led to sustained lightning activity topping out at 16 fl min$^{-1}$. Between 2121 UTC and 2201 UTC, OT temperatures dropped from 203 K to 196 K. Temperatures were sustained near 197 K. This OT
dissipated at 2316 UTC without causing more damage and the AACP dissipated soon after.

4.1.2.3 Wakeeney, Kansas Hail Scar

This storm developed into a large MCS. By 2351 UTC, an isolated hail report occurred near Wakeeney, KS. Hail at this location was measured at 44.5 mm by a trained storm spotter. At this point, there were several areas of convection within the storm. The OT that caused this hail damage began at 2301 UTC. It began in a cluster of bubbling convection. Temperatures in this time period were around 196 K. It was some of the coldest cloud top temperatures observed. At the time of the hail damage, an AACP was not observed. However, a small AACP formed after the hail was reported. This small AACP formed around 0006 UTC on the 14th. It had temperatures around 217 K. Lightning activity decreased to an average of 7 fl min$^{-1}$. This was the highest lightning area within this storm at this time.

4.1.2.4 Wind Damage

This storm produced significant wind damage southeast of the hail damage. The storm made the transition from hail to wind damage as it converted from a supercell to a MCS around 0000 UTC. The first wind report after the hail ceased occurred at 2301 UTC. The first significant wind report occurred at 0055 UTC. The first report measured a wind gust of 26 m s$^{-1}$.

The OT that caused the first two hail scars dissipated at 2316 UTC. Another OT developed shortly after the original dissipated around 2331 UTC. GLM detected
a brief increase in lightning activity at 2315 UTC. At this time FED increased to 13 fl min$^{-1}$ before dropping back to 7 fl min$^{-1}$. At 2326 UTC, OT temperatures spiked to 203 K before dropping to 197 K at 2341 UTC. An AACP developed from the OT at 2356 UTC. This occurred 20 minutes before a large increase in lightning activity. Figure 4.11 shows the storm as it developed into a wind damage producing storm. Maximum reflectivity was around 65 dBZ. At 0026 UTC, FED measured at 26 fl min$^{-1}$. OT temperatures dropped 195 K at 0046 UTC. The AACP had temperatures sitting around 222 K. After the OT reached their minimum peak, temperatures gradually began to increase to 211 K at 0336 UTC. An OT and AACP were present at least until 0126 UTC when the sunset. Lightning activity was very active between 0026 UTC and 0303 UTC, maxing at 30 fl min$^{-1}$. This can be observed in Figure 4.12. By 0315 UTC, lightning activity dropped to 7 fl min$^{-1}$. 0310 UTC was the last reported strong wind gust with this storm.

![Image of radar reflectivity from KGLD on 14 August 2019 at 0026 UTC showing the storm bowing out indicating that the storm was producing strong winds.](image-url)

**Figure 4.11**: Radar reflectivity from KGLD on 14 August 2019 at 0026 UTC showing the storm bowing out indicating that the storm was producing strong winds.
Figure 4.12: A time series graph showing the FED, which is the number of flashes per minute, from the GLM. Lightning activity increased rapidly towards the end of the storm as it transitioned into a strong wind damaging storm.

4.1.2.5 Summary

OT and AACP signatures were present in all of the damage areas. In the hail storms, OT were observed before hail damage was reported. All of the hail storms, except the one near Wakeeney, KS, exhibited an AACP prior to hail damage being reported. This AACP was noted 15 minutes after the initial hail report. The wind storm already had wind damage reported before the OT and AACP formed. However, the wind storm had warmer overall cloud tops and higher lightning activity.
4.1.3 19 April 2020

In the early hours of 19 April 2020, a large storm system moved through the state of Alabama. A Mesoscale Convective System (MCS) developed over western Mississippi around 0700 UTC before it moved eastward into Alabama. This complex caused several wind damage reports and a total of three hail reports. The hail reports were made between 1200 UTC and 1206 UTC near Alexander City, Alabama. MODIS observed a 32 km long swath of hail damage (Fig. 4.13). Two hail reports occurred within the area of hail scarring. The other one occurred roughly 20 km northeast from the hail damage. This is the only hail scar observed within the Southeast United States in this study.

![Figure 4.13](image)

**Figure 4.13:** (Left) An image from MODIS before the hail storm occurred near Alexander City, AL (3 April 2020). (Right) The same area but after the hail damaging storm moved through (26 April 2020).

Elevated storms formed across parts of the ArkLaMiss into AL as a southwesterly low-level jet strengthened over this region. RAP showed some variability
regarding storm coverage and placement. Regardless, modestly steepened mid-level lapse rates contributed to MUCAPE around 1000 J/kg -1500 J/kg. In combination with strong deep-layer shear, at least isolated large hail was possible with any elevated storms that formed. As the sun rose, the change in temperatures also caused higher chances of hail by causing a decrease in stability. Hail that occurred in the damage area was estimated by National Weather Service radar measurements to be 45 mm while the lone hail report outside the damage area was estimated to be 25.4 mm.

RAP indicated that mean shear from 0-6 km was around 13 m s\(^{-1}\) km\(^{-1}\) at 0900 UTC. Between 1000 UTC and 1030 UTC, a cluster of thunderstorms west of Birmingham, Alabama with maximum reflectivity of 65 dBZ merged into one larger cell. Reflectivity values indicated that cloud tops were all the way to 13 km. During the 30 minute time period, 1000 UTC to 1030 UTC, the maximum MESH value of 32 mm occurred at 1021 UTC (Fig. 4.14). GOES-16 Channel 13 estimates that temperatures dropped from 208 K to 200 K between 1020 UTC and 1025 UTC (Fig. 4.15). Rather than there being a smaller cluster of colder cloud tops, there was a more broad region of colder cloud tops. By 1040 UTC, a cluster of cold cloud tops began to protrude from the cloud shelf, marking the beginning of an OT. The highest FED for this time period was measured at 14 fl min\(^{-1}\) at 1030 UTC (Fig. 4.16). However, the storm continued to grow with the top of reflectivity measuring at 14 km after the period of growth. At 1042 UTC, maximum MESH was recorded at 18 mm.
Figure 4.14: A graph showing the maximum MESH (mm) vs time (UTC). MESH peaked before the largest hail fall occurred.

Figure 4.15: A graph showing the relationship between CTT (K) and time (UTC).

At 1049 UTC, FED increased to 27 fl min\(^{-1}\) before dropping down to 11 fl min\(^{-1}\) at 1055 UTC. RAP indicated that mean shear from 0 km to 6 km increased
to 16.5 m s\(^{-1}\) km\(^{-1}\). This helped the storm environment be more conducive for hail production because it tilts the updraft [Dennis and Kumijan, 2017]. MESH values measured at 53 mm at 1119 UTC which occurred several minutes before maximum reflectivity jumped again. Maximum reflectivity increased at 1125 UTC from 60 dBZ to 70 dBZ. Cloud heights reached levels around 15 km. At 1129 UTC, FED jumped again to 29 fl min\(^{-1}\). At 1146 UTC, the first clear visible images were available. It shows a clear OT with temperatures around 194 K. These were the coldest cloud tops recorded. At 1141 UTC, an AACP formed with temperatures around 210 K. Visible and IR imagery show these features from GOES-16 in Figure 4.17. This occurred 19 minutes before the first hail report. This AACP was smaller in area compared to the previous storms in this study. Reflectivity at this time showed a tilted updraft with maximum reflectivity around 70.5 dBZ. The maximum reflectivity values occurred at heights around 6 km.

**Figure 4.16:** A graph showing the relationship between FED fl min\(^{-1}\) and time (UTC). FED units are in fl min\(^{-1}\) and time is in UTC.
Figure 4.17: (Left) Visible imagery from GOES-16 depicting an OT and a tiny AACP associated with a hail scar producing storm. (Right) IR imagery as in Top. The small cluster of dark green and dark blue pixels is the cold cloud tops associated with the OT. Coldest temperatures are around 194 K. The AACP has temperatures around 210 K.

At 1138 UTC, FED jumped to the highest value recorded during this storm at 34 fl min$^{-1}$. This jump can be seen in the largest peak in Figure 4.16 after 1130 UTC. Lightning activity began to decrease at 1151 UTC. Brightness temperatures also increased between 1146 UTC and 1151 UTC. Temperatures increased from 194 K to 198 K. At 1145 UTC, NEXRAD showed three pixels with reflectivity values at 70.5 dBZ. Maximum MESH occurred at 1158 UTC, with maximum size estimated at 90 mm. At 1201 UTC, NEXRAD measured over 30 pixels that were between 70.0 dBZ and 75.0 dBZ. By 1211 UTC, there were two pixels that measured at 71.0 dBZ. This was the last time that reflectivity reached above 70.0 dBZ. MESH decreased sharply from 90 mm to 35 mm between 1158 UTC and 1210 UTC. It continued to decrease until it reached 0 mm at 1307 UTC. It is important to note that at 1155 UTC, the cell began to bow into a backwards “c” shape, indicating that strong winds punched through the rear of the storm and pushed the front of the storm forward (Fig. 4.18). Data from KMXX at 1200 UTC showed maximum reflectivity values
at 76.0 dBZ with the typical features associated with strong winds. Temperatures gradually increased from 1201 UTC through the end of the storm.

**Figure 4.18**: NEXRAD reflectivity from KMXX at 1200 UTC depicting high reflectivity values around 76 dBZ. The bowing structure shows that there were high winds associated with this storm.

At 1231 UTC, visible imagery showed that the cloud top dome descended into the top of the anvil meaning the OT dissipated. The area of maximum reflectivity dropped below 3 km indicating that it dropped 3 km. The AACP was short, lasting only 10 minutes when the previous case studies had AACPs that lasted several hours. It was also one of the smallest AACP in this study. By 1241 UTC, the cell dissipated into the surrounding storms. It is hypothesized that the AACP did not have adequate time to last for a longer time due to the updraft collapsing before more cloud particles could be ejected into the lower stratosphere. The OT occurred 80 minutes before the first hail report and it lasted approximately 111 minutes total. From the OT, a
tiny AACP formed 19 minutes before the hail was reported. GLM observed 3 major lightning jumps before the hail was reported. The lightning jump with the highest lightning activity, 34 fl min$^{-1}$, occurred 22 minutes before hail fall. GLM was able to observe higher flash rates in this storm compared to the previous storms. There are several possible reasons for this observation. 1) The storm occurred in an area that GLM viewed better. 2) Cloud tops were not dense enough to block all lightning activity from being viewed by GLM. 3) Or it can be a combination of the two reasons.

This storm is unique for several reasons. This was the only hail scar producing storm in this study that occurred within a MCS. The Alabama storm also showed some of the highest overall FED values in this study. This could be due to the location of the storm within the GLM FOV. This will be discussed further in Chapter 5. This storm is also the only storm to occur over a deciduous forest. The majority of the hail scars occurred over grassland and crops.

### 4.2 Hail Scar Producing Storm Characteristics

#### 4.2.1 Environment

The environmental parameters were computed using the WDSS-II algorithms. MUCAPE, PW, WB0, BS, and WS were calculated for the 15 hail scar storms (Table 3.2). MUCAPE had an average value of 2500 J/kg with a maximum value of 4000 J/kg and a minimum value of 1000 J/kg. The minimum occurred in Alabama and the maximum value occurred in New Mexico. PW was also measured with an average value of 3 cm, a maximum value of 4 cm, and a minimum value of 2.5 cm. WB0 had
an average height of 4000 m, with a maximum height of 4800 m, and a minimum height of 3200 m. BS had a spread from 5 m s$^{-1}$ km$^{-1}$ to 10 m s$^{-1}$ km$^{-1}$ with an average of 7 m s$^{-1}$ km$^{-1}$. Finally, WS averaged 13 m s$^{-1}$ and had a range from 8 m s$^{-1}$ to 20 m s$^{-1}$. Figure 4.19 shows the distribution of the environmental variables from each hail scar. The orange line represents the mean of the data.
Figure 4.19: The environmental variables that were pulled from the 15 hail scar producing storms.
4.2.2 OT and AACP Duration

As discussed in the Chapter 3, 15 hail storms were chosen based on a visible hail scar in MODIS imagery. These damaging hail storms can occur all over the continental United States but in this study 13 of the 15 hail scars occurred in the central United States. One occurred in the southeastern United States and the final occurred in New Mexico. Of the 15 hail scars, all 15 exhibited OTs. This means that 100% of the hail scar producing thunderstorms had updrafts strong enough to penetrate the tropopause. All of the OT had durations ranging from 70 minutes to 481 minutes. Figure 4.20 shows the frequency of OT and AACP duration. The highest frequency for OT duration is near 255 minutes. The two hail scars occurred on 13 August 2019 and 27 July 2018. A single cell quickly developed into a supercell that merged into a squall line. The hail scar occurred while the storm was in its supercell phase. This storm was discussed in more detail in Section 4.1.2. The OT duration lasted 260 minutes. The storm that occurred on 27 July 2018 began in an area of instability that had several storms moving across the area. The updraft quickly penetrated the tropopause and an OT developed and that lasted 255 minutes. While 100% of hail scar thunderstorms had OT, not every hail scar thunderstorm had an AACP. Approximately, 80% of storms that produced a hail scar had an AACP. AACP that are associated with hail scars had durations between 10 minutes and 360 minutes. A Pearson’s correlation coefficient shows that there is a strong positive (r=0.78) relationship between OT duration and AACP duration. This is not unexpected due to the close relationship of an OT and AACP. Once an OT ejects cloud particles
into the lower stratosphere, an AACP forms. Once the updraft weakens and the OT decays, cloud particles are no longer injected into the stratosphere.

![Figure 4.20: The frequency of OT and AACP duration for hail scar producing thunderstorms.](chart)

**4.2.3 IR and FED Characteristics**

It is important to characterize the CTT and FED values that are associated with hail scar producing thunderstorms. Figure 4.21 shows the histograms of hail scar producing thunderstorms for minimum CTT and maximum FED. The study shows that when MESH values are considered severe, BT are typically lower in hail scar producing thunderstorms. Minimum BT have two areas of higher frequencies when MESH $\geq 25.4$ mm. The temperature with the highest KDE (0.05) occurred around 209 K. The second KDE (0.04) of BT in this range occurred at 198 K. Most
temperatures are distributed between 195 K and 210 K. 50% of the CTT for this group occurred between 199 K and 211 K (Fig. 4.21).

When looking at MESH < 25.4 mm, minimum CTT peak at 211 K (0.13 density) which is 2 degrees higher than the peak for MESH ≥ 25.4 mm. This group also has a secondary peak of minimum CTT at 225 K (0.0195). 50% of the temperatures measured are distributed between 210 K and 220 K. One also has to examine maximum FED values. Maximum FED offers unexpected results. When MESH is considered severe (≥25.4 mm), FED has the highest peak at 0-2 fl min$^{-1}$ with a KDE of (0.12). It was expected to see FED skewed towards higher values with severe hail. Despite the data being skewed to lower values, there is still a substantial amount of higher fl min$^{-1}$. In fact, there is a secondary histogram peaks at around 5 fl min$^{-1}$ and has a tertiary peak at around 10 fl min$^{-1}$. There is an even smaller peak that occurs at around 15 fl min$^{-1}$. There are several outliers in this group that are measured from 19 fl min$^{-1}$ to 31 fl min$^{-1}$. Examining values where MESH < 25.4 mm shows a similar distribution. There are more fl min$^{-1}$ < 5 in this category. This is an expected result. When compared to severe hail, FED has more than twice the amount of 0-2 fl min$^{-1}$ and most of the values are skewed to the left of the graph. This indicates that FED has a higher quantity of lower values (< 5 fl min$^{-1}$) than severe hail. This group also has several very high outliers ranging from 9 fl min$^{-1}$ to 40 fl min$^{-1}$.

When correlating FED and CTT using a Pearson correlation, the severe hail group had a correlation of -0.126. This indicates that there is very little correlation
between the two variables. The non-severe points from the hail scar shows a Pearson
correlation of 0.046, which is less than the previous correlation.

Using a MVN PDF, we are able to see which combination of FED and CTT
values are more likely to occur within a hail storm. This distribution showed that
when \( \text{MESH} \geq 25.4 \ \text{mm} \), the highest likelihood (0.004) of a hail scar occurs when
maximum FED values are 4 fl min\(^{-1}\) to 9 fl min\(^{-1}\) and minimum CTT around 205 K
to 211 K. When you keep a constant CTT, for example 208 K, and increase FED to
20 fl min\(^{-1}\) then the relative likelihood decreases to 0.0015. This indicates that the
original CTT and FED discussed are 4 times more likely to occur when a hail scar is
occurring. Other relationships and their likelihood of occurring can be seen in Figure
4.21. When looking at values that occur when hail is non-severe (MESH < 25.4),
it is easy to discern that CTT are higher and FED are even lower when compared
to severe hail values. In this group, CTT occurring in the highest likelihood (0.0035)
ranged from 210 K to 215 K. FED values range from 1 fl min\(^{-1}\) to 5 fl min\(^{-1}\) (Fig.
4.21).
Figure 4.21: Top Row: The box-and-whisker plots of minimum CTT and maximum FED. Middle Row: The distribution of minimum CTT and maximum FED. Bottom Row: The PDF of severe (nonsevere) values for CTT and FED on the left (right). This is the relative likelihood of a hail scar occurring with the given values.
4.3 Non-Hail Scar Producing Thunderstorm Characteristics

4.3.1 OT and AACP Duration

The NHS part of this study examined 9 case days across the United States. In total there were 130 severe storms that did not produce a hail scar. For non-severe storms, there were a total of 188. These case days appeared east of the Rockies and west of the Mississippi River. Out of 130 severe storms, 92 storms had OT develop. This indicates that 70.8% of severe storms developed OT. The OT duration ranges from 15 minutes to 330 minutes. It was observed that 25 of the 92 OT storms produced AACP leading to a percentage of 29.3%. Duration of these AACP ranged from 10 minutes to 185 minutes. Pearson’s correlation indicates that severe storms’ OT duration and AACP duration are moderately correlated to one another (r= 0.66). Non-severe storms had 19 OTs develop from 188 total storms. This leads to a percentage of 10.1% of non-severe storms developing an OT. The OT on these storms were shorter in duration compared to severe storms and hail scar producing storms. Times for these OT ranged from 15 minutes to 120 minutes. Moving onto AACP, only 3 of the storms that produced an OT produced an AACP (15.8%). The 3 AACPs observed lasted for approximately 10 minutes, meeting the minimum requirements to be called an AACP. Two of the AACP occurred on the same case day and the other occurred on a different case day. Pearson’s correlation indicates that OT and AACP duration in non-severe storms are weakly correlated with one another (r =0.26). Figure 4.22 shows the frequency for the durations of OT and AACP for both severe and non-severe storms.
Figure 4.22: The frequency of OT (Left) and AACP (Right) duration for non-hail scar producing thunderstorms.

4.3.2 IR and FED Characteristics

As with the hail scar producing thunderstorms, it is important to describe the associated FED and CTT that occur with severe and non-severe hail. For MESH values that met the severe storm criteria (MESH $\geq 25.4$ mm), minimum CTT formed a nearly uniform distribution with a mean temperature around 215 K. KDE at this temperature is 0.075. There is a secondary peak at 221 K with a KDE value of 0.025. 50% of the data can be grouped between 210 K and 220 K.

Minimum CTT values that are associated with non-severe hail (MESH $< 25.4$) are found to be warmer than values associated with severe MESH. There is also a near uniform distribution of values with a mean temperature around 220 K. At 220 K, KDE is around 0.05. It is important to note that this group of data has numerous outliers that range on the high side. 50% of data can be found between 217 K and
227 K. At least 2 values occurred near 300 K. One possible explanation for these warm temperatures is that WDSS-II pulled values from earlier in the storms’ life before CTT had a chance to cool. The complete distribution for CTT can be found in Figure 4.23.

It is also important to note the FED characteristics in these groups. As with the FED observed in hail scar producing storms, FED results are unexpected. We observe a similar distribution with the highest frequency of values falling between 0 fl min\(^{-1}\) to 2 fl min\(^{-1}\) in severe hail values. This group has a mean FED of 4 fl min\(^{-1}\) and most of the data falls to the left of the mean indicating lower values. There is still a fair amount of higher FED values in this group. The top 50% of the data occurs from 4 fl min\(^{-1}\) to 14 fl min\(^{-1}\) with outliers occurring from 15 fl min\(^{-1}\) to 31 fl min\(^{-1}\).

The values associated with non-severe MESH, are skewed similar to the values associated with non-severe MESH in hail scar producing thunderstorms. The lower 50% of the data can be found from 0 fl min\(^{-1}\) to 4 fl min\(^{-1}\). The upper 50% of the data ranges from 4 fl min\(^{-1}\) to 10 fl min\(^{-1}\). Outliers show that there are several large values occurring where MESH is non-severe. Outliers range from 13 fl min\(^{-1}\) to 35 fl min\(^{-1}\). Figure 4.23 shows the complete distribution for FED.

As with the hail scar producing thunderstorms, Pearson’s correlation is a good indicator to notice if there is a relationship between CTT and FED. Pearson’s correlation indicates that there is no correlation between FED and CTT that fall into the severe value criteria (r= -0.065). The same is true for FED and CTT that meet the criteria for non-severe storms (r=0.181).
A MVN PDF allows for discerning which CTT and FED values are more likely to occur in severe and non-severe storms. The highest likelihood of severe storms occurring (0.0064) are met when CTT ranges from 209 K to 211 K and FED values range from $3 \text{ fl min}^{-1}$ to $5 \text{ fl min}^{-1}$. For example, when keeping a constant CTT of 210 K and increasing FED to $20 \text{ fl min}^{-1}$, the relative likelihood decreases to 0.0016, which is 4 times lower compared to the FED being $4 \text{ fl min}^{-1}$. The complete distribution can be seen in Figure 4.23.

The same can be done for values that don’t meet the criteria of severe. The highest likelihood of a non-severe storm occurring (0.0056) is met when CTT ranges from 218 K to 221 K and FED ranges from $1 \text{ fl min}^{-1}$ to $4 \text{ fl min}^{-1}$. The complete distribution for this set can be found in Figure 4.23.
Figure 4.23: Top Row: The box-and-whisker plots of minimum CTT and maximum FED in non-hail scar storms. Middle Row: The distribution of minimum CTT and maximum FED in non-hail scar storms. Bottom Row: The PDF of severe (nonsevere) values for CTT and FED in non-hail scar storms on the left (right). This is the relative likelihood of a severe (nonsevere) storm occurring with the given values.
4.4 Maximum MESH

It was found that hail scars have overall higher maximum MESH values when separating maximum MESH by only hail scar or non-hail scar. The highest frequency of maximum MESH occurs around 49 mm. The highest maximum MESH frequency for non-hail scars is located around 10 mm (excluding 0 mm). The overlap that occurs between the two is not as great as the overlap in FED and CTT. Figure 4.24 shows the distribution of maximum MESH for hail scar and non-hail scar storms.

![Maximum Expected Size Hail](image)

**Figure 4.24:** The total maximum MESH divided by the presence of a hail scar. Hail scars had overall higher MESH compared to non-Hail Scars.

4.5 Summary

This study aimed to answer 3 questions pertaining to hail scars producing thunderstorms and those that did not produce hail scars.
1. What is the frequency and duration of OT and AACP within hail scar and non-hail scar producing storms?

2. What is the difference between hail scar and non-hail scar producing storms from a remote sensing point of view?

3. What is the likelihood of a hail scar occurring solely based on the cloud top characteristics?

The 3 in-depth case studies indicated that every hail scar producing storm had an OT develop before the hail scar occurred. All but one AACP formed before a hail scar occurred. Minimum CTT for OT were around 198 K. AACP were found to be warmer than the anvil below. FED had overall rates higher within the Alabama storm most likely due to storm location and storm type. The storm’s location occurs in an area where the flash detection efficiency (DE) is higher than the Plains. Within the other cases, FED increases as the sun sets, possibly indicating issues with GLM sensors observing the lightning. After the sun sets, the Nebraska/Kansas case increases FED by 20 fl min$^{-1}$. In the Texas case, FED increases by 10 fl min$^{-1}$ after the sun sets. Typical reflectivity values were around 65 dBZ to 70 dBZ, indicating large hail.

Hail scars occur in environments that are conducive to hail storms. MUCAPE had an average value of 2500 J/kg. PW was also measured with an average value of 3 cm. WB0 had an average height of 4000 m. BS had an average of 7 m s$^{-1}$ km$^{-1}$. Finally, WS averaged 13 m s$^{-1}$.

Comparing thunderstorms that produced hail scars to thunderstorms that were severe and non-severe but did not produce hail scars allows for us to characterize
the maximum FED, minimum CTT, OT count and duration, and AACP count and
duration. When counting the frequency and duration of OT and AACP, storms
that observed any MESH value \( \geq 25.4 \) mm were classified as severe and the storms
that had no MESH values \( \geq 25.4 \) mm were classified as non-severe. All 15 hail scar
producing thunderstorms were classified as severe. Out of 318 storms, 130 storms
were found to be severe while 188 storms were found to be non-severe. The 15
thunderstorms that produced hail scars were observed to all have OT leading to a
100% rate. Whereas, only 70.8% of severe storms developed an OT and 10.1% of
non-severe storms developed an OT. In the severe thunderstorms that produced a
hail scar, 80% of hail storms produced an AACP. In non-hail scar producing storms,
29.3% of severe storms that produced an OT produced an AACP.

Despite the small sample size, the results indicate that the presence of an OT
is a good indicator of a hail scar producing storm. AACP is also a good indicator of
a hail scar being formed.

This next section will summarize the findings of FED and CTT within hail
scar producing storms and severe and non-severe thunderstorms that did not produce
hail scars. In this section, CTT and FED values that correspond to MESH values
\( \geq 25.4 \) mm values pulled from both hail scar producing storms and non-hail scar
producing storms were labeled as severe. Where values \( < 25.4 \) mm, FED and CTT
are labeled as non-severe. The lowest CTT were found in severe hail scar producing
thunderstorms. These values range from 195 K to 230 K with several outliers greater
than 230 K. The highest FED values were also found in hail scar producing storms
but within the non-severe category. Most of the data fell within 0 fl min\(^{-1}\) to 9 fl
Multiple outliers range from 10 fl min$^{-1}$ to 42 fl min$^{-1}$. Within severe values that produce hail scars, a hail scar is most likely to occur when CTT are between 205 K and 211 K and FED are between 4 fl min$^{-1}$ and 7 fl min$^{-1}$. Within non-severe values that produce hail scars, a hail scar is most likely to occur when CTT are between 210 K to 215 K and FED values are between 1 fl min$^{-1}$ to 5 fl min$^{-1}$. For values that are severe in non-hail scar producing storms, severe storms are more likely to occur when CTT are 209 K to 211 K and FED values range from 3 fl min$^{-1}$ to 5 fl min$^{-1}$. When values are non-severe and do not make a hail scar, non-severe storms in this study are when CTT range from 218 K to 221 K and FED range from 1 fl min$^{-1}$ to 4 fl min$^{-1}$.

This section shows that there are overlaps between CTT and FED within the different storm categories. Hail scar storms have slightly lower overall CTT and higher overall FED values. Severe storms fall between thunderstorms that produce hail scars and non-severe thunderstorms. Overall, FED and CTT are not the best indicators of whether a hail scar forms at the surface. The greatest difference in overlap occurs in maximum MESH with a mean of 49 mm (hail scar) and 10 mm (non-hail scar).
This study hypothesized that hail scar producing thunderstorms would exhibit colder CTT, higher maximum FED, and higher rates of OT and AACP compared to non-hail scar producing thunderstorms. The best predictor for a hail scar producing thunderstorm is the presence of an OT and AACP. While this study did find a difference in CTT and FED between hail scar producing thunderstorms and non-hail scar producing thunderstorms, the difference was not a significant value. Specifically, maximum FED values were expected to be higher within the severe values of hail scar producing thunderstorms. The non-severe values of hail scar producing thunderstorms had larger FED values in the outliers. Chapter 5 will examine the possible reasons for lack of discernible satellite characteristics.

5.1 Post-Results Speculation

5.1.1 Lightning Observation from GLM

The GLM instrument was designed to reduce false alarms by creating a background field and background threshold. Each pixel of GLM is checking for an optical brightness difference between the cloud top and background threshold. So only points
that meet this criteria are saved as actual flashes. Cummins [2020] illustrated the best case thresholds for a night time and a mid-level threshold for daytime viewing from GLM (Fig. 5.1). The threshold values can explain the lower detection efficiency (DE) in the NW CONUS. Sunlight can also inhibit flash detection by filling up the sensor’s threshold. Energy photons reflected from the Sun on the cloud tops make it back to the GLM sensor. This causes less photons from the lightning flash to be recorded by the sensor making the sensor think that there is less lightning than there really is. Even high-flash rate storms can fill the threshold and make it hard for smaller, subsequent flashes to be seen by the sensor [Cummins, 2020].

Bateman and Mach [2020] found an average DE value of 0.73 out of 1 for the majority of the CONUS but DE values drop off towards NW CONUS as threshold values increase. The DE over Alabama is around 0.73 meaning GLM is seeing more lightning than the Plains. DE ranges from 0.25 to 0.5 from the Plains to NW CONUS. The majority of cases in this study occur within this area. This is resulting in storms having to produce flashes that have higher energy compared to the background threshold. This threshold is determined by the minimum detectable event energy. GLM is able to detect near 100% of the energy from cloud tops at nadir. When moving further away from nadir, the minimum event energy that makes it to the sensor is higher because the energy has to travel further in the atmosphere. The atmosphere acts as a filter and absorbs and scatters the smallest energy before it reaches the sensor. This explains why, as distance from nadir increases, so does the threshold.
Figure 5.1: Adapted from Cummins [2020]. An image showing the background thresholds over the CONUS for best-case nighttime (Top) and mid-level threshold for daytime (Bottom).

Figure 5.2 shows the minimum event energy for a hail scar producing storm that occurred in Nebraska at 2350 UTC and a regular thunderstorm that occurred in southern Colombia near nadir at the same time. It is clear to see that there is higher minimum event energy coming from the Nebraska storm. GLM is registering
a higher frequency of 0.8 fJ of energy, whereas the storm near nadir registers a lower minimum energy with the greatest frequency occurring at 0.3 fJ. Nebraska has a higher threshold of 3 fJ to trigger a flash being recorded so GLM sees less flashes than what is truly occurring.

5.1.2 Intense Convective Storms

Rutledge et al. [2020] found that GLM DE is particularly low in anomalous storms due to two main factors, intense cloud water and cloud ice contents and compact flashes at mid-to-low levels within these storms. Anomalous storms are intense storms that form in semiarid environments causing high cloud bases and wide updraft regions. These features work to reduce entrainment and promote large supercooled liquid water content [Fuchs and Rutledge, 2018]. Due to the processes involved in lightning formation, these storms can easily produce flash rates exceeding 100 fl min$^{-1}$ [Fuchs et al., 2015]. These storms are mostly found in the western and upper Great Plains regions [Zajac, B. A. and Rutledge, 2001]. It is worth noting that the majority of hail scar producing thunderstorms occurred in semiarid regions. The
large cloud structure increases the attenuation of smaller flashes. Optical scattering in the cloud tops works to reduce light intensity to values below the GLM threshold. This aligns with what Brunner and Bitzer [2020] observed. They demonstrated that the light intensity at cloud tops is sensitive to both concentration of ice particles between the flash and cloud top and the optical emission height.

It is speculated that a combination of GLM instrumentation and storm structure is attributing to lower lightning rates within the storms. Further research is needed to determine whether hail scar producing storms are in fact anomalous storms.

5.1.3 Satellite Comparisons

As mentioned in Chapter 2, OT and AACP have been shown to be good indicators of severe storms. Dworak et al. [2012] found that 75% of OTs detection occurred before severe weather events. Bedka [2010] showed that the OT-severe weather relationship is strong for large hail (53%). Another study conducted by Mikuš and Mahović [2013] showed that hail is observed in the vicinity of OT 38% of the cases. This study found that for hail scar producing storms, 100% of storms had an OT. Severe storms that did not produce a hail scar produced an OT 70.8% of the time. Non-severe storms produced an OT 10.1% of the time. For severe storms, the results of this study are in line with previous studies. To the best of the author’s knowledge, no study has looked at the frequency of OT in hail scar producing storms. Increasing the number of hail scar producing storms in a future study could lead to a smaller percentage of OT.
Bedka et al. [2018] found that 88% of significant hail cases were associated with AACP. For hail scars, AACP were generated 80% of the time in this study. Severe non-hail scar producing storms were found to have AACP 29.3% of the time. This is far lower than what Bedka et al. [2018] observed in storms with severe weather (73%).

Murillo and Homeyer [2019] determined that hail storms are best viewed through radar metrics rather than satellite. They found that satellite parameters displayed the greatest overlap between hail and no-hail populations. This study found similar results to Murillo and Homeyer [2019]. Hail scar producing storms and severe storms had similar mean minimum CTT (210 K). It was found that hail scar producing storms had slightly colder CTT compared to severe storms and non-severe storms. There is little practical advantage to using CTT as a discriminator for forecasters.

5.1.4 Land Cover

It is also important to examine the land underneath the damaging hail storms. Figure 5.3 shows the 2016 National Land Cover Database (NLCD) through the United States Geological Survey (USGS). The NLCD is computed by sorting each 30 m plot of land into 16 categories. The NLCD shows that the hail scars occurred mainly in grassland/herbaceous and cultivated crops areas. A rare hail scar that occurred in Alabama happened in a deciduous forest area. This was an outlier when comparing it to the locations of other hail scars.

Bell et al. [2020] studied the hail scar using synthetic aperture radar (SAR). He found that damage to corn and soybeans by hail storms caused the normalized
vegetation difference index (NDVI), a measure of plant health, to lower within 2 days of a hail storm moving over the fields. Depending on where in their life cycle the crops are, can be a factor in how damaged they’ll become. It has been observed in other studies that shrubland and grass fields can be completely shredded by hail stones. Corn and soybeans can have damage to the leaves and stems of the plants that can result in a total loss of crop. It is recommended that further research be done on the types of land that hail scars are occurring on.

Figure 5.3: Adapted from the USGS. An image showing the 2016 NLCD. The NLCD shows that the hail scars occurred mainly in grassland/herbaceous and cultivated crops areas.
CHAPTER 6

CONCLUSION

6.1 Summary

The purpose of this study was to characterize hail scar producing thunderstorms using the GOES-16 satellite. It was hypothesized that hail scar producing thunderstorms will exhibit colder cloud top temperatures, higher maximum FED rates, and a higher number of OT and AACP compared to non-hail scar producing thunderstorms. Hail scar producing storms are very unique storms. In this study, 9 hail scars were recorded from 9 case days with a total of 327 storms (0.028%). This resulted in only 15 hail scars used in this study. The results of this study can be summarized as:

- OT were found in 100% of the hail scar producing storms. Their durations ranged from 70 minutes to 481 minutes. Their duration depended on the storms’ total duration. Usually, longer hail scars were associated with longer duration OT. This can be attributed to OT being caused by strong updrafts. Sustained updrafts will cause more hail generation by repeatedly lifting hail stones into very cold air towards the top of the cloud where they can accumulate more layers
of ice. This corresponds to hail scar producing thunderstorms having higher maximum MESH values compared to non-hail scar producing thunderstorms.

- Severe non-hail scar producing thunderstorms formed OT 70.8% of the time. These OT durations ranged from 15 minutes to 330 minutes. Severe non-hail scar producing storms produced less OT and shorter duration OT compared to hail scar producing storms. This shows that hail scar producing thunderstorms are more intense because of their sustained updraft. Non-severe non-hail scar producing thunderstorms produced OT 10.1% of the time. Their durations lasted 15 minutes to 120 minutes. OT that form in non-severe storms are rare.

- AACP occurred in 80% of the hail scar storms in this study. They are still a rather strong indicator of hail scar producing thunderstorms. Severe non-hail scar producing storms that developed OT developed AACP 27% of the time. Non-severe non-hail scar producing thunderstorms that developed OT developed AACP 15.8% of the time.

- The average minimum CTT found in hail scar producing storms was around 210 K. When MESH values were severe in hail scar storms, CTT were between 194 K to 230 K. This category was the lowest range in the study. The average maximum FED was 5 fl min$^{-1}$. This is lower from what we were expecting to see. This deficiency can be explained by storms’ location (storms occurring in areas with lower DE) and more intense storm type.
• The average value for minimum CTT found in severe storms that don’t produce hail is slightly higher than hail scar producing storms, 215 K. Maximum FED average at 4 fl min \(^{-1}\). Once again, this is lower than expected but can be explain by the location of the storms.

• Non-severe non-hail scar had an average minimum CTT of 219 K which is slightly warmer than severe storms and hail scar storms. They also had an average FED of 3 fl min \(^{-1}\).

• A MVN PDF was computed for discussing the probability of a hail scar occurring only using points that are associated with severe MESH. The highest likelihood (0.004) of a hail scar occurs when maximum FED values are 4 fl min \(^{-1}\) to 9 fl min \(^{-1}\) and minimum CTT around 205 K to 211 K.

• For hail scar storm non-severe values, CTT occurs in the highest likelihood (0.0035) when ranging from 210 K to 215 K. FED values range from 1 fl min \(^{-1}\) to 5 fl min \(^{-1}\).

• The highest likelihood of severe storms occurring without a hail scar (0.0064) are met when CTT ranges from 209 K to 211 K and FED values range from 3 fl min \(^{-1}\) to 5 fl min \(^{-1}\).

• The same can be done for values that don’t meet the criteria of severe. The highest likelihood of a non-severe storm occurring (0.0056) is met when CTT ranges from 218 K to 221 K and FED ranges from 1 fl min \(^{-1}\) to 4 fl min \(^{-1}\).
• The highest frequency of maximum MESH occurs around 49 mm for hail scars. The highest maximum MESH frequency for non-hail scars is located around 10 mm (excluding 0 mm).

While the hypothesis is correct, CTT and FED are not great for discriminating hail scar storms from non-hail scar storms. There is too much overlap between the CTT in both categories and the same occurs in FED. OT and AACP show the highest difference between hail scar, severe storms, and non-severe storms. MESH shows the greatest difference between hail scars and non-hail scars. It is suggested that a combination of all of these factors, lower CTT, higher FED, the presence of an OT, an AACP, and high MESH values can distinguish a hail storm from a severe storm.

6.2 Future Work

In addition to any recommendations listed in earlier chapters, there are multiple lines of future work found in this study. Examining the charge structure in hail scar producing storms is imperative in determining the frequency of hail scar producing storms that are anomalous. This could be done by utilizing the Colorado LMA (COLMA). The COLMA is collocated to where many of the hail scar storms occur. As in Fuchs and Rutledge [2018], COLMA can be utilized to classify the simplified charge structure within these storms. There are more LMA- detected VHF sources that occur in the positive region of the storm which can be inferred to be near the altitude of the storm maximum source density within a storm. The mode of LMA
source density in a normal storm is near -40 °C while the mode in an anomalous storm is near -20 °C.

It is also worth investigating when an optical extinction occurs. Optical extinctions have been studied due to the noticeable DE in GLM over the Plains and NW CONUS. They occur when light from a lightning flash is scattered so much by cloud ice and water to the point that the optical sensor will not detect it [Thomson, L. W. and Krider, 1982]. Rutledge et al. [2018] noted reduced DE when there is more cloud ice and water. Future studies can examine dual-polarization radar products and hydrometeor identifications in hail scar storms. This can help determine the role that cloud ice and water are playing in light scattering.

When examining storm reports over hail scars, it was noted that 2 of the 3 case studies had severe wind reports at the time of the hail scar occurring. It is worth investigating the relationship between wind-driven hail and hail scars. There have been numerous photographs that show the effects of wind driven hail on buildings and crops.

It would be helpful in future studies to have a way to identify hail scars more easily. The current method of finding hail scars relies on a combination of storm reports, high resolution MODIS imagery, and a sharp pair of eyes. The tiniest of hail scars can be difficult to find with the current available resolution of satellite imagery. Hail scars are easily identified when there is an abundance of green vegetation. Usually, the crops in the hail scar have turned brown due to crop damage. Bell et al. [2020] has developed a way of using SAR to measure the NDVI within hail scars.
This technique can be used over different plant and crop types to help characterize hail scars.

Lastly, an analysis of what kind of crops are being damaged by hail can help inform if hail scar producing thunderstorms are unique from other severe storms, or if a hail scar occurring is determined by the land cover.
REFERENCES


