P471 A CLIMATOLOGY OF TROPICAL CYCLONE-INDUCED TORNADOES IN THE FLORIDA KEYS

Kennard B. Kasper
NOAA/National Weather Service, Key West, Florida

1. INTRODUCTION

The Florida Keys are home to a vulnerable population at risk to the hazards associated with tropical cyclones (TCs). These hazards include storm surge, damaging winds, flooding rains, and tornadoes. On occasion, tornadoes associated with TCs have caused numerous injuries and extensive property damage in the Florida Keys. For example, at least three tornadoes associated with Tropical Storm Agnes (1972) affected several Florida Keys communities, injuring 40 people and causing over $500,000 in damage (DOC 1972). The Agnes tornadoes moved through the Keys during the dark of night, over 400 kilometers (km; 249 miles (mi)) from the center of a northward-moving, intensifying tropical storm. A November tornado associated with Tropical Storm Mitch (1998) injured 20 people and damaged over 600 homes in the upper Florida Keys, causing an estimated $25,000,000 in damage (NCDC 1998). The path length of this tornado was 19.3 km (12 mi), nearly parallel to the narrow island of Key Largo. More recently, a tornado within the southern sector of the nascent Hurricane Katrina (2005) moved through portions of Vaca Key (Marathon), causing considerable damage to a new airport hangar (NCDC 2005).

Several TC tornado climatologies have been constructed over the years, documenting the locations, times, and atmospheric environment with which TC tornadoes have been associated (Sadowski 1962; Smith 1965; Pearson and Sadowski 1965; Hill et al. 1966; Novlan and Gray 1974; Gentry 1983; McCaul 1991; Verbout et al. 2007; Schultz and Cecil 2009; Edwards 2010). Climatological descriptions of the frequency and variation of hazardous weather events are important to a wide variety of groups, including weather forecasters, emergency managers, insurance companies, and the public (Brooks et al. 2003). Weather forecasters routinely integrate local climatology into their diagnoses of the current atmospheric state (Moller 2001). Emergency managers assess the climatology of hazardous weather events in order to mitigate potential harmful impacts in their communities, as well as to bolster public hazardous weather awareness and disaster preparedness efforts. This investigation was motivated by a need to better understand the characteristics of tornadoes associated with TCs in the Florida Keys. Several TC tornadoes have affected Florida Keys communities since the late 1990s, and a scrutiny of this particular TC hazard is timely.

The purpose of this paper is to conduct an examination of TC tornado reports in the Florida Keys, compare the results with those from some of the larger TC tornado climatologies in the literature, and present the results so that local weather forecasters and emergency managers may integrate knowledge of this hazard into their diagnostic routines and mitigation and preparedness activities, respectively.

* *Corresponding author address*: Kennard B. Kasper, NOAA/National Weather Service, 1315 White Street, Key West, Florida 33040; e-mail: kennard.kasper@noaa.gov

2. DATA

Tornado records were obtained from the nationwide Storm Prediction Center one-tornado (ONETOR) database. Each tornado report includes information concerning start time and location, path length and width, injuries, fatalities, Fujita-scale (F-scale; Fujita 1971) or Enhanced Fujita-scale (EF-scale; WSEC 2006) rating[1], and damage estimates. This database is described by Schaefer and Edwards (1999), and some of the caveats are discussed by Doswell and Burgess (1988), Brooks and Doswell (2001), and McCarthy (2003). Tropical cyclone data were obtained from the National Hurricane Center best-track records (Hurricane Data, or "HURDAT"). The HURDAT database provides the name, date, winds, central pressure, and location of the center of circulation at six-hourly intervals. The HURDAT database is described by Jarvinen et al. (1984) and Landsea (2004). Individual tornadoes were subjectively matched with specific tropical cyclones based upon the analyzed TC best track. Linear hourly interpolation between six-hourly HURDAT center positions resulted in an estimate of the TC center at tornado time.

Waterspouts associated with TCs were not included in this climatology. A cursory inspection of *Storm Data* reports in the Florida Keys during TC landfalls or when TCs are nearby indicate that actual waterspout entries were infrequent prior to the 1990s. However, anecdotal data from *Storm Data* reports indicate that several of the TC tornadoes in this study likely originated as waterspouts. In addition, warning meteorologists at the NOAA/National Weather Service (NWS) Weather Forecast Office in Key West commonly identify offshore supercells within the spiral rainbands of nearby TCs using Weather Surveillance Radar-1988 Doppler (WSR-88D; e.g., see Devanas et al. 2008). One such rainband supercell spawned a large waterspout over the Straits of Florida during the afternoon of 23 October 2005 (Fig. 1). The long-lived waterspout moved within three miles west of Old Town (western) Key West as Hurricane Wilma approached from the southwest. Analysis of WSR-88D base data revealed a well-defined hook echo (Lemon and Doswell 1979) and a deep, persistent mesocyclone. This "offshore tornado" likely would have caused considerable damage had it

[1] The NWS implemented the EF-scale in February 2007.

followed a path over the densely populated island community of Key West rather than one safely over the tidal flats and channels a few miles west of Key West. Despite this notable exception, the lack of observers either offshore or onshore, especially during a tropical cyclone threat[2], precludes an accurate assessment of the frequency of TC waterspouts offshore the Florida Keys.

Fig. 1. Photograph of a large waterspout over Hawk Channel southwest of Key West, Florida. Photograph by Tim Chapman.

Rawinsonde data were obtained from the University of Wyoming College of Engineering/Department of Atmospheric Science upper air archive (available online at http://weather.uwyo.edu/upperair/soundings.html.) Proximity criteria of 3 h and 185 km (115 mi) were used to determine which TC tornado events were close to rawinsonde observation sites. These are the same criteria employed by both Novlan and Gray (1974) and McCaul (1991). These proximity criteria yielded only seven rawinsonde observations.

3. RESULTS

During the period 1950–2009, 65 tornadoes were reported officially in the Florida Keys. Of these, 23 (35.4%) were associated with 13 TCs (see Table 1), including nine F0-rated tornadoes, eight F1-rated tornadoes, and four F2-rated tornadoes. Two storm ratings were "unknown". Two of the F2-rated tornadoes caused all 60 recorded injuries (the Big Coppitt Key tornado of 18 June 1972 (Tropical Storm Agnes) and the Key Largo tornado of 4 November 1998 (Tropical Storm Mitch). Fortunately, no deaths associated with a TC tornado were recorded in the Florida Keys between 1950 and 2009. Figure 2 is a map of the Florida Keys with names and locations of the communities affected by TC Tornadoes.

3.1 *Temporal Distribution*

3.1.1 *Interdecadal Trends*

An increasing trend in the number of Florida Keys TC tornado reports is evident since the 1950s (see Fig. 3). However, the limited sample size requires interpretation with caution. Nevertheless, similar trends have been noted in the tornado record for both TC tornadoes and overall tornado reports (Edwards 2008).

TABLE 1. List of TC tornadoes by date, TC, and impact location; "TD", "TS", and "H" refer to "tropical depression", "tropical storm", and "hurricane", respectively.

DATE	TROPICAL CYCLONE	LOCATION
4 Jun 1953	TS Alice	Key West
8 Sep 1965	H Betsy	Marathon
8 Sep 1965	H Betsy	Big Pine Key
24 May 1970	TD Alma	Big Pine Key
18 Jun 1972	TS Agnes	Big Coppitt Key
18 Jun 1972	TS Agnes	Key West
18 Jun 1972	TS Agnes	Conch Key
16 Aug 1981	TS Dennis	Plantation Key
2 Jun 1982	TD 1 (Alberto)	Plantation Key
3 Jun 1982	H Alberto	Stock Island
3 Jun 1982	H Alberto	Cudjoe Key
11 Oct 1987	TS Floyd	Rock Harbor
4 Nov 1998	TS Mitch	Islamorada
4 Nov 1998	TS Mitch	Rock Harbor
4 Nov 1998	TS Mitch	Key Largo
15 Oct 1999	H Irene	Boca Chica Key
15 Oct 1999	H Irene	Craig Key
26 Aug 2005	H Katrina	Marathon
1 Jun 2007	TS Barry	Sugarloaf Key
18 Aug 2008	TS Fay	Big Pine Key
18 Aug 2008	TS Fay	Ramrod Key
9 Sep 2008	H Ike	Key Largo
10 Sep 2008	H Ike	Lower Matecumbe Key

3.1.2 *Monthly*

Figure 4 shows the TC tornado distribution by month. The month with the most TC tornadoes is June. Tropical cyclones Agnes (1972) and Alberto (1982) produced six of the eight June tornadoes. Some evidence exists to support the assertion that Agnes was associated with up to six tornadoes in the Florida Keys (Hagemeyer and Spratt 2002). Two of the tornadoes associated with Agnes were rated F2 on the F-scale. This is significant because only six F2-rated tornadoes have been reported in the Florida Keys since 1950[3], with four of these associated with TCs (two with Agnes (1972), and one each with Mitch (1998) and Katrina (2005). See Fig. 5 for the TC tornado distribution by F-scale/EF-scale damage rating.

[2] A significant percentage of the population of the Florida Keys evacuates to the mainland when potential for a major hurricane impact exists.

[3] The Marathon, Florida tornado of 8 September 1965 associated with Hurricane Betsy was rated F2 by Grazulis (1993), whereas the ONETOR database shows an F1 rating.

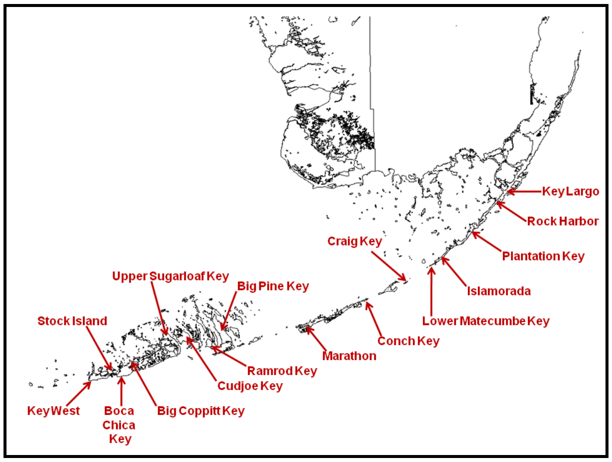

Fig. 2. Map of the Florida Keys with locations and names of communities affected by TC tornadoes (1950–2009).

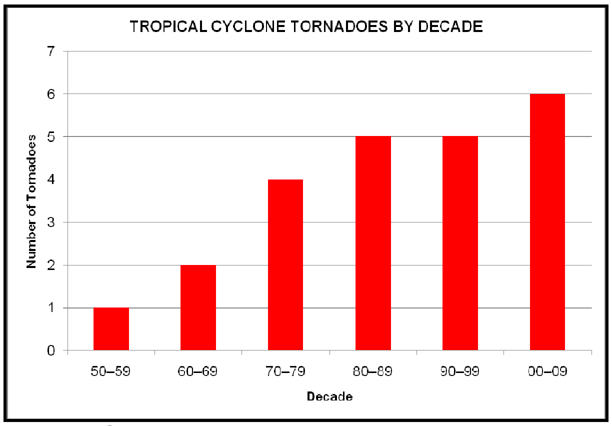

Fig. 3. TC tornadoes by decade, 1950-2009.

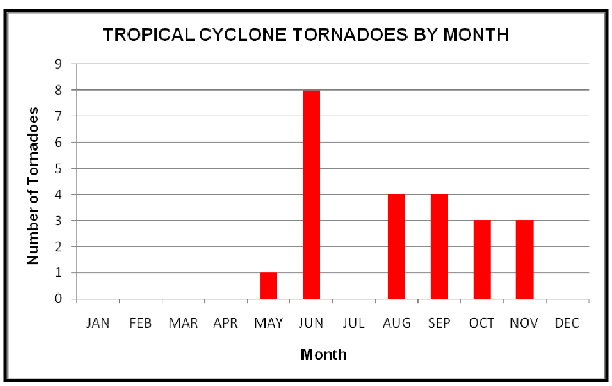

Fig. 4. TC tornadoes by month, 1950-2009.

No TC tornadoes have been reported in July, and only one was reported during the month of May (in 1970, associated with Tropical Depression Alma). Four TC tornadoes each were reported in August and September, with three each in October and November.

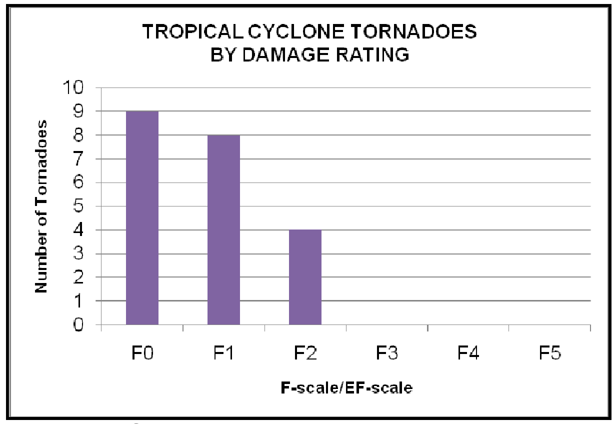

Fig. 5. TC tornado distribution by F-scale/EF-scale damage rating.

3.1.3 *Time of Day*

The distribution of TC tornadoes by time of day is shown in Fig. 6. Over one third (35%) of all TC tornadoes occurred during the two hours between 1600 and 1800 EST (2100–2300 UTC). This maximum in TC tornado activity during the late afternoon hours is in general agreement with results from some of the larger TC tornado climatologies (e.g., Gentry 1983, McCaul 1991, and Schultz and Cecil 2009).

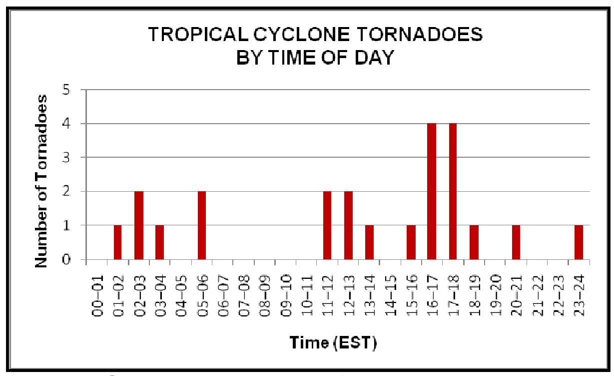

Fig. 6. TC tornadoes by time of day.

3.2 *Spatial Distribution*

The azimuth and range of each tornado with respect to the TC center were calculated relative to true north. The resulting polar coordinate plot is presented in Fig. 7. All tornadoes occurred in the eastern Cartesian quadrants between 20° and 170° azimuth, with the northeastern quadrant containing 65% of the tornadoes. For the tornadoes beyond 200 km (124 miles) from the TC center, over two thirds (69%) of the tornadoes occurred between 60° and 90° azimuth.

With respect to radial distance, a bimodal distribution was evident with 30% of the tornadoes occurring less than 100 km (62 mi) from TC center and 52% occurring beyond 400 km (249 mi) from the TC center (see Fig. 8). Nearly half (43%) of the tornadoes occurred between 400 and 500 km (249–311 mi) from the TC center. The mean azimuth and range of all TC tornadoes was 86° and 303 km (188 mi). For "outer rainband" tornadoes (defined as those tornadoes beyond 200 km (124 mi) from TC center, following Schultz and Cecil 2009), the mean azimuth and range were 77° and 458 km (285 mi), whereas for "core region" tornadoes, the mean azimuth and range were 98° and 102 km (63 mi).

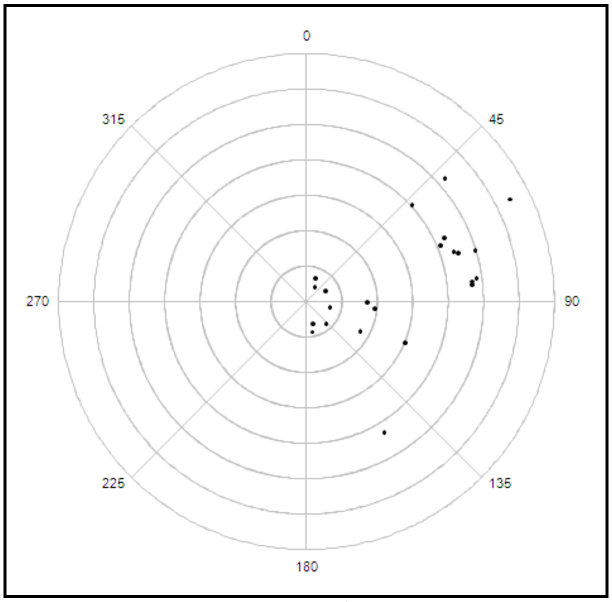

Fig. 7. Polar coordinate plot of tornadoes with respect to TC center relative to true north. Range marks at intervals of 100 km (62 mi).

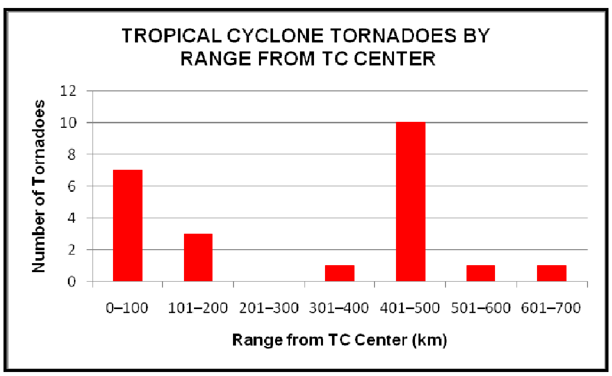

Fig. 8. Range distribution of reported TC tornadoes, 1950–2009.

Figure 9 shows all TC center locations near tornado time. The TC centers are tightly clustered over the extreme southeastern Gulf of Mexico, mostly west and southwest of the Florida Keys. Note that no TC centers are plotted east of 80.5° west longitude. Figure 10 is a mean sea level pressure composite analysis prepared using National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis data (Kalnay et al. 1996). The six-hourly reanalysis closest in time to each TC tornado start time was selected to complete the composite. Duplicate analyses were omitted from the composite. Note that the composite cyclone is centered just north of western Cuba such that the northeastern quadrant is positioned directly over the Straits of Florida, Florida Keys, and adjacent southeastern Gulf of Mexico.

3.3 *Rawinsonde Observations*

Table 2 enumerates mean geopotential height, temperature, dewpoint depression, wind direction, and wind speed for several pressure levels from seven proximity rawinsonde observations taken at Key West, Florida. Of interest are the mean values for wind speed and direction. The mean wind speed increases from 9.9 meters per second (m s^{-1}; 19 knots (kt)) to 18.3 m s^{-1} (35 kt) between the surface and 850 hPa, while the wind direction veers from 116° (east-southeast) to 208° (south-southwest) between the surface and 850 hPa. Such a highly sheared lower troposphere has long been observed to be characteristic of tropical cyclone tornado environments (e.g., Novlan and Gray 1974).

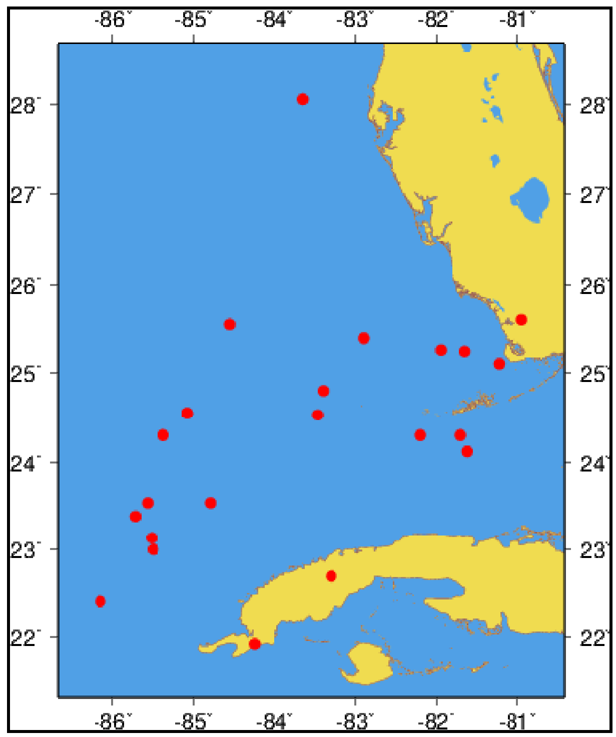

Fig. 9. Locations of TC centers at associated tornado start times; latitude in one-degree intervals is listed on the vertical axes; longitude in one-degree intervals is listed on the horizontal axes.

3.4 *TC Track and Intensity*

Figure 11 shows the tracks of all tropical cyclones associated with tornadoes in the Florida Keys, from 1950 through 2009. Eight of the 13 TCs (62%) originated over the western Caribbean Sea, while three TCs (23%) developed initially over the central or eastern tropical Atlantic Ocean (Cape Verde storms). Two TCs (15%) developed in the vicinity of the Greater Antilles east or southeast of the Florida Keys and thence moved westward or west-northwestward.

Over half (52%) of all TC tornadoes developed in association with tropical storms, while 39% were associated with hurricanes, and 9% occurred with tropical depressions. A large majority (79%) of outer rainband tornadoes developed in association with TCs below hurricane intensity, while 30% of core region tornadoes developed from TCs below hurricane intensity. A comparison of time of day between outer rainband and core region tornadoes did not reveal any significant pattern of occurrence between the two modes, in contrast to the findings of Schultz and Cecil (2009).

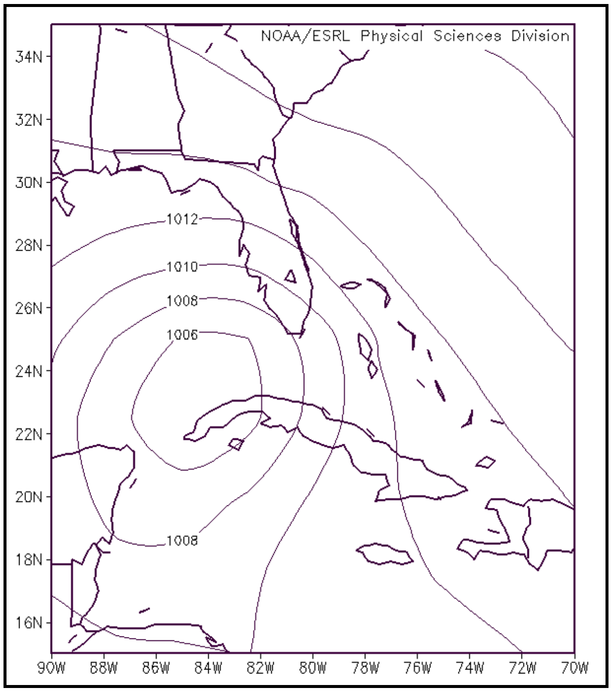

Fig. 10. Mean sea level pressure composite analysis for Florida Keys TC tornadoes, 1950–2009; units in hPa; image provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado from their web site at http://www.esrl.noaa.gov/psd/.

4. DISCUSSION AND IMPLICATIONS

Results from this work are consistent in many ways with those obtained in other studies, despite the small sample and limited geographic scope considered here. The majority (61%) of the TC tornadoes studied here occurred in association with non-hurricanes (i.e., tropical depressions and tropical storms). Edwards (2010) found that 73% of the tornadoes in the new TC tornado dataset (TCTOR; 1995–2009) occurred with non-hurricanes. In addition, over half (52%) of all Florida Keys TC tornadoes occurred beyond 400 km (249 mi) from the TC center of circulation. Many of the Keys TC

Table 2. Mean proximity rawinsonde data (Key West, Florida, site 72201); LEVEL = pressure level (hPa); GPH = geopotential height (m); T = air temperature (°C); T-Td = dewpoint depression (°C); DIR = wind direction (°); SPD = wind speed (m s^{-1} (kt)); M = missing data rendered calculation of mean impossible.

LEVEL	GPH	T	T-Td	DIR	SPD
surface	0	26.2	2.7	116	9.9 (19)
1000	52	25.9	2.4	150	10.1 (20)
850	1463	18.5	2.7	208	18.3 (35)
700	3111	10.7	4.6	218	18.1 (35)
500	5841	-4.4	3.4	226	21.4 (41)
400	7566	-14.4	4.6	233	20.7 (40)
300	9691	-28.1	9.2	236	16.9 (33)
250	10974	-38.0	6.9	245	15.1 (29)
200	12469	-50.8	7.0	233	13.0 (26)
150	14274	-66.7	6.5	201	13.8 (27)
100	M	-78.0	6.0	177	6.0 (12)

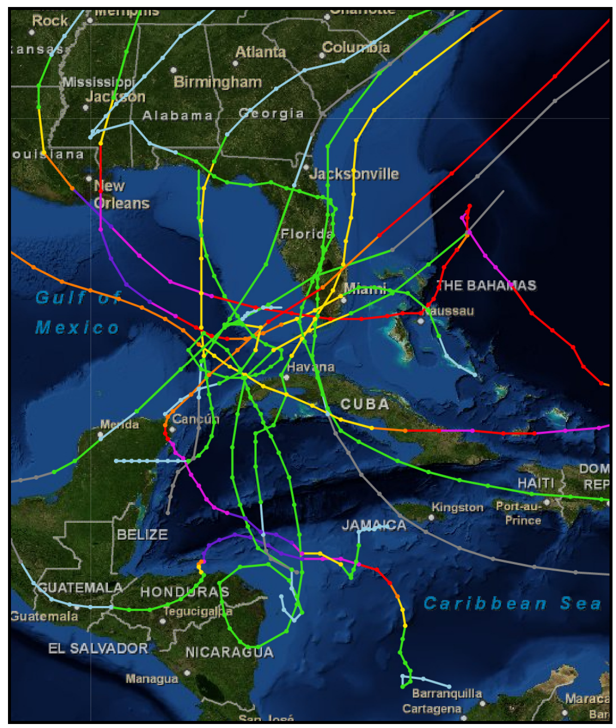

Fig. 11. Tracks of tropical cyclones associated with tornadoes in the Florida Keys, 1950–2009; image courtesy of the NOAA Coastal Services Center.

tornado situations involved a poleward-moving tropical storm centered just northwest or north of the western tip of Cuba (see Figs. 9 and 10), with many of the cyclones re-curving northeastward toward the Florida Keys (Fig. 11). Numerous operational challenges emerge quickly and simultaneously with the onset of a heightened TC tornado threat. Among these are coordination and issuance of tropical cyclone advisories, elevated decision support activities (e.g., emergency manager briefings and consultations), increased telephone and walk-in traffic, and evacuation orders. Therefore, NWS field forecasters and warning meteorologists must maintain focus while prioritizing the TC tornado threat appropriately in the face of increasing operational challenges. Many of these challenges have been described further in papers by Hagemeyer and Hodanish (1995); Spratt et al. (1997); and Hagemeyer (1998). In addition, both Spratt et al. (1997) and Edwards (2010), and references therein, offer excellent recommendations regarding basic forecast techniques and practices and environmental, rainband, and storm-scale assessment, respectively.

The Florida Keys TC tornado climatology revealed two distinct radial modes in the spatial distribution of tornadoes. This result is in agreement with similar findings by Gentry (1983), Weiss (1987), McCaul (1991), and Schultz and Cecil (2009).

A significant percentage of TC tornadoes occurred during the two-hour period of 1600–1800 EST (2100–0100 UTC). This late-afternoon maximum also is consistent with results from several previous studies.

The increasing trend in TC tornado reports since 1950 may be a local reflection of the overall national increase in tornado reports, probably due to a combination of factors including more aggressive NWS storm spotting and verification programs, increased media coverage, increasing population, and greater photographic documentation capabilities; see McCarthy (2003), Brooks et al. (2003), and Edwards (2008) for further discussion. Notwithstanding this interdecadal upward trend in TC tornado reports, only 13 TCs have been associated with tornadoes since 1950 in the Florida Keys. Why so few? Figure 12 shows 87 TCs having tracked just within 200 km (124 mi) of Key West, Florida between 1950 and 2008, and, as shown in Section 3, over half of the Florida Keys TC tornadoes occurred beyond 200 km (124 mi) from TC center. One may speculate that given the sparse population still present in some of the Florida Keys, especially during evacuation orders, some tornadoes simply travel harmlessly undetected across the mangroves. However, other factors surely are at play. Many of the larger climatologies already referenced have shown that the interaction of buoyancy and vertical wind shear in the lower troposphere is critical to tornado production in tropical cyclones. In addition, recent papers have underscored the importance of boundaries with respect to TC tornadoes (e.g., Edwards and Pietrycha 2006; Devanas et al. 2008). Certainly, further research on the topic is warranted, especially in light of the increasing availability and diversity of data from satellites, dropwindsondes, and numerical models.

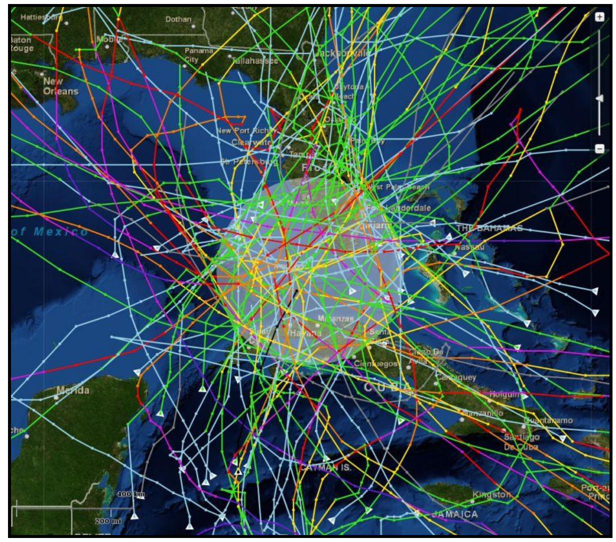

Fig. 12. Tracks of all TCs passing within 200 km (124 mi) of Key West, Florida (as measured by the center of circulation); image courtesy of the NOAA Coastal Services Center.

5. SUMMARY

Some of the key findings from this climatology are as follows:

- Sixty-one percent of all TC tornadoes in the Florida Keys between 1950 and 2009 were associated with cyclones of less than hurricane intensity.
- The data revealed a bimodal spatial distribution of tornadoes with respect to radial distance from the cyclone center.
- Tropical cyclone centers of circulation associated with tornadoes were tightly clustered over the southeastern Gulf of Mexico; no centers occurred east of -80.5 west longitude.
- Over a third (35%) of tornadoes occurred during the two-hour period between 1600 and 1800 EST (2100–2300 UTC).
- Over half (62%) of the tornado reports examined are associated with poleward-moving tropical cyclones of Caribbean origin.

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