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TROPICAL CYCLONE TORNADOES: SYNOPTIC SCALE INFLUENCES AND FORECASTING APPLICATIONS

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1. INTRODUCTION

Several observational studies have shown characteristics of the spatial distribution of tornadoes reported with landfalling tropical cyclones (TC). This study follows the recent analysis by Schultz and Cecil (2009) and references therein.

TC tornadoes generally occur within a few hundred km of the TC center, with a small number exceeding 500 km distance. A disproportionate number occur near the coast, with a small number several hundred km inland. Relative to the TC center, preferred sectors have been identified toward the east-northeast, or the forward-right side (relative to storm motion). Tornado reports are maximized during the afternoon. The diurnal signal is strong for counts of outer core (beyond 200 km from the center) TC tornadoes, but weak for those near the center.

This study aims to develop quantitative guidance on the location and magnitude of the tornado threat associated with a landfalling tropical cyclone, in a format appropriate for use by the Storm Prediction Center (SPC) in issuing tornado watches and convective outlooks (out to 72 h). From the multi-year TC tornado climatology, an empirical model of TC tornado likelihood on a latitude-longitude grid can be developed as a function of TC center location. The distance and azimuth of each grid point relative to the TC center, along with the distance from each grid point to the coast, determines a spatial outline of the tornado threat. The magnitude of this threat can be scaled by a climatological mean number of TC tornadoes per TC landfall, and refined by factors such as time of day and synoptic support. A simple estimate of 200 hPa divergence is found to be useful, with more tornadoes occurring in cases with strong divergence aloft.

2. IDEALIZED EMPIRICAL MODEL

The United States TC tornado database described by Schultz and Cecil (2009) is restricted here to the period 1982-2007 and merged with the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005) training data for the same period, and with operational SHIPS products from 2003-2007.

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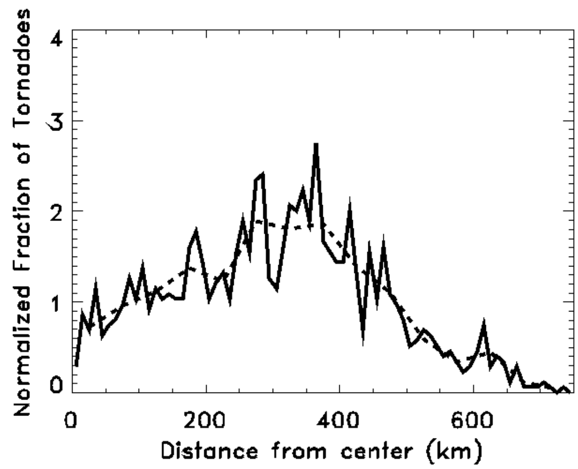

Fig. 1. Fraction of TC tornado records as a function of distance from the TC center. Fraction is normalized on abscissa by the number of bins used on the ordinate. Solid line: 75 10-km bins; dashed line: 15 50-km bins.

In the simplest model, a given number of TC tornadoes *N* would be distributed radially around the TC center using the 50-km bins in Fig. 1. For example, ~5% (0.05*N*) of the tornadoes are distributed evenly around the 0-50 km ring, and about 12% are distributed evenly around each of the 50-km rings between 250 and 400 km distance from the center. The 50-km rings are used hereafter, because the sample size does not support using smaller rings.

In reality, TC tornadoes are not distributed evenly in rings around the center. Fig. 2 provides a basis for distributing the tornadoes more appropriately. At all radii, the number of tornadoes in a particular azimuthal bin is scaled up or down by the solid curve in Fig. 2. The east-northeast (60°-80°) bin gets almost four times as many tornadoes as it would if there were no accounting for azimuth. The south through northwest (180°-320°) sides are scaled down to almost zero. This scaling does not change the total number of tornadoes, since each line in Fig. 2 averages to 1.0. It merely re-distributes the tornadoes azimuthally (Fig. 3).

The storm motion heading or the environmental shear vector (200-850 hPa GFS wind shear, averaged around a large radius, taken from the SHIPS databases) could alternately be used to distribute the tornadoes azimuthally. It is tempting to use the deep-layer shear vector, since this provides a more dynamical basis and favors the downshear direction about as strongly as the north-relative coordinates favor the east-northeast. The north-relative coordinates are used in this study, because using either shear or storm-motion would introduce an unnecessary source of error for operational forecasts.

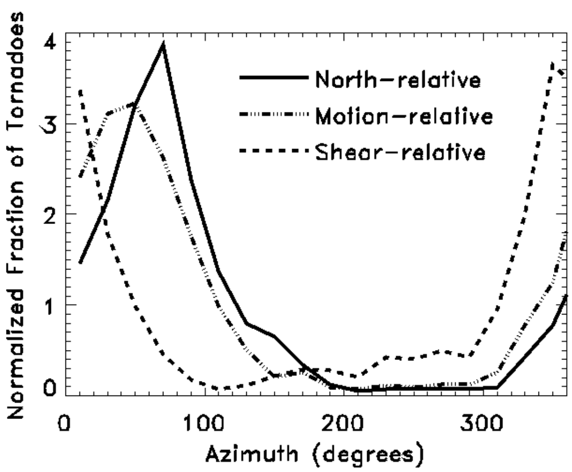

Fig. 2. Fraction of TC tornadoes as a function of azimuth from the TC center, normalized as in Fig. 1 for 18 20-degree bins. Azimuth is rotated relative to TC forward motion for dash-dot line, and relative to 200-850 hPa downshear direction (from SHIPS) for dashed line.

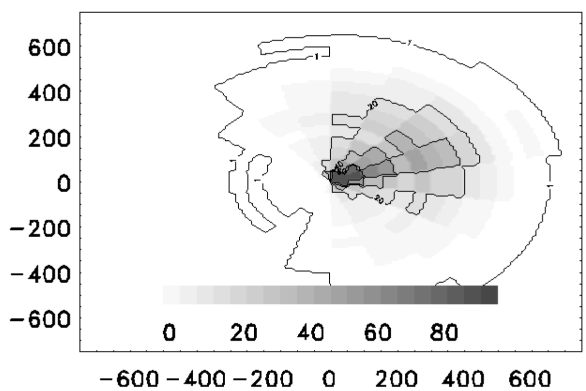

Fig. 3. Idealized spatial distribution of an arbitrary number of tornadoes on a 10 km x 10 km grid, from combining Fig. 1-2. All grid points in the same 50-km radius ring and 20° azimuth bin are assigned the same number of tornadoes. The inner region has the highest density of tornado reports, with tornadoes spread across a broader region at large radius.

To first order, the idealized distribution in Fig. 3 compares well with the observational distribution of TC tornado records in Schultz and Cecil (2009) (Fig. 4). The observational distribution has a peak density ~300 km east-northeast of the TC center. In the raw data, the preferred azimuth shifts from northeast toward east-northeast with increasing radius. This is not yet accounted for in the idealized model.

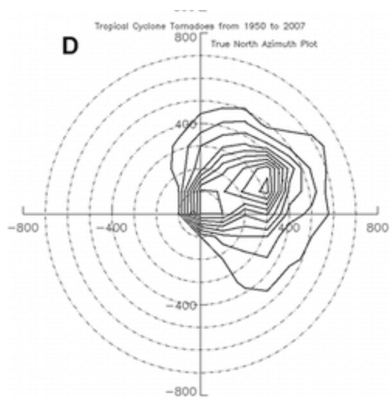

Fig. 4. North-relative range-azimuth distribution of TC tornadoes from Schultz and Cecil (2009).

Next, the idealized distribution in Fig. 3 was normalized such that the sum of all the grid points is 1.0 (that is, each grid point represents the probability that a single TC tornado would have that precise location). The distribution was then applied to all 918 six-hourly TC locations near the United States in the 1982-2007 SHIPS training database. Every six hours, the probabilities were summed for those grid points that were over land (restricted to the domain north of 23° and west of 65°, since the tornado database is only from the U.S). This gave a value ranging from 0 (completely offshore) to 1 (completely inland) for the fraction of the TC that was inland, *weighted by the preferred sectors for TC tornado occurrence*. A TC centered on the Outer Banks of North Carolina would count as being almost completely offshore, since the preferred sectors would be over the ocean in this case. A TC straddling the Gulf Coast would count as mostly inland, since the favored northeast sector would be over land. Summing these fractions gave an effective number of landfall cases (540 six-hourly periods) in the database. While the mean number of tornadoes per TC was 1.1 per six hours, the effective mean using these weighted landfall counts was 1.9 per six hours.

TC tornadoes are also favored near the coast in the multi-year climatology, with 44% of the records located within 50 km of the coast and 94% within 400 km of the coast. Similar to the way the azimuthal scaling from Fig. 2 was used to multiply the distribution of tornadoes from Fig. 1 (yielding Fig. 3 as a result), we compute a distance-from-coast scaling in Fig. 5 and multiply the spatial distribution from Fig. 3 by the scaling for a particular coastline geography. The sequence in Fig. 6 shows the idealized distribution applied to part of Hurricane Ivan's (2004) track. With Ivan centered well inland near Chattanooga, TN, probabilities are low everywhere but are highest to the east-northeast and near the closest coasts. As Ivan moves closer to Chesapeake Bay, probabilities increase across Virginia and the Mid-Atlantic region, due to a combination of being in the favored sector, within a few hundred km of the TC center, and being a short distance from the coast.

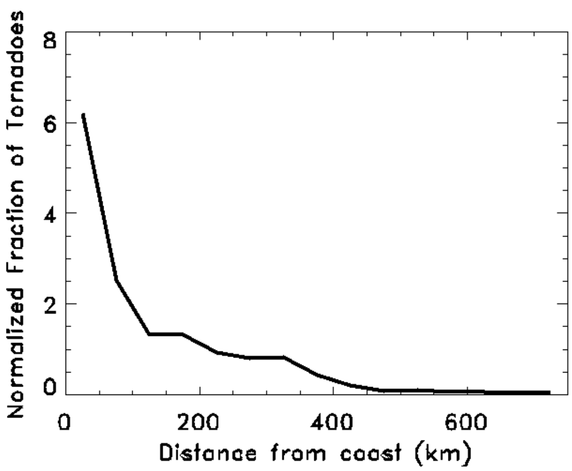

Fig. 5. Fraction of TC tornadoes as a function of distance from the coast, normalized as in Fig. 1 for 15 50-km bins.

The relationships above describe the spatial distribution of the tornado threat around a TC. Given no further information, an empirical forecast would distribute the weighted mean 1.9 tornadoes per 6 hours among the grid points as in Fig. 6. Instead, the expected number of tornadoes can be scaled up or down based on time of day (Fig. 7). Roughly twice as many tornadoes would be expected at 4 pm than if the diurnal cycle were not considered.

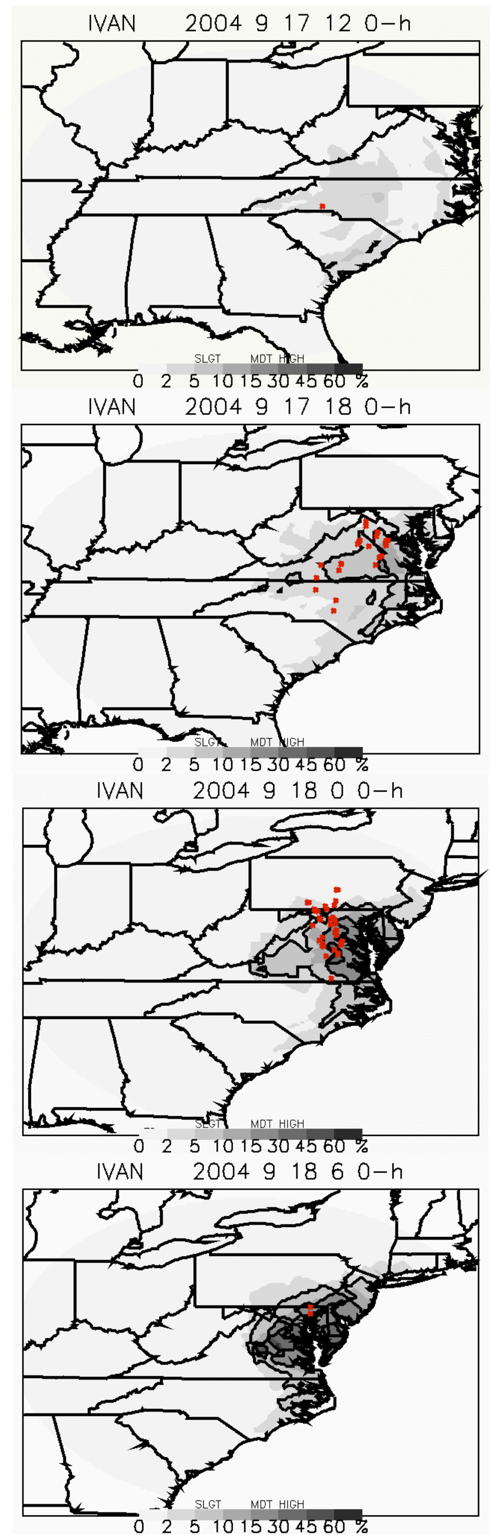

Fig. 6. Idealized distribution modified by distance from coast for Hurricane Ivan locations, 12 UTC 17 Sep 2004 - 06 UTC 18 Sep 2004. Red dots indicate recorded tornado locations within +/- 3 h. Scaling is for probability of a tornado within 40 km of a point, consistent with SPC outlooks.

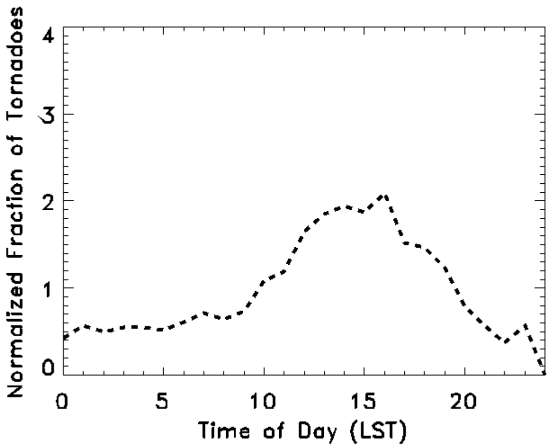

Fig. 7. Fraction of TC tornadoes as a function of local solar time, normalized as in Fig. 1 for 24 one-hour bins.

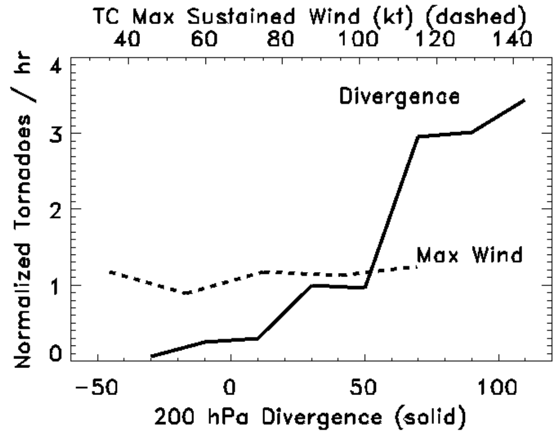

Fig. 8. Fraction of TC tornadoes as a function of 200 hPa divergence (solid, units: 10^{-7} s^{-1}) and TC maximum sustained wind (dashed), normalized as in Fig. 1 for 10 bins of 20 units each for divergence and 5 bins of 20 kt each for maximum sustained wind.

Similarly, time periods with very large values of 200 hPa divergence from SHIPS have 3-4 times more tornadoes than otherwise. The TC intensity (maximum sustained wind) has little relationship to the number of tornadoes, and is not used hereafter. Several other parameters from the SHIPS training database were considered (for example, shear magnitude, relative humidity, relative eddy flux convergence, among others), but had much more scatter in their relationships to tornado count than did 200 hPa divergence.

3. FORECAST APPLICATION

To generate forecasts, the spatial distribution as in Fig. 6 is multiplied by the product of the weighted mean number of tornadoes per case, the diurnal scaling (Fig. 7), and the 200 hPa divergence (Fig. 8). In the extreme, a mid-afternoon case with strong environmental divergence would have a forecast of ~ $1.9 * 2 * 3.5 \approx 13$ tornadoes per six hours. If the preferred sector is inland near the coast, this could be further increased.

Maps of the forecast TC tornado threat are generated using the observed conditions (actual TC track and 200 hPa divergence from analysis) and also using operational forecasts of the TC track and 200 hPa divergence. The hindcasts using observed conditions generally do well, with most of the large TC tornado events being properly identified. Hurricane Ivan (2004) was particularly well-behaved in this framework (Fig. 9). The tornado threat diagnosed from 24-h forecast data for Ivan identified the correct locations, but underestimated the magnitude of the threat. The 200 hPa divergence was under-forecast by about 50 ($*10^{-7}$ s^{-1}) during this time period, causing the forecast probabilities in Fig. 10 to be so much lower than the analyzed probabilities in Fig. 9.

There are many busts using both analyses and forecasts, particularly for afternoons when the TC is near the Gulf Coast or inland near the Mid-Atlantic or New England. The forecasts have considerably more error than the analyses, largely because of errors in the TC track forecast. Some large events are properly identified despite this.

This approach appears promising, but a forecaster should keep certain limitations in mind, and adjust the forecast accordingly. Some of these limitations (marked with a *) may be addressed in revisions to this product:

- Mesoscale features (e.g., boundaries, dry slots) are completely absent from this model
- Synoptic forcing is only addressed by the divergence term
- *Forecast TC location is subject to error
- Unusual storm motion or environmental shear vector may favor a region other than that identified in the model
- *Observed diurnal signal is small near TC center, large at outer radii
- *Preferred azimuth for tornadoes shifts clockwise with increasing radius in observations
- *Distance from coast appears to have too strong an effect in model

4. ACKNOWLEDGEMENTS

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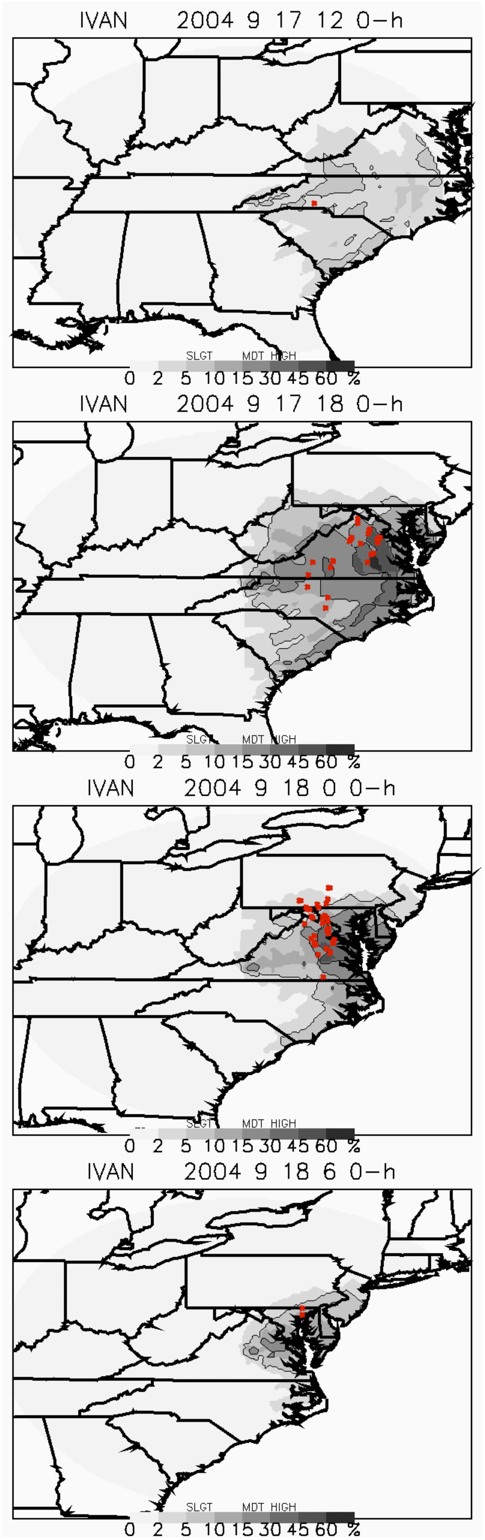

Fig. 9. As in Fig. 6, but modified to account for local time of day and 200 hPa Divergence.

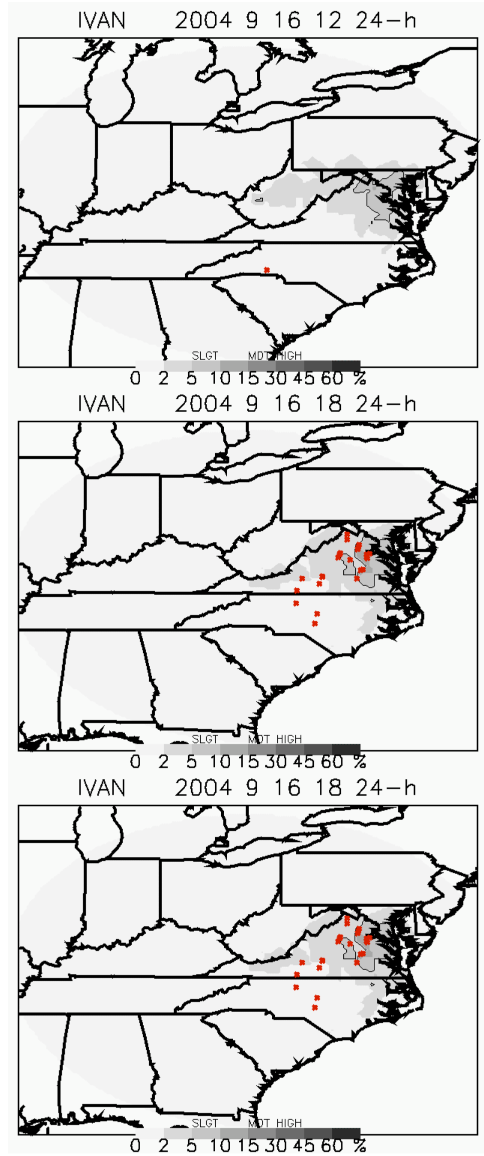

Fig. 10. As in Fig. 9, but using the operational 24-h forecasts of Ivan's location and divergence. No forecast was generated from 6 UTC 17 Sep because the National Hurricane Center had discontinued its advisories.

5. REFERENCES

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