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Some Common Ingredients for Tornadogenesis Associated with Landfalling Tropical Cyclones Impinging on Frontal Boundaries

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Abstract

Landfalling Tropical Cyclones (TCs) may induce tornadoes, while less frequent than their midwestern counterparts, are still able to produce the damage potential leading to additional billion-dollar costs. This research seeks to find some common ingredients for tornadogenesis associated with landfalling TCs impinging on synoptic frontal boundaries, during which the TC's circulation has been strongly affected on both the vorticity, upward velocity, and other surrounding environmental, convective, and tornadic parameters. This research found that by increasing the vorticity and vertical velocity associated with a cold frontal boundary, moving or stalled, and placing it into a moist convectively primed environment surrounding the TC increases the chance for a tornado outbreak to occur. The most frequent outbreaks occur when a cold frontal boundary has a direct interaction with the circulation of an approaching TC, such as seen in Hurricane Michael (2018) when it was moving through North Carolina (NC) Piedmont into the Virginian Coastal Plains. In this case, the vorticity, surface moisture, vertical velocity, and surface convergence are all observed to have modestly large increases leading to the environment conducive to tornadogenesis. This prefrontal environment also has an area of moderate to large Convectively Available Potential Energy (CAPE) with values over 500 J kg^{-1} as well as Potential Instability (PI) index with the vertical gradient of potential temperature ($\partial\theta/\partial z$) becoming negative. Storms interacting with a stalled frontal boundary, such as Hurricane Florence (2018), also have this increase in vorticity though to a lesser extent. During the interaction with Florence vorticity peaked in southeast NC and northeast South Carolina associated with the outer band that was located near the stalled front. This area was in the favorable front right quadrant and experiencing a boost in CAPE from the flow of warm moist air off the Gulf Stream. The main driver of vorticity in this location was mainly due to the vertical vorticity stretching generated by the low-level flow convergence associated with the interaction of the flow around the TC and the stalled front, which occurred over the southern coastal areas of NC. In the case of tornado outbreaks not associated with a frontal boundary, such as Hurricane Allen (1980), the largest driver tends to be the TC itself with Allen strong vorticity advection, abundant moisture, and large CAPE, from the moist and unstable airstream from the Gulf of Mexico, into southern Texas, a region that is typically favorable for tornado development being near the crossroads of Tornado Alley and Dixie Alley (Klemp, 1987), a zone that frequently combines the conditions needed for tornadogenesis with hot dry air from the north and west meeting warm moist air from the south and east.

Keywords: frontal boundary, Hurricanes, tropical cyclones, tornadogenesis, tornado ingredients, tornado outbreak, tropical cyclone landfall

1. Introduction

Tornadoes and tropical cyclones (TCs) are the most destructive weather systems that have affected the United States (U.S.) leading to large losses in life and property. As shown in Figure 1, hurricanes on average impact portions of the U.S. coastline as frequent as once every 5-7 years in portions of the Carolinas, Florida, and Louisiana. The number of billion-dollar disaster events has increased dramatically since the year 2000 with the majority occurring because of TC and severe weather events (Smith 2023; Fig. 2). On average, 1000 tornadoes were generated nationwide in a single year with an average of 80 causing life to lose and 1500 injuries (NWS, 2024). As revealed in Figure 3, most of these come from tornado outbreaks in the mid-section of the U.S. known as Tornado Alley and across the southern states in what is commonly called “Dixie Alley.” However, as of 2012 there has been a total of 1,163 tornadoes associated with TCs affecting the U.S. in the Storm Prediction Center (e.g., SPC, 2024) archives. This data amount, while low, still accounts for 6 percent of the total tornadoes that occurred in the U.S. Thus, it is important to understand the cause of the TC-generated tornadoes to improve their predictions.

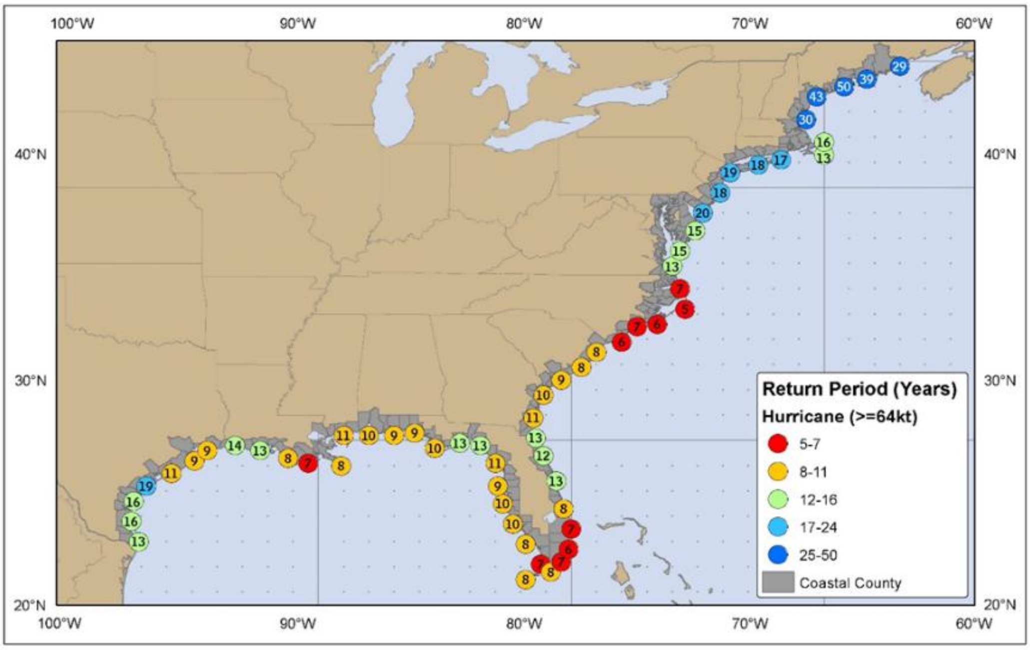

Figure 1. The return period for TCs in the coastal U.S. Note that the frequency is higher in the Carolinas, Florida, and the central Gulf Coast States with many areas in the 5–7 year period (NHC-TCC, 2024)

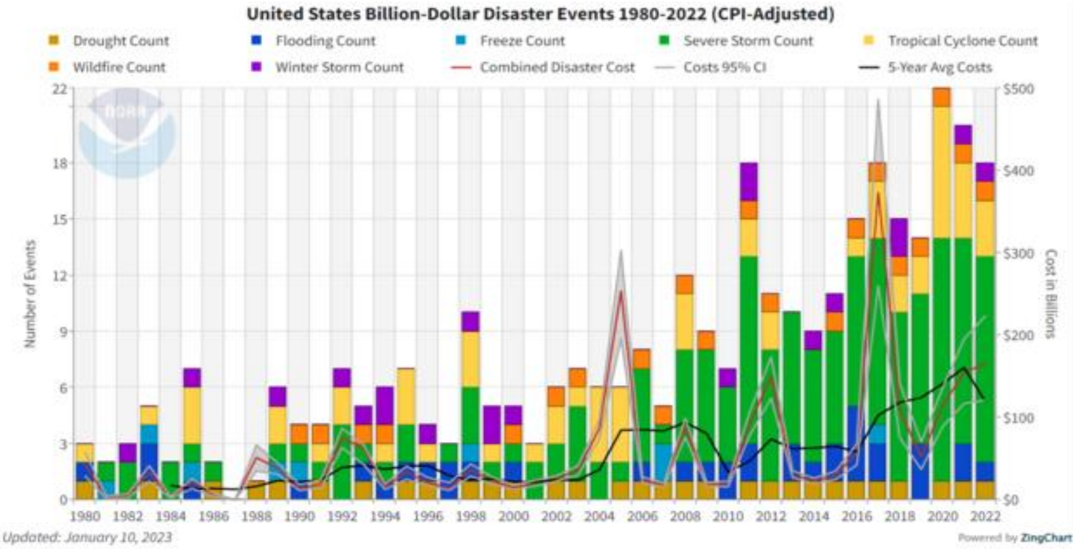

Figure 2. The number of billion-dollar meteorological disasters, broken down by type, in the U.S. from 1980 to 2022. Note the rapid increase in both severe storm and hurricane count (Smith, 2023)

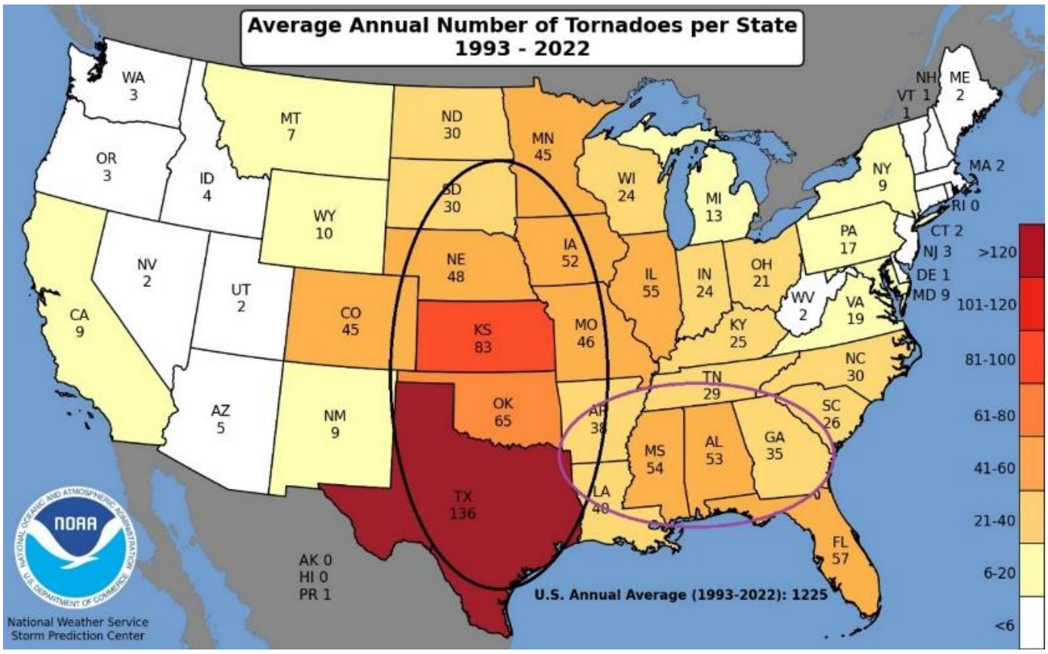

Figure 3. The U.S. annual average of tornado occurrence during 1993-2022 are denoted in the figure. The Tornado Alley and Dixie alley are encircled by black and purple contours, respectively. The southern states outside of these two tornado alleys also have increased tornado activities, which is due to increased landfalling TC's. (Adapted from SPC, 2024)

Tornado outbreaks associated with landfalling TCs on the coastline of the Gulf of Mexico and Eastern Seaboard of the U.S. can be organized into three main categories, depending on the presence and type of frontal boundary found near the tropical or post tropical cyclone circulation (Pete, 2013), as the following:

(a) Type A Outbreak: due to an interaction with, tracking ahead of, or total merging with a cold frontal boundary.

(b) Type B Outbreak: due to interaction or merger with a stalled frontal boundary.

(c) Type C Outbreak: lack of interactions with a cold front.

In the past, most landfalling hurricanes in the U.S. typically occurred with Type A outbreaks as a front eroded the semipermanent subtropical high-pressure area allowing the TCs to recurve into the subtropical westerly flow over the continental U.S. Type B cases were rarer but occurred primarily in the Gulf of Mexico and the immediate southeast coast and occurred as a stalled front slowly gave way and allowed the TC circulation to be pulled into the southern U.S. Type C was the typical mode for a TC that traveled around a subtropical ridge of high pressure. In this outbreak type, the ridge is typically a westward expansion of the Bermuda Azores ridge found in the North Atlantic Ocean.

A typical tornado in the Tornado Alley or the Dixie Alley is often formed from a mesocyclone associated with a supercell thunderstorm and a formation frequency of around 20% (NOAA). These supercell thunderstorms are typically found in a high vertical wind shear with moderate to high CAPE or high PI index environment most commonly in the middle of the U.S. in Tornado Alley and in the southern U.S. in the Dixie Alley (Klemp, 1987). However, some tornado outbreaks associated with mini-low topped supercells can occur in the presence of high shear and lower CAPE (HSLC) if surrounding environmental parameters are favorable for tornado development such as the states in the southern part of both Tornado and Dixie alleys. This is because, although not as frequent, TCs can replicate a similar environment with moderate to high shear in the lowest levels of the troposphere and low to moderate CAPE found in both the outer bands as well as the eyewall associated with a TC (Eastin and Link, 2009).

Tornado formation may increase when the environment of a TC is associated with mid-level (e.g., 700 mb) dry air on top of a lower layer (e.g., surface to 900mb) (Curtis, 2004). This helps increase the potential instability by steepening the low-level lapse rate that the mini low topped supercells in the outer bands can feed on. However, if the atmosphere becomes drier at the low levels, it tends to elevate the lifting condensation level (LCL) and leads to difficulty for the tornadic vortex to reach the surface.

Supercells and tornadoes also need an environment that has favorable lifting to tilt the horizontal vorticity generated by the sheared low to mid-level flow vertically and then strengthen by vertical vorticity stretching. This environment in the classical sense is most often seen along cold fronts, warm fronts, and dry lines in the Midwest and Southern U.S., which provide the lifting necessary for rotating, convective updraft development. The strong vertical velocity in the low to mid-levels associated with the TC can act to mimic this lifting mechanism leading to mini low topped supercell development. In the TC environment, especially in the vicinity of the eyewall, there is no lack of strong upward velocity, however, there is no evidence of the existence of supercells. Thus, it is essential to investigate whether it is required to have the existence of supercells.

Most landfalling TCs have the potential to produce tornadoes as they are associated with broad areas of vorticity that can interact with increased low-level shear caused by the friction of land. Given an environment around a TC that is already primed for convection then a tornado outbreak can occur as is the case with our Type C interaction.

We hypothesize that when a TC interacts with a front, it will gain added vorticity and more importantly, its pre-existing vertical velocity can enhance tornado development if this interaction occurs in the front right quadrant of the tropical cyclone. Therefore, based on this hypothesis, a frontal boundary acts like an obstacle to the flow around the TC and combined with the latent heat released from the stronger convection typically found in the front right quadrant leads to an increase in the vertical velocity strength by wave of increased surface convergence that can lead to an increase in the stretching term of the vorticity budget equation.

This study aims at verifying the hypothesis that a moving or stationary cold front has on the associated vorticity and environment factors in aiding the development of tornadogenesis associated with the TC as it moves over the eastern and/or southern U.S.

The methodology and data used in the analysis are described in Section 2. The results are presented in Section 3, which are divided into four parts: (a) general results, (b) results of Type A outbreaks are illustrated by Hurricane Michael (2018), (c) results of Type B outbreaks are illustrated by Hurricane Florence (2018), and (d) results of Type C outbreaks are illustrated by Hurricane Allen (1980). Discussions of the results, including a discussion of how they fit in with the larger atmospheric picture of TC induced tornadogenesis, will be presented in Section 4. Finally, concluding remarks and future research related to the outbreak types and their development will be presented in Section 5.

2. Methodology

An “interaction” is defined as a direct influence on the track of, circulation of, and/or the eventual merger of the TC with a cold or stalled frontal boundary. If a TC approaches a front, most commonly a stalled front but there is no interaction and the TC track, intensity, and circulation continues to be influenced by only the ridge of high pressure, then the storm falls into the Type C category. This also includes storms that officially make landfall in Mexico, but their bands brought tornado outbreak conditions to portions of landmass of the U.S. continent surrounding the Gulf of Mexico. Only systems that have a frontal boundary begin to influence the tropical cyclonic circulation either before or during the tornado outbreak are added to the Type A or Type B count. The front also must be interacting with the TC during the period that the tornado outbreak occurred.

Additionally, an outbreak is considered when five or more tornadoes occurred with the TC during its lifetime while impacting the coastline that borders the Atlantic and Gulf of Mexico of the U.S. This cutoff, while low, is used to include systems that only skirted the coastal areas of the U.S. during their recurve/landfall but produced an outbreak in that limited spatial and temporal area. This is more commonly seen along the East Coastal regions with systems riding along the coastline and with systems officially making landfall in Mexico but having a significant impact on regions in southern Texas.

Then, the TCs were analyzed using parameters, adapted from Schneider and Sharp (2006), shown in Figure 4. During the period of producing tornadoes, we examined the CAPE, PI index, 1000 to 700 mb average vorticity, vertical velocity, 0-1 km shear, 0-3 km Helicity, and humidity differences (900-700mb)-(1000-900mb), to examine the frontal boundaries impacts on the larger scale environment favorable for tornadogenesis (Schneider and Sharp, 2006).

Table 1. Environmental ingredients needed for tornado development are associated with landfalling TCs. Values are broken down into what would support the Low Risk or a High Risk of tornado development. On average it requires a high energy environment with high helicity and high surface moisture. (Adapted from Schneider and Sharp, 2006 and Curtis, 2004)

Parameters Needed for Tornado Outbreak Occurrence	Low	High
CAPE	Less than 500 J kg^{-1}	Greater Than 500 J kg^{-1}
0-1 km shear	Less than 20 ms^{-1}	Greater Than 20 ms^{-1}
0-3 km Helicity	Less than 100 m^2s^{-2}	Greater Than 100 m^2s^{-2}
Low-Level Humidity	Dry Below 900 mb	Moist Below 900 mb
Mid-Leve Humidity	Moist above 700 mb	Dry above 700 mb
Lower average lifting condensation level (LCL)		

Vorticity, vertical velocity, vertical shear, and helicity fields are examined to search for environmental ingredients needed for tornado development associated with landfalling TCs. Areas with large scale cyclonic rotation are more favorable for the development of tornadoes as there is an established area of cyclonic motion. Areas with higher helicity values show the favorability for any convection that forms to both rotate and tilt upward leading to mesocyclone development and tornado development.

In addition, relative humidity, CAPE, and PI index are also examined to determine the environmental ingredients needed for convective development in the vicinity of the TC and the frontal boundary. Without organized deep convection the rotation has no method of becoming concentrated enough for tornadogenesis to occur. This energy can come from two sources with CAPE being parcel based meaning the parcel has the energy to lift and Potential Instability being layer based and is typically seen as a dry mid-level layer over a moist surface layer (Curtis, 2004). As there is strong lift associated with both frontal boundaries and TCs, either of these sources can be used for convective development and tornadogenesis.

2.1 Data

In this study, we will be using the National Hurricane Center (NHC) storm data, as well as tornado report data from the SPC from 1960 to 2018. The data is updated hourly on a 31 km horizontal grid size with 137 pressure levels. Additionally, hurricane tracking data was taken from the NHC, confirmed tornado reports data was adapted from a combination of the SPC and NHC, and frontal analysis came from a combination of the Weather Prediction Center and the Climate Prediction Center daily weather maps dataset. The environmental data sets used include the ECMWF Reanalysis v5 (ERA5) data from the European Centre for Medium-Range Weather Forecasts.

2.2 Analysis

TCs were grouped by their outbreak types (i.e., Types A, B, and C) and then case studies from each outbreak type were selected looking at a range of storm intensities and landfall locations. Analyses were performed by looking at the tornado characteristics listed above to examine the influence of frontal features on the cyclone's ability to produce enough tornadoes to qualify as an outbreak with the cutoff threshold being 5 tornadoes. This was done by examining the impact the frontal feature had on modifying both the thermodynamic and kinematic environmental terms mentioned in Table 1 above along and ahead of the TC moving into the region.

3. Results

During the period of 1960 – 2018, there were a total of 100 TCs that produced the minimum of 5 tornadoes needed to qualify as a tornado outbreak (Fig. 5). We use this cutoff so that it will include both larger outbreaks of TCs moving deep inland as well as TCs that have clipped the coastline producing this number of tornadoes over a smaller spatial area equating to a localized tornado outbreak such as often the case with storms affecting the eastern coast of the U.S.

During this period, the 100 TCs can be categorized as Types A, B, and C, TCs, which had 46, 21, and 25 tornado outbreaks, respectively. Note that there were 8 outbreaks that could not be narrowed down into a subcategory and include systems, such as tropical storm Allison (2001) that had many different frontal interactions as well as phase changes of the cyclone from tropical storm to subtropical and extratropical in nature.

Type A has more TCs than the other categories, which is to be expected based on climatology. A majority of TCs reaching our target area of the U.S. reveals so because a frontal system and its associated upper-level trough weakening the Atlantic subtropical ridge enough to allow the TC to recurve.

An analysis of the breakdown of the TC intensity, as shown in Figure 6, the most common TCs were tropical storms (29), category 1 (22), and category 3 (19) strength equating to a total of 70 of the 100 TCs. Subtropical storms (4), tropical depressions (6), category 2 hurricanes (11), category 4 hurricanes (6), and category 5 hurricanes (3) make up the remaining 30 TCs.

When looking at intensity vs frequency of tornado outbreaks, there is no direct correlation observed. Typically, in each season a larger majority of TC development is at the weaker end of the spectrum with *tropical storms and category 1 hurricanes being more frequent than the much more intense major hurricanes*.

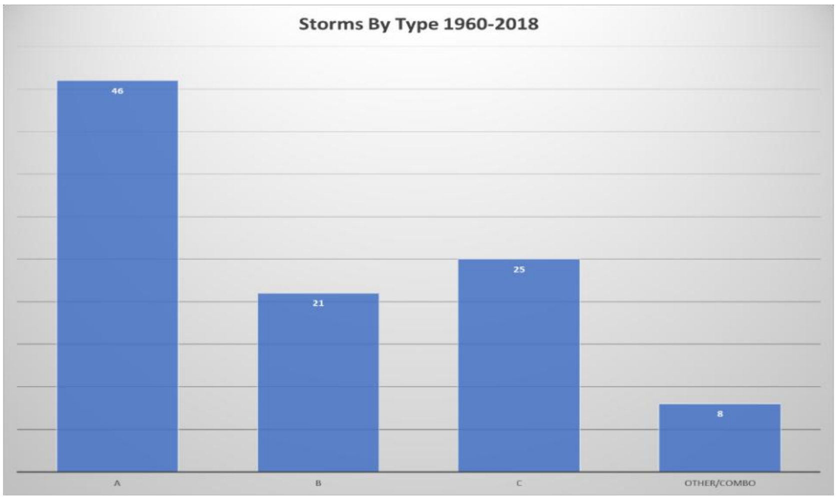

Figure 4. Breakdown of the tornado producing cyclones by type for the period 1960-2018. The most common was type A with 46 outbreaks followed by an almost equal number of type B and C induced outbreaks

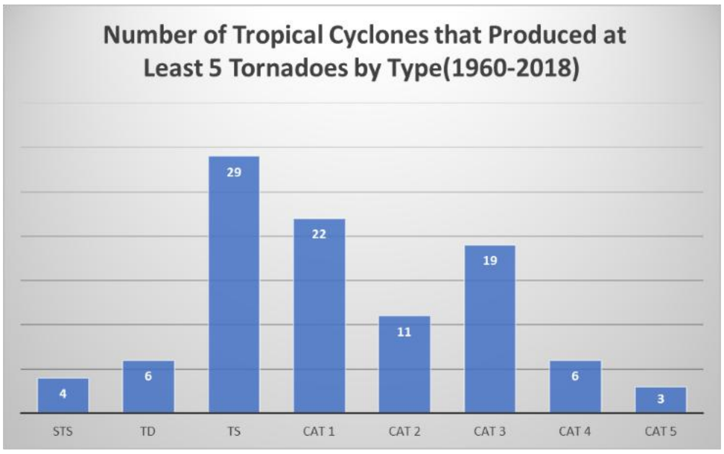

Figure 5. Breakdown of the tornado producing cyclones by category for the period of 1960-2018. The most common category was tropical storm strength with 29 TC's followed by category 1 with 22 TC's and finally category 3 strength with a value of 19 TC's

3.1 Type A - Interaction with A Cold Front

Type A tornado outbreaks occur the most often with a total occurrence of 46 events in the period from 1960 to 2018. The TCs in this outbreak type tend to travel up and ahead of the frontal boundary until eventual absorption by the front and/or extratropical transition occurs. The TC keeps a stronger area of vorticity during this lifetime as it gets an influx from the approaching frontal boundary during the merging and eventual absorption process.

An example of a strong Type A, seen in Figure 6, event was Hurricane Michael (2018). Hurricane Michael was an extremely rare category 5 hurricane that made landfall on the Florida Panhandle during the afternoon of October 10th, 2018. The hurricane continued inland passing through the southeastern states and eventually mid-Atlantic states while undergoing extratropical transition as the frontal boundary advancing from the north and west overtook and captured the center of the former hurricane. The extratropical remnants then moved off the Delmarva coast ending the tornado threat. The TC produced 16 tornadoes during its life cycle with a strong concentration over central and eastern Virginia during the merger with the cold frontal boundary and extratropical transition phase.

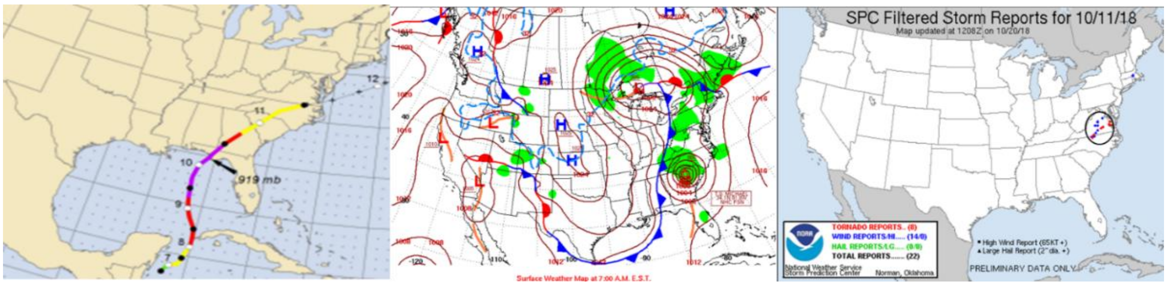

Figure 6. The Official Track from the NHC, Frontal Analysis from the Weather Prediction Center, and SPC significant weather reports for Hurricane Michael (2018). Hurricane Michael produced a localized tornado outbreak when it passed through Virginia during the transition to an extratropical cyclone and moving out into the North Atlantic Ocean

Figure 7 reveals the cold frontal boundary approaching from the northwest and impinging on the circulation of Hurricane Michael (2018) with the maximum interaction occurring in Virginia. This caused the elongation of the vorticity to the north and east as well as increasing the positive vertical velocity located over this area. This area also corresponded with increased 0-1 km low-level shear to 15 to 20 ms^{-1} leading to the development of high, relative to the environment, helicity values of 400 to 500 m^2s^{-2}, strongest in the 0-3 km layer. These values remained high but shifted into an unfavorable location relative to the TC circulation by 00Z on October 12th as the former TC moved offshore into the Atlantic Ocean.

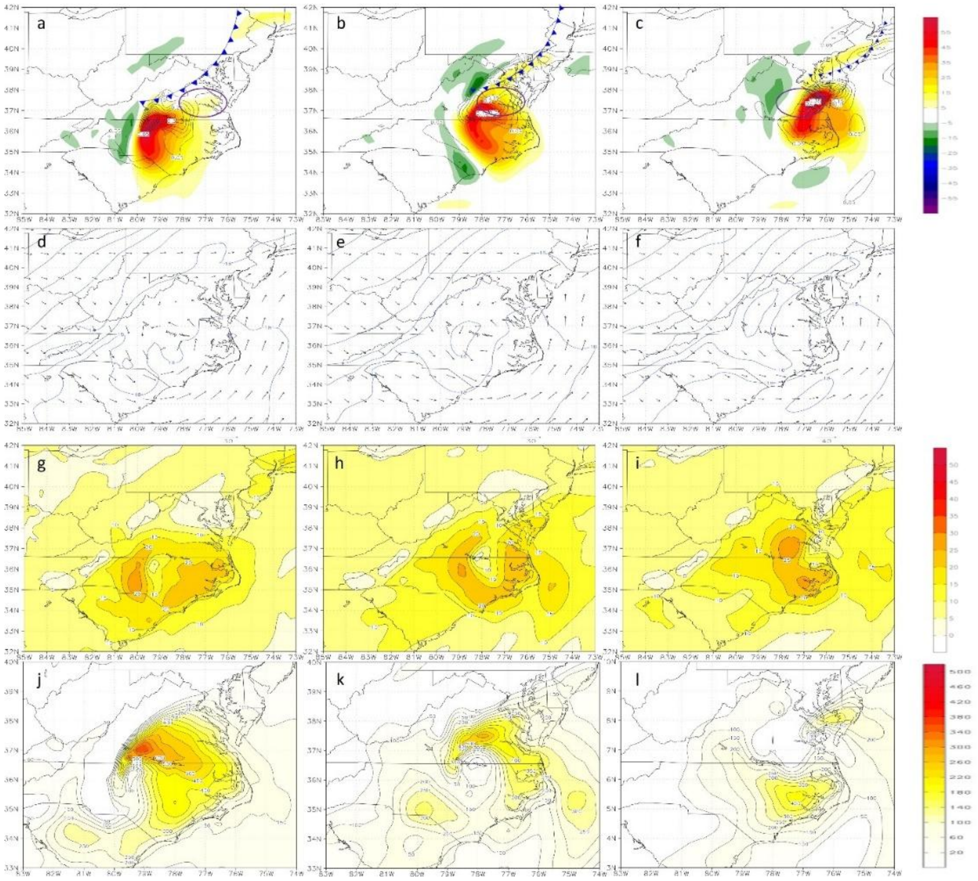

Figure 7. Vertical vorticity (shading; x10^{-4} s^{-1} and upward vertical velocity ms^{-1}) (a-c), 1000-700mb temperature anomaly (d-f), 0-1 km wind shear (ms^{-1}) (g-i), and 0-3 km helicity (m^2s^{-2}) (j-l) for Hurricane Michael (2018) from 20Z/10/11/18 to 00Z/10/12/18. There was an overlap of kinematic variables over northeastern North Carolina and coastal Virginia with high vorticity being collocated with high shear values and helicity in the region TC Michael was approaching the frontal boundary

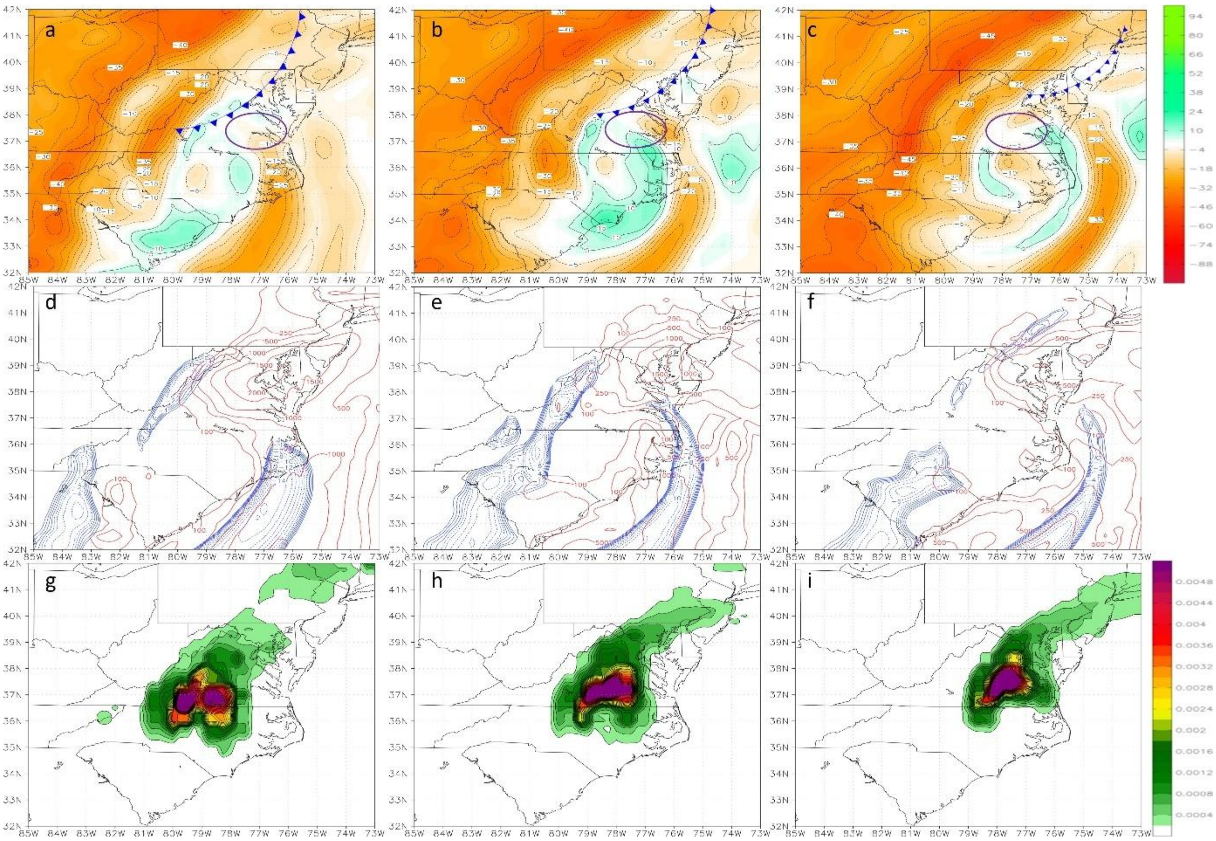

Figure 8. Moisture Anomaly: mid-level (900 to 700mb) – low-level (1000-900mb) (a-c), CAPE in red and Potential Instability in blue (d-f), and Precipitation Rate (g-i) for Hurricane Michael (2018) from 20Z 10/11/18-00Z 10/12/18 During this period tornadoes developed in eastern Virginia in association of the TC

Coupled with strong rotation, the environment also exhibited an enhancement of PI index as the dry mid-level air seen in the second row of Figure 8, overspread an area of high low-level moisture. This caused a narrow band of increased PI index, acting itself as a pseudo moisture enhanced boundary with lapse rates -2 to -6 K km^{-1} km to form along and ahead of the former TCs path through the region of tornado development. This also helped to offset the low value of CAPE, below 500 Jkg^{-1}, which was found in the region. *These two energy sources (i.e., potential instability and conditional instability) combined lead to the environment becoming unstable enough for the development of supercellular convection in the developing warm sector*.

3.2 Type B- Interaction with A Stationary Front

Type B tornado outbreaks are less frequent with 21 systems causing tornado outbreaks during the period. These TCs tend to move slower and have a weaker, more stretched-out area of vorticity in the direction of the stalled fronts vorticity maximum. This tends to occur because the area around a stalled front typically has weak steering currents. These systems tend to bring the stalled frontal boundary with them with it evolving into a slow-moving warm front until eventual Extratropical Transition and the development of the systems own frontal boundaries.

One example of a slow-moving Type B outbreak is Hurricane Florence (2018). Figure 9 reveals that this slow-moving system lumbered into the Carolinas as a large category one hurricane with landfall on the 14th of September. This slow-motion leads to multiple rounds of tornado development each day until its eventual ejection by the 17th of September.

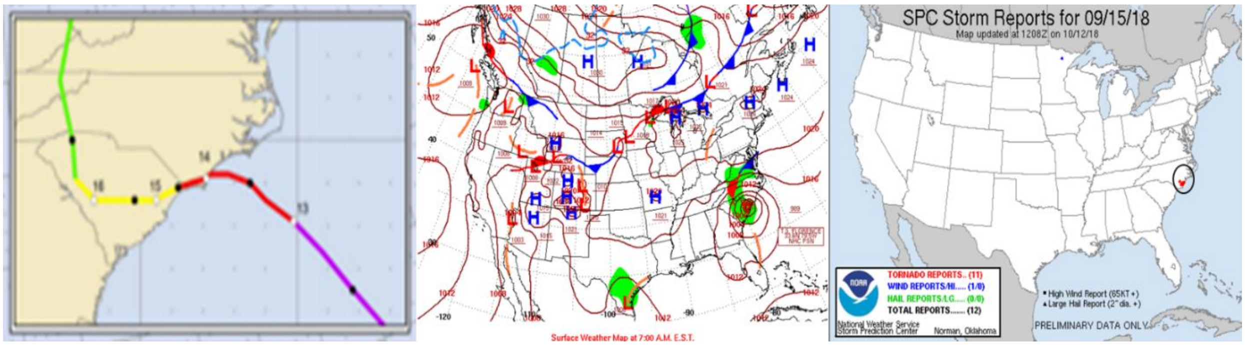

Figure 9. The Official Track from the NHC, Frontal Analysis from the Weather Prediction Center, and SPC significant weather reports for Hurricane Florence (2018). During this time, an outbreak of Tornadoes occurred in the region north of TC Florence and south of the stationary frontal boundary in eastern North Carolina

Analysis seen in Figure 10 reveals that during one of the early outbreaks associated with Hurricane Florence, the stalled front acted less in aiding the vorticity but more as a focus of lift and positive vertical velocity. This increased the strength of a rainband north of the circulation which became the primary focus of tornado development. The region between them also promoted moderate to high low level wind shear leading to helicity values of 250-500 m^2s^{-2} in the areas associated with the outbreak. However, the strongest core of higher kinematic parameters located in a section of TC circulation that is less favorable for tornado development with the outbreak confined to coastal southeast North Carolina along the smaller tongue of environmental conditions.

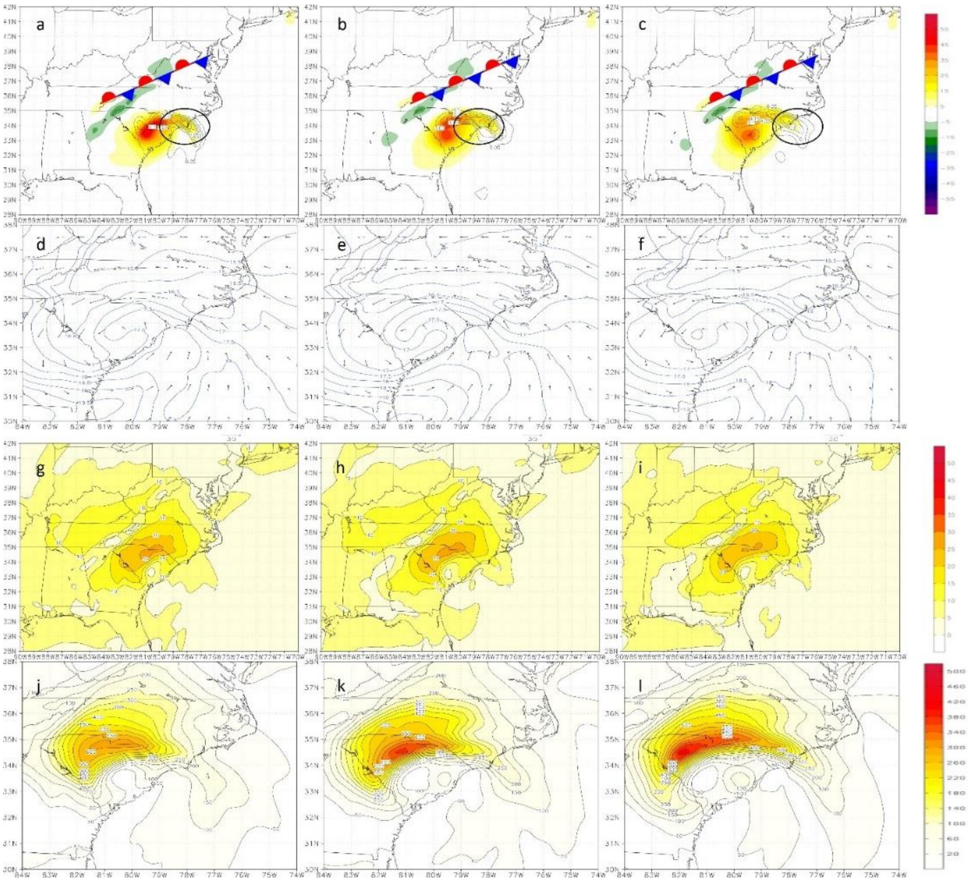

Figure 10. Vertical vorticity (shading; x10^{-4} s^{-1} and upward vertical velocity ms^{-1}) (a-c), 1000-700mb temperature anomaly (d-f), 0-1 km wind shear (ms^{-1}) (g-i), and 0-3 km helicity (m^2s^{-2}) (j-l) for Hurricane Florence (2018) from 02Z-06Z on 09/16/18. During this time, the vorticity associated with the stationary frontal boundary began to merge with a strong convective outer band associated with TC Florence. This region became collocated with an area of intense helicity

The region along the coast of southeast North Carolina that had an outbreak, shown in Figure 11, was characterized by high relative humidity in both the low and mid-levels leading to low potential instability. *CAPE, however, did peak near 1000 J kg^{-1} near the immediate coast as it advected off the warmer air associated with the warm waters of the Gulf Stream. This is the more limiting factor for widespread tornado development as it did not spread inland into regions with better shear and vorticity*. There was a lack of overlap among the convective and dynamic parameters but allowed for tornadogenesis in the areas where brief overlap of favorable parameters could occur.

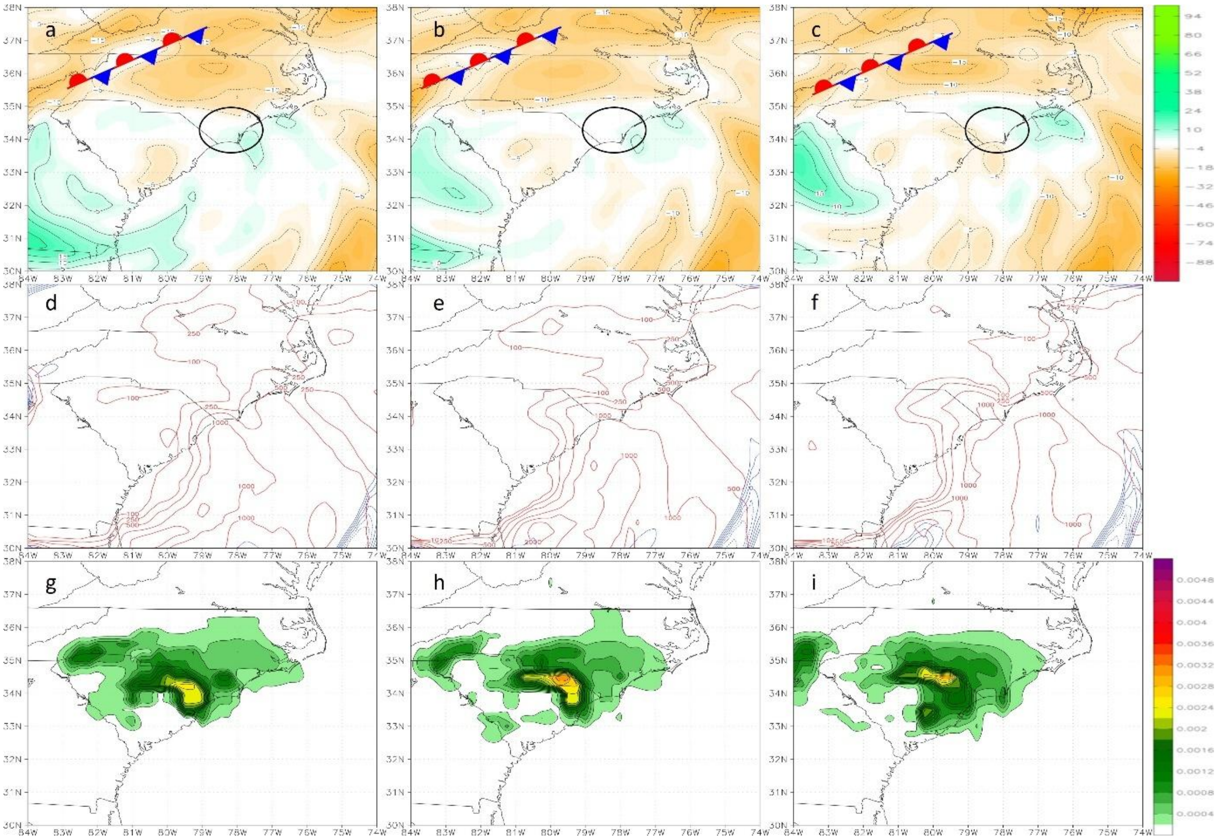

Figure 11. Moisture Anomaly: mid-level (900 to 700mb) – low-level (1000-900mb) (a-c), CAPE in red and Potential Instability in blue (d-f), and Precipitation Rate (g-i) for Hurricane Florence (2018) from 02Z-06Z 09/16/18. The tornado outbreak region consisted of moderate CAPE collocated with higher values of surface moisture

3.3 Type C No Interaction with A Front

Type C tornado outbreak events are nearly tied with Type B outbreaks with 25 outbreaks occurring during the research period. These outbreaks are confined to the Gulf of Mexico from Mississippi to deep south Texas as they occur associated with a TC moving around an established large scale high-pressure area without the influence of any frontal boundaries.

Hurricane Allen (1980), shown in Figure 12, was a major category 3 hurricane that made landfall in southern Texas bringing an associated tornado outbreak. The outbreak produced 29 tornadoes, with several significant tornadoes in bands north of the circulation over the southern and central portion of Texas in the right frontal quadrant of the TC.

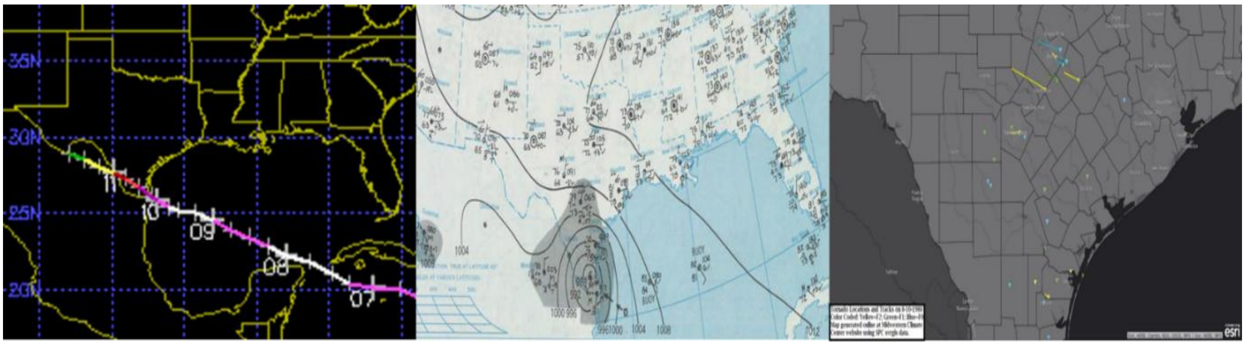

Figure 12. The Official Track from the NHC, Frontal Analysis from the Weather Prediction Center, and SPC significant weather reports (As seen in ESRI adapted from Curtis 2018) for Hurricane Allen (1980). Numerous tornadoes, including several intense tornadoes developed north of TC Allen during this period as the TC made landfall along the Texas/Mexico border

Shown in Figure 13, vorticity and positive vertical velocity are strong along and north of the center of the TC. This region is also characterized by moderate to strong low level wind shear with values approaching 15- 20 ms^{-1}. The overlap leads to the development of moderate to strong helicity values of 250-700 m^{2}s^{-2} in the outbreak area.

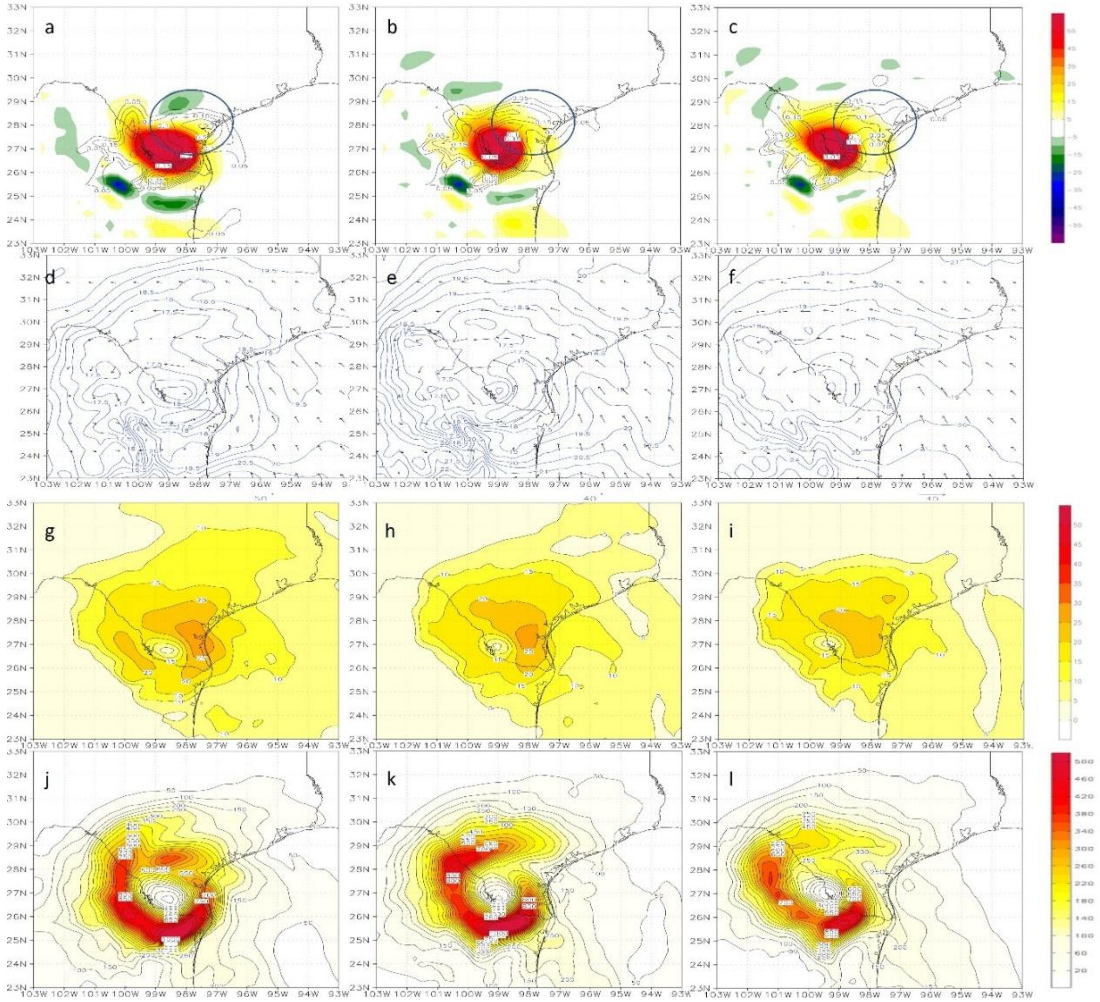

Figure 13. Vertical vorticity (shading; x10^{-4} s^{-1} and upward vertical velocity ms^{-1}) (a-c), 1000-700mb temperature anomaly (d-f), 0-1 km wind shear (ms^{-1}) (g-i), and 0-3 km helicity (m^{2}s^{-2}) (j-l) for Allen (1980) from 14Z-18Z 08/10/80 Vorticity was strong and compact associated with TC Allen. This vorticity overlapped with moderate low-level shear and high helicity

Figure 14 reveals that dry continental air off the U.S. wrapped into the midlevels of the circulation associated with Hurricane Allen (1980). This lead to the development of a moisture graident and an influx of potential instability with values of -2 to -6 K km^{-1}. During this time closer to the circulation of the hurricane high values of CAPE rich air moved inland from the Gulf with values approaching 2000 J kg^{-1}. *This lead to the TC having multiple sources of moderate to even strong energy for stronger convective development along and north of the center of the TC.*

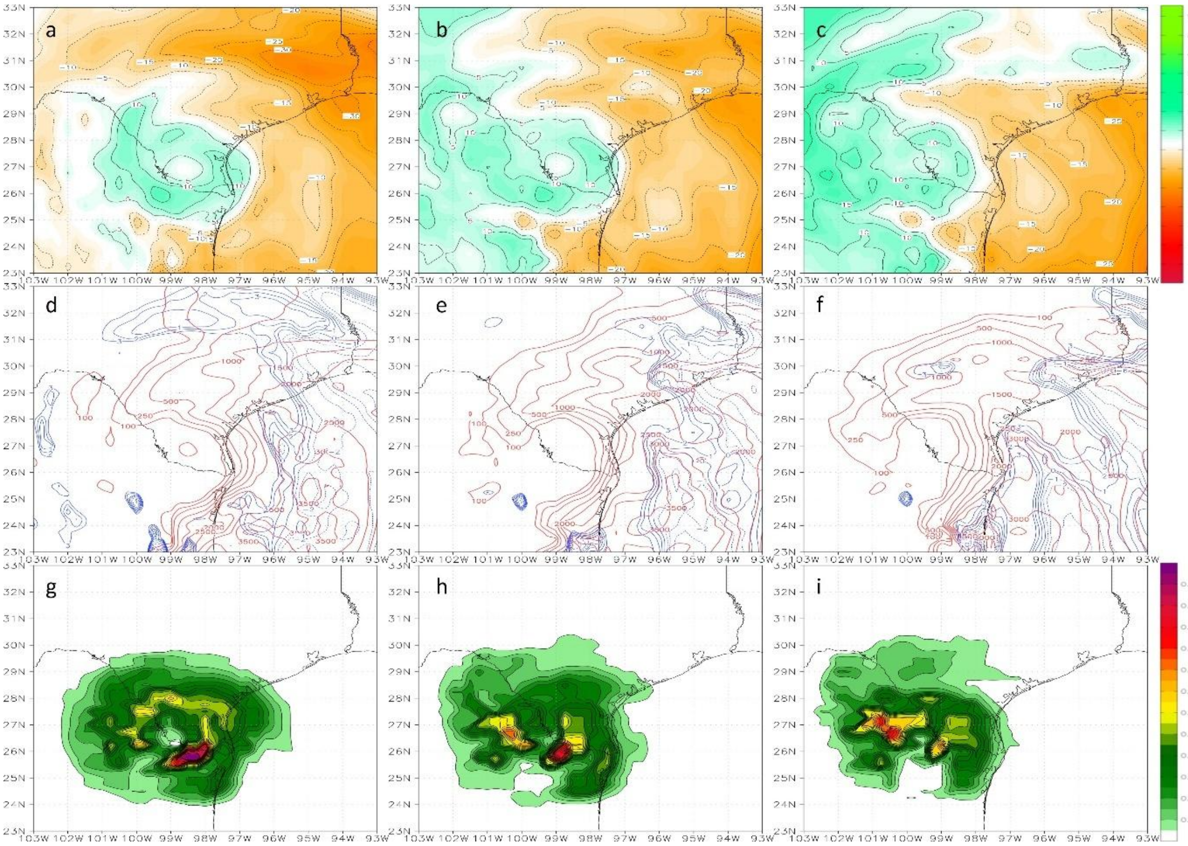

Figure 14. Moisture Anomaly: mid-level (900 to 700mb) – low-level (1000-900mb) (a-c), CAPE in red and Potential Instability in blue (d-f), and Precipitation Rate (g-i) for Hurricane Allen (1980) from 14Z-18Z 08/10/80. During this period an outbreak of tornadoes developed north of the center of circulation in bands in the energy rich quadrant. This energy was associated with both CAPE and PI index

4. Discussions

Table 2. Environmental Variables for a selection of the tornado outbreak types. Generally, Type A and B outbreaks move faster and have higher vertical velocities as compared to Type C outbreaks

Outbreak Type	TC Name	Vorticity x10^{-4} s^{-1}	Vertical Velocity ms^{-1}	CAPE Jkg^{-1}	Potential Instability K km^{-1}	Relative Humidity Anomaly %	Shear ms^{-1}	Helicity m^{2}s^{-2}	Movement ms^{-1} (mph)
Type A	Michael (2018)	55	0.35	250-500	-10	-20	25	550	10.3 (23)
	Tropical Storm Lee (2011)	35	0.2	500	18	-20	15	300	3.1 (7)
	Charley (2004)	55	0.2	1000	12-14	-5	20	500	11.2 (25)
	Wilma (2005)	5	0.05	1000-1500	~0	-25	15-20	200	8 (18)
	Gilbert (1988)	5	0.05	500-1000	0-6	-15	15	500	6.9(15.4)
Type B	Florence (2018)	35	0.2	500-1000	16-30	-5	15	500	2.7 (6)
	Cindy (2005)	15	0.1	500	8 - 14	-10	10 - 15	500	15.6 (35)
	Harvey (2017)	40	0.2	500-1000	8 - 12	-5	15	450	0.4 (1)
	Danny (1985)	50	0.2	100-500	14-28	-15	20	400	4.5-6.7 (10-15)
	Hermine (2016)	15	0.1	500-1500	16-20	-5	15	200	6.2(13.8)
Type C	Allen (1980)	50	0.1	1500	-3	-15	20	300	2.7 (6)
	Isaac (2012)	55	0.15	500	0 - 14	-10	25	700	2.7 (6)
	Alex (2010)	5	0.05	1000	12- 18	-10	10	200	3.1 (7)
	Emily (2005)	5	0.1	500-1000	3- 6	-10	15-20	175	3.6(8)
	Celia (1970)	5	0.05	1000	12- 14	-15	10	125	4.5-6.7 (10-15)

For all the outbreak typing's the common environmental factors need to be over 500 J of CAPE, RH anomaly over 5%, and shear typically over 15m/s. This large-scale environment supports a marginally convectively unstable regime with low to moderate amounts of wind shear, allowing the convective that develops in association with the tropical cyclone to blossom and in some cases grow into embedded (mini) supercell structures capable of producing tornadogenesis.

Examining at the speed of the tropical cyclones, Type A outbreaks tended to move generally faster in the flow ahead of the cold frontal boundary with average speeds of 7.9 ms^{-1} while Type C is slower with average speeds of 3.3 ms^{-1}. Type B outbreaks tended to be a mixed bag with systems ranging from nearly stalling as seen with Hurricane Harvey (2017) to over 15 m/s with Hurricane Cindy (2005) with the average value being near 5.9 ms^{-1}. This correlates well with outbreak location and size with faster moving TC's producing tornado outbreaks well inland from the initial landfall point.

The 0-1 km helicity ranged from 125 m^{2}s^{-2} on the low end to over 700 m^{2}s^{-2} on the high end with an average value near 377 m^{2}s^{-2}. This environment, while at the lower end of favorability for classical supercell development, is still high enough with the other environmental factors in play associated with a tropical cyclone overland to support mini supercell development.

Type A outbreaks associated with central convection typically have increased vertical velocity collocating with enhanced vorticity. Type B outbreaks are typically similar in nature to type A except weaker. Type C tends to have much lower values than the other outbreak types at the synoptic scale.

The TCs associated with Type A outbreaks move along and ahead of the cold front leading to tornado formation over both a larger area and for an extended temporal range. These outbreaks have a large influx of extra vertical vorticity and upward velocity as the front impinges and, in many cases, eventually merges with the TC circulation as the system undergoes extratropical or post tropical transition. This was most clearly seen in Major Hurricane Michael (2018) as the storm moved rapidly from the Gulf Coastal states into the Mid-Atlantic region before moving back offshore of the Delmarva during extratropical transition. While there were scattered tornado development along the TCs path, the most concentrated area was in Virginia where the TC was finally absorbed into the front leading to the completion of transition.

Type B TCs are on average, typically much slower than their Type A counterparts as they wind up within the synoptic environment that caused the frontal boundary to stall. Also, the area of enhanced upward velocity is more diffused typically north and east of the TC circulation while vorticity is extremely weak associated with the stalled front with a majority of the vorticity coming from the TC or the convergent surface flow interaction between the stalled front and TC. This structure was best seen in Hurricanes Florence (2018) with the slow movement of the hurricane south of the stalled front in the Carolinas. This also leads to an enhanced area of shear between the two synoptic/mesoscale features which coupled with a source of lift, leads to an enhanced area of helicity.

In general, Type C TCs are more confined to the coastal counties along the Gulf Coast of the U.S. In most cases, these TCs begin to decay rapidly once inland as they are cut off from the area associated with the warm sea surface temperatures and lack of an influx of baroclinicity associated with a frontal boundary. This is seen with the quick decay of Hurricane Allen (1980) after its landfall in southern Texas. The outbreak peaks earlier, near landfall, as the powerful TC made landfall. These outbreaks also depend more highly on the surrounding environmental features with Allen (1980) moving into a part of Tornado Alley that was primed for tornado development.

CAPE does not have a clear connection with a specific TC type but depends more on the surrounding larger-scale synoptic environment around the TC. Near the coastal areas, the CAPE rich air associated with the warmer waters, may push inland aiding in the convective development needed for tornadogenesis however as it pushes inland CAPE tends to decrease. This was seen with Hurricanes Allen (1980) and Florence (2018) both having stronger CAPE along their north side with flow coming off the Gulf of Mexico and Atlantic respectfully. Another source of energy is Potential Instability which is commonly seen in situations where dry continental air can wrap around the circulation of the TC at the mid-levels while still being moist at the lower levels. This tends to be the energy source associated with convective bands farther away from the center of the TC that are interacting with the drier continental air. The impact of Potential Instability was seen associated with both Hurricane Michael (2018) as drier continental air arrived with the frontal boundary and with Hurricane Allen (1980) as its large circulation brough drier air from the surrounding arid and semi-arid regions associated with Texas and Mexico. The areas that see a potential overlap of these energy sources typically had the greatest tornado development risk in portions of the outer TC circulation as the bands begin to take on semi frontal structure.

5. Conclusion

There appears to be no significant correlation between TC intensity and tornado development threat with tornado outbreaks occurring from TC's, the strength of tropical depressions up to category 5 hurricanes. Outbreak types are more common with Type A (TC-moving cold frontal interactions) vs Type B (TC-stalled cold front interactions) and Type C (lack of TC- cold front interactions). This is caused by the fact that a frontal system is what climatologically erodes the Bermuda high enough to allow the TC to recurve into the U.S.

Fronts also play a vital role in the development of tornadoes associated with landfalling TCs. They can aid in the development by priming the environment with added vorticity as well as increasing the levels of shear around the cyclone. This increases the supercell potential which sets the stage to increase the tornadogenesis as well as allowing the event to extend well inland instead of being confined to the coastal areas.

Also of interest is the increased energy that is ahead of the front and the impacts that it could have on the environment's ability to support a tornado outbreak vs an isolated tornado or general severe threat. The tornado threat is maximized when you have an environment that is naturally favorable for tornado development with the combination of the TC and the frontal boundary being the final spark needed to set off the outbreak.

It also becomes clear the stronger the front the more impact that the boundary has on both the convectively enhanced environment around the TC as well as the vorticity associated with the TC circulation itself. Cold frontal, or Type A Outbreak, interaction situations tend to evolve to eventual merger and extratropical transition which continues to keep the outbreak potential going as the increased moisture, shear, and vorticity coupled with the prefrontal environment set the stage for tornado development well inland from the initial landfall position of the TC.

The environment associated with type C outbreaks tends to be modified by the TC itself with the cyclone being the main large-scale source of the moisture and vorticity that advects onshore from the maritime tropical airmass. These tornadoes tend to form closer to the coastal areas and more confined to the right front quadrant as opposed to Type A systems that tend to have tornadoes in the developing in a "pseudo warm sector" between the TC and ahead of the incoming cold frontal boundary.

Continued research on this topic needs to occur with a focus on numerical modeling, which will provide greater detailed data in the vicinity of the frontal boundary to aid the analysis in the outbreak potential and if an outbreak could still develop in associated with the systems without the frontal boundary being nearby.

A second area of research is vorticity budget analysis that is required to discover what the main sources of vorticity are that can allow the outbreaks to continue or even flourish well inland from the coastal areas as the TC beings to spin down away from its energy source.

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Authors contributions

Dicky Lee Armstrong was responsible for data collection, data analysis, and drafting the manuscript. Prof. Lin was responsible for conception, editing and revising the manuscript. Both authors read and approved the final manuscript.

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