METEOROLOGICAL APPLICATIONS
Meteorol. Appl. (2014)

(wileyonlinelibrary.com) DOI: 10.1002/met.1437

Factors contributing to tornadogenesis in landfalling Gulf of Mexico tropical cyclones

Cory L. Rhodes[a]* and Jason C. Senkbeil[b]
[a] *Department of Earth Sciences, University of South Alabama, Mobile, AL, USA*
[b] *Department of Geography, University of Alabama, Tuscaloosa, AL, USA*

ABSTRACT: Tropical cyclone tornadoes (TCTs) are brief and often unpredictable events that can produce fatalities and create considerable economic loss. Given these uncertainties, it is important to understand the characteristics and factors that contribute to tornado formation within tropical cyclones. This research analyses this hazardous phenomenon, examining the relationships among tropical cyclone intensity, size and tornado output. Furthermore, the influences of severe weather parameters on tornado output near the time of tornado formation were assessed between two phases of a tropical cyclone's life cycle: during hurricane and tropical storm intensity, termed tropical cyclone tornadoes (TCTs), and during tropical depression and remnant low intensity, termed tropical low tornadoes (TLTs). Results show that tornado output is significantly influenced by tropical cyclone intensity. Values for storm relative helicity, energy helicity index, and severe weather threat index are significantly higher within TCT environments, thus resulting in more tornadoes.

KEY WORDS tropical cyclones; tornadoes; hazards

Received 16 May 2013; Revised 14 July 2013; Accepted 27 August 2013

1. Introduction

Tropical cyclone (TC) tornadoes in the United States have contributed to an estimated 4% of all TC-related fatalities (Rappaport, 2000) and have accounted for $1.4 billion in damages since 1950 (Schultz and Cecil, 2009). Hurricane Beulah (1967), which spawned approximately 115 tornadoes during its lifetime, accounted for five fatalities and over $1.9 million in tornado-related damages (Orton, 1970). Moreover, Hurricane Ivan spawned 118 confirmed tornadoes in September 2004, including 18 F2- and 1 F3-ranked tornadoes. Of these, two F2 tornadoes in Florida accounted for over $5 million in damages (National Climatic Data Centre, 2011). Compared to other hazards within TCs, such as surge and inland flooding (Pielke *et al.*, 1999; Rappaport, 2000; Blake *et al.*, 2011), tornadoes account for a smaller percentage of fatalities and monetary damage. Nevertheless, TC tornadoes (TCTs) are a substantial atmospheric hazard because of the increased uncertainty associated with predicting the number, location, and intensity within landfalling systems.

TCTs are generally weaker, smaller, and of shorter duration than synoptic baroclinic tornadoes. Most tornadoes occur within TCs as a result of a sharp gradient in wind shear, brought on by the transition from water to land as a TC makes landfall (Moore and Dixon, 2011). The majority of land-falling hurricanes ($>33\,\mathrm{m\,s^{-1}}$) are capable of producing tornadoes, while approximately half of all tropical storms ($17-33\,\mathrm{m\,s^{-1}}$) exhibit an environment that is favourable for tornado production (Gentry, 1983). TC tornadoes can develop before, during or after TC landfall. Furthermore, TCTs can occur in both coastal and inland regions, increasing the difficulty in predicting economic loss, fatalities, forecasting, and detection. It has been well-documented that tornadoes associated with land-falling TCs can occur outside the envelope of known gale force winds (Pearson and Sadowski, 1965; Hill *et al.*, 1966; Orton, 1970), where tornado awareness is lower. This increases the risk to residents beyond the TC path (Weiss, 1985; McCaul, 1991; Spratt *et al.*, 1997).

Numerous climatologies of TCTs have been performed with different applications such as temporal and spatial distribution, frequency and intensity variations, outbreak potential, and fatalities and hazards (Malkin and Galway, 1953; Pearson and Sadowski, 1965; Smith, 1965; Hill *et al.*, 1966; Novlan and Gray, 1973; Gentry, 1983; McCaul and Weisman, 1996; Curtis, 2004; Verbout *et al.*, 2007; Schultz and Cecil, 2009; Edwards *et al.*, 2010; Moore and Dixon, 2011). McCaul's (1991) analysis of tornado output based on storm size and intensity suggests that the quantity and intensity of tornadoes increases with both TC intensity and size. McCaul further emphasizes the importance of this study, stating that future analyses employing these parameters would be beneficial to forecasters in the tornado detection process within land-falling tropical systems.

Other researchers have followed a case study approach to understand atmospheric dynamics and environmental parameters that enhance or contribute to tornado formation within a TC (Novlan and Gray, 1973; Gentry, 1983; Weiss, 1985). As with tornado output within given stages of TC lifecycle, however, researchers have analysed this objective using dynamic parameters (McCaul and Weisman, 1996; Curtis, 2004; Edwards *et al.*, 2010). Although beneficial from the operational standpoint, synoptic perspectives provide additional understanding of the atmosphere in which tornado formation occurs. Furthermore, this outlook would provide an insight that may better predict tornado quantity and location within a storm. Cohen (2010) used a synoptic-based analysis to assess tropical cyclones along the Gulf Coast that produced a large quantity of tornadoes during their respective life cycles.

---

* Correspondence: C.L. Rhodes, University of South Alabama, Department of Earth Sciences, 5871 North Drive, Life Sciences Classroom Building (LSCB) 136, Mobile, AL 36688-0002, USA
E-mail: cory.rhodes@gmail.com

This research consists of hybrid methods of creating a size and intensity climatology of TCTs, and analysis of severe weather parameters that occur during the cyclone phase of a storm and during the dissipating tropical or remnant low stage. No previous research has isolated the characteristics of TCTs within these two stages of formation. This research has two primary objectives:

1. to revisit and explore the independent and interactive relationships between TC size and TC intensity and their effects on tornado output, because many recent significant tropical cyclones have made landfall in the Gulf Coast region of the USA since the study by McCaul (1991), and,
2. to determine dynamic factors contributing to output and intensity differences between TCTs and tropical low tornadoes (TLTs) within land-falling TCs.

Methods, results and discussion, and a conclusion follow the introduction. The methods section consists of several subsections describing storm criteria, data and statistical methods. The results and discussion section follows an outline similar to the methods.

2. Data and methods

2.1. Storm criteria

This study encompasses not only hurricanes, which have been the primary focal point of many previous studies (Malkin and Galway, 1953; Pearson and Sadowski, 1965; Smith, 1965; Novlan and Gray, 1973; Gentry, 1983; McCaul, 1991; McCaul and Weisman, 1996; Verbout *et al.*, 2007; Moore and Dixon, 2011) but also tropical storms, which can produce tornadoes during their life cycle. All TCs that made landfall along the states that border the Gulf of Mexico (Texas, Louisiana, Mississippi, Alabama, and the panhandle, western portion and southern tip of the Florida peninsula) are included in this research. The interior states of Georgia and Arkansas are also included, as many TCs recurve after landfall, and have commonly spawned tornadoes within these two states. TCs that made landfall in Mexico within 250 km of the Texas border and spawned tornadoes in the United States were also included in the dataset. A total of 95 TCs made landfall along the Gulf Coast during the 1950–2010 study period (61 hurricanes and 34 tropical storms), resulting in a total of 1194 tornadoes within the study area. All TCs that made landfall within the study area are detailed in the Supporting Information (Table S1). Within this dataset, 13 of the 95 TCs displayed fluctuating intensities at landfall or inland. This possibly produces discrepancies between the official intensity rating from the National Hurricane Centre (NHC) and the intensity of the storm at the time of tornado formation. Although listed by NHC assigned rating, these TCs are referred to by their inland status at the time of tornado formation in this research. In order to fully assess the objectives of the study, many data sources were used.

2.2. Data

2.2.1. *National Climatic Data Centre (NCDC)*

All tornadoes that occurred during the Atlantic hurricane seasons of 1950–2010 were extracted from the NCDC Storm Events database (NCDC, 2011). Tornadoes within the NCDC Storm Events database were documented using the Fujita Scale (F-Scale) rating. The Fujita Scale was revised in 2007 to the Enhanced Fujita Scale (EF-Scale), adjusting wind parameters for each category. The final 3 years of this dataset fall into the EF-Scale adjustment; however, NCDC has continued documenting tornadoes using the Fujita Scale throughout the duration of this study period, allowing for consistent documentation of tornadoes. The Fujita and Enhanced Fujita Scales, along with the Operational Scale used by the Storm Prediction Centre (SPC) can be viewed at http://www.spc.noaa.gov/faq/tornado/ef-scale.html (SPC, 2013).

An additional database that examines tornadoes within a land-falling TC, entitled TCTOR (Tropical Cyclone TORnado) is also available (Edwards, 2010). TCTOR was used within this research as a comparison to the NCDC database. TCTOR is archived from 1995 to the present; therefore, the information provided was used for comparison purposes to the Storm Events database for the years listed.

2.2.2. *National Oceanic and Atmospheric Administration (NOAA)'s Coastal Services Centre Historical Hurricane Tracks*

To associate these tornadoes with a Gulf of Mexico land-falling TC, the NOAA Coastal Services Centre (CSC) Historical Hurricane Tracks database was used (CSC, 2011) and is available online (http://csc.noaa.gov/hurricanes/#). This database employs an interactive GIS-based mapping approach detailing the path of each TC from inception to dissipation. The database uses colour-coding to display intensity variations during the life cycle of the TC in shapefile format. In addition, the CSC provides advisories at 6 h intervals (0000, 0600, 1200, and 1800), recording the date and time (in GMT) of each advisory, latitudinal and longitudinal position of the storm, pressure, maximum sustained winds (MSW) and SS category at the time of advisory. The SS category changes for each TC were monitored using this database in order to assign tornado output among two phases of a TC life cycle. Tornadoes that spawned during the TC hurricane or tropical storm phase were listed as TCTs, while those that spawned during the tropical depression or remnant low phases were labeled TLT. The tornadoes extracted from the NCDC Storm Events database were then placed into one of these two groups based on TC intensity level at the time of occurrence.

2.2.3. *HURDAT, Best Track and Extended Best Track datasets*

The NHC HURricane DATabase (HURDAT) was devised to better understand the track and forecast observations of land-falling TCs of the North Atlantic Basin (Jarvinen *et al.*, 1984). Amidst technological advances in succeeding years leading to numerous revisions, the current database includes a detailed account of each TC advisory, including 6 h observations of latitude, longitude, surface winds (1 min sustained maximum), minimum sea-level pressure, and status (tropical, subtropical, or extratropical, respectively) for each known land-falling TC dating back to 1851 (NOAA, 2012). The HURDAT database was used to document storm size using the Radius to Outermost Closed Isobar (ROCI) variable.

The Best Track dataset includes landfall information for each TC and is a reanalysis of the original HURDAT database. The update to the HURDAT database included clearing errors in documentation, using new analysis techniques in order to correctly identify location, time and intensity measurements

Table 1. List of the top 15 storms with the greatest TCT:TLT and TLT:TCT ratios, 1950–2010. The sounding locations, dates and times correspond to the time nearest to peak tornado activity. Storms are ranked in descending order by total tornado output in each category.

Storm	Sounding Date/Time	Location (Station)	TCT Output	TLT Output
Tropical Cyclone Tornadoes				
Hurricane Beulah (1967)	20 September 1967 0000 UTC	Brownsville, TX (KBRO)	117	0
Hurricane Rita (2005)	25 September 2005 1200 UTC	Jackson, MS (KJAN)	104	0
Hurricane Ivan (2004)	17 September 2004 0000 UTC	Charleston, SC (KCHS)	49	5
Hurricane Georges (1998)	29 September 1998 0000 UTC	Tallahassee, FL (KTLH)	35	14
Hurricane Katrina (2005)	30 August 2005 0000 UTC	Peachtree City, GA (KFFC)	49	0
Hurricane Andrew (1992)	27 August 1992 0000 UTC	Jackson, MS (KJAN)	42	6
Hurricane Gilbert (1988)	17 September 1988 1200 UTC	Corpus Christi, TX (KCRP)	39	0
Hurricane Allen (1980)	11 August 1980 0000 UTC	Corpus Christi, TX (KCRP)	34	0
Hurricane Ike (2008)	13 September 1908 0000 UTC	Lake Charles, LA (KLCH)	33	0
Hurricane Danny (1985)	17 August 1985 0000 UTC	Birmingham (Shelby Co), AL (KEET)	20	11
Hurricane Cindy (2005)	6 July 2005 1200 UTC	Tallahassee, FL (KTLH)	17	11
Hurricane Lili (2002)	3 October 2002 1200 UTC	Slidell, LA (KLIX)	26	1
Hurricane Audrey (1957)	28 June 1957 0000 UTC	Jackson, MS (KJAN)	22	1
Hurricane Alicia (1983)	18 August 1983 0000 UTC	Lake Charles, LA (KLCH)	22	0
Hurricane Carla (1961)	11 September 1961 0000 UTC	Lake Charles, LA (KLCH)	20	1
Tropical Low Tornadoes				
Tropical Storm Fay (2008)	26 August 2008 0000 UTC	Tallahassee, FL (KTLH)	14	20
Tropical Storm Bill (2003)	2 July 2003 0000 UTC	Charleston, SC (KCHS)	6	9
Tropical Storm Fay (2002)	9 September 2002 0000 UTC	Corpus Christi, TX (KCRP)	3	8
Tropical Storm Hermine (2010)	9 September 2010 0000 UTC	Fort Worth, TX (KFWD)	3	8
Tropical Storm Chris (1982)	12 September 1982 0000 UTC	Jackson, MS (KJAN)	3	6
Tropical Storm Allison (1989)	28 June 1989 0000 UTC	Jackson, MS (KJAN)	1	8
Tropical Storm Frances (1998)	12 September 1998 0000 UTC	Lake Charles, LA (KLCH)	3	6
Tropical Storm Candy (1968)	25 June 1968 0000 UTC	North Little Rock, AR (KLZK)	2	5
Hurricane Bonnie (1986)	27 June 1986 1200 UTC	Lake Charles, LA (KLCH)	0	5
Tropical Storm Debra (1978)	29 August 1978 0000 UTC	Lake Charles, LA (KLCH)	1	3
Tropical Storm #1 (1964)	6 June 1964 1200 UTC	Jacksonville, FL (KJAX)	0	3
Tropical Storm #1 (1960)	26 June 1960 1200 UTC	Shreveport, LA (KSHV)	1	2
Tropical Storm Jenny (1969)	2 October 1969 1200 UTC	Jacksonville, FL (KJAX)	0	2
Tropical Storm Becky (1970)	22 July 1970 1200 UTC	Charleston, SC (KCHS)	0	2
Tropical Storm Beryl (1994)	16 August 1994 1200 UTC	Peachtree City, GA (KFFC)	0	2

Table 2. Results of two-way ANOVA test. Descriptives results (a), main and interactive results (b), and *post hoc* results (c) are presented.

(a) Descriptives Intensity	Size	Mean	*s*	*n*
Major	Large	31.50	38.40	17.00
	Small	22.50	16.10	6.00
	Total	29.10	33.90	23.00
Minor	Large	16.50	14.80	11.00
	Small	8.70	9.80	14.00
	Total	12.10	12.60	25.00
Weak	Large	7.10	9.20	14.00
	Small	5.50	4.20	27.00
	Total	6.00	6.30	41.00

Main and Interactive Effects

(b) Variables	*F*	df	*p*	Partial η^2
Intensity and tornado output	7.10	2.00	<0.01*	0.15
Size and tornado output	1.90	1.00	0.18	0.02
Intensity × size and tornado output	0.31	2.00	0.74	0.01

Post hoc

(c) Intensity	*Versus* Intensity	Mean difference	*p*
Major	Minor	17.00	0.01*
	Weak	23.00	<0.01*
Minor	Weak	6.00	0.42

*Significance at the 0.05 level.

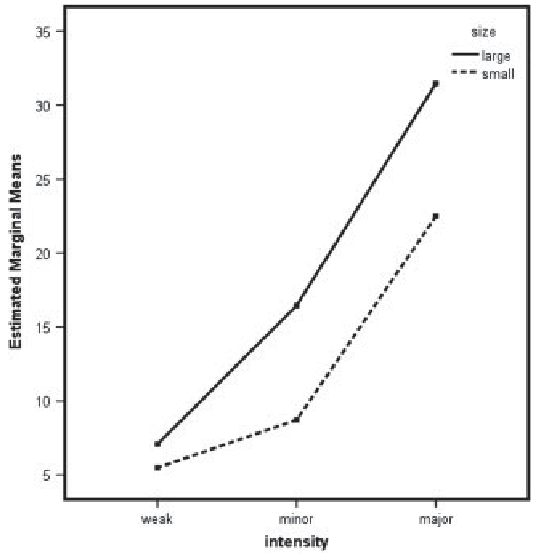

Figure 1. Two-way ANOVA profile plot depicting average tornado output and intensity for large and small TCs. In general, mean tornado output increases as intensity increases for both large and small storms.

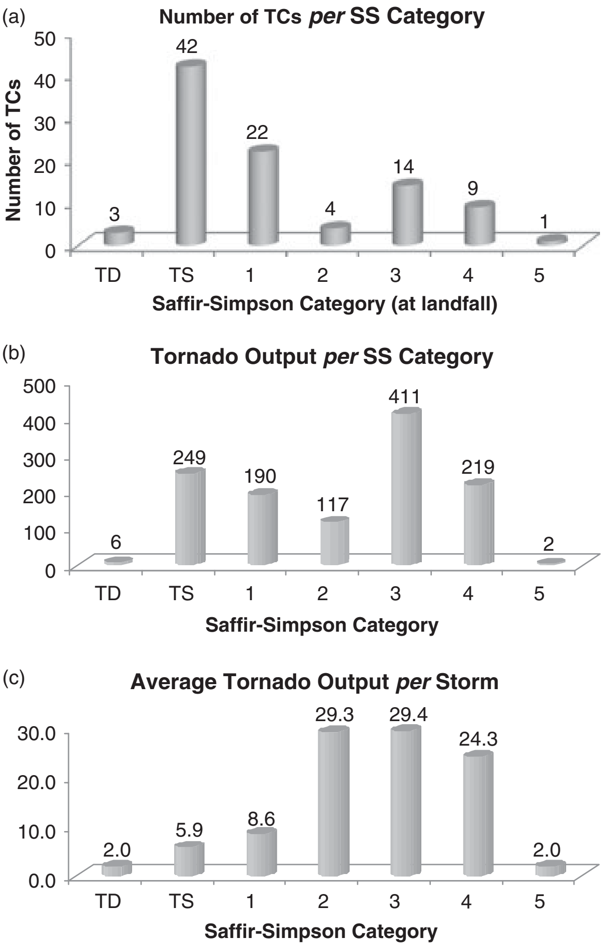

Figure 2. The number of TCs within each Saffir-Simpson (SS) category (a), tornado output for each Saffir-Simpson category (b) and average tornado output for each Saffir-Simpson category (c).

at landfall, and incorporating previously undocumented TCs (Landsea *et al.*, 2004).

In 2004, the Extended Best Track (EBT) dataset was created to include size and structural parameters such as wind radii at the 17.5 m s^{-1}, 30.9 m s^{-1}, and 38.1 m s^{-1} levels among each quadrant of the storm, radius of maximum wind (RMW) and Eye Diameter (ED) readings, as well as the pressure of the outmost closed isobar (POCI) that could be analysed statistically throughout the storm quadrants (Kimball and Mulekar, 2004; Demuth *et al.*, 2006). This information has been estimated for land-falling TCs from 1988 to the present for the North Atlantic Basin, with various size parameters available for select storms dating back to 1851.

2.2.4. *Upper-level sounding data*

A dynamic approach was chosen to examine the tornadic environment accompanying or preceding a land-falling TC. Sounding data nearest the time of formation was extracted using Plymouth State Weather Centre's RAOB Selector for Archived Contiguous United States Data, available online (http://vortex.plymouth.edu/raob_conus-u.html) (Plymouth State University, 2012). Because RAOB data is obtained twice daily (0000 and 1200) and in limited locations, dynamic information was gathered at the location, time and date closest to tornado occurrence. Specific parameters assessed included Convective Available Potential Energy (CAPE), 0–3 km Storm Relative Helicity (SRH), Energy Helicity Index (EHI), Bulk Richardson Number (BRN), K-Index and Severe Weather Threat Index (SWEAT). Each parameter is an indicator of tornadic or severe weather potential and definitions can be found at the National Weather Service Louisville (KY) website (http://www.crh.noaa.gov/lmk/soo/docu/indices.php).

2.3. Statistical analysis

2.3.1. *Two-way ANOVA*

A two-way ANOVA was performed to evaluate the effects of TC size and intensity on tornado output within the study area. This test was used to determine two things: (1) if each independent variable or factor had a main effect on the dependent variable, and (2) if both independent variables had a combined interaction upon tornado output.

A total of 89 TCs had sufficient data for analysis. Each independent variable was categorized into groups. Radius to outermost closed isobar (ROCI) size at landfall was divided into two groups based on the overall median ROCI measurement: small (0–175 nm) and large (>175 nm). The median value also proved to be a reliable natural break in the ROCI dataset. A total of 47 TCs were categorized as small while 42 TCs fell into the large TC group. Intensity values were divided into three categories roughly based on SS hurricane wind categories: 'weak' (17–33 m s^{-1}), 'minor' (34–51 m s^{-1}) and 'major' (>51 m s^{-1}). Overall, 41 TCs were listed as 'weak', 25 as 'minor' and 23 as 'major'. Tornado output in this analysis includes only tornadoes spawned within the study area; therefore, it may not represent the total count of all tornadoes in association with a land-falling TC. Tornado counts were restricted to the domain of the study area so that phase transitions between TLT and extra-tropical cyclone stage were more easily identified. Furthermore, with increasing distance inland the numbers of tornadoes greatly diminished in most storms. Nevertheless, a second analysis was performed to assess the validity of restricting the tornado output to the study area.

Table 3. Parameter values for top 15 TCT and TLT storms.

	K Index	SWEAT Index	CAPE ($\mathrm{J\,kg^{-1}}$)	EHI	BRN	SRH ($\mathrm{m^2\,s^{-2}}$)	Tornado Output
Tropical Cyclone Tornadoes							
Hurricane Beulah (1967)	35.6	382	336	1.1	3.0	603	117
Hurricane Rita (2005)	33.5	415	580	2.3	5.0	674	104
Hurricane Ivan (2004)	26.8	408	2279	1.6	61.7	113	54
Hurricane Georges (1998)	34.1	285	592	0.7	12.4	215	49
Hurricane Katrina (2005)	40.8	338	886	2.6	6.5	549	49
Hurricane Andrew (1992)	33.3	255	526	2.5	6.6	565	48
Hurricane Gilbert (1988)	38.5	318	5257	8.1	114.5	264	39
Hurricane Allen (1980)	31.9	291	629	1.3	6.1	377	34
Hurricane Ike (2008)	34.6	394	524	2.6	3.6	825	33
Hurricane Danny (1985)	37.8	419	1108	2.5	10.5	386	31
Hurricane Cindy (2005)	23.9	285	457	0.4	13.8	148	28
Hurricane Lili (2002)	34.9	359	650	1.9	9.9	489	27
Hurricane Audrey (1957)	31.4	316	37	0.1	0.5	299	23
Hurricane Alicia (1983)	32.8	275	708	0.5	22.1	122	22
Hurricane Carla (1961)	35.2	350	349	0.7	3.4	387	21
Mean	33.7	339	994	1.9	18.6	401	45
Standard Deviation	4.2	55.2	1281.9	1.9	30.4	214.0	28.6
Tropical Low Tornadoes							
Tropical Storm Fay (2008)	34.9	329	2006	1.8	35.1	163	34
Tropical Storm Bill (2003)	29.1	401	169	0.3	1.0	298	15
Tropical Storm Fay (2002)	40.1	244	1635	0.5	16.1	8	11
Tropical Storm Hermine (2010)	39.1	403	2042	3.4	27.1	215	11
Tropical Storm Chris (1982)	31.5	264	692	0.6	14.8	125	9
Tropical Storm Allison (1989)	33.3	232	1684	0.6	68.3	54	9
Tropical Storm Frances (1998)	38.1	423	596	0.8	12.6	212	9
Tropical Storm Candy (1968)	23	393	392	0.8	6.0	350	7
Hurricane Bonnie (1986)	28.1	182	2380	1.2	316.2	72	5
Tropical Storm Debra (1978)	31.2	272	109	0.1	9.2	63	4
Tropical Storm #1 (1964)	33.5	215	1289	0.7	42.5	79	3
Tropical Storm #1 (1960)	25.5	203	143	0.1	3.0	176	3
Tropical Storm Jenny (1969)	30.4	297	19	0.0	0.3	151	2
Tropical Storm Becky (1970)	31	219	985	0.8	64.9	113	2
Tropical Storm Beryl (1994)	33	229	26	0.0	0.7	199	2
Mean	32.1	287	944	0.8	41.2	152	8
Standard Deviation	4.8	82.4	831.0	0.9	79.3	93.8	8.1

The two-way ANOVA test was performed a second time, with the tornado count for the 15 most prolific tornado-producing TCs adjusted to include all tornadoes spawned during the life cycle of each storm. This was performed for comparison purposes only, to see if any changes occurred in the relationships between the variables. Any significant changes to the output within this study would be primarily affected by the top 15 tornado-producing TCs.

2.3.2. *Dynamic analysis of tornado output*

General inferential statistics were used to describe the dynamic environments among TCs with high TCT or TLT output (Table 1). In order to capture the environment that best represents respective TC tornado production, TCs with the highest TCT to TLT output ratio were chosen. A Kolmogorov–Smirnov test showed that all parameters assumed a normal distribution despite a small sample size of 15. Therefore, independent sample t-tests were performed in conjunction with Mann–Whitney U tests to ensure that all statistical assumptions were met. Independent sample t-tests and Mann–Whitney U tests were used to determine significant differences in parameter values between tornadic environments for TCT and TLT storms.

3. Results and discussion

3.1. Influences of size and intensity on tornado output

3.1.1. *Two-way ANOVA*

A two-way ANOVA was performed to evaluate the effects of TC size and intensity on tornado output within the study area. When testing for main effects, it was determined that intensity had a statistically significant effect on tornado output within the study area, with intense storms generating more tornadoes ($p < 0.01$). When examining *post hoc* results among the various levels of intensity (Table 2), the mean differences between ‘major’ and ‘minor’ TCs, along with ‘major’ and ‘weak’ TCs were significant, with p-values of 0.01 and <0.01, respectively. No significant relationship, however, existed between ‘minor’ and ‘weak’ categorized TCs. Size had a non-significant influence on tornado output ($p = 0.18$). This influence shows that tornado output has the potential to be abundant in TCs that are categorized as large in size, but is not necessarily the case among all large TCs. Large TCs can produce very few tornadoes, as with the case of Hurricane Claudette (2003), or an abundant amount, as seen in Hurricane Beulah (1967). No relationship could be determined by analysing the interaction

Table 4. Probability values of both independent sample t-tests (a) and Mann–Whitney U tests (b) for significant differences between parameters for TCT and TLT storms.

(a)

Variable	Group	n	Mean	s	df	t	p
K index	TCT	15	33.70	4.24	28.00	0.94	0.35
K index	TLT	15	32.10	4.76			
SWEAT	TCT	15	339.00	55.20	28.00	2.04	0.05*
SWEAT	TLT	15	287.00	82.40			
CAPE	TCT	15	994.00	1281.00	28.00	0.13	0.90
CAPE	TLT	15	944.00	831.00			
EHI	TCT	15	1.93	1.93	28.00	2.12	0.04*
EHI	TLT	15	0.77	0.86			
BRN	TCT	15	18.60	30.40	28.00	−1.03	0.31
BRN	TLT	15	41.10	79.30			
SRH	TCT	15	401.00	214.00	28.00	4.13	<0.01*
SRH	TLT	15	152.00	93.80			
Tornado output	TCT	15	45.20	28.60	28.00	4.80	<0.01*
Tornado output	TLT	15	8.40	8.10			

(b)

Variable	Group	n	Mean rank	Rank sum	U	p
K index	TCT	15	17.60	263.00	81.50	0.35
K index	TLT	15	13.40	202.00		
SWEAT	TCT	15	18.70	281.00	64.00	0.05*
SWEAT	TLT	15	12.30	184.00		
CAPE	TCT	15	15.30	230.00	110.00	0.90
CAPE	TLT	15	15.70	235.00		
EHI	TCT	15	19.30	289.00	56.00	0.04*
EHI	TLT	15	11.70	176.00		
BRN	TCT	15	14.00	211.00	91.00	0.31
BRN	TLT	15	16.90	254.00		
SRH	TCT	15	20.80	312.00	33.00	<0.01*
SRH	TLT	15	10.20	153.00		
Tornado output	TCT	15	22.50	338.00	7.50	<0.01*
Tornado output	TLT	15	8.50	128.00		

*Significance at the 0.05 level.

effects of intensity and size on tornado output within the study area.

The results of these relationships are shown in Figure 1. Regardless of size, TCs categorized as 'weak' produced a low average tornado total, with increasing output as intensity increased. This relationship is not absolute, however, as many TCs of higher intensity values within the study area (e.g. Category 4 and 5) produced relatively few tornadoes (e.g. Hurricanes Betsy (1965) and Camille (1969)). Many TCs with Category 3 intensity spawned a substantial amount of tornadoes (Figure 2). This category was placed under 'major' for intensity, which may explain the results of this relationship. The results echo that of Moore and Dixon (2011), who state that there is a statistically significant relationship between TC intensity and tornado output. However, the majority of tornadoes were associated with Category 3 storms.

The two-way ANOVA was performed a second time, with tornado output adjusted for the 15 most tornado-prolific storms in the dataset. The original dataset for this sample included only tornadoes that were spawned within the study area. This adjustment was made to include all tornadoes within the life cycle of the TC, as these 15 TCs would possibly show the greatest amount of variance within the dataset. Results were nearly identical to those in Table 2 and thus are not presented.

3.2. Severe weather parameters for TCT and TLT phases

Parameters for TCT and TLT environments were gathered nearest the time of heightened tornado output (Table 3). The majority of parameters within a TCT environment are higher than among the TLT environment as a result of intensity. When analysing total parameter values among each storm (see Table 3), 0–3 km SRH values are noticeably higher among TCT storms, displaying greater amounts of potential rotation within the atmosphere near the time of tornado formation, e.g. Hurricanes Beulah (1967), Rita (2005), and Ike (2008). Tornadoes spawned among the hurricane and tropical storm phases are primarily shear-driven, while CAPE is stronger in the TLT environment, which is especially evident for tropical storms Bonnie (1986), Fay (2008) and Hermine (2010).

The results of t-tests (Table 4) are significant for EHI and SRH, with p-values of 0.04 and <0.01, indicating significantly higher SRH and EHI for TCT environments. SWEAT was also significant ($p = 0.05$). Mann–Whitney tests showed that SWEAT, EHI and SRH were statistically significant, with p-values of 0.05, 0.02 and <0.01, respectively. These findings suggest that higher levels of wind shear, and to a lesser extent instability, are imperative in the production of tornadoes within a given TC. Upon individual analysis of the results among these two parameters, EHI values among the TCT environment average twice as high as those of the TLT environment. With EHI resulting from a combination of CAPE and SRH, and

SRH playing a statistically significant role in tornado formation, it can be concluded that wind shear is the primary factor in tornado output, regardless of the TC phase.

The results of this research are not without limitations, however, as average environmental parameters that were assessed within the synoptic and dynamic environments of Gulf Coast land-falling TCs may not accurately represent each land-falling TC. Furthermore, limited environmental sounding times and locations may not be indicative of the atmosphere at the precise time and location of tornado formation. Likewise, tornadoes associated with East Coast land-falling TCs may not imitate the environments presented in this research. Furthermore, case studies of the synoptic conditions associated with each tornado producing storm may help explain some of the anomalous high and low producing storms when dynamics are either favourable or unfavourable.

4. Conclusion

This research had two primary objectives: (1) to determine a possible relationship between TC size, intensity, and tornado output, and (2) to analyze environmental differences contributing to tornadogenesis among the TCT and TLT phases of a land-falling system. Multiple statistical tests were performed in an attempt to determine a relationship for the first objective. A two-way ANOVA test revealed that there is a significant relationship between storm intensity and tornado output. This was also confirmed by a general linear model using output as the dependent variable and storm intensity and storm size as covariates. Additionally, storms classified as ‘major’ hurricanes produced significantly more tornadoes than ‘minor’ and ‘weak’ tropical cyclones. TC size did not have a statistically significant influence on tornado output. For the majority of TCs within the period of study, those classified as large in size and as having major intensity produced a greater amount of tornadoes.

For the second objective, TCT environments were dominated by significantly higher SRH, EHI and SWEAT values. There was no significant difference in CAPE, although most TCTs had lower CAPE environments with one extreme outlier. TLT environments produce fewer tornadoes and only four storms had an output greater than 10. Of these four storms, three were characterized by CAPE environments $>1600\,\mathrm{J\,kg^{-1}}$ and the remaining storm had a 0–3 km SRH of $298\,\mathrm{m^2\,s^{-2}}$. TLT environments are more chaotic and are generally characterized by stronger CAPE compared with SRH; however, the CAPE values are not significantly different from TCT environments. The presence of mesoscale interactions was not discussed in this research, and features at this scale could explain some of the anomalous tornado output for TLT storms.

These results are beneficial to operational forecasters and climatologists alike and serve as an enhancement to traditional forecasting of tornadoes associated with land-falling TCs. By understanding the contributing dynamic factors and characteristics associated with TCs of various size and intensity parameters, better forecasting can be developed.

Supporting information

The following material is available as part of the online article:

Table S1. List of all landfalling TCs in study area, 1950–2010, including landfall date, intensity, Saffir-Simpson category and total tornado output within the study area.

References

Blake ES, Landsea CW, Gibney EJ. 2011. The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2010 (and other frequently requested hurricane facts) (*NOAA Technical Memorandum NWS NHC-6*) National Oceanic and Atmospheric Administration. http://www.srh.noaa.gov/www/images/tbw/1921/DeadliestHurricanes.pdf (accessed 4 September 2013).

Cohen AE. 2010. Synoptic-scale analysis of tornado-producing tropical cyclones along the Gulf Coast. *National Weather Digest* **34**(2): 99–115.

CSC (Coastal Services Centre). 2011. *Historical Hurricane Tracks*. National Oceanic and Atmospheric Administration, Coastal Services Centre: Charleston, SC. http://csc.noaa.gov/hurricanes/# (accessed 4 September 2013).

Curtis L. 2004. Midlevel dry intrusions as a factor in tornado outbreaks associated with land-falling tropical cyclones from the Atlantic and Gulf of Mexico. *Weather and Forecasting* **19**(2): 411–427.

Demuth JL, DeMaria M, Knaff JA. 2006. Improvement of advanced microwave sounding unit tropical cyclone intensity and size estimation algorithms. *Journal of Applied Meteorology and Climatology* **45**(1): 1573–1581.

Edwards R. 2010. Tropical cyclone tornado records for the modernized NWS era. In *Preprints*, *25th Conference on Severe Local Storms*, Denver, CO, P**3.1**. http://ams.confex.com/ams/25SLS/techprogram/paper_175269.htm (accessed 4 September 2013).

Edwards R, Dean AR, Thompson RL, Smith BT. 2010. Objective environmental analyses and convective modes for U.S. tropical cyclone tornadoes from 2003–2008. In *Preprints*, *25th Conference on Severe and Local Storms*, Denver, CO, **3.2** http://ams.confex.com/ams/25SLS/techprogram/paper_175397.htm (accessed 4 September 2013).

Gentry RC. 1983. Genesis of tornadoes associated with hurricanes. *Monthly Weather Review* **111**: 1793–1805.

Hill EW, Malkin JW, Schulz A. 1966. Tornadoes associated with cyclones of tropical origin-practical features. *Journal of Applied Meteorology* **5**: 745–763.

Jarvinen BR, Neumann CJ, Davis MAS. 1984. A tropical cyclone data tape for the North Atlantic Basin, 1886–1983: Contents, limitations, and uses. Tech. Memo. NWS NHC 22, National Oceanic and Atmospheric Administration.

Kimball SK, Mulekar MS. 2004. A 15-year climatology of North Atlantic tropical cyclones. Part I: Size parameters. *Journal of Climate* **17**(18): 3555–3575.

Landsea CW, Anderson C, Charles N, Clark G, Dunion J, Fernandez-Partagas J, Zimmer M. 2004. The Atlantic hurricane database re-analysis project: Documentation for 1851–1910 alterations and additions to the HURDAT database. *Hurricanes and Typhoons: Past, Present and Future*: 177–221.

Malkin W, Galway JG. 1953. TORNADOES ASSOCIATED WITH HURRICANES: As Illustrated by Franconia, Va., Tornado, September 1, 1952. *Monthly Weather Review* **81**(9): 299–303.

McCaul EW. 1991. Buoyancy and shear characteristics of hurricane-tornado environments. *Monthly Weather Review* **119**(8): 1954–1978.

McCaul EW Jr, Weisman ML. 1996. Simulations of shallow supercell storms in land-falling hurricane environments. *Monthly Weather Review* **124**(3): 408–429.

Moore TW, Dixon RW. 2011. Climatology of tornadoes associated with Gulf coast-land-falling hurricanes. *Geographical Review* **101**(3): 371–395.

NCDC (National Climatic Data Centre). 2011. *Storm Event Database*. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Climatic Data Centre: Asheville, NC. http://www.ncdc.noaa.gov/stormevents/ (accessed 18 November 2010).

NHC (National Hurricane Centre). 2011. *NHC Archive of Hurricane Seasons: Hurricane Season Tropical Cyclone Report*. Miami, FL: National Oceanic and Atmospheric Administration, National Weather Service, National Hurricane Centre. http://www.nhc.noaa.gov/pastall.shtml (accessed 4 September 2013).

NOAA (National Oceanic and Atmospheric Administration). 2012. *Atlantic Hurricane Research Division*. U.S. Department of Commerce. http://www.aoml.noaa.gov/hrd/hurdat/easyread-2012.html (accessed 4 September 2013).

Novlan DJ, Gray WM. 1973. *Hurricane Spawned Tornadoes*. Colorado State University: Department of Atmospheric Sciences.

NWS (National Weather Service). 2013. *Convective Season Environmental Parameters and Indices*. NWS: Louisville, KY http://

www.crh.noaa.gov/lmk/soo/docu/indices.php (accessed 4 September 2013).

Orton R. 1970. Tornadoes associated with hurricane Beulah on September 19–23, 1967. *Monthly Weather Review* **98**(7): 541–547.

Pearson AD, Sadowski AF. 1965. Hurricane-induced tornadoes and their distribution. *Monthly Weather Review* **93**(7): 461–464.

Pielke, RA, Simonpietri C, Oxelson J 1999. Thirty Years after Hurricane Camille: Lessons Learned, Lessons Lost. National Center for Atmospheric Research. 202.197.144.234 accessed 5 April 2012.

Plymouth State University. 2012. Plymouth State Weather Centre RAOB Selector for Archived CONUS Data. http://vortex.plymouth.edu/raob_uconus-u.html (accessed 3 February 2012).

Rappaport EN. 2000. Loss of life in the United States associated with recent Atlantic tropical cyclones. *Bulletin of the American Meteorological Society* **81**(9): 2065–2073.

Schultz LA, Cecil DJ. 2009. Tropical cyclone tornadoes, 1950–2007. *Monthly Weather Review* **137**(10): 3471–3484.

Smith JS. 1965. The hurricane-tornado. *Monthly Weather Review* **93**(7): 453–459.

Spratt SM, Sharp DW, Welsh P, Sandrik A, Alsheimer F, Paxton C. 1997. A WSR-88D assessment of tropical cyclone outer rainband tornadoes. *Weather Forecasting* **12**(3): 479–501.

SPC (Storm Predication Centre). 2013. Fujita Tornado Damage Scale. National Oceanic and Atmospheric Administration, National Weather Service, Storm Prediction Centre: Norman, OK. http://www.spc.noaa.gov/faq/tornado/ef-scale.html (accessed 4 September 2013).

Verbout SM, Schultz DM, Leslie LM, Brooks HE, Karoly DJ, Elmore KL. 2007. Tornado outbreaks associated with land-falling hurricanes in the North Atlantic Basin: 1954–2004. *Meteorology and Atmospheric Physics* **97**(1–4): 255–271.

Weiss SJ. 1985. On the operational forecasting of tornadoes associated with tropical cyclones. In *Preprints*, *14th Conference on Severe Local Storms*, Indianapolis, IN; 293–296.