Investigating Variability in the Number of Tornadoes Among Landfalling Hurricanes

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ABSTRACT

There is large variability in the number of tornadoes spawned by landfalling tropical cyclones (TCs). However, our understanding of why this variability exists remains incomplete. Hence, this study statistically analyzes differences in the characteristics of episodes of low and high numbers of tornadoes in landfalling TCs using multidecadal tornado and TC track data. These results show that low numbers of tornadoes tend to spawn near the coastline, whereas high numbers of tornadoes occur further inland. Similar, episodes with low numbers of tornadoes are associated with TCs near the coastline, whereas episodes of high numbers of tornadoes are associated with a TCs typically further inland in the Deep South. Tornadoes also spawn closer to the TC center with the downshear left quadrant during episodes of low numbers of tornadoes, whereas high numbers of tornadoes typically occur at outer radii in the downshear right quadrant. Episodes of high numbers of tornadoes are also characterized by stronger diurnal variability than low numbers of tornadoes. Finally, more damaging tornadoes are favored during episodes of high numbers of tornadoes. Together, these results provide the foundation for the improvement of tornado forecasts in landfalling TCs.

1. Introduction

Landfalling tropical cyclones (TCs) spawn tornadoes that can exacerbate other storm hazards (e.g., storm surge, inland flooding; Blake and Zelinsky 2018; Stewart and Berg 2019). The fundamental characteristics of TC tornadoes have been well studied (Novlan and Gray 1974; Edwards 2012). Approximately, 88% of TC tornadoes are typically spawned from supercells, which often tend to be “miniature” (Edwards et al. 2012). These supercells are typified by weaker reflectivity and rotational velocities, smaller mesocyclone diameters, shallower updrafts, and shorter lifetimes compared to their Great Plains counterparts (Spratt et al. 1997; McCaul and Weisman 1996). Most tornadoes occur in the outer rainbands of the northeast quadrant of landfalling TCs during the daytime hours (McCaul 1991; Edwards 2012). Prior research suggests that strong ($>\sim$10 m s^{-1}) deep-tropospheric (850–200-hPa), synoptic-scale (ambient) vertical wind shear (VWS) promotes the development of supercells within TCs upon landfall (Schenkel et al. 2020, 2021). Additionally, TCs with larger outer sizes often spawn more tornadoes than smaller TCs (Paredes et al. 2021). Despite the breadth of research conducted prior to this investigation, the large variability observed in TC tornado production is not well understood. Hence, this study examines the characteristics of tornadoes and TCs during periods of enhanced and suppressed numbers of tornadoes.

In order for a TC to maintain or increase its intensity, it must exist in an environment with minimal VWS and sea surface temperatures (SSTs) $\geq$27°C (Gray 1968). When a TC makes landfall, interaction with terrain substantially increases surface friction and reduces surface fluxes. Both of these factors work in tandem to weaken the TC (Chen and Chavas 2020; Hlywiak and Nolan 2021). However, the enhanced surface friction over land provides favorable kinematic environments for tornadic supercells (Novlan and Gray 1974; Gentry 1983). Furthermore, as the TC moves poleward it is typically weakened by strong ambient VWS associated with the subtropical or polar jet. While VWS is undesirable for the persistence of TCs (Tang and Emanuel 2010; Rios-Berrios and Torn 2017), both strong speed shear and, in particular, directional shear are important for tornadogenesis. The strong VWS associated with the subtropical or polar jet is responsible for vertically tilting the TC. The response of the TC to this tilting helps prime the atmosphere for tornadoes (Schenkel et al. 2020, 2021).

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As previously mentioned, episodes of enhanced tornadic activity occur in either TCs with large outer sizes or TCs embedded in strong VWS (Schenkel et al. 2020; Paredes et al. 2021). Previous investigations note that TCs with larger outer sizes have a broader set of radii with favorable kinematic environments for tornadic supercells (Paredes et al. 2021). More specifically, smaller TCs tend to spawn fewer tornadoes in the eastern half of the TC close to the center of the TC. Conversely, larger TCs tend to spawn more tornadoes in the eastern sector of the TC and further from the TC center. Additionally, strong VWS is associated with more tornadoes particularly in the downshear sector of the storm (Schenkel et al. 2020). Given typical westerly VWS, the downshear sector is defined as the eastern half of the TC (Corbosiero and Molinari 2003; Schenkel et al. 2020). Strong VWS is associated with the following response in the TC (Schenkel et al. 2020):

1. *Circulation response*: The TC tilts in the direction of the VWS vector. The vertical overturning circulation (i.e., TC secondary circulation) in the downshear sector of the storm strengthens yielding enhanced ascent and moisture throughout the troposphere. The strengthening of the secondary circulation also enhances the veering and boundary layer speed shear.

2. *Convective response*: The strengthening of circulation in the downshear sector causes convection to be asymmetrically located in the downshear sector of the TC. Convection is observed to spiral clockwise from the inner core in the downshear left quadrant outward into the outer periphery of the downshear right quadrant.

3. *Kinematic response*: Strong VWS enhances the veering of TC winds in the downshear sector. In particular, ambient winds most constructively superimpose in the downshear right quadrant. This veering of the ambient winds during TC landfall is typically associated with an upstream trough or downstream ridge ahead of the storm (Verbout et al. 2007).

4. *Baroclinic response*: In the presence of strong VWS, the TC wind field deforms the ambient baroclinic zones that is typically associated with the strong VWS. This baroclinic deformation leads to the advection of drier, cooler air in the upshear quadrants and warmer, moister air in the downshear quadrants.

The four aforementioned TC responses to strong VWS leads to more tornadoes that are asymmetrically located around the TC center. Specifically, VWS thermodynamically and kinematically enhances the environment favoring the generation of supercells in the downshear sector of the TC. However, too much VWS appears to suppress tornadogenesis (Schenkel et al. 2020). Despite this prior work, there is an incomplete understanding of why some TCs spawn >100 of tornadoes while a majority of TCs produce few, if any at all. Hence, this study will analyze the difference in characteristics of low and high numbers of tornadoes in landfalling TCs. Specifically, we will be investigating TC tornado location, time of occurrence, and damage rating. We will be conducting this analysis using TC tornado reports and TC tracks from 1995–2020. Specifically, our study will attempt to address the following questions:

1. Which locations are typically associated with high numbers of tornadoes?

2. Do periods of enhanced tornado production often occur inland?

3. Are high numbers of tornadoes more strongly concentrated in the afternoon and evening?

2. Data and methods

a. TC data

TC data from 1995–2020 are obtained from the National Hurricane Center (NHC) provided version 4, revision 0 of the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010). For a given 6-h time, we will define a TC as capable of producing a tornado if the downshear sector of the TC intersects the continental United States (CONUS) coast. We define the outer extent of the downshear sector as the radius at which the azimuthal-mean 925-hPa azimuthal wind equals 6 m s^{-1} as derived from ERA5 reanalysis data (Paredes et al. 2021).

b. Tornado data

The locations of tornadogenesis and damage ratings are retrieved from the 25-yr (1995–2020) Storm Prediction Center (SPC) TC tornado archive (Edwards 2010). This period is characterized by enhanced tornado detection resulting from the completion of the WSR-88D network and the implementation of improved tornado warning and verification approaches (Spratt et al. 1997; Edwards 2010). Each tornado has been subjectively analyzed to confirm its association with a TC (Edwards 2010). Our research examines 1629 tornadoes in 100 TCs. However, prior work discusses the undersampling of TC tornadoes (e.g., TC traverses an observation-deficient locale), which should be considered when interpreting the results of our research (Edwards et al. 2012).

c. VWS

Given its importance in determining the TC-relative azimuthal location of tornadoes (Schenkel et al. 2020, 2021),

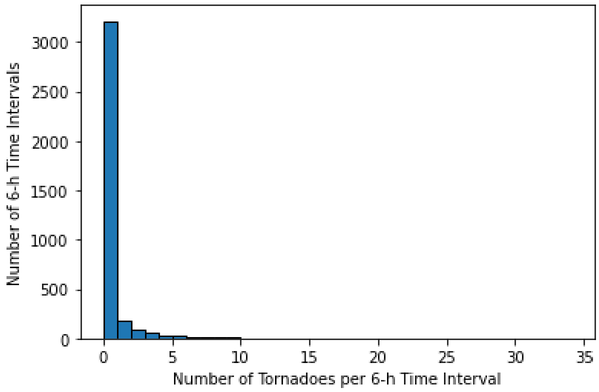

FIG. 1. Histogram showing the number of tornadoes per 6-h TC time interval.

we calculate VWS for use in plotting the tornado location. These data are calculated using 850-hPa and 200-hPa ERA-5 reanalysis winds (Paredes et al. 2021). Ambient winds are partitioned from the total wind field by subtracting the nondivergent and irrotational TC winds derived using a Poisson equation with homogeneous boundary conditions (Davis et al. 2008). Next, we compute the mean ambient zonal and meridional winds within a 500-km radius of the TC center. Lastly, we calculate the difference between 850-hPa and 200-hPa area-averaged zonal and meridional winds to obtain the direction and magnitude of the VWS vector (Rios-Berrios and Torn 2017).

d. Categorization criteria for TC tornadoes

Figure 1 shows the number of tornadoes within 3 hours of each TC track point. This figure shows that most TC track point are associated with no tornadoes. Focusing on those track points with $\geq$1 tornadoes, our study examines enhanced periods of tornadoes by objectively grouping observations according to the terciles of 6-h TC tornado count:

- Low (bottom 33rd percentile): 1 tornado within ($\pm$3-h) of a 6-h TC track point;
- Moderate (middle 33rd percentile): 2–3 tornado within $\pm$3-h) of a 6-h TC track point;
- High (upper 33rd percentile): 1 tornado within ($\pm$3-h) of a 6-h TC track point.

We will focus our investigation on events that fall in the lower and upper 33rd percentiles and will henceforth be used to differentiate between suppressed and enhanced periods of tornadic production. Our analysis of the results will focus specifically on comparing the characteristics of TCs and their tornadoes during episodes of low and high numbers of tornadoes.

3. Results

a. TC location

TCs that spawn high numbers of tornadoes are more concentrated in the eastern Gulf coast compared to cases with low numbers of tornadoes (Fig. 2). Specifically, TCs that produce low numbers of tornadoes are shifted south and west over a broader region compared to TCs that produce high numbers of tornadoes. Low-producing TCs are observed to spawn tornadoes along the coastline from southeastern Texas, east to Florida, and north to the Delmarva Peninsula. High-producing TCs are observed to spawn tornadoes in an area that is more concentrated to the Deep South. These results may suggest a preferred region of occurrence for large numbers of tornadoes at or just after landfall.

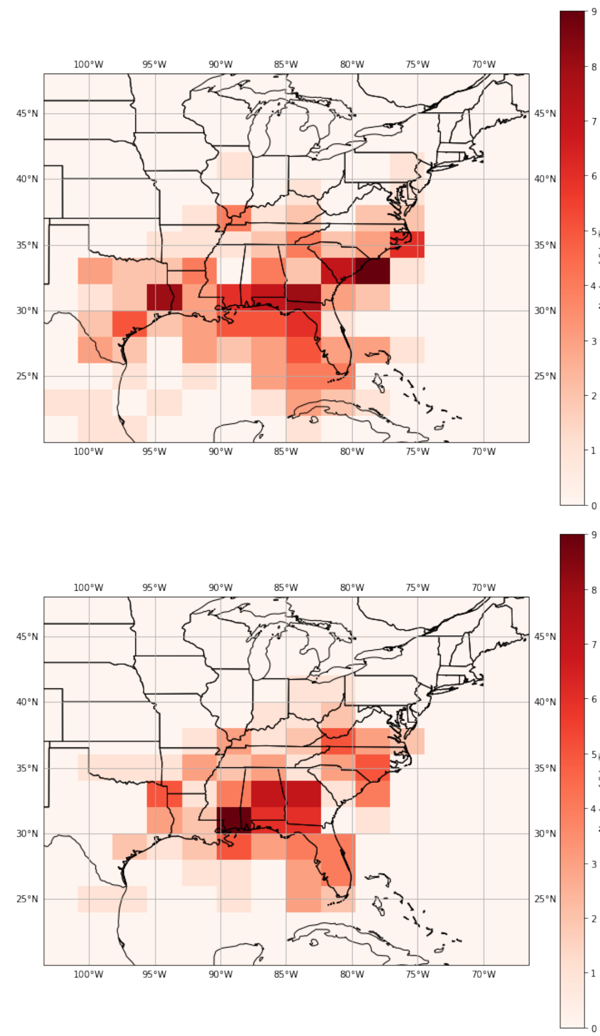

FIG. 2. Map view of TC location during episodes of (top) low numbers of tornadoes and (bottom) high numbers of tornadoes.

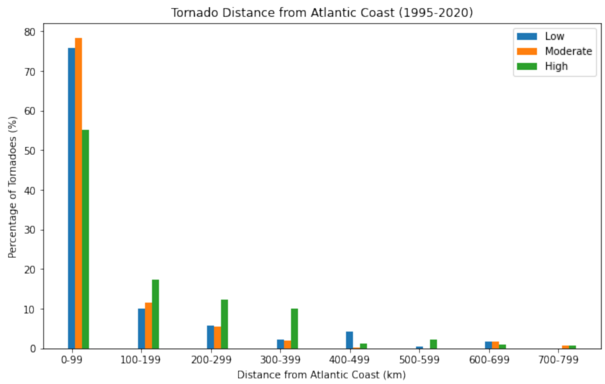

FIG. 3. Histogram of tornado distance from the coast (km) for the low, moderate, and high number of tornadoes.

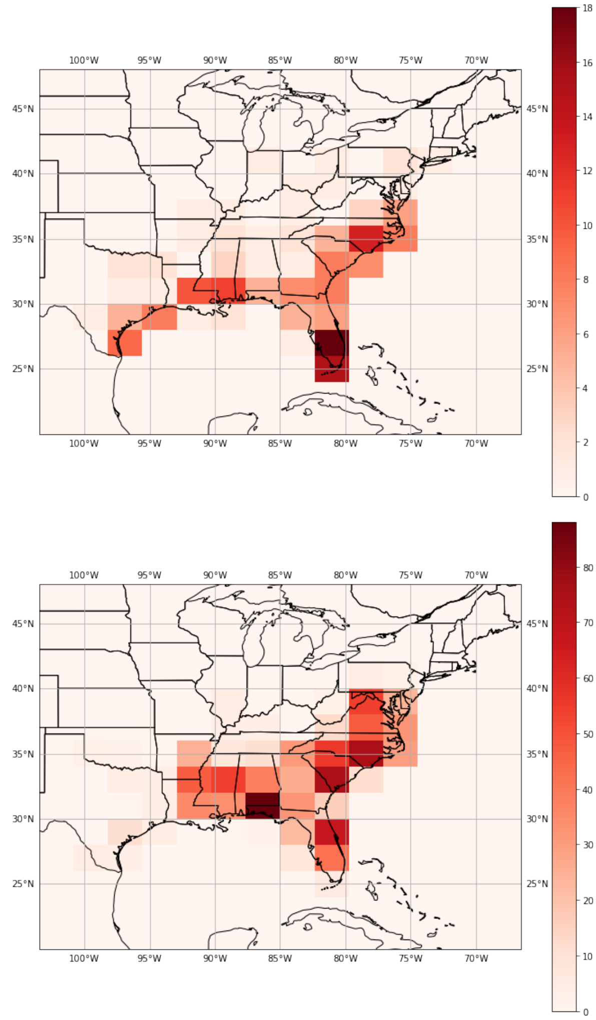

FIG. 4. Map view of tornadogenesis location for a) low- and b) high-producing TCs.

b. Tornado location

TCs that produce a high number of tornadoes are observed to spawn tornadoes further inland than TCs that produce low numbers of tornadoes (Fig. 3). Approximately 76% of all low-producing TCs have been observed to spawn tornadoes within 0–99 km of the Atlantic coastline compared to 55% of tornadoes in high-producing TCs. A significant drop-off in tornadoes in the low category is observed beyond 100 km of the coastline compared to the percentage of tornadoes in the high category.

Tornadogenesis location during episodes of low numbers of TC tornadoes covers a broader region of the coast compared to TCs associated with high numbers of tornadoes (Fig. 4). For TCs that produce high numbers of tornadoes, tornado initiation coverage area appears to be concentrated not only along the coastline, but further inland along a smaller sector of the coast. Both categories show a marked drop-off in observations northward of the 40°N.

TCs that produce high numbers of tornadoes are observed to spawn their tornadoes in differing parts of the TC (Fig. 5). Our results show a shift in tornado initiation points from closer to the TC center and within the downshear left quadrant in episodes of low numbers of tornadoes to further from TC center and more heavily concentrated in the downshear sector–predominantly downshear right. These results are broadly consistent with Schenkel et al. (2021) suggesting that episodes of high numbers of tornadoes are associated with inland tornadoes in strongly sheared TCs.

c. Tornado initiation time

Differences in the time of day of tornadogenesis also exist between episodes of low and high numbers of tornadoes (Fig. 6). Specifically, our results show strong diurnal variability of episodes of high number of tornadoes. This contrasts with the weaker diurnal variability observed in episodes of low numbers of tornadoes. Despite these differences in diurnal variability, all three categories of TC tornadoes peak in the afternoon local time (McCaul 1991; Schultz and Cecil 2009).

d. Tornado damage rating

TCs that produce high numbers of tornadoes are observed to favor more damaging tornadoes (Fig. 7). Episodes of high numbers of tornadoes tend to have a greater percentage of EF-1+ tornadoes when compared to episodes of low numbers of tornadoes. Despite the observed shift in damage ratings, most TC tornadoes ultimately are classified with weak-to-moderate damage ratings. There are no reliable records of EF-3 tornadoes in the low or moderate categories. These results suggest that

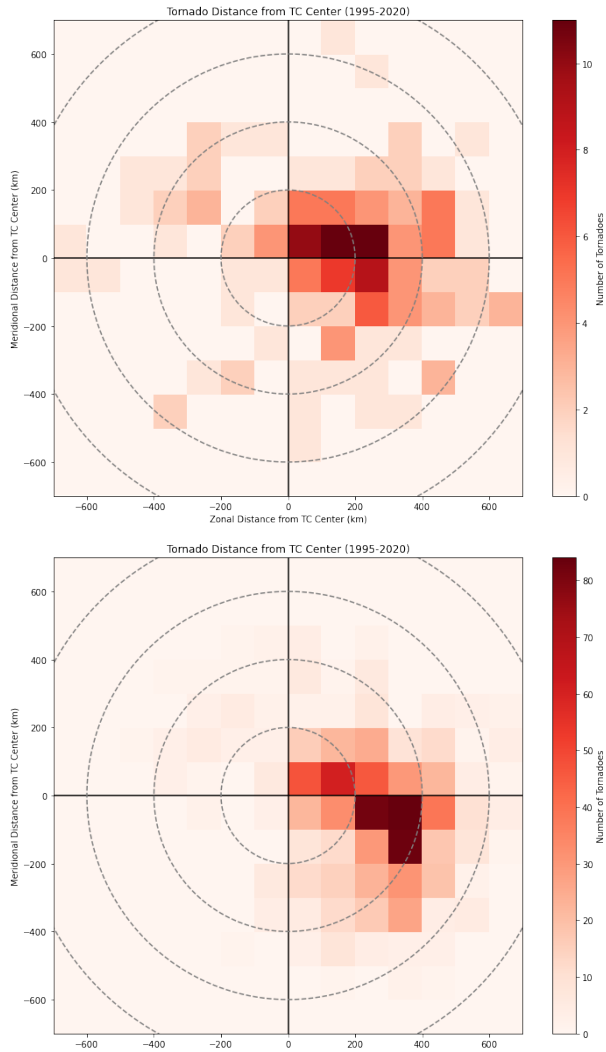

FIG. 5. TC-relative plot of tornado location in a VWS-relative coordinate in both low-producing (top) and high-producing (bottom) TCs. The VWS vector is pointing to the right side on each plot

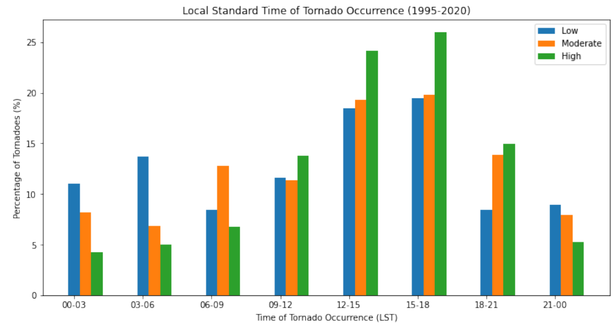

FIG. 6. Histogram showing the number of confirmed tornadoes per 6 h binned by local standard time.

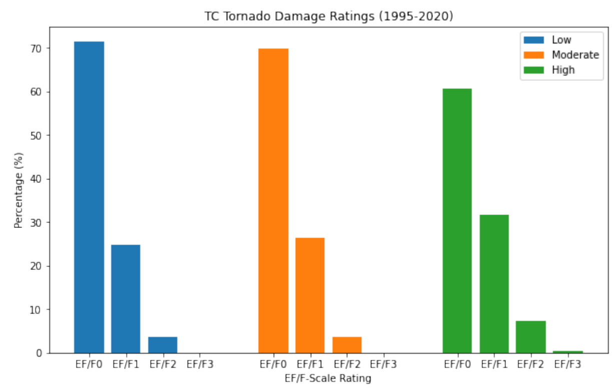

FIG. 7. Histogram of the damage ratings of TC tornadoes for low, moderate, and high numbers of tornadoes.

more damaging tornadoes favor environments with more tornadoes.

4. Summary and discussion

This study investigated the variability that exists in the number of tornadoes in landfalling hurricanes. Specifically, we attempted to identify the characteristics of both episodes of low numbers and high numbers of tornadoes from observed TC tornado reports. Our analysis examined both differences in the location of TCs and tornadoes during episodes of high and low number of tornadoes. We also analyzed tornado location using this data, as well as tornadogenesis time, and damage rating.

Our results show that TCs that generate high numbers of tornadoes were concentrated near the eastern Gulf coast whereas episodes of low numbers of tornadoes are spread more broadly across the continental United States. High-producing TCs also tend to spawn tornadoes further inland than low-producing TCs, whereas low-producing TCs are observed to spawn tornadoes near the coastline as the TCs approaches and/or makes landfall. With regards to the TC-relative location, high number of tornadoes are concentrated in the outer periphery of the downshear right quadrant, whereas TCs that produce low numbers of tornadoes spawn tornadoes more radially inward and closer to the center of circulation most frequently in the downshear left quadrant. Stronger diurnal variability is observed among episodes of high numbers of tornadoes compared to episodes of low numbers of tornadoes. Last, there is a marginal shift towards more damaging tornadoes when high numbers of tornadoes compared to episodes of low numbers of tornadoes.

Our investigation of TC tornadoes suggests that there are distinct characteristics that differentiate episodes of high numbers of tornadoes from low numbers of tornadoes, and lays further groundwork for continued investigation. Future research into episodes of enhanced TC tornado production would benefit from the analysis of extreme individual events such as Ivan, which produced 118 tornadoes (Edwards 2012; Schenkel et al. 2020). Further, analysis of archived radiosonde data could aid in understanding differences in convective-scale environments between TC with high and low numbers of tornadoes. Finally, the results from our research could potentially be used to improve forecast skill in landfalling TCs, which is typically lower skill than non-TC environments (Edwards 2012; Martinaitis 2017).

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