Assessing the Role of Tropical Cyclone Size in Tornado Production

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ABSTRACT

Tornadoes in tropical cyclones have large amounts of variability in their behavior from year to year and even through the lifetime of a single storm. While these tornadoes are weaker on average than those occurring in midlatitudes, they still pose a hazard that can bring potential harm. Previous studies have attempted to establish the relationship between tropical cyclone size and tornado production and behavior and concluded larger tropical cyclones will produce more tornadoes at a further distance from the storm center. However, these previous studies used an antiquated, highly subjective dataset and outer size metric to establish this relationship. Revisiting prior work, uses a less subjective, more reliable outer size metric from a modern outer size dataset to conduct a statistical analysis to determine the validity of the relationship. Our analysis show that tropical cyclone size was determined to not be a strong factor in determining either tornado radius or number. While outer size may not provide a direct influence on tornado behavior, a more extensive look at convective evolution in tropical cyclones would greatly benefit the field in future work.

1. Introduction

The mechanisms behind tornado genesis in the midlatitudes have been well studied. However, despite requiring similar ingredients (i.e., sufficient moisture, instability, lifting mechanisms, vertical wind shear) and occurring in supercells (Edwards 2010, 2012), landfalling tropical cyclones (TCs) are known for producing tornadoes with different properties from their midlatitude counterparts. Firstly, TC supercells have smaller convective available potential energy (CAPE) than midlatitude supercells, and, thus only reach 3–4 km in height whereas midlatitude heights can reach up 10 km. Despite their lower CAPE, tornadoes are able to form in TCs though because of strong vertical wind shear in the lower troposphere, which yields modest helicity (McCaul 1991). Secondly, TC tornadoes are weaker than midlatitude tornadoes. Analysis of 1995–2010 tornadoes found 93.2% were weak (EF0–EF1), 6.8% strong (EF2–EF4), and no tornadoes were violent (Schultz and Cecil 2009). In comparison, all US tornadoes are rated 74.4% weak, 20.6% strong and 2% violent (Edwards 2012). Regardless of these differences, TC tornadoes pose similar hazards to midlatitude tornadoes, especially since they occur with other hazards (e.g., storm surge).

TC tornadoes have large amounts of variability in their frequency and location from year to year and even TC to TC (Novlan and Gray 1974; Schultz and Cecil 2009; Edwards 2012). Many studies have been conducted over the past few decades to try to understand this variability in tornado behavior. Firstly TC tornadoes have been observed to occur anywhere between 0–750 km from the TC center (Smith 1965; Novlan and Gray 1974; McCaul 1991). There are however areas within TCs that tornadoes prefer to spawn. Tornadoes have a tendency to form in the storm environments present in the rainbands of the TC, which includes the primary, secondary, and distant rain bands. A schematic depicting the convective structure of these features is shown in Fig. 1.

The occurrence of tornadoes within the rainbands could be because the CAPE and vertical wind shear are both favorable at these radii (McCaul 1991). These storm environments are also not subject to the vortex environment of the inner core which would normally not allow tornadoes to form due to small CAPE (McCaul 1991). However, tornadoes have have been known to occassionally spawn in the inner core region, particularly the eyewall. However, observations and particularly observations of tornadoes in the inner core are limited especially in intense TCs. Regardless of TC radii, tornadoes tend to cluster in the north-

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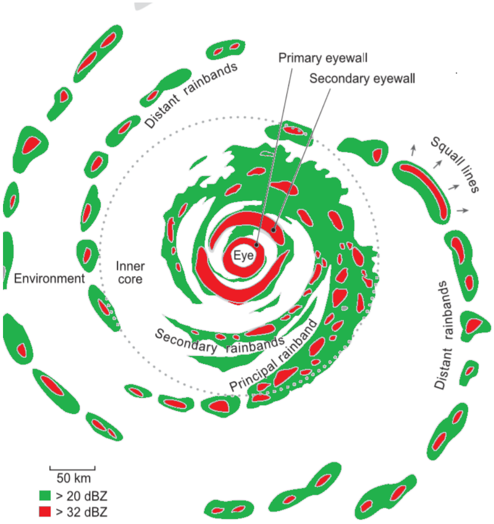

FIG. 1. Plot of the relevant characteristics of the convective structure of mature TCs (Willoughby et al. 1982; Houze 2010).

east quadrant of the TC, or equivalently right-front quadrant in a TC motion relative framework (Edwards 2012).

One final key fact is the role of environmental deep-tropospheric vertical wind shear in creating favorable environments for tornadoes, supercells, and deep convection (McCaul 1991; Corbosiero and Molinari 2002; Green et al. 2011; Molinari and Vollaro 2008).

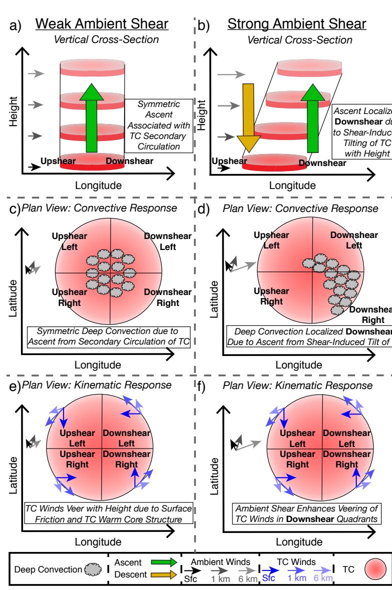

FIG. 2. Schematic depicting: (a & b) The effects of weak and strong ambient shear on a TC. (c & d) Convective structure in weak and strong shear environments. (e & f) Vertical wind profile in weak and strong shear Adapted from the results of prior work (Jones 1995; Ritchie and Holland 1999; Molinari and Vollaro 2008).

As depicted in Fig. 2, increasing deep-tropospheric vertical wind shear causes the TC to increasingly tilt with height. If ambient vertical wind shear is assumed to be westerly, the TC can be divided into quadrants based on location. A westerly shear will cause the normally symmetrical column to tilt with height toward the downshear half of the TC (i.e., half of TC in the direction of shear). This causes a vertical difference in vorticity advection with height and ascent that occurs to restore balanced flow in the TC (Jones 1995; Ritchie and Holland 1999). This ascent yields an increase in convection in the downshear regions of the storm. There is a more convection at outer radii in the downshear right region (i.e., to right of shear vector in downshear half of TC), whereas inner core convection is typically concentrated in the downshear left region (i.e., to left of shear vector). The kinematic response to strong shear also creates a vertical wind profile that veers with height in the downshear regions, especially the downshear right quadrant, providing favorable kinematic environments for supercells.

There are also several additional proposed factors that could contribute to the variability of TC tornado behavior including coastal fronts (Knupp et al. 2006; Green et al. 2011), coastline geometry (Gentry 1983), intensity (Novlan and Gray 1974), (Gentry 1983),and possibly TC size (McCaul 1991). Regarding this last factor, McCaul (1991) notes that on average, TCs that produced large numbers of tornadoes had a larger average outer size, as measured by the radius of closed isobar (ROCI), then the average outer size of non-tornadic TCs. However, ROCI is a subjective outer size metric with large uncertainty for two reasons. First, ROCI is subjectively estimated by forecasters. Second, ROCI is strongly influenced by environmental pressure fields, so any changes in strength in the surrounding ridges or troughs can impact ROCI (John Knaff 2013, personal communication). Hence, this paper will utilize a modern, less subjective outer size dataset that is more independent ofthe TC environment. A statistical climatological analysis will be conducted using this outer size metric to establish a relationship between the number of TC tornadoes and the location they form. The present study will employ multidecadal observed estimates of TCs and their outer size along with tornadoes during these storms to conduct our analysis. A better understanding of TC tornado formation could prove beneficial for forecasters to produce more accurate watch and warning areas. Also, our study can serve as a proxy for understanding supercell and deep convective evolution in TCs.

The remainder of this paper is divided into 3 parts. Section 2 will discuss the data and methods used. Section 3 will show the results, while Section 4 summarizes the paper and discusses future work.

2. Data

a. TC Track, Intensity, and Outer Size Data

This study examines all landfalling TCs in the North Atlantic from 1995–2018 with 1-min sustained 10-m winds of 34 kt greater (i.e., at least tropical storm strength storms) from the National Hurricane Center (NHC) HURDAT2 dataset (Landsea and Franklin 2013). 237 total storms meet the study's criteria. Some variables this study considers are TC track and intensity.

Our study uses the radius of 34 kt winds as an outer sie metric. Outer size data from 2004–2018 were obtained from archived HURDAT-2 Landsea and Franklin (2013), whereas data from 1995 to 2004 were taken from the Extended Best Track (Demuth et al. 2006). HURDAT-2 differs from Extended Best Track because it is subject to rigorous post-season analysis while the latter is not, which means it is prone to greater uncertainty (Carrasco et al. 2014). Radius of 34-kt wind data is provided each the northeast (NE), northwest (NW), southwest (SW), and southeast quadrants (SE). Unless mentioned otherwise, our analysis will use the average of the four quadrants for the radius of 34 kt wind excluding quadrants with an unreported value or value of 0 (Carrasco et al. 2014).

b. TC Tornado Data

This study observes the number of tornadoes that each TC produces from 1995–2018 and the position of the tornado both radially away from the center of the cyclone, and azimuthally in the TC. We obtain this data from Storm Prediction Center TC tornado (TCTOR) dataset (Edwards 2010). Surface and upper air maps, and satellites data are subjectively examinied for each TCTOR tornado to determine if it formed in association with a TC. Then, with data from the NHC, tornado position is analyzed at 6-hr intervals. This paper uses the most current data at the time of writing this paper.

c. Ambient Deep-Tropospheric Vertical Wind Shear

Ambient deep-tropospheric ertical wind shear profiles for every Atlantic TC, regardless of landfall, was collected from the 6-h 0.7° $\times$ 0.7° European Center for Medium-Range Forecasts (ECMWF) Interim Reanalysis (ERA-Interim) data (Dee et al. 2011) and calculated by removing the TC from the wind environmental wind field prior to calculating the 850–250-hPa vertical wind shear (Davis et al. 2008; Rios-Berrios and Torn 2017).

3. Methods

a. Tornado Location

This study established criteria to include storms that came close to the US coastline. TCs do not necessarily have to make landfall since tornado production does not require landfall. Storms qualify for this study if they occur north of 25°, between 60–97°W, and remains tropical in nature in the study.

In the present study, we use terciles of the radius of 34 kt winds for all North Atlantic TCs to define small, medium, and large storms. The distribution of radius of 34 kt winds in this study is shown in Fig. 3. The distribution is lognormal with a mean value of 250 km (Merrill 1984; Chavas and Emanuel 2010; Knaff et al. 2014).

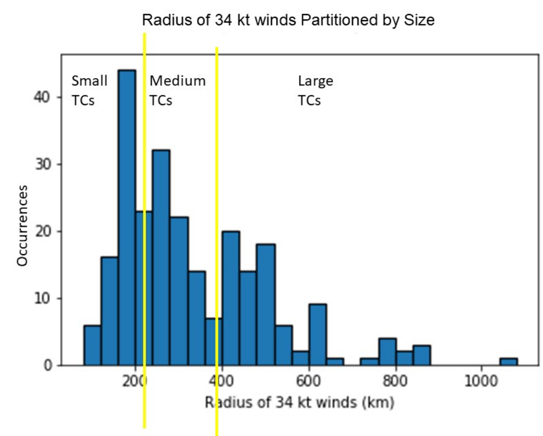

FIG. 3. Histogram of the radius of 34 kt winds (km) for the landfalling TCs examined in the present study. Small, medium, and large TCs are defined according to the first, second, and third terciles of the radius of 34 kt wind distribution (yellow lines).

Next, tornado radius, or distance from TC center where tornadoes spawned, was evaluated from the TCTOR dataset using the same filtering criteria mentioned above. Then the tornado radius was divided by the radius of 34 kt winds to create a normalized radius for TC tornadoes, and observing if the location of TC tornadoes scales with the size of TC wind fields. This normalized radius could be applied to each of the four quadrants (NE, NW, SW, and SE) of a TC to evaluate how the different environments influence tornado production. This paper also evaluates normalized tornado radius in an ambient-shear relative coordinate system. Shear-relative coordinate was evaluated by taking the azimuthal location of the tornadoes and subtracting the angle of environmental shear, thus allowing the effects of ambient shear on the tornado distribution in conjunction with size to become visible. Tornadoes were then plotted on this shear relative coordinate with their normalized radius. Finally, within an ambient shear relative coordinate, the magnitude of shear can be changed to determine its effect on tornado location. Ambient deep-tropospheric vertical wind shear is classified based on the terciles of the distributionfor all Atlantic TCs: 1) Weak ($<$6.3 m/s), 2) moderate (6.3–10.6 m/s), and 3) strong ($>$10.6 m/s) similar to Rios-Berrios and Torn (2017).

b. Tornado Number

To assess how TC tornado number changes with cyclone size, radius of 34 kt winds was taken from the HURDAT and Extended Best Tracks and binned by tornado production per 6-h which includes 0, 1–2, 3–4, and 5+ tornadoes per 6-h.

c. Statistical Significance Testing

In some of our plots, we have calculated the 95% confidence interval of the median using a 1000-sample bootstrap approach with replacement according to a two-tailed test. This test involves initially resampling the distribution from the existing data 1000 times and calculating a median from each of the 100 distributions. The spread of these median values represent our confidence intervals.

4. Results

The results will first discuss how tornado radius varies as the outer size of TCs change. Then a normalization scheme between tornado radius and TC size is established and plotted to determine the relationship between the two. Next, the relationship between shear and tornado radius is shown. Finally, the relationship between TC outer size and numbers of tornadoes produced is established before finally.

a. Tornado Radius Of Varying Sized Storms

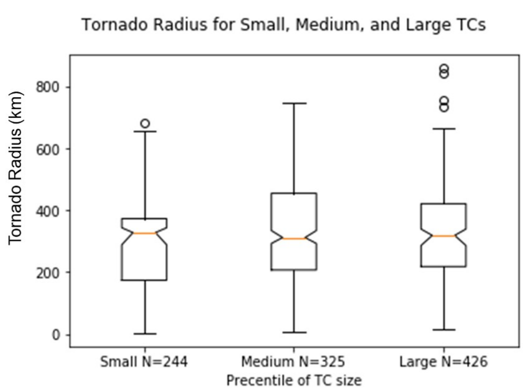

FIG. 4. Tornado radius (km) binned by terciles of TC outer size (small, medium, large.

Box-and-whiskers plots of tornado radius or tornado location from the center of the TC were created for small, medium, and large TCs in Fig. 4. The distribution has a lognormal shape for small TCs and a nomral shape for medium and large TCs. The results show a large amount of overlap in the distribution and even in the confidence intervals indicating that the median values are not different. These results seem to suggest outer TC size has little effect on the distance of tornado production.

b. Normalized Radius in True North Coordinates

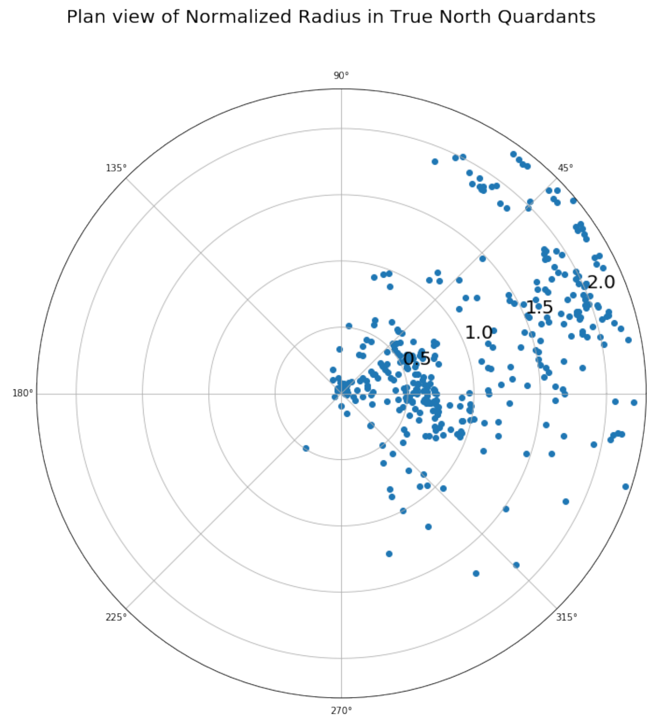

FIG. 5. Plan view of normalized tornado radius in a True North Quadrant. Radius of 34 kt winds are at radii mark 1.0. Each dot represents a location of a tornado from outer study.

Dividing the tornado radius by the radius of 34 kt winds of the quadrant that the tornado occurred in produces a normalized relationship to determine if tornado radius appears to scale with outer TC size. A plan view plot depicting the overall distribution of tornado location with normalized radii in a TC is shown in Fig. 5. Figure 5 shows many tornadoes do occur in the NE quadrants as previous studies suggested. There seems to be a clustering of tornadoes at two times and half the distance of the radius of 34 kt winds. There are also few tornadoes that occur beyond twice the radius of 34 kt winds. However, the absence of tighter clustering of tornado location suggests that outer size may not play a salient role in determining tornado location.

c. Effects of Ambient Shear and Outer Size on Tornado Radius

Figures 6 and 7 show tornado locations in TCs that are under the influence of weak and strong shear, respectively. Notice how there are few tornado locations in the upshear

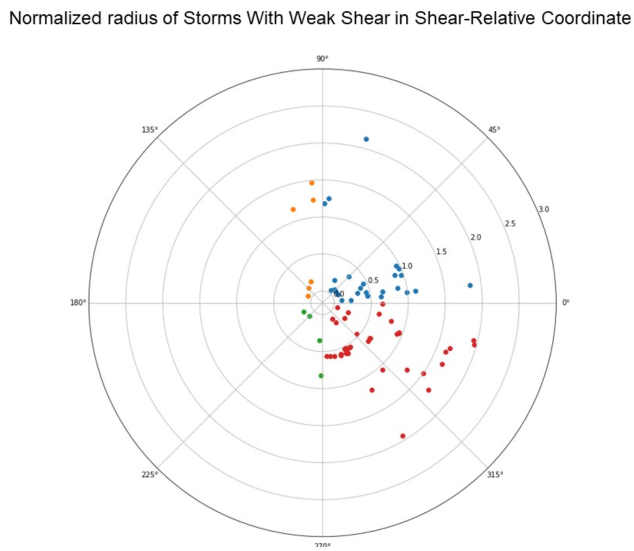

FIG. 6. As in Fig. 5, but for an ambient shear azimuthal coordinate for TCs in weak ambient deep-tropospheric vertical wind shear.

region in both figures, consistent with expectations from prior work (Corbosiero and Molinari 2002, 2003). While some tornadoes spawn within the radius of 34 kt winds in both TCs in weak and strong shear, there appears to be a clustering at twice the radius of 34 kt winds particularly in the downshear right region, where convection extends the furthest in strongly sheared TCs (Fig. 7).

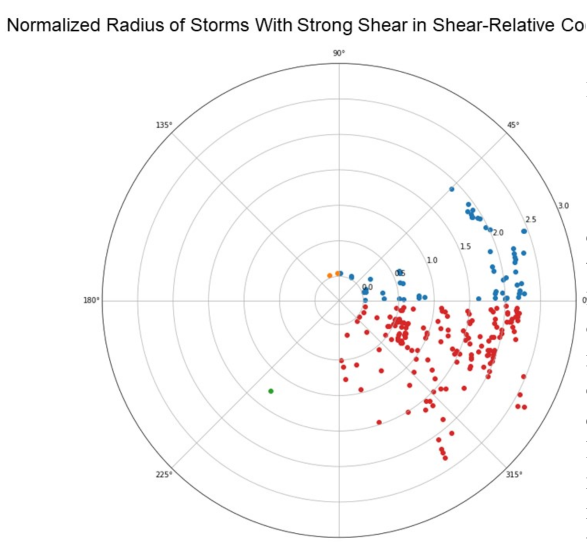

FIG. 7. As in Fig. 5, but for an ambient shear azimuthal coordinate for TCs in strong ambient deep-tropospheric vertical wind shear.

Under the influence of strong shear, tornadoes almost exclusively spawn in the downshear regions and extend further out in greater numbers as shown in Fig. 7. In the downshear left region there is a gap much like TCs in standard coordinates, but the gap is nonexistent in the downshear right quadrant. This could possibly be because in shear relative coordinates, more convection occurs in the downshear right quadrant but as the rainbands move into areas of less favorable conditions, the convection fails to support tornadic supercells. Together, these results suggest that outer size does not play a dominant role in impacting the radius of tornado occurrence regardless of ambient deep-tropospheric vertical wind shear conditions. Perhaps this indicates a greater importance of other factors that influences the individual supercell within rainbands interact with the environment, rather than how ambient synoptic-scale environment interacts with supercells.

d. Variation in Tornado Number with TC Outer Size.

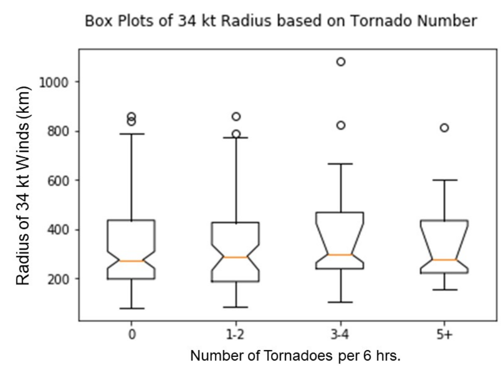

FIG. 8. Outer TC radius (km) binned by the number of tornadoes produced.

Box-and-Whisker plots of radius of 34 kt winds are shown for TCs that produced 0, 1–2, 3–4, and 5+ tornadoes in a 6 hour interval in Fig. 8. Outer size for storms that produced 0 tornadoes in 6 hours generally varies from 200 km to 400 km. Once again, there is a large amount of overlap in notches and little change in shape, suggesting outer size is also not a strong factor for tornado production. This is in stark contrast to earlier studies which claimed that the TCs that produced more tornadoes were larger in size (McCaul 1991). However, radius of closed isobars (ROCI) was the size metric used at the time. ROCI is subjectively determined and prone to large amounts of uncertainty, especially given the age of the data used.

5. Summary and Discussion

This study utilizes a modern, more objective dataset to revisit prior work to examine the relationship between TC outer size and tornado production and location. The key findings of this paper are: 1) as TC outer size increases, the tornado radius distribution does not change and 2) increased tornado production is not associated with TCs that have larger outer size. Thus, it would seem TC outer size has a rather small influence on tornado production.

There are many factors and uncertainties that could lead to this null hypothesis. Firstly, the process of reporting TC tornadoes is not simple. Often times, discerning tornado damage from the damage of the TC is quite difficult. Also, TCs make it hard see tornadoes both visually or through radar (Edwards 2012). Secondly, the radius of 34 kt wind can be prone to uncertainties especially when in situ observations are absent (Carrasco et al. 2014). Finally, these results suggest that there is not a linear relationship between the size of the envelope of deep convection and the wind field of the TC.

Together, these results suggest that the original hypothesis has been disproven. This study serves as a first step toward understanding what influences convective environments in TCs and suggests that the understanding behind TC convection and its relationship to the wind field is lacking. A possible future avenue for research is to conduct this investigation using inner size metrics (i.e., radius of maximum winds). Tornadoes may not be influenced by the outer edge of the gale envelope, but as the inner edge of the TC increases, the tornado radius might change. Finally, studying the relationship between convection especially in the rainbands, and wind fields will greatly benefit this study and the rest of the field.

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