AN EXAMINATION OF THE RELATIONSHIP BETWEEN SUPERCELL COMPOSITE PARAMETER AND TORNADO OCCURRENCE IN U.S. LANDFALLING TROPICAL CYCLONES

By

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ABSTRACT

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For many years it has been known that tornadoes accompany most, if not all, landfalling Tropical Cyclones (TCs) in the United States. Much research has been done on the thermodynamic and kinematic environments of TCs to determine why this is, and to determine if there is a way to forecast the number of tornadoes a landfalling TC is likely to produce. Past research has indicated that many TC Tornadoes are produced by shallow supercells embedded in the rainbands of TCs. As the Storm Prediction Center has a metric, Supercell Composite Parameter (SCP), for determining potential formation of supercell thunderstorms, the question is asked whether SCP can be applied to TCs as well, and whether it can be used to discriminate between "outbreak" and "non-outbreak" TCs. All U.S. landfalling TCs from 2000-2010 are studied and statistical methods are applied to determine that SCP is correlated with tornado occurrence and that SCP can be used as a discriminator between “outbreak” and “non-outbreak” TCs.

CHAPTER 1

1. Introduction

It has long been known that tornadoes accompany many landfalling TCs. As early as the 1910s this was documented (Gray, 1919; Barbour, 1924), and certainly in the past fifty to sixty years has been observed time and time again. Numerous studies have been done on the matter, as not all landfalling TCs are created equal. Some will spawn a massive tornado outbreak that will carve destructive swaths through many states, while others will form only one or two tornadoes. This phenomenon has been studied many times from multiple different angles and with varying complexities, all trying to understand just exactly what is it about the structure of a landfalling TC that makes it conducive to the formation of one, two, ten, or many more tornadoes.

Hill, *et al.* (1966) was one of the very first studies that tried to explain tornado formation in TCs. While the authors built on some limited previous studies, Hill *et al.* (1966) was the first to comprehensively examine the phenomenon of tornadoes associated with landfalling TCs. Unfortunately at the time of the study, tornado reports in TCs were few; however, reports had been steadily increasing since the early 1950s. Storm damage surveying and assessment was still in its infancy at the time, hence the lack of reports compared to more recent TCs.

They investigated all TC related tornado occurrences from as early as 1918 through 1964. However, due to the aforementioned scarcity of reports through most of the study period, the authors focused mostly on the decade of 1954-1964 when tornado reports were felt to be most reliable. For this period, Hill *et al.* attempted to tie tornado occurrence to several factors: 1) the TC life cycle, i.e. what stage of development the TC was in when it made landfall and produced tornadoes, 2) TC heading at landfall, 3) TC intensity, 4) the "sector" or quadrant of the landfalling TC, 5) the radial distance from the center of the TC, and 6) the lowest central pressure of the TC. Of these, utilizing the lowest central pressure of the TC was discarded as having no correlation. All other factors considered met with at least limited success. However, what was most interesting about Hill *et al.* is that the authors noticed a pattern in rain band radar echo returns on the weather surveillance radar of the time. They found that many tornadoes formed from discrete cells in the outer rainbands of landfalling TCs, or more intense cells embedded within those same rainbands.

At the time, "supercell" thunderstorms had not been identified, however with the advantage of reexamining these findings with current understanding of supercell thunderstorm structure, it is evident that this was some of the first indication of the existence of supercell thunderstorms embedded in tropical cyclone rainbands.

A few years later, Novlan and Gray (1974) also contributed to the study of TC tornadoes. In their paper, they attempted to investigate the underlying causes of tornadogenesis in landfalling TCs. Their study examined landfalling TCs in the United States from 1948-1972, and in Japan from 1950-1971. They found that one of the most important differences between tornado-producing TCs and non-tornado-producing TCs was a large disparity in vertical wind shear between the surface and 850 hPa. Storms that produced tornadoes had much larger low level vertical wind shear; on the order of 40 knots compared to the 20 knots of non-tornado producing storms.

Novlan and Gray then went on to theorize that dissipating or filling TCs; i.e. those that were losing tropical characteristics and becoming increasingly cold-core, baroclinic and sheared (i.e., TCs undergoing extratropical transition), were the ones that would produce most tornadoes. They postulated that strong vertical shear mixes down higher velocity air from near 850 hPa to the surface, which results in strong horizontal shear that produces the vorticity necessary for tornadogenesis. Curiously, to this point, very little thermodynamic instability had been observed in TCs, leading Novlan and Gray to conclude that it was dynamic processes, not thermodynamic ones, primarily responsible for tornado production in TCs.

Following Novlan and Gray, and a paper in the mid-1980s (Gentry 1983), the next major papers on this subject were authored by Eugene McCaul. McCaul (1987) is a case study of a specific TC induced tornado outbreak. The outbreak occurred as part of Hurricane Danny (1985) as the storm made landfall in Alabama and produced several tornado families near the Redstone Arsenal near Huntsville, AL. This paper is notable as the first to perform a radar survey of tornado producing cells, as well as a photographic survey.

The tornadoes that struck near the Redstone arsenal were notable in that they spawned from long-lived, long-track, rotating thunderstorms that were easily identifiable on radar, in this case the WSR-74C at Huntsville, AL. (Fig 1). Though shallower (~10km) these thunderstorms displayed many similarities with their Great Plains counterparts, including long track and longevity. One thunderstorm persisted for approximately 3 hours during its tornado producing stage and traveled some 150km. Further, photographs of these tornadoes showed that they behaved much the same as their Great Plains cousins, forming from well-defined wall clouds with attendant tail clouds and other visual features. There was even one documented multiple-vortex tornado.

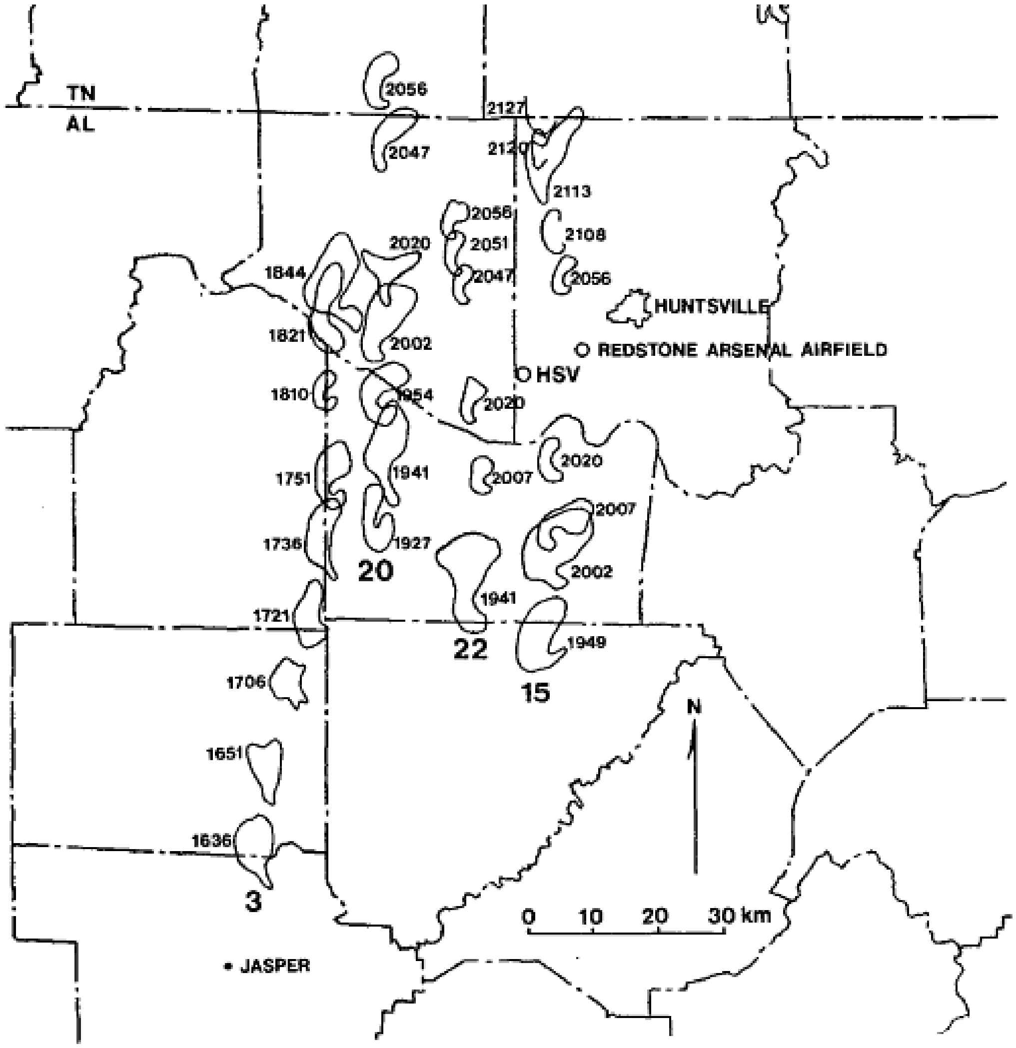


Fig. 1: Radar summary of four long-track hook echoes as seen by the Huntsville, AL WSR-74C. These storms formed in the rainband of Hurricane Danny as it made landfall in Alabama, producing several long-track tornadoes. (McCaul 1987, Fig. 3

Following the case study of Hurricane Danny, McCaul (1991) investigated the buoyancy characteristics of landfalling TCs. The paper expanded upon observations made in the Hurricane Danny case study, created a 38–year tornado climatology, and generated composite soundings and hodographs for tornado-producing and non-tornado-producing TCs. McCaul (1991) found that some 59% of landfalling TCs produce tornadoes, indicating that the phenomenon was much more common than originally thought. Additionally, it was found that most TC tornadoes are weak (< F2 strength) and that most tornadoes occur in the right front quadrant (RFQ) of the TC. It was found that the RFQ contains enhanced shear and helicity important for tornado formation. Interestingly, amounts of Convective Available Potential Energy (CAPE) were lower in the RFQ. This absence of CAPE can be explained by studies such as Baker et al. (2009) and McCaul (1987), that found that the instability required for supercell (and tornado) formation could be explained by dry air entrainment into the TC, which served to enhance CAPE in the RFQ. Further, McCaul (1991) found that similar to Great Plains tornado outbreaks, TC tornado outbreaks tended to peak in afternoon hours, and most tornadoes tended to occur within a day of landfall. Lastly, it was found that TCs with faster forward translational speeds also tend to produce more tornadoes due to added forward velocity to RFQ shear.

Fast forwarding through the 1990s, there are two papers written by Easton and Link (2009) and Baker *et al.* (2009) that dealt with radar case studies of landfalling TCs. Both utilized some of the same radar data taken from the penetration of Hurricane Ivan in 2004 by WP3-D "Hurricane Hunter" aircraft, which was instrumental in identifying supercells forming far offshore.

Baker *et al.* (2009), focuses more on the environmental aspects of Hurricane Ivan (2004), utilizing data from some 62 radiosondes, (some land-based, some dropsondes dropped by NOAA aircraft) to paint a thermodynamic picture of the environment of the

TC. Radar analysis, both from on-shore radar sites and from NOAA aircraft, identified miniature supercells embedded within the rainbands of Ivan as it came ashore. They showed that both the Vertically Integrated Liquid (VIL) and mesocyclone strength of these offshore supercells increased upon landfall, and often these supercells produced tornadoes immediately upon or shortly after making landfall. Further, a dual-Doppler analysis of three embedded supercells revealed that their updrafts were highly helical in the lower troposphere, suggesting ingestion of significant amounts of streamwise vorticity. In addition to a radar analysis, they utilized several SPC composite parameters, including Supercell Composite Parameter (SCP), to investigate their use in a TC environment. The study also compared Hurricane Ivan with Hurricane Jeanne (2004). Jeanne made landfall in a similar situation, similar location, and with a similar heading; however, it did not produce the same prolific number of tornadoes as Ivan did upon landfall. Utilizing dropsondes and onshore data, it was found that Hurricane Ivan ingested a significant band of dry air as it made landfall. This dry air entrainment is what destabilized the atmosphere and contributed to the large increase in CAPE in Ivan, which in turn fostered the development of tornadic supercells.

Utilizing the same radar dataset was Easton and Link (2009). While Baker *et al.* focused on the thermodynamics of Ivan and comparisons to Jeanne, as well as performing a dual-Doppler analysis, Easton and Link focused on the details of the embedded supercells offshore. It was found that these offshore cells may develop more often than previously thought, and that they often maintain intensity right up until landfall. They were previously undetected, as they were both shallow enough and far enough offshore to be outside the range of shore-based Doppler radar. The mesocyclones only extended to 6-7km AGL. They were persistent as well, existing for ~3 hours between initial observation and landfall, with one displaying signs of cyclical mesocylonegenesis and two others producing tornadoes almost immediately upon landfall. It was also found that the cellular nature of the rainband, with discreet spacing of these supercells, likely helped in the maintenance of the storms. It is entirely possible that waterspouts were being produced offshore as well, but with no direct observation of the mesocyclone at ground level there is no way to tell.

Finally, Tropical Storm Andrea in 2013 produced a striking radar image over the Florida Keys (Fig. 2). The southernmost storm in this radar image is a classic radar supercell signature, and at the time a powerful waterspout was reported underneath the hook echo.

Fig. 2: Radar image from Tropical Storm Andrea showing at least two supercells in the vicinity of the Florida Keys. The southernmost storm is displaying an impressive hook echo. Source: John Morales, NBC 6 South Florida. (2013)

Throughout the past 50 years, research has led to the conclusion that supercells are embedded in the rainbands of certain landfalling TCs, and that these supercells are responsible for a large number of tornadoes reported with landfalling TCs. Given that, the question arises that if TC tornadoes are mostly supercell initiated as suggested by Eastin and Link (2009), Baker *et al.* (2009), McCaul (1987), and earlier findings by Hill *et al.*, then can a parameter for predicting Midwestern supercell thunderstorms also be used to predict TC tornadoes? This study will attempt to answer this question by comparing Supercell Composite Parameter (SCP) among multiple tornado-producing landfalling TCs.

CHAPTER 2

2. Data and Methods

a. Supercell Composite Parameter

In order to investigate Supercell Composite Parameter (SCP), it must first be defined. SCP was introduced in 2003 by the Storm Prediction Center and it combines several existing meteorological parameters into a composite index that indicates areas where conditions are favorable for supercell development. The idea is to combine known ingredients necessary for the formation of rotating thunderstorms into a normalized parameter that can be plotted so that a forecaster may, with a glance at one single parameter, deduce where the environment is favorable for the development and maintenance or intensification of a supercell. This parameter was first defined in Thompson *et al.* (2003) to be:

(1) $SCP = (MUCAPE/1000\ J\ kg^{-1}) \times (0\text{-}3km\ SRH/150\ m^2s^{-2}) \times (BRN\ shear/40\ m^2s^{-2})$

where MUCAPE is Most Unstable CAPE, SRH is Storm Relative Helicity from 0-3km, and BRN Shear is Bulk Richardson Number Shear over the lower 6 kilometers of the atmosphere. The equation is normalized so that values above 1.0 indicate conditions favorable for the development of supercells.

Thompson (2004) updated the equation after further study. This new SCP number was generated by calculating the "effective inflow" layer for each SRH and shear. Effective inflow SRH is designed to only calculate SRH that would be ingested into the storm by its inflow, and thus the SRH relevant to storm dynamics. The new version proved to discriminate strongly between surface-based supercells and discrete non-supercells.

Advantages to utilizing the effective inflow SCP included a more representative value for marginal-supercell conditions, and a better handling of shallow- and surface-based convection. While these would both be advantageous for investigating SCP in a TC environment, calculating effective inflow layers for supercells (which would involve generating and then examining a vertical sounding profile for every point on the North American Regional Reanalysis (NARR) grid) proved to be computationally inefficient for the scope of this project. Thus, the decision was made to use the original SCP equation, modified slightly for ease of processing in Integrated Data Viewer (IDV).

The following equation was used for this study, based on an SCP climatology study conducted by Smith (2005).

(2) $\text{SCP} = (\text{MUCAPE}/1000\ \text{J kg}^{-1}) \times (\text{0-3km SRH}/150\ \text{m}^{2}\text{s}^{-2}) \times (\text{10m – 500 hPa bulk shear} / 20\ \text{ms}^{-1})$

b. Data

For the purposes of this study, a dataset of all tornadoes associated with CONUS landfalling TCs from 1995-2010 was obtained from the Storm Prediction Center (Edwards, 2010). After viewing and noting dates and times of tornado occurrences and examining available data, a master TC list was created. Due to missing storm reports from 1995-2000, the dataset was instead truncated to a 10-year set from 2000-2010 that included the TCs listed in Table 1. It is important to note that there are no TCs listed for 2009 because no TCs made landfall in the U.S. in 2009. Additionally, the number of tornadoes per TC is the count according to Edwards (2010). The actual number of useable tornado data points varied from TC to TC depending on factors discussed below.

Table 1: US Landfalling TCs, 2000-2010 (Edwards, 2010), with number of tornadoes and date of first and last tornado occurrence.

TC Name, Year	First Tornado Date	Last Tornado Date	Number of Tornadoes
Gordon, 2000	16 Sept 2000	18 Sept 2000	11
Helene, 2000	22 Sept 2000	23 Sept 2000	13
Allison, 2001	5 June 2001	15 June 2001	26
Barry, 2001	2 Aug2001	7 Aug 2001	4
Gabrielle, 2001	13 Sept 2001	14 Sept 2001	18
Michelle, 2001	5 Nov 2001	5 Nov 2001	2
Fay, 2002	7 Sept 2002	9 Sept 2002	11
Gustav, 2002	10 Sept 2002	10 Sept 2002	1
Hanna, 2002	14 Sept 2002	15 Sept 2002	2
Isidore, 2002	25 Sept 2002	26 Sept 2002	10
Lili, 2002	3 Oct 2002	2 Oct 2002	25
Kyle, 2002	8 Oct 2002	8 Oct 2002	8
Claudette, 2003	15 July 2003	15 July 2003	2
Henri, 2003	9 Sept 2003	9 Sept 2003	1
Isabel, 2003	18 Sept 2003	18 Sept 2003	3
Bonnie, 2004	12 Aug 2004	13 Aug 2004	16

Charley, 2004	13 Aug 2004	14 Aug 2004	20
Gaston, 2004	29 Aug 2004	30 Aug 2004	18
Frances, 2004	4 Sept 2004	9 Sept 2004	108
Ivan, 2004	15 Sept 2004	18 Sept 2004	118
Jeanne, 2004	26 Sept 2004	28 Sept 2004	42
Arlene, 2005	11 June 2005	13 June 2005	3
Cindy, 2005	6 July 2005	8 July 2005	48
Dennis, 2005	9 July 2005	12 July 2005	48
Emily, 2005	20 July 2005	20 July 2005	11
Katrina, 2005	26 Aug 2005	31 Aug 2005	59
Rita, 2005	24 Sept 2005	26 Sept 2005	98
Tammy, 2005	6 Oct 2005	6 Oct 2005	1
Wilma, 2005	23 Oct 2005	24 Oct 2005	8
Alberto, 2006	12 June 2006	14 June 2006	17
Ernesto, 2006	30 Aug 2006	31 Aug 2006	5
Barry, 2007	6 June 2007	7 June 2007	2
Erin, 2007	16 Aug 2007	19 Aug 2007	7
Humberto, 2007	13 Sept 2007	13 Sept 2007	1
Olga, 2007	16 Dec 2007	16 Dec 2007	2
Dolly, 2008	23 July 2008	24 July 2008	6
Fay, 2008	18 Aug 2008	28 Aug 2008	50
Gustav, 2008	31 Aug 2008	4 Sept 2008	49
Hanna, 2008	6 Sept 2008	6 Sept 2008	1

Ike, 2008	9 Sept 2008	14 Sept 2008	33
Hermine, 2010	7 Sept 2008	9 Sept 2008	13

The master list was then used to aid in the creation of two datasets: one utilizing the National Climactic Data Center's Storm Data database and consisting of tornado event dates, times, and start and end position (in latitude/longitude coordinates, discussed below) and one dataset consisting of North American Regional Reanalysis (NARR) data to compute SCP (both data sources as described below).

1. NARR DATASET

The NARR dataset is a reanalysis that uses the 2003 operational ETA model as its base. It has a horizontal resolution of 32 km and a vertical resolution of 45 layers. The domain covers North America, and data are available in 3-hour increments (00z, 03z, 06z, etc.) Further details on the NARR can be found in Mesinger *et al.* (2006), as only details relevant to this research are highlighted here.

As mentioned above, after examination of Edwards (2010), a comprehensive list of dates for every landfalling TC-produced tornado was put together. For each TC, the date of the first and the date of the last tornado were noted and recorded, as well as the total number of tornadoes produced and the "peak" tornado-producing day or days. Following this, a list of TC names, followed by month and then the dates required for that month was fed into a Perl script to download the relevant data from the NARR server. A grib file was downloaded for every three hours for each day of tornado occurrence per TC (i.e. 00z, 03z, 06z, and so on.) The following parameters were downloaded for each file:

-500 hPa wind u and v components

-10m wind u and v components

-0-180 hPa Most Unstable CAPE (MUCAPE)

-0-3km Storm Relative Helicity (SRH)

-Mean sea level pressure (MSLP)

2. STORM DATA DATASET

Similarly, utilizing the same master list of TCs and dates, a CSV file for each TC was downloaded from the NCDC Storm Data servers that contained every tornado report recorded in the United States during the period of TC landfall. Each report contained information such as the tornado date and time, starting latitude/longitude and ending latitude/longitude, Fujita scale ranking, injuries and fatalities, and estimated or actual damages caused. For the purposes of this research, however, only the date, time, and latitude/longitude coordinates of the tornado's starting point were required, so each downloaded CSV file was processed via another Perl script to extract the pertinent information and format the data for ingestion by IDV.

As part of the processing for each tornado file, the time of the tornado report was converted to UTC. Additionally, to allow for direct comparison to the 3-hourly computed SCP (described above), the time of each tornado occurrence was rounded to the nearest 3-hourly NARR data time. It would perhaps have been preferable to use a scheme to weight tornado start times to the nearest 3-hour synoptic observation, or to use only tornadoes that occurred within ±1 hour of synoptic observations, however it was not felt that this was a significant source of error.

3. HURDAT 2 DATASET

Lastly, information from HURDAT2 was utilized. This dataset is a comprehensive listing of all TCs in the Atlantic basin since 1851 through the previous year, updated yearly by the National Hurricane Center. Data are listed every 6-hours coinciding with synoptic information, and include TC name, date, center position (latitude and longitude), maximum sustained wind and minimum central pressure. A file for each TC in the study was created and HURDAT2 data were downloaded. Data fields for the study were date, time, and center position. The HURDAT2 data were used together with mean sea level pressure data to locate TC centers and size of the TC for this study.

c. Methodology

These three datasets, NARR grib files, tornado reports, and HURDAT2 positions, were then combined in Unidata's Integrated Data Viewer for each TC. NARR data was utilized to generate Supercell Composite Parameter maps for each TC using Equation 2. In addition to SCP, sea level pressure was plotted to indicate TC location. This was intended to supplement HURDAT positioning, as HURDAT data were available only every 6 hours as opposed to the 3-hourly data provided by the NARR. Lastly, tornado positions and times were overlaid onto the map over SCP values. A sample image, taken from Hurricane Katrina making landfall, is illustrated below in Fig. 3, with the image legend shown in Fig. 4. Tornado positions are indicated by the red triangles, while the TC center is indicated by the hurricane symbol.

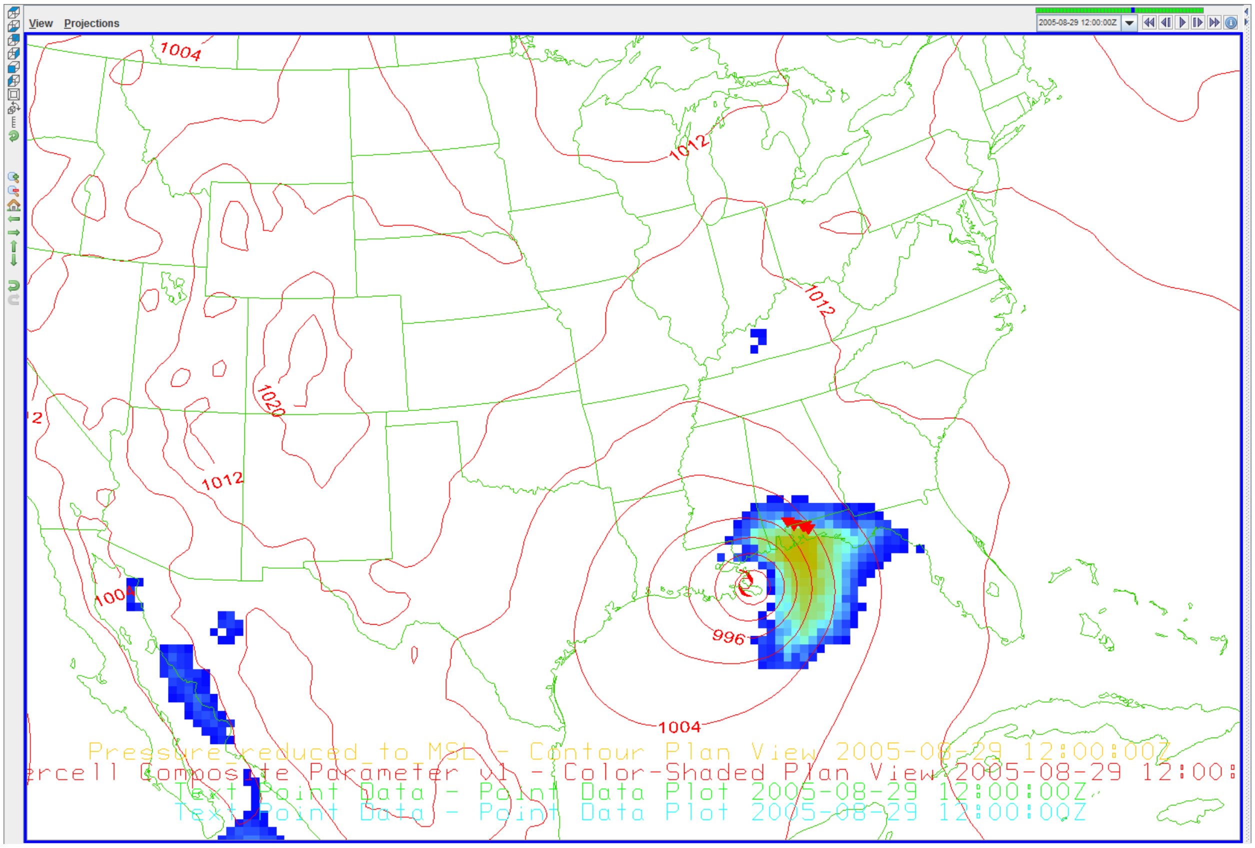
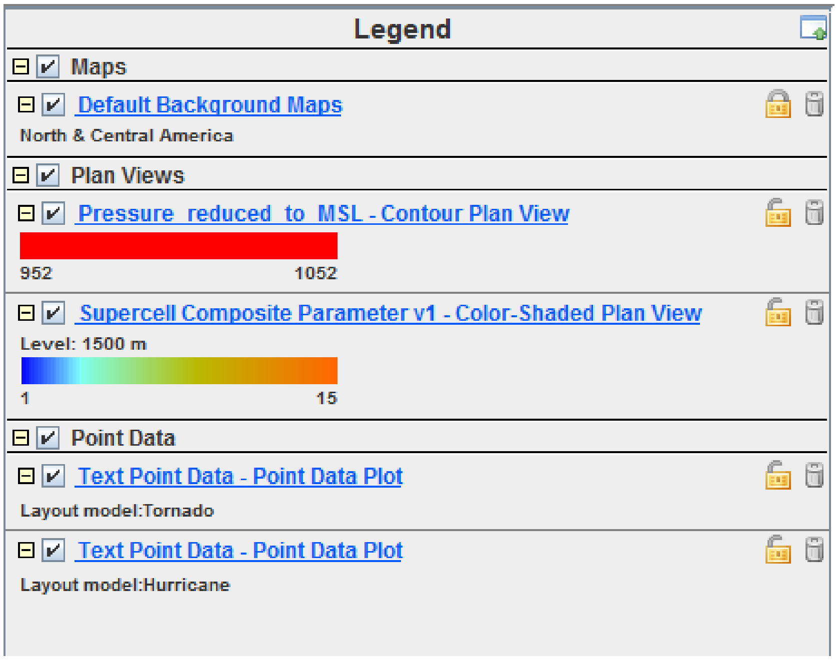


Fig. 3: Example IDV image from Hurricane Katrina at 12Z on 29 August 2005. SCP is the color shaded contour, and tornado reports are indicated by red triangles. MSLP is contoured in red isobars with hurricane center indicated by the hurricane symbol.



Legend

⊟ ☑ Maps

⊟ ☑ Default Background Maps
North & Central America

⊟ ☑ Plan Views

⊟ ☑ Pressure reduced to MSL - Contour Plan View
952 1052

⊟ ☑ Supercell Composite Parameter v1 - Color-Shaded Plan View
Level: 1500 m
1 15

⊟ ☑ Point Data

⊟ ☑ Text Point Data - Point Data Plot
Layout model:Tornado

⊟ ☑ Text Point Data - Point Data Plot
Layout model:Hurricane

Fig. 4: Legend to accompany Fig. 3. SCP is indicated by color shaded contour while MSLP is indicated by a red contour. Additional data points are tornado report locations and TC center.

After setting up an IDV file for each TC, IDV's Image Probe function was used to obtain point SCP values for each tornado. Since the data are in 3-hour time steps, obtaining data from the moment of tornado formation or touchdown (as estimated by the investigating National Weather Service Office, and after modifying touchdown time to coincide with the closest NARR file timestamp, as mentioned above) was determined to be most representative of conditions leading to development of a tornadic supercell, as opposed to observing values immediately previous to tornado formation as an attempt to identify for example a supercell before the tornado formed. Thus it is assumed that the obtained values are representative of SCP at the time of tornado formation.

The Image Probe function was selected to use a weighted average approach to determine SCP at each point. Using the list of tornado times and lat/long for each TC, SCP values were manually recorded for each reported tornado. This process was repeated for each time step of each TC. However, during the logging of SCP values, it was determined that several of the Storm Data reports (most notably several from the 2004 and 2005 hurricane seasons) had had longitudes mistyped into them (as revealed by tornadoes being marked in unrealistic locations, such as the middle of the Atlantic Ocean). For these tornadoes, a missing data flag of -999 was recorded for the SCP value since it was impossible to determine what the actual longitude was supposed to be. Additionally, tornadoes that occurred outside the domain of the TC being studied (determined by the extent of closed MSLP contours; several TCs made landfall while unrelated tornado outbreaks were occurring across the central plains) were also tagged with a -999 marker, and the largest of these outbreaks were removed from the TC datasets entirely.

d. Statistical Analysis

Once data files were completed for each of the TCs listed, they were concatenated into one master data file that could be imported into a statistical analysis program. The R Project for Statistical Computing was chosen for this task, mostly due to its open source nature and the author's familiarity with the program.

Upon importing data to R, quality control was performed by eliminating all tornado reports with missing data. As mentioned above, the -999 tag was applied to tornadoes that either were not related to a landfalling TC or that had missing or incorrect longitudes. When cleaning of the data was finished there were 872 remaining TC related tornadoes left in the dataset, which was determined to be an appropriate population for a 10-year dataset.

After quality control of the data was complete, basic statistics were run. The master dataset was split by TC so that the following could be calculated for each TC: number of tornadoes, mean SCP, median SCP, and the standard deviation of SCP. The objective of the statistical analysis was to find any link between SCP values and severity of a tornado outbreak. The severity of an outbreak is defined by number of tornadoes per TC. After generating bulk statistics, each such statistic was plotted on a box-and-whisker plot to allow for the examination of trends in the data. A correlation was then run for each variable (unmodified, mean, and median) between the variable and the tornado count (per TC).

Additionally, 3-hourly tornado counts were investigated. The number of tornadoes in one 3-hour time step was computed, and median and mean SCP values were computed for that 3-hour time step. A general linear model was created for both the 3-hourly mean and median, and then a correlation was run upon that as well.

OUTBREAK ANALYSIS

With SCP defined, the term "outbreak" must be defined, and for that we turn to the statistical composition of all landfalling TCs. As illustrated by the histogram in Fig. 5, most TCs produced between 1 and 20 tornadoes, with a smaller subset producing between 1 and 10. There are four TCs that produced extreme numbers of tornadoes in the dataset: Ivan (2004) with 115, Rita (2005) with 104, Frances (2004) with 94, and Katrina (2005) with 64. It is important to note that these numbers are the number of tornadoes in each TC after data cleaning has been applied, so the numbers do not match those in Edwards (2010).

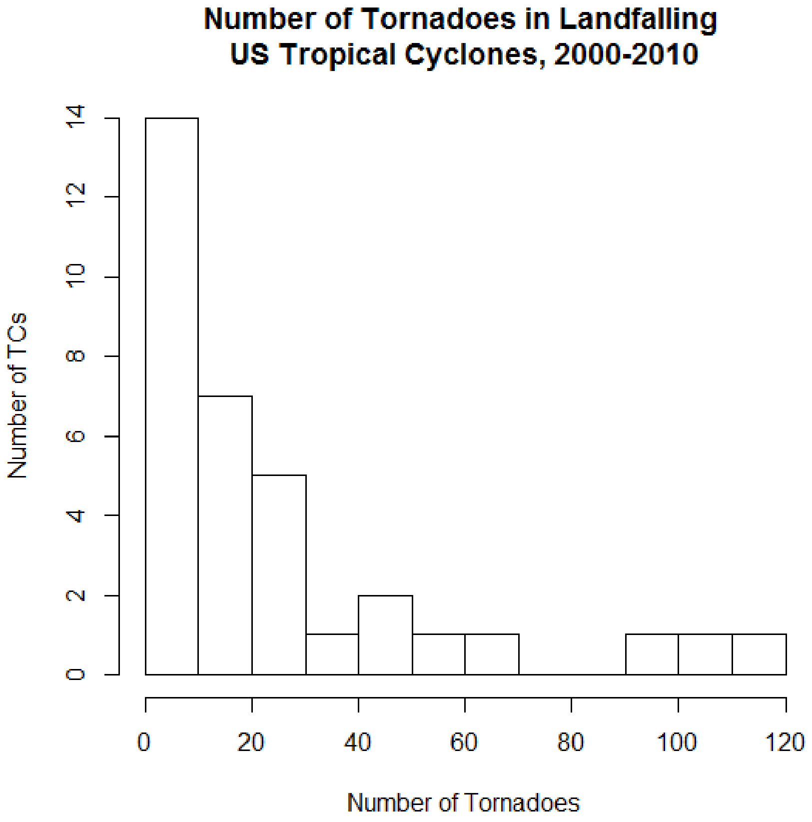


Fig. 5: Histogram of the number of tornadoes produced per TC. Most TCs produced between 1 and 20 tornadoes.

With this data, the average number of tornadoes in each TC is 25.4 with a median of 14 and a standard deviation of 29.5. For a normal dataset, this would put the more extreme tornado outbreaks at a minimum of 1 standard deviation, and maximum of two standard deviations outside of normal. The dataset is not normal, however, so Median

Absolute Deviation (MAD) was used instead, as calculated by the R Statistical Computing Package. For the entire list of TCs, the MAD was 15.56.

Additionally, those four extreme events, a total of 377 tornadoes, represent 43% of the 872 tornadoes included in the study. Removing those four TCs gives a very different statistical picture. Instead, the average number of tornadoes per TC drops to 16.26, while the median becomes 12.5 and the MAD becomes 11.86. Standard deviation becomes 14.21.

Based on the MAD of the dataset with extreme events removed, and the histogram shown in Fig. 5, it was decided to provide two definitions of a tornado “outbreak” to test independently. Thus, each TC in the dataset was classified into an “outbreak” TC and “non-outbreak” TC based upon two criteria: one where an outbreak was defined as a TC having more than 10 tornadoes, and one where an outbreak was defined as a TC having more than 20 tornadoes. Thus, the SCP of “outbreaks” and “non-outbreaks” could be compared to one another. Results of this comparison are discussed below.

CHAPTER 3

3. Results

Upon compiling all SCP results into one list, it was found that values ranged from 0 to 12 with a singular maxima of 32.9, which originated from Hurricane Jeanne in 2004. After some investigation, it was decided to discard the single 32.9 value as a very extreme outlier. While this outlier was included in the dataset, the data had a Standard Deviation of 2.04, placing the 32.9 outlier nearly twenty-five standard deviations outside the bulk of the data. After removing this data point, the standard deviation of the data dropped to 1.76. The mean SCP for the dataset was 1.69, and the median SCP value was 1.2. The data were seen to have a non-normalized positively-skewed distribution. This is illustrated in Fig. 6. Most SCP values are small, falling between 0 and 1 or between 1 and 2. An SCP value of 1 is the conventional threshold where conditions become favorable for the development of supercell thunderstorms, and values above 1 are therefore considered more favorable. SCP values slightly greater than 1, but less than 2, made up the second most numerous group of SCP values. Only a few events exceeded an SCP of 3 or 4, with the maximum value (after removal of the previous maximum of 32.9) being 11.8.

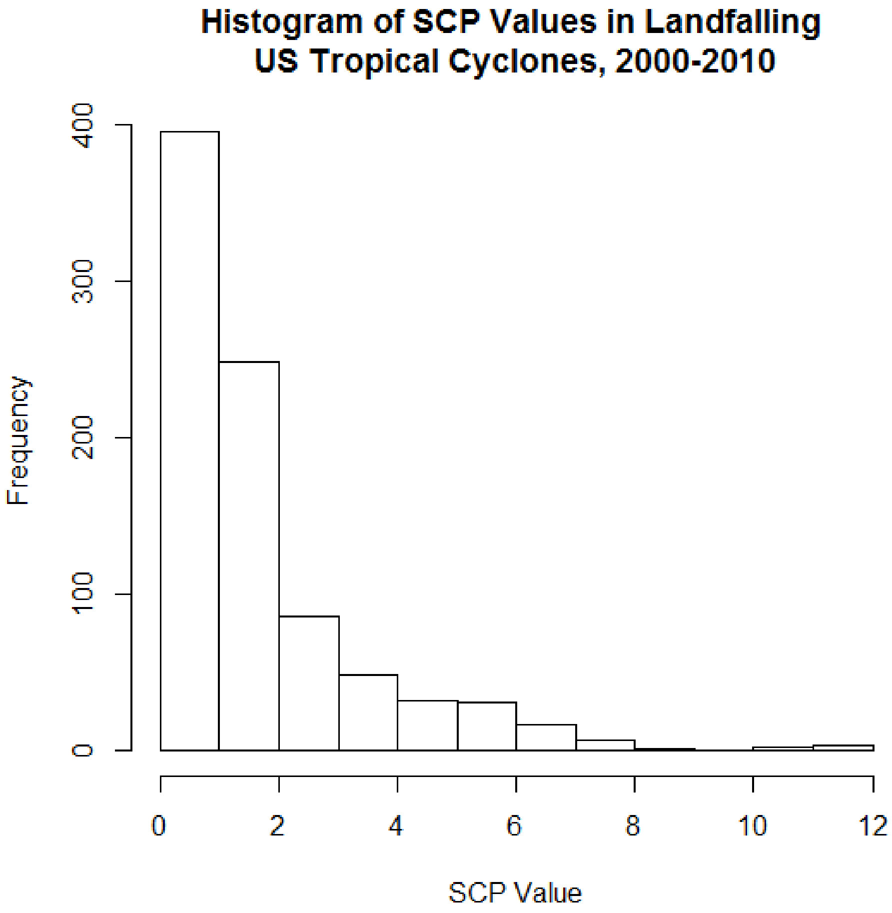


Fig. 6: Histogram of SCP values in landfalling TCs, after removal of extrema. Most values are SCP <1.

Values within TCs sometimes fluctuated wildly, as is illustrated in Fig. 7. Some TCs had SCP values that were all well within 1 of each other, however others had values that ranged from 0 all the way through 11. After producing the boxplot shown in Fig. 7, a trend line was added to the plot. The line indicates a slight increase in SCP values for TCs that produced more tornadoes, however if one looks only at SCP the relationship is very subtle. As the plot shows, there does not appear to be any obvious major correlation.

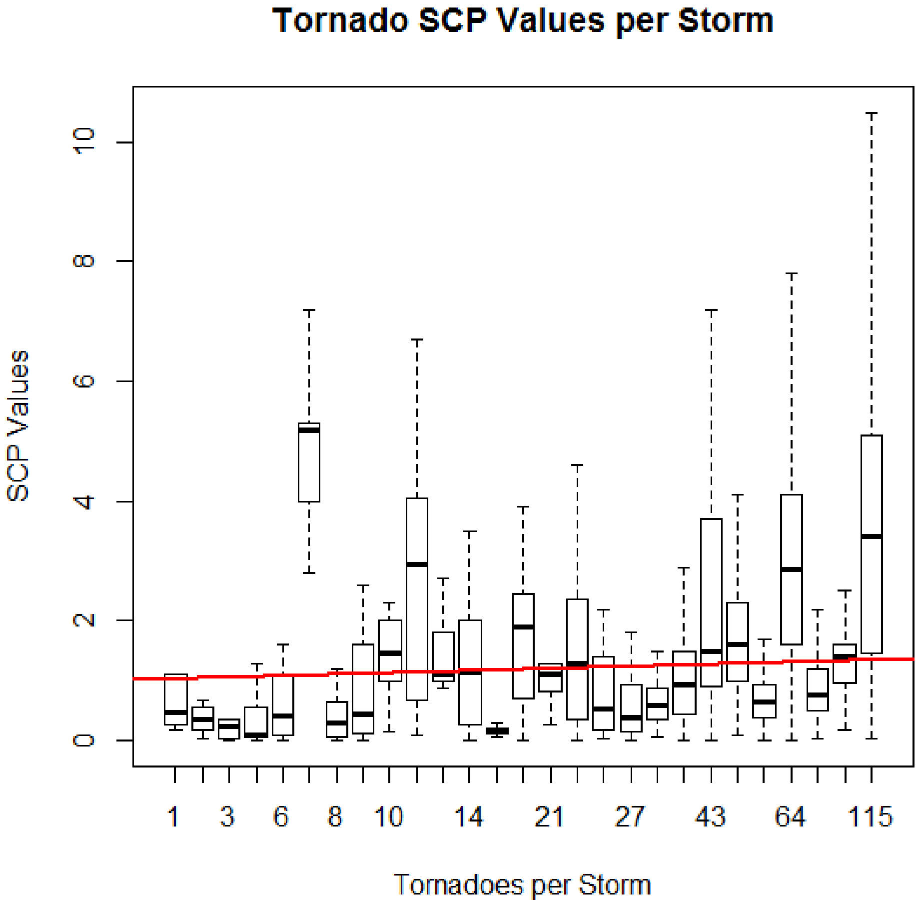


Fig. 7: Box plot illustrating SCP variance within each TC. X-axis is number of tornadoes produced by the TC. This number is not for each individual TC, but rather for every TC that produced n number of tornadoes. Y-axis is value of SCP. The red trend line shows a slight increase in SCP as TCs produced more tornadoes, however SCP can vary wildly within each TC.

Fig. 8 describes again the number of tornadoes per TC as a function of SCP, with a trend line added as before. The line on this graph shows a more noticeable trend and correlation. However, Fig. 8 does indicate that TCs with fewer tornadoes tend to have lower values of SCP associated with those tornadoes.

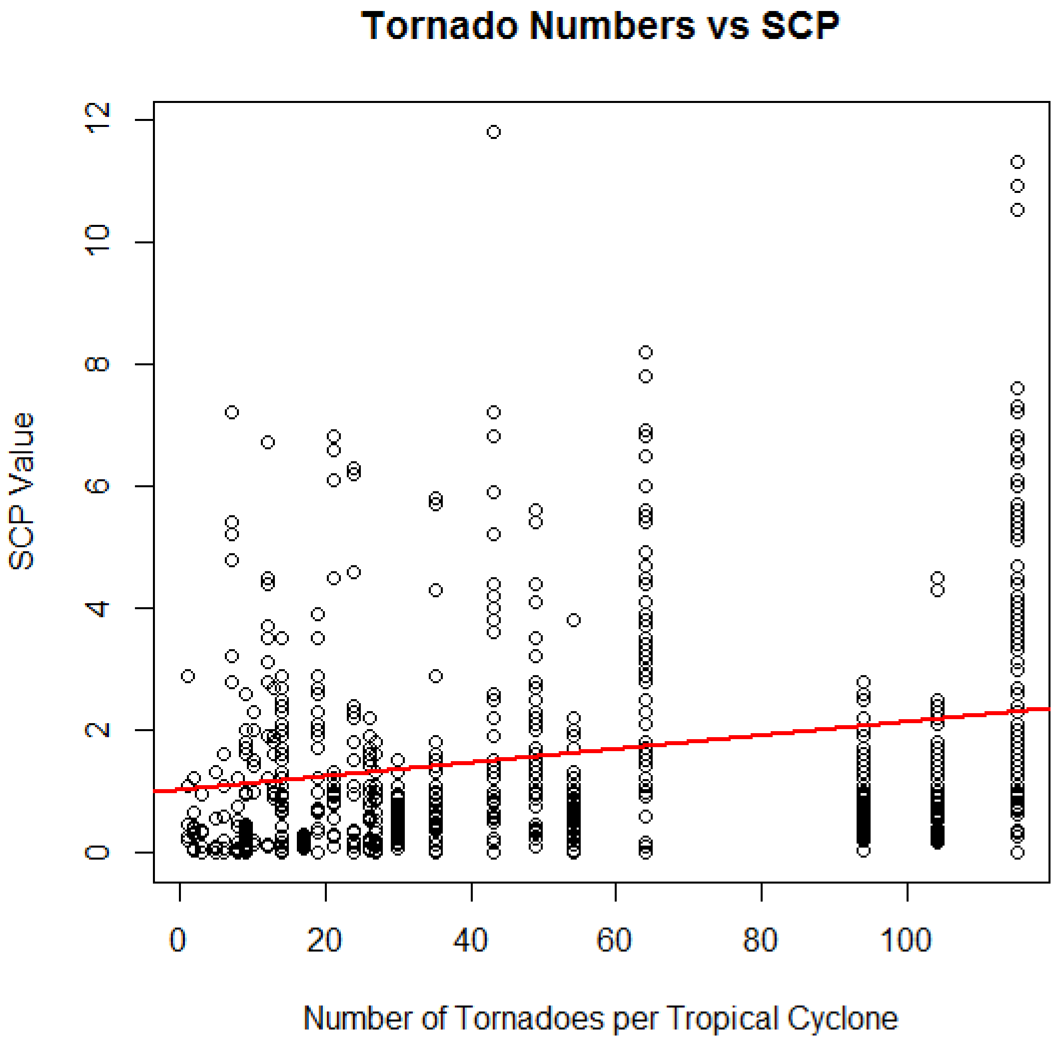


Fig. 8: Plot of Tornadoes per TC (X-axis) versus SCP value at tornado formation (Y-axis.) Most tornadoes have lower values of SCP. This is particularly true of tornadoes from TCs that did not produce many tornadoes. The red trend line indicates a slight correlation between SCP values and the number of tornadoes produced by the TC.

After examining the raw SCP values, an examination of statistical SCP values was the next logical step. By taking mean and median SCP for each TC, a direct one-to-one comparison could be made for the tornado count each TC produced. Firstly, mean SCP was examined, as is detailed in the graph in Fig. 9. A clearer trend now emerges in the relationship between SCP and tornado count. Fewer tornadoes tend to occur with a lower mean SCP.

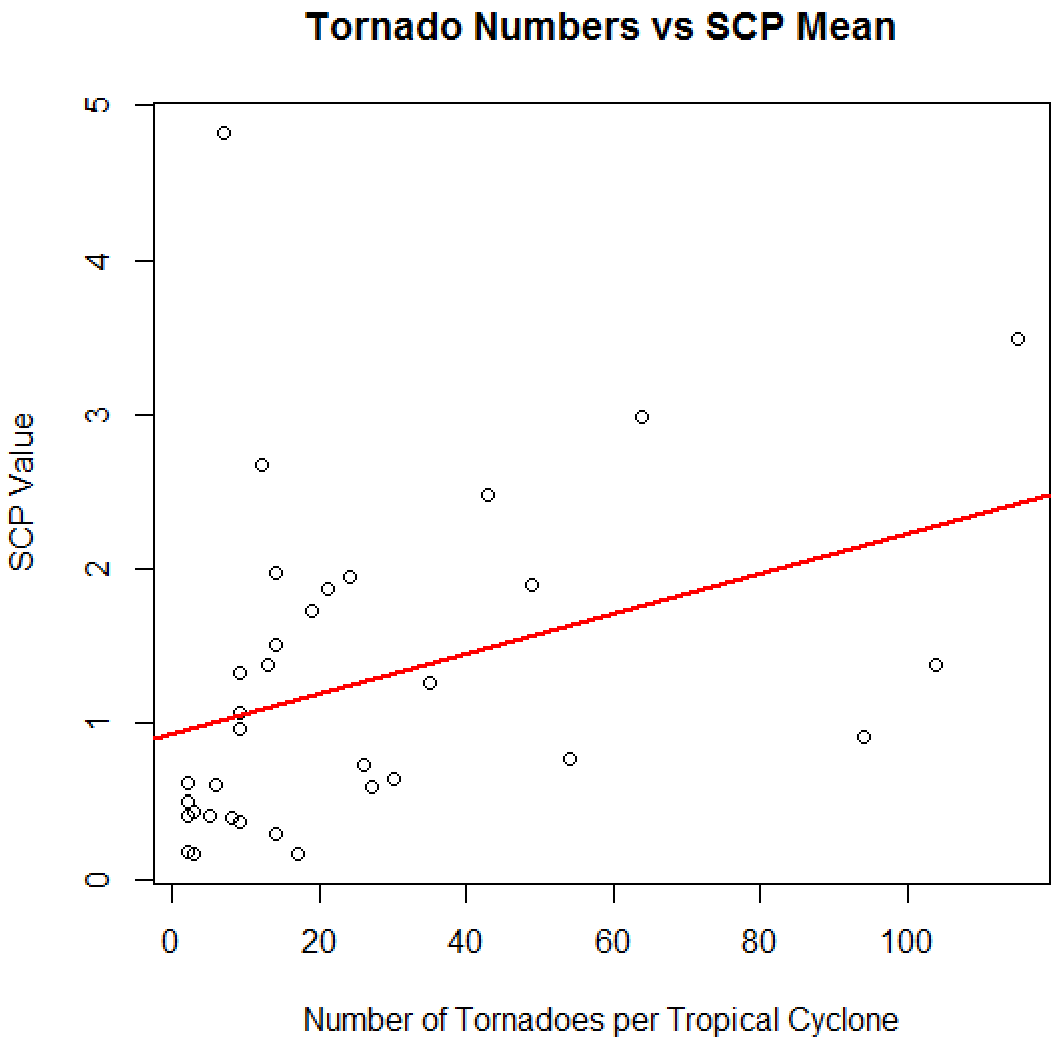


Fig. 9: Tornadoes per TC (X-axis) versus mean SCP value per TC (Y-axis.) The red trend line shows a clearer trend utilizing mean SCP per TC instead of the raw SCP numbers.

However, given the number of large SCP values in certain TCs, mean SCP may not be the best tornado predictor since it is easily skewed by large values. Median will provide a slightly better indication of trend since it is not as easily influenced by extrema. Fig. 10 is a plot of SCP Median compared to tornado count, with line of best fit added. As in Fig. 9, the trend indicates that higher median SCP results in a greater number of tornadoes produced by the TC.

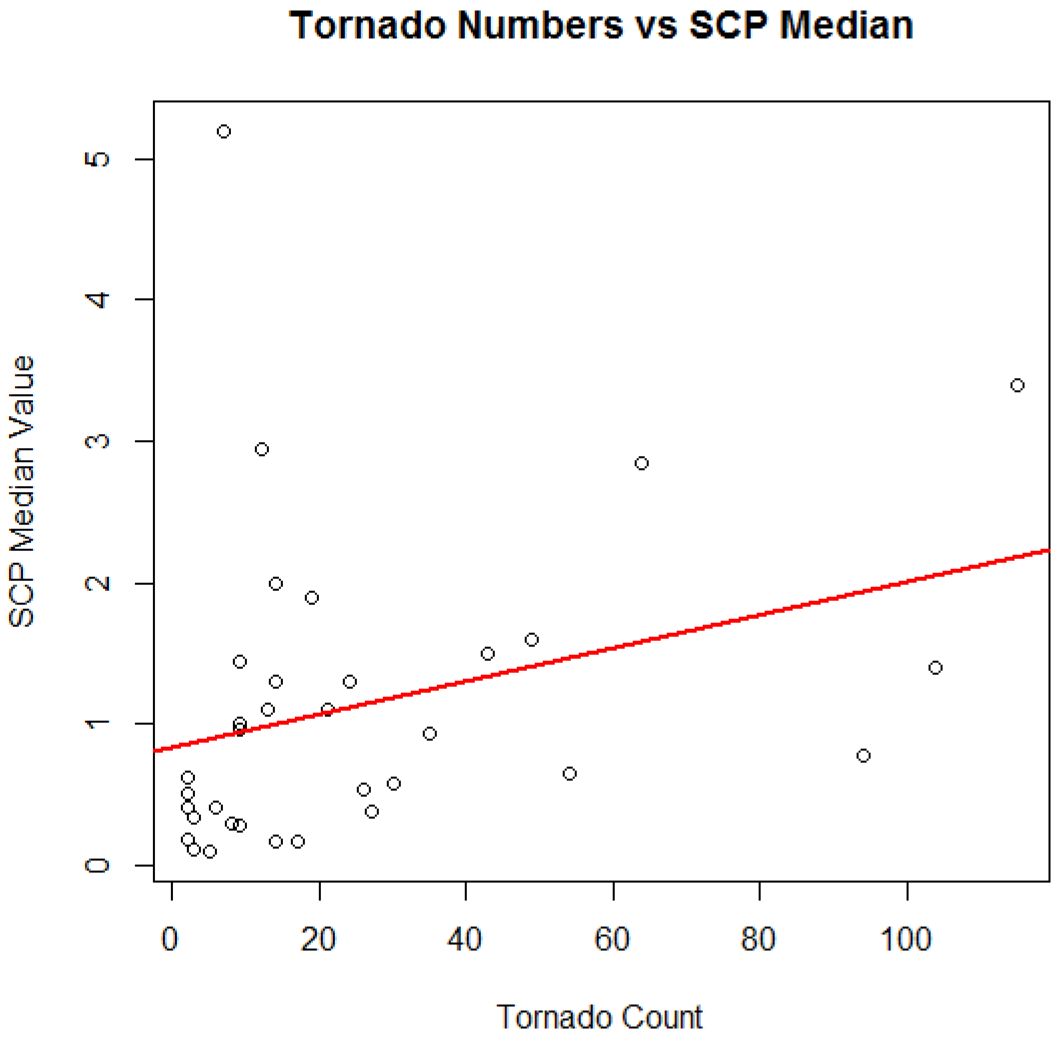


Fig. 10: Tornadoes per TC (X-axis) versus median SCP value per TC (Y-axis.) Similar to Fig. 9, the red trend line shows a clearer trend utilizing median SCP per TC instead of the raw SCP numbers.

Thus, both mean and median SCP have similar trends showing that higher SCP generally means a larger number of tornadoes per TC.

Because the data do not follow a standard, “normal” curve, the Spearman method was used for calculation correlation coefficients. As mentioned before, correlations were calculated not only for the raw SCP values, but also for SCP mean and median values for each TC. Each correlation compared the number of tornadoes per TC to the raw SCP value, the mean SCP for that TC, and the median SCP for that TC. Results are summarized in Table 2. Utilizing mean SCP per TC produced the best R-value correlation coefficient of approximately 0.52. Coming in second was median SCP per TC, and unmodified SCP produced the worst correlation.

Table 2: Correlation coefficients for Raw SCP, Mean SCP, and Median SCP per TC.

	Correlation Coefficient
Raw SCP	0.315386
SCP Mean per TC	0.5180262
SCP Median per TC	0.4704899

The correlations for both the SCP mean and median utilized a smaller dataset than the raw SCP correlation. As there were 34 TCs that were examined, there are only 34 distinct means and medians, one for each TC. This is substantially less than the 871 observations of SCP that were used to run correlation for only the raw SCP value, so there is some uncertainty as to whether the sample size is sufficient for proper analysis or not.

As values of SCP will vary greatly in a TC, utilizing raw SCP numbers as an analysis will result in a low correlation, as the data shows. The much more meaningful numbers are those of mean and median SCP since those provide insight into the overall environment of the TC, not just the environment at the point and time of tornado occurrence. The only better indication of the total tornado production of an entire TC would be a globally weighted and averaged aggregate of all SCP values at every grid point within the TC itself. However, this is well beyond the scope of this research.

SCP averaged over the entire tornado producing region of the TC is an effective indicator of tornado outbreak severity. The correlation of mean SCP to tornadoes supports this idea, and the fact that the mean SCP per TC correlates strongest to tornado production validates the observations of Easton and Link (2009) and McCaul (1987) of tornadoes spawning from supercells embedded in the rainbands of TCs.

a. Tornado Outbreaks

As was described previously, an effort was made to separate the landfalling TCs into "outbreak" and "non-outbreak" categories. This was done in the hopes of linking SCP to tornado activity. From the definitions of "outbreak," described above (10 and 20 tornadoes, respectively) two box plots were created. Fig. 11 shows the box plot where and outbreak is defined as more than 10 tornadoes, and Fig. 12 shows the same plot where an outbreak is defined as more than 20 tornadoes.

For an outbreak defined as more than 10 tornadoes, there is a marked difference in both the enclosed upper and lower hinge values in non-outbreak TCs and in the median of SCP for non-outbreak and outbreak TCs. For outbreak TCs, median SCP is 1.2, while for non-outbreaks the median is a much lower 0.432. A Student's T-test run on actual SCP for outbreak- and non-outbreak cases returns a P-value of 0.0001945, while a similar test run for mean SCP returns a P-value of 1.168×10^{-6}. Additionally, TCs containing tornado outbreaks had a significantly greater number of extreme positive outliers.

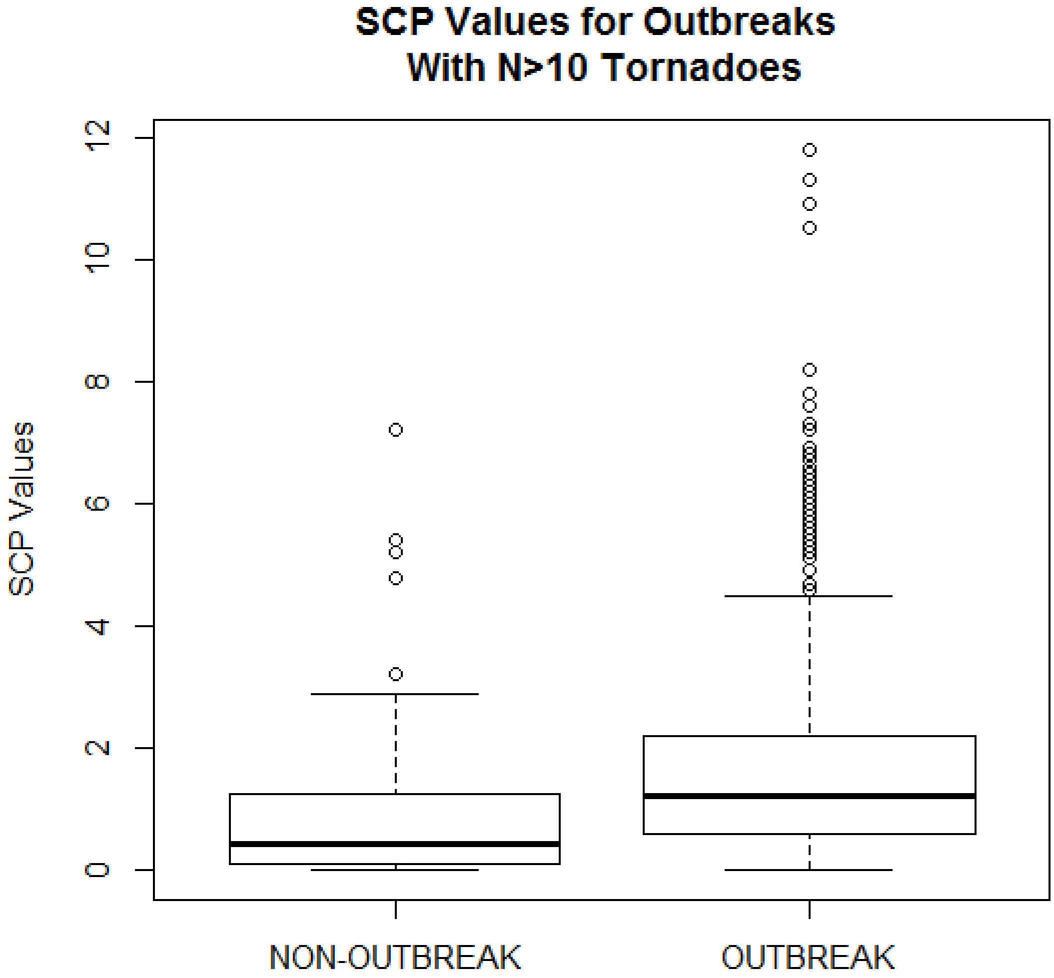


Fig. 11: Box plot of tornado SCP values for "Outbreak" and "Non-Outbreak" TCs where an outbreak is defined as a TC with N>10 tornadoes. For N>10 tornadoes, the median and upper and lower hinge values of SCP per TC are significantly higher in “outbreak” TCs than “non-outbreak” TCs. Additionally, there are many more extreme outlier values of SCP for “Outbreak” TCs.

Where an outbreak is defined as a TC with more than 20 tornadoes, the differences between outbreak and non-outbreak cases are much less apparent. Outbreak cases still have a far greater number of extreme outliers; however, the median SCPs are closer, as are the upper and lower hinges of the data. Outbreak TCs have a median SCP of 1.2, while non-outbreak TCs have a median SCP of 0.931. T-tests returned P-values of $2.21X10^{-5}$ and $2.469x10^{-11}$ for actual SCP and mean SCP values respectively. It is interesting to note that the median SCP of outbreak TCs of both definitions of "outbreak" are the same.

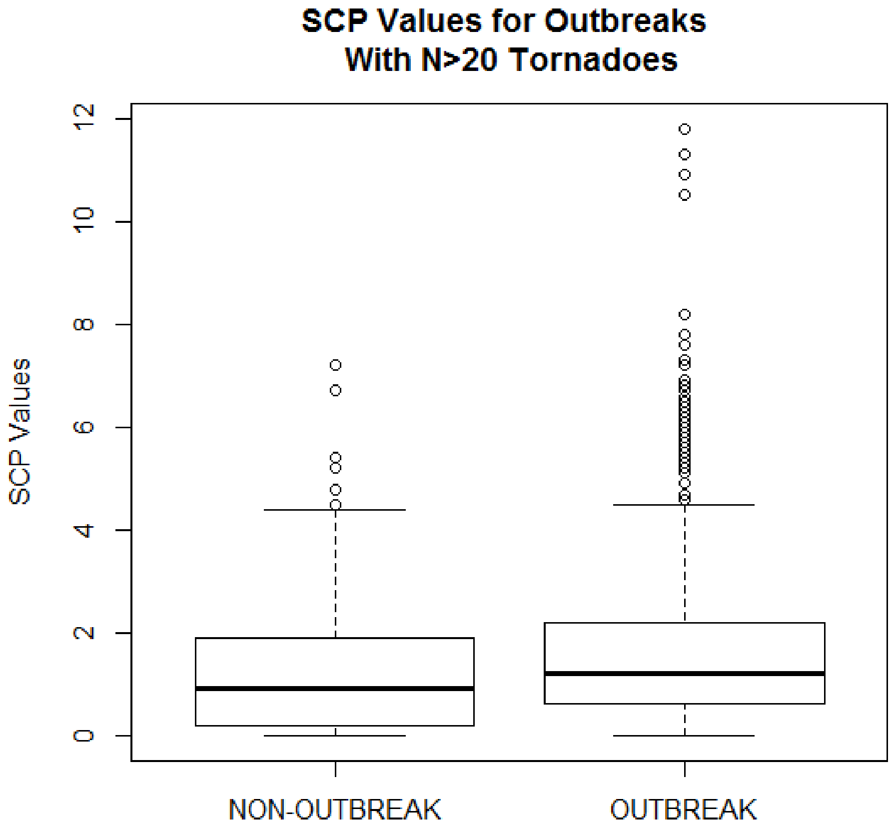


Fig. 12: Box plot of tornado SCP values for "Outbreak" and "Non-Outbreak" TCs where an outbreak is defined as a TC with N>20 tornadoes. For N>20 tornadoes, there is a less clear distinction between “outbreak” and “non-outbreak” TCs, as the upper and lower hinge values, as well as the median, are only slightly higher than those of “non-outbreak” TCs. TCs classified under the “outbreak” category still have a larger number of extreme SCP values.

For both definitions of “outbreak”, the outbreak TCs shared similar characteristics. In addition to the identical SCP medians of 1.2, in both cases outbreak TCs had a higher number of positive extrema and had higher hinge values than non-outbreak TCs. Though this trend is much more pronounced for cases where “outbreak” is defined as N>10 tornadoes, it is present for both definitions.

CHAPTER 4

4. **Conclusions**

Through multiple statistical analysis techniques it was shown that there is a link between Supercell Composite Parameter and the severity of a tornado outbreak in a landfalling TC, with "severity" defined as the number of tornadoes the TC produced during and after landfall. Mean SCP was the most highly correlated value tested, with median SCP being a close second. The mean and median represent a rough overview of overall levels of SCP in each TC.

Utilizing SCP as a discriminator between "outbreak" and "non-outbreak" TCs proved successful. Though it is perhaps not of immediate applicability to operational use, the fact is that SCP was able to discriminate between events statistically classified as outbreaks and non-events. This fact confirms the findings of a statistically significant correlation of SCP to tornado number per TC.

The finding that SCP is an indicator of tornado production reinforces the idea that miniature shallow supercells embedded in the rainbands of TCs are responsible for most, if not all, tornado production. This confirms findings and observations by Novlan and Grey (1974), McCaul (1987), and Easton and Link (2008).

However, the use of SCP as a forecasting tool may not be as clear-cut. The Storm Prediction Center already uses SCP in Great Plains forecasts, but due to the shallow nature of TC supercells (which share environmental characteristics with that of "marginal" supercell environments) and the rapidly changing conditions in a landfalling TC, other forecast methods may still remain superior. The advent of super resolution dual-polarization Doppler weather radar is one superior diagnostic tool, able to identify tornado debris signatures at close range. Further research, using the newer version of SCP that more readily distinguishes between marginal and shallow-based supercell environments would be needed to investigate further.

a. Future Work

A broader study, expanding beyond the 10-year time span of this study, would be desirable. As always, more data is always better. Additionally, as discussed as a possible source of error, in the future it would be preferable to use the updated SCP that takes into account effective storm inflow layers, instead of the older method presented in this study. Further, in addition to the use of bulk statistics such as the mean and median SCP values per TC, a weighted average of both tornado-producing and non-tornado-producing SCP values for the entire TC would be immensely useful so as to see where high SCP values did not correlate with any reported tornadoes. A similar weighted average of SCP from a landfalling TC that did not produce any tornadoes would also be useful. Additionally, producing charts of SCP similar to those of CAPE and SRH in McCaul (1991) would be desirable.

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