Diurnal Variability in Tropical Cyclone Tornado Occurrence

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ABSTRACT

This study investigates the relationship between the diurnal variability of tropical cyclone (TC) tornadoes and their location. Observed TC and tornado data are used to characterize how the diurnal cycle of tornadoes varies with distance from the TC center and distance from the coast. Our results show that TC tornado occurrence quickly increases in the late morning, peaks in the late afternoon, and sharply decreases thereafter. The largest diurnal variability is associated with tornadoes located on the eastern half of the TC within 100–500 km from its center. Our analysis also showed that the diurnal variability of tornadoes becomes larger with increasing distance from the coast. Specifically, there is an order of magnitude more inland tornadoes during the late afternoon than at any time during the night. Our study also considered the diurnal variability jointly associated with TC-relative and geographic location finding that: 1) inland tornadoes typically occur during the late morning and afternoon within the outer region of the eastern half of the TC and 2) coastal tornadoes largely occurred throughout the day in the northeast quadrant. These results may aid forecasts of TC tornadoes and, more fundamentally, deep convection as TCs move inland.

1. Introduction

Our current understanding of the location and number of tornadoes in landfalling tropical cyclone (TC) remains incomplete. Hence, forecasts of TC tornadoes are less skillful than non-TC environments (Edwards 2012; Martinaitis 2017). Improvement in TC tornado forecasts is necessary since 3% of TC deaths are caused by tornadoes (Rappaport 2014). Prior work has shown that TC tornadoes differ from non-TC tornadoes in several key ways. Specifically, TC tornadoes are primarily produced by miniature supercells, which are smaller, shallower, weaker, and shorter-lived (Edwards et al. 2012; Edwards 2012). Moreover, these tornadoes typically occur during the afternoon in the TC outer rainbands (McCaul Jr. 1991; Edwards 2012). Prior work has shown that most tornadoes occur within 48 hours before and after TC landfall, mainly in the range of 0–500 km from the coastline (McCaul Jr. 1991; Schultz and Cecil 2009). From a TC-relative framework, most TC tornadoes occur in the northeast quadrant of the TC within 750 km of its center (McCaul Jr. 1991; Edwards 2012). Finally, these tornadoes are often associated with light damage (i.e., Enhanced Fujita/Fujita Scale 0–1; Schultz and Cecil 2009; Edwards 2012). However, the reasons why TC tornadoes typically occur in the afternoon have not been identified. More fundamentally, the spatial variability of the diurnal cycle of TC tornadoes has not been well-documented and, hence, is the focus of the present study.

The diurnal cycle of TC tornadoes refers to the variability in their occurrence during the day. An increase in the frequency of tornado reports at all radii during the late morning into the evening has been shown previously (McCaul Jr. 1991; Schultz and Cecil 2009). However, there is less diurnal variability associated with tornadoes in the inner TC core (i.e., $\leq$200 km from TC center) compared to those in the outer region (i.e., $\geq$200 km from TC center; Schultz and Cecil 2009). However, prior work has yet to identify why this variability exists.

One possible reason for the diurnal variation in TC tornadoes may be associated with the diurnal cycle of convective available potential energy (CAPE). CAPE quantifies the potential energy of air parcels associated with temperature and moisture differences with its surrounding environment. Prior work has suggested that more favorable conditions for tornadogenesis occur during the daytime hours due to higher CAPE associated with the diurnal heating of the land, which provides the necessary fuel for tornadic convection (Edwards 2012; Schenkel et al.

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2020). However, a previous study of TC tornado proximity soundings has shown marginal CAPE differences between daytime versus nighttime cases (Edwards and Thompson 2012), consistent with prior studies of non-TC tornadoes (Reames 2017). (Edwards and Thompson 2012) showed that CAPE values were even slightly higher at nighttime. This result may suggest that diurnal variations in CAPE may be small in TCs and not a primary driver of the diurnal cycle of tornadoes. Alternatively, this study may also suggest that the minimum CAPE threshold for tornadogenesis is consistent between day and night (Edwards and Thompson 2012). Moreover, the sample size of these soundings was limited (i.e., 21 nighttime versus 67 daytime soundings), which also adds uncertainty to this analysis (Edwards and Thompson 2012).

A second potential forcing for the diurnal variability of tornadoes is the TC diurnal (Dunion et al. 2014). The TC diurnal cycle is characterized by a ring of colder cloud tops that propagates outwards from the TC center during the early morning and reaching the TC outer region by late afternoon (Dunion et al. 2014). This ring of colder cloud tops is often associated with the propagation of convective rainbands and lightning away from the TC center (Ditchek et al. 2019b, 2020). Prior work has also shown episodic rings of colder and warmer cloud tops propagating away from the TC center out of phase with the diurnal cycle (Ditchek et al. 2019b,a). The reasoning for the occurrence of the TC diurnal cycle and other similar episodic ring structures in the TC has yet to be identified. However, prior work has suggested it may result from diurnal variations in radiation or through radiative-convective feedbacks (Dunion et al. 2014).

Before identifying which of these factors may be responsible for the diurnal cycle of TC tornadoes, we must first fully characterize its spatial variability. Hence, this study will examine the diurnal variability in the location of TC tornadoes. Specifically, we will first analyze TC and tornado data from 1995–2020 to examine diurnal variations in the TC-relative location of tornadoes followed by an examination of their geographic location. Finally, we will examine diurnal variations associated with the joint variability of the TC-relative and geographic location of TC tornadoes. Specifically, our study seeks to address several key questions:

1. Is there diurnal variability in where tornadoes occur relative to the TC center?

2. Does the diurnal cycle of TC tornadoes with greater distance from the coast?

3. How does the diurnal cycle of TC tornadoes jointly vary as a function of TC-relative and geographic location?

Answering these questions may improve forecasts of TC tornadoes and may ultimately save lives (Rappaport 2014; Martinaitis 2017).

2. Data and methods

a. TC tornado data

TC tornado data for landfalling TCs in the continental United States was obtained by the Storm Prediction Center (SPC) TC tornado dataset (TCTOR; Edwards 2010). This data includes damage, track, and time data, and the TC that is associated with 1995–2020 (N=1652 tornadoes). To identify tornadoes associated with TCs, SPC forecasters subjectively analyze their timing and location relative to the TC together with forecast model data along with radar and other conventional observations.

b. TC track and intensity data

North Atlantic TC data was obtained from the National Hurricane Center (NHC) HURDAT2 dataset (Landsea and Franklin 2013). This data includes TC intensity and track data at 6-h intervals from 1995–2020 for the tropical, non-tropical, and extratropical phases of landfalling storms. Our analysis focuses on the 103 TCs that produce tornadoes during this period. NHC forecasters subjectively verified the information given by HURDAT2 to fortify the accuracy of the dataset.

c. Coastal data

Data from the 1-km $\times$ 1-km Global Self-consistent, Hierarchical, High-resolution Geography (GSHHG) are used to calculate the distance of tornadoes from the U.S. coastline (Wessel and Smith 1996). Following Schenkel et al. (2021), we use the GSHHG data to separate tornadoes into three regimes based upon the terciles of their distance from the coast: 1) coastal ($<$21; bottom 33rd percentile), 2) transition (21–123 km; middle 33rd percentile), and 3) inland ($>$123 km; upper 33rd percentile).

d. Analysis methodology

All TC tornado data times were converted from coordinated universal time (UTC) to local standard time (LST) for our analysis. We then use the local standard time data to study the diurnal variability in the TC-relative location of tornadoes. As part of our geographic analysis of tornado data, TCs will be binned by their coastal distance to study how the diurnal cycle varies. Our overarching goal is to comprehensively analyze diurnal variability in the location and number of TC tornado observations as the first step towards understanding why the diurnal cycle exists.

3. Results

This study first revisits the diurnal variability for all TC tornadoes followed by examining TC-relative location. We then focus on how the diurnal variability of TC tornadoes changes with geographic location. Last, our analysis examines the diurnal variability jointly associated with the geographic and TC-relative location of tornadoes.

a. Diurnal cycle overview

We first examine the diurnal variability of TC tornadoes as shown in a histogram stratified by local standard time (Fig. 1). Relatively few tornadoes are reported during the nighttime hours. Conversely, tornado reports quickly increase throughout the late morning into the afternoon peaking between 14–16 LST. Reports quickly decrease thereafter until 20 LST. These results are consistent with prior work (Schultz and Cecil 2009; Edwards 2012).

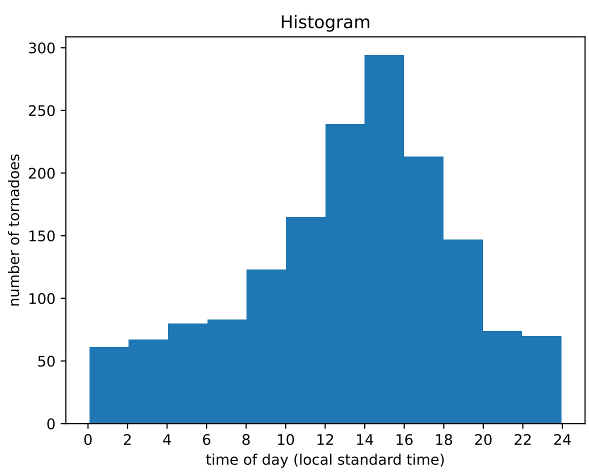

FIG. 1. Histogram of TC tornadoes stratified by their local standard time.

b. TC-relative location

Next, we examine how the diurnal variability changes a function of distance from the TC center. Figure 2 shows that the diurnal variability of inner-core tornadoes is much smaller than outer-region tornadoes, consistent with prior work (Schultz and Cecil 2009). Specifically, variability is strongest between 100–500 km from the TC center with the 300–400 km radial bin showing the sharpest peak. The peak occurrence of tornadoes also differs slightly among radii with a 12–14 LST peak for the 100–300 km bin, and 14–16 LST for the 300–500 km bin. This timing and its offset among these radii broadly agree with the conceptual model of the TC diurnal cycle (Dunion et al. 2014), but the remaining radii do not suggest that it is a primary factor. Outside of a 500-km radius, variability is much smaller.

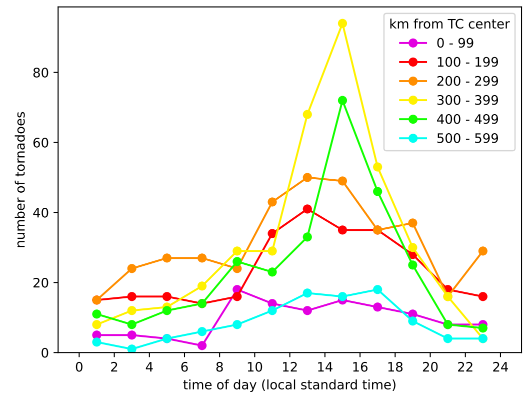

FIG. 2. Diurnal distribution of tornado number stratified by their distance from the TC center.

Next, we show the diurnal variability of the TC-relative tornado location in Fig. 5. These plots show that the diurnal variability of TC tornadoes is strongest in the eastern half of the TC. In particular, the outer region of the northeast quadrant shows the greatest variability in tornado occurrence with a sharp peak in activity concentrated between 12–16 LST. A secondary peak of tornado reports occurs in the outer periphery of the southeast quadrant that also peaks from 12–16 LST. In comparison, inner-core diurnal variability is comparatively muted in both the northeast and southeast quadrants.

c. Geographical location

Map view plots of TC tornado reports stratified by 4-h time intervals characterize the diurnal variability both at the coast and inland (Fig. 3). Tornado reports increase across the southeastern US towards the afternoon, especially from 12–16 LST. At the coast, tornadoes can occur throughout the day with a peak in the late afternoon. However, inland environments show more drastic diurnal changes in the number of tornadoes. In particular, there are few tornado reports inland during the nighttime with a rapid increase during the late morning up until the peak between 12–16 LST followed by a rapid decrease thereafter. This inland tornado diurnal cycle closely matches the results for TC outer region tornadoes and will be explored further later on.

To better quantify the diurnal cycle of coastal versus inland TC tornadoes, we show histograms of tornado occurrence stratified by the coastal regimes identified earlier (Fig. 4). Specifically, this figure shows a stronger diurnal peak in the inland tornadoes compared to those at the coast. The number of inland tornadoes quickly increases from the late morning through the late afternoon, which is an order of magnitude higher between 14–16 LST than during the night. In contrast, the coastal tornadoes show

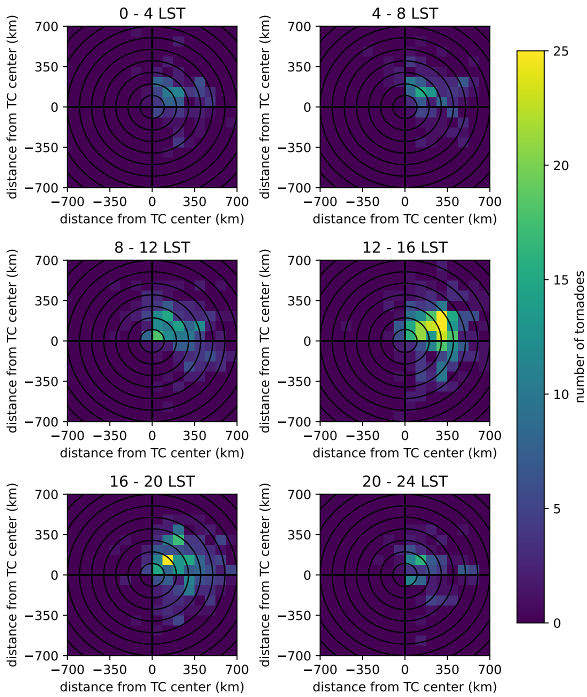

FIG. 3. TC-relative joint histogram of tornado occurrence in a true-North coordinate separated into 4-h LST bins.

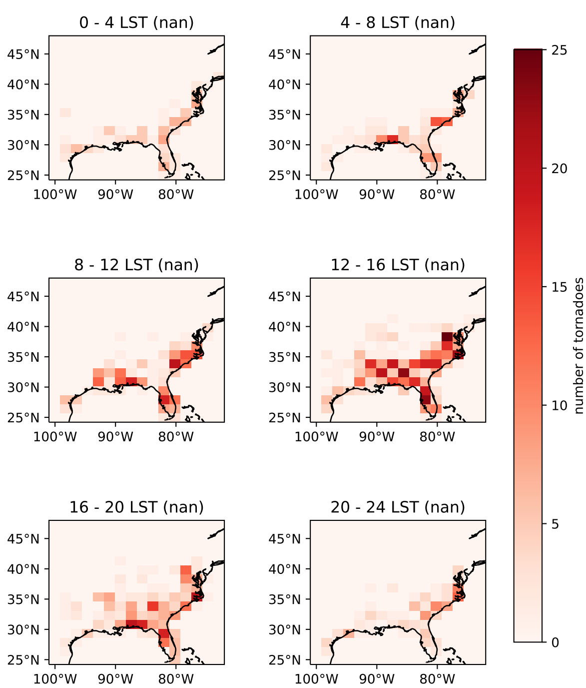

FIG. 4. Map view of joint histogram showing the number of TC tornadoes across the US stratified by 4-h LST intervals.

a broader peak between 10–18 LST during the afternoon that is 3 times higher than at nocturnal numbers. The transition tornadoes have characteristics of both terciles with a similar, yet less drastic peak around 14–16 LST compared to inland tornadoes.

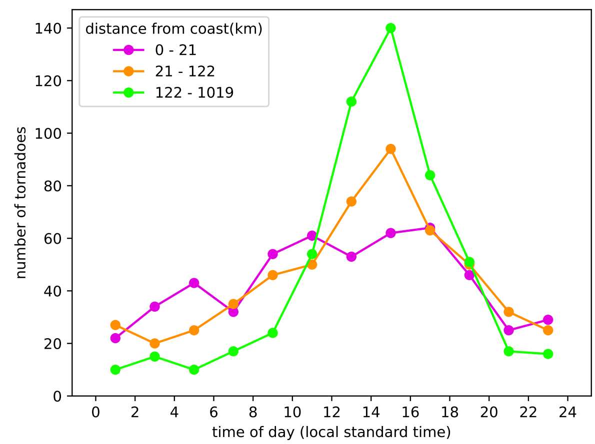

FIG. 5. As in Fig. 2, but stratified by TC tornado distance from the coast.

d. Joint influence of coastal and TC-relative location

Finally, we focus on examining how the diurnal variability of tornadoes jointly varies with the coastal distance and TC-relative location (Figs. 6–8). Figure 6 shows that coastal tornado reports do not vary much throughout the day as they primarily occur in the northeast quadrant. This implies that diurnal variability lies in the other terciles (as shown previously) and that the tornadoes observed in the southeast quadrant are further from the coast. In comparison, transition tornadoes (Fig. 7) share characteristics of both coastal and inland tornadoes. Diurnal variability is more pronounced with tornadoes spread more widely across the eastern half of the TC with peak occurrence located directly due east during 12–16 LST. Finally, Fig. 8 shows strong diurnal variability for inland tornadoes spread across the eastern side of the TC. Peak inland tornado occurrence is concentrated in the northeast quadrant primarily from 12–20 LST in the TC outer region between 200–400 km from the TC center.

4. Summary and discussion

This study examined the diurnal variability associated with the location of TC tornadoes, which has yet to be investigated. This was achieved through analyzing observed TC and tornado track data. Our study first analyzed diurnal variability associated with the TC-relative

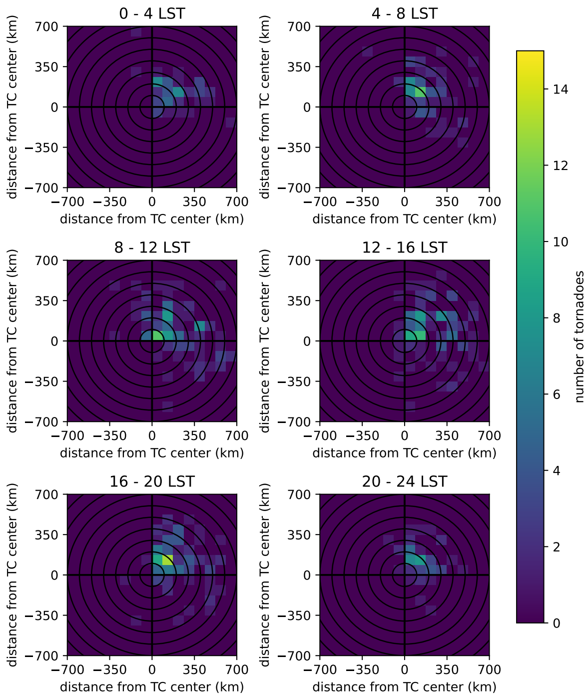

FIG. 6. As in Fig. 5, but for coastal tornadoes.

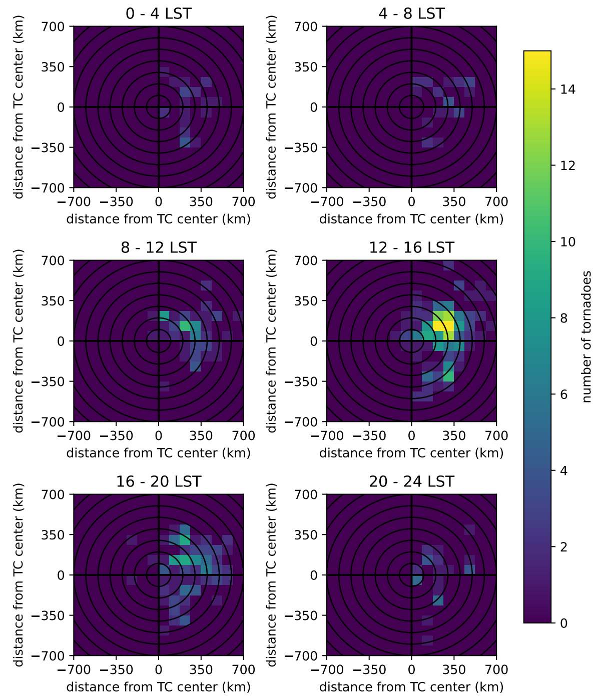

FIG. 8. As in Fig. 5, but for inland tornadoes.

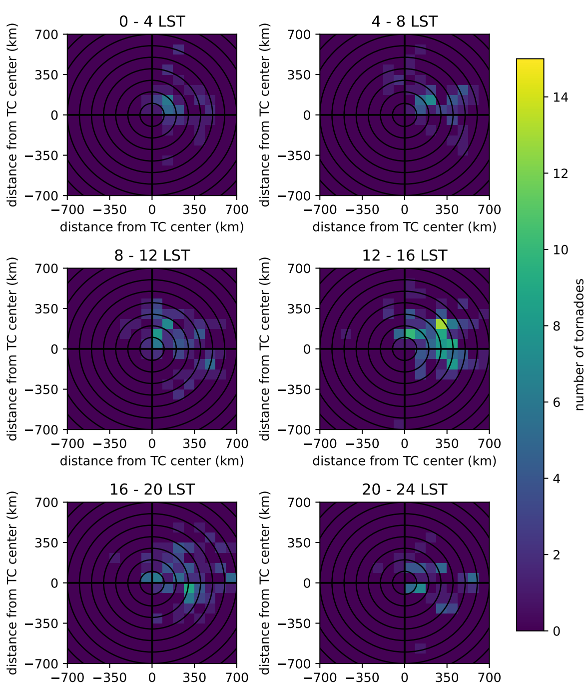

FIG. 7. As in Fig. 5, but for transition tornadoes.

location of tornadoes followed by their geographic location. We then analyzed the diurnal variability jointly associated with both of these factors. This study found substantial diurnal variability associated with the TC-relative and distance of tornadoes from the coast.

Specifically, TC tornadoes show pronounced diurnal variability with a peak in occurrence during the mid-to-late afternoon. TC outer region tornadoes (i.e., >200 km from TC center), and particularly those within 300–500 km from the TC, showed stronger diurnal variability than inner-core tornadoes. Most of the diurnal variability was associated with tornadoes on the eastern half of the TC primarily in the outer northeast quadrant.

Regarding geographic location, inland TC tornadoes exhibited greater variability compared to those at the coasts with a sharp peak during the mid-to-late afternoon. Accounting for diurnal variability in both TC-relative and geographic location, coastal tornadoes almost exclusively occupy the northeast quadrant with weak diurnal variability. In contrast, inland tornadoes tend to occur in the late afternoon in the eastern side of the TC with a peak in the outer northeast quadrant

Overall, this study found substantial diurnal variability in both the TC-relative and geographic location of tornadoes. Namely, the strongest variability occurred for tornadoes in the outer region and inland environments. This work may more broadly indicate how the diurnal cycle of deep convection changes in different parts as storms move inland. These results can be used as guidance for improving TC tornado forecasting, which tends to be less skillful compared to non-TC environments (Edwards 2012; Martinaitis 2017). Future work will focus on examining which aspects of convective-scale environments in TCs show similar diurnal variability and the processes responsible for these patterns in tornado occurrence.

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