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BASELINE CLIMATOLOGY OF SOUNDING-MEASURED VARIATES ASSOCIATED WITH ATLANTIC AND GULF COAST TROPICAL CYCLONE TORNADO CLUSTERS

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ABSTRACT
Radiosonde sounding-measured variates are analyzed for 55 cases of tornado outbreaks associated with tropical cyclones from 1995-2010. We define a tropical cyclone tornado outbreak as six or more tornadoes occurring in a six-hour period. All the tornadoes are associated with a landfalling or post-landfall translating tropical cyclone. Previous studies have examined the role of the atmospheric environment in an individual tropical cyclone or individual tornado. An earlier study of these tropical cyclone tornado clusters produced a baseline climatology of stability and wind shear parameters. The goal of this study is to provide a climatology of sounding-measured variates for each tropical cyclone tornado outbreak. Sounding variates provide information on characteristics of the atmospheric column such as height of standard pressure surfaces, temperature, moisture, and winds. Descriptive statistics for the sounding-measured parameters are presented to document the central tendency and variability of atmospheric conditions associated with these outbreaks. A hierarchical cluster analysis produced three clusters with significant difference in the North/South wind parameter for cluster 3. A principal components analysis revealed that the north/south wind contributed significantly to the occurrence of tornado outbreaks with dew point contributing the least.

KEYWORDS: Tropical cyclone tornadoes, radiosonde, mesoscale, climatology

Approximately 25 percent of tropical cyclones spawn tornadoes (Novlan and Gray 1974). The vast majority of tornadoes in the world occur in the United States. Tornados can cause catastrophic damage and kill hundreds of people in a single year which was the case for 553 people in 2011 (NOAA). Though hurricane force winds cannot reach the maximum speed of the most powerful tornadoes, they can do a lot of damage simply because of their sheer size. Depending on the path, a hurricane's impact on a particular location can last for many hours and cause vast destruction across a large region. The unpredictability of the systems is culpable, to a large extent, of the destruction and death that occur.

Tropical cyclone tornadoes mostly form in the outer rain bands with some forming in the eye wall (McCaul 1991). The front right quadrant of tropical cyclones tends to produce more tornadoes than the other quadrants (Verbout, et al. 2007). This means tornadoes are more probable with tropical cyclones that make landfall from the Gulf of Mexico than the Atlantic. Direct exposure of the right front quadrant to the coast is less likely in the Atlantic due to recurvature and if it does occur, usually the eye has already come ashore causing considerable weakening of the system. The number of tornadoes that a tropical cyclone produces can vary significantly with more than 100 tornadoes recorded for Hurricane Ivan (Verbout, et al. 2007).

A synoptic climatological approach is taken with this study to gain insight into the conditions necessary for tornado production within tropical cyclones. This study follows the US Standard Atmosphere (NOAA, NASA, U.S. Air Force 1976) approach by using measured values such as dew point, temperature and wind speed. Previous studies have looked at spatiotemporal clusters of individual hurricanes (Moore and Dixon 2015), a baseline climatology of using sounding-derived parameters (Dixon, Moore and Townsend 2016), the synoptic and mesoscale environments involved in tornado production (Yura 2006), and the birth of tornadoes from hurricanes (Gentry 1983). This study will reveal insight on the environment in which tropical cyclone produced tornadoes occur given baseline climatology of traditional parameters. This study provides a statistical analysis of parameters from radiosonde data (ROAB) gathered on 25 tropical cyclone systems that produced 55 tornado outbreaks which will shed light on the environment in which this weather phenomenon forms.

Data and Methods

The data for this study were gathered from the Storm Prediction Center's one-tornado database (ONETOR) with tornadoes that were determined to be produced by tropical cyclones. Tropical cyclone in this context refers to hurricanes, tropical storms, tropical depressions, subtropical storms and subtropical depressions. The timeframe of the data ranges from June to October between1995 and 2010. A tornado cluster is defined as at least six tornadoes in a six hour period centered on 0000, 0600, 1200 and 1800 UTC (Dixon, Moore and Townsend 2016). Data were gathered from the closest RAOB stations to the tropical cyclone via the Plymouth State University Weather Center (Plymouth State University). Tornado data on 55 clusters were gathered which were produced by 25 tropical cyclones (Edwards 2010). Clusters with center times of 0000 and 0600 were assigned to 0000 RAOB. Cluster centers of 1200 and 1800 were assigned to 1200 RAOB. Table 1, located in the appendix, contains a list of RAOB stations and Table 2 provides a list of the parameters and units used in this study. Figure 1 illustrates the study area and the location of RAOB stations. Table 3 provides a list of the tropical cyclones and the number of tornadoes produced. Figure 2 shows tropical cyclone tracks created from shapefiles provided by NOAA's National Climatic Data Center (NOAA).

With the exception of surface pressure, parameters are measured at specific air pressure levels from 1000hPa to 300hPa. Height, wind, dew point and temperature are parameters. The wind parameter was originally provided by two parameters: direction in degrees and magnitude. It was transformed into two other parameters which combined the direction and magnitude into a north/south wind component and an east/west component with a (-) sign delaminating whether the wind was from the south or the west. All of the data were analyzed using descriptive statistics and tests in SPSS. All of the data are continuous level measurements.

This study provides results from several statistical measures including: centrality, variability, goodness of fit, cluster analysis and principal components. Due to data discrepancies with some locations having elevations with surface pressure lower than 1,000hPa, the surface and 1,000hPa air pressures were omitted from the cluster analysis and principal components analysis.

Results

This study complements previous research analyzed and presented in the article "Baseline Climatology of Sounding-Derived Parameters Associated with Atlantic and Gulf Coast Tropical Cyclone Clusters" (Dixon, Moore and Townsend 2016). This study differs from previous studies by focusing on a unique combination of parameters and spatiotemporal dimension.

Measures of Central Tendency

The measures of central tendency were found by exploring the descriptive statistics of the dataset. Table 4 shows the mean, median and the upper and lower values of the dataset on a percentile scale. The analysis reveals that the east wind provides most of the wind energy with the north/south wind providing the rotation from south at the ground to north in the upper levels of the system. The north wind syphons off energy from the east wind in lower pressure environments. The dew point and temperature remain closely related throughout the system, changing relatively little near the surface with more significant changes occurring at 850hPa and below. Winds can vary drastically illustrated by the vectors in the 10-percentile and 90-percentile columns.

Measures of Variability

The measures of variability illustrate the distribution of the data. The standard deviation (STDEV) is the average displacement of a data point from the mean. The range is the largest data point minus the smallest one. The semi-interquartile range (SQR) is the 75th percentile minus the 25th percentile. The coefficient of variation (CV) is calculated by dividing the standard deviation by the mean. The CV is a measure of spread which indicates the variability in relation to the mean. According to results of the CV in Table 5, variation is greatest for the north/south wind between 700hPa and 400hPa. The standard deviation remains fairly constant for the north/south wind from 925hPa to 300hPa and the range does not change greatly. This indicates that the data points are more spread from the mean, but the individual values are not more extreme. The range in dew point is much higher than temperature in the higher levels of the atmosphere. However, according to Table 4, their means are very similar. This indicates that the dew point variable has a wider distribution.

Goodness of Fit to the Normal Distribution

Skew is a measure of asymmetry of the probability distribution of a real-valued random parameter about its mean. A positive skew indicates the right tail of the distribution is longer or fatter than the tail to the left. The contrary is true for a negative skew. Kurtosis illustrates how the tails and peak are different from a normal distribution. Higher kurtosis indicates that the variance is the result of infrequent extreme deviations instead of more frequent smaller deviations. According to Table 6, most parameters exhibit a small amount of negative skew, which indicate that outliers tend to be on the lower end of the range. Most parameters display a small amount of positive kurtosis, which signifies a light-tailed distribution. The dew point at

400hPa exhibits the highest amount of kurtosis. This means it has a larger number of outliers relative to the others. The Kolmogorov-Smirnov test answers whether the data are normally distributed. Any p-value <0.05 means that the data are not normally distributed.

Clustering of TCTOR Outbreaks

A hierarchical cluster analysis was used to produce a dendrogram which links each cluster from the bottom up. Z-scores were used for cluster comparison. The Ward Method was used in combination with Euclidean distance to calculate linkage. Table 7 shows the cluster centers and the number of outbreaks per cluster. Clusters one and two have 23 and 24 outbreaks respectively, whereas cluster three only has four. Four outbreaks were omitted from the analysis because of missing data.

Table 8 illustrates the parameters that show a significant statistical mean difference among clusters. An ANOVA was performed for Table 8 in which a Post-Hoc analysis was done using the Tukey Test and the Tamhane Test. Statistical significance was determined first by a test of homogeneity of variances. If the parameter failed to reject the null hypothesis that the data is homogeneous, the result of the Tukey Test was used, otherwise the result of the Tamhane Test was used. Each (X) in Table 8 represents a parameter with a p-value less than 0.05 according to the Tukey or Tamhane tests. The purpose of this table is to show whether the variance between groups is statistically significant. If it is statistically significant, the variance can be considered different or drawn from different populations. The results show that Cluster 3 is significantly different in terms of north/south wind; whereas Cluster 1 has significant difference from Cluster 3 concerning the east/west wind at all levels air pressure levels.

Principal Components Analysis of RAOB Parameters

Principal components analysis is a data reduction technique that reduces the number of parameters by creating a matrix which shows how much each parameter contributes to a component. Each component represents an amount of variance in the dataset with the first component contributing the most and the last contributing the least. The results of the analysis, shown in Table 9, listed six components which cumulatively represent 84.56% of the variance. According to the analysis, the north/south wind constitutes the strongest component accounting for 19.51% of the total variance. The next principal component is represented by height. Changing winds with height create the rotation necessary for tornado formation. The height variable contains measurements of height in relation to air pressure. Air pressure has a close link to buoyancy which gives rise to the necessary updrafts and downdrafts to create a vertical spinning parcel of air. Temperature has a larger variance than dew point. Temperature is inherently a measure of molecular motion. Increased molecular motion causes a decrease in the local air density, which causes an upward buoyant force from the surrounding air mass that contributes to changes in air pressure. As many of the tornadoes are formed in outer rain bands, changes in daytime heating may be more likely to trigger tornado formation than dew point given that the study area is dominated by a humid environment where land cover change and cloud formation can lead to local changes in temperature. Previous research has found a correlation between dry air mass intrusion and tornado outbreaks (Curtis 2004). However, there have also been studies which have found TCTOR outbreaks which have occurred without this condition (Moore and Dixon 2013). This is in stark contrast to tornadoes that form in the central United States which depend on frontal boundaries that exhibit large changes in humidity (Markowski and Richardson 2014).

Limitations

A limit of this study is the spatial input from the nearest station to where the outbreak occurs. Because the outbreaks are at different distances from the station used, some data may be more representative of the local air mass than others. A future study could include interpolated surfaces from multiple stations which provide data more characteristic of the location in question. The geographic center of the tornadoes in the outbreak can be found by using the x-coordinates and y-coordinates to calculate a mean center. Then a statistical surface could be created using an interpolation method in a GIS. Gathering the data from the mean center over the lifetime of each outbreak could yield insights into the conditions necessary to start, maintain and end the outbreak. Then a comparison could be done to isolate the defining meteorological inputs. A caveat with using this method is deciding where the spatial limit of station input would be or whether to have a spatial limit.

Conclusion

This report conveys a baseline climatology of the environment in which tornado outbreaks form in tropical cyclones. The results of the analysis revealed that wind, height and temperature were key components in the complex interactions that cause tornado outbreaks. Variability is most notable from the north/south wind. Winds at the ground begin from the south and shift to the north the lower the pressure becomes. This provides much of the rotation. The east wind provides the bulk of the wind energy, increasing from a slow wind at the surface to a maximum around 850hPa, leveling off slowly with decreasing pressure. The range in possible dew point values increase dramatically with height. However, the dew point accounts for very little variability in the system. This suggests that dew point has relatively less influence in the overall creation of TCTORs compared to other parameters.

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Appendix

Figure 1: The Study Area and the distribution of RAOB stations.

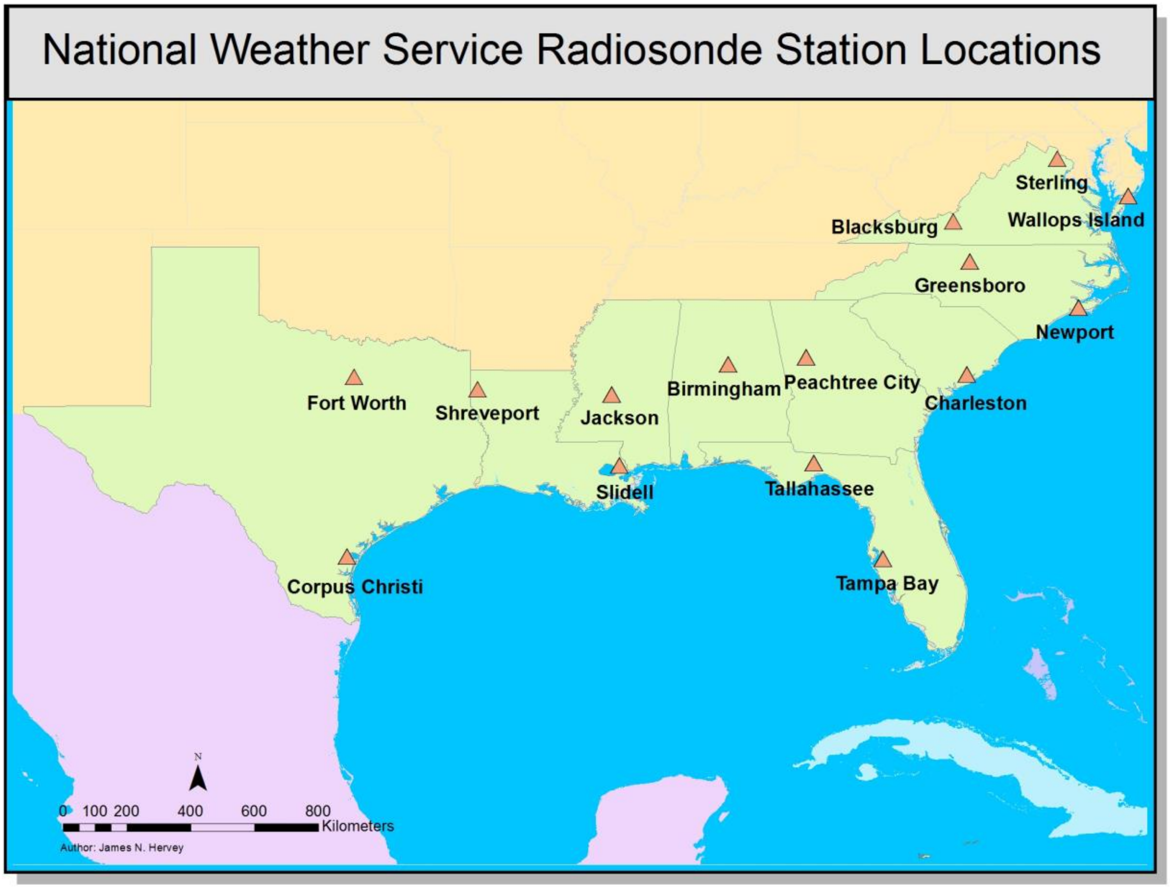

Table 1: ROAB stations used in baseline climatology.

WMO ID	Station Name
72208	Charleston, SC
72210	Tampa Bay, FL
72214	Tallahassee, FL
72215	Peachtree, GA
72230	Birmingham, AL
72233	Slidell, LA
72235	Jackson, MS
72248	Shreveport, LA
72249	Fort Worth, TX
72251	Corpus Christi, TX
72305	Newport, NC
72317	Greensboro, NC
72318	Blacksburg, VA
72402	Wallops Island, VA
72403	Sterling, VA

Table 2. ROAB parameters used in baseline climatology

Parameter	Units
Pressure	hPa
Height	meters
Temperature	°C
Dew Point	°C
North/South Wind	meters/sec
East/West Wind	meters/sec

Table 3. Analyzed tropical cyclones

Name	Month	Year	# of Tornadoes
Opal	October	1995	35
Bertha	July	1996	15
Josephine	October	1996	26
Bonnie	August	1998	8
Georges	September	1998	48
Floyd	September	1999	18
Allison	June	2001	28
Isidore	September	2002	10
Lili	October	2002	26
Bill	July	2003	33
Bonnie	August	2004	18
Charley	August	2004	21
Gaston	August	2004	20
Frances	September	2004	103
Ivan	September	2004	120
Jeanne	September	2004	42
Cindy	July	2005	44
Emily	July	2005	11
Katrina	August	2005	59
Rita	September	2005	89
Fay	August	2008	50
Gustav	September	2008	49
Ike	September	2008	33
Alex	June	2010	12
Hermine	September	2010	13

Figure 2: Tropical cyclone tracks

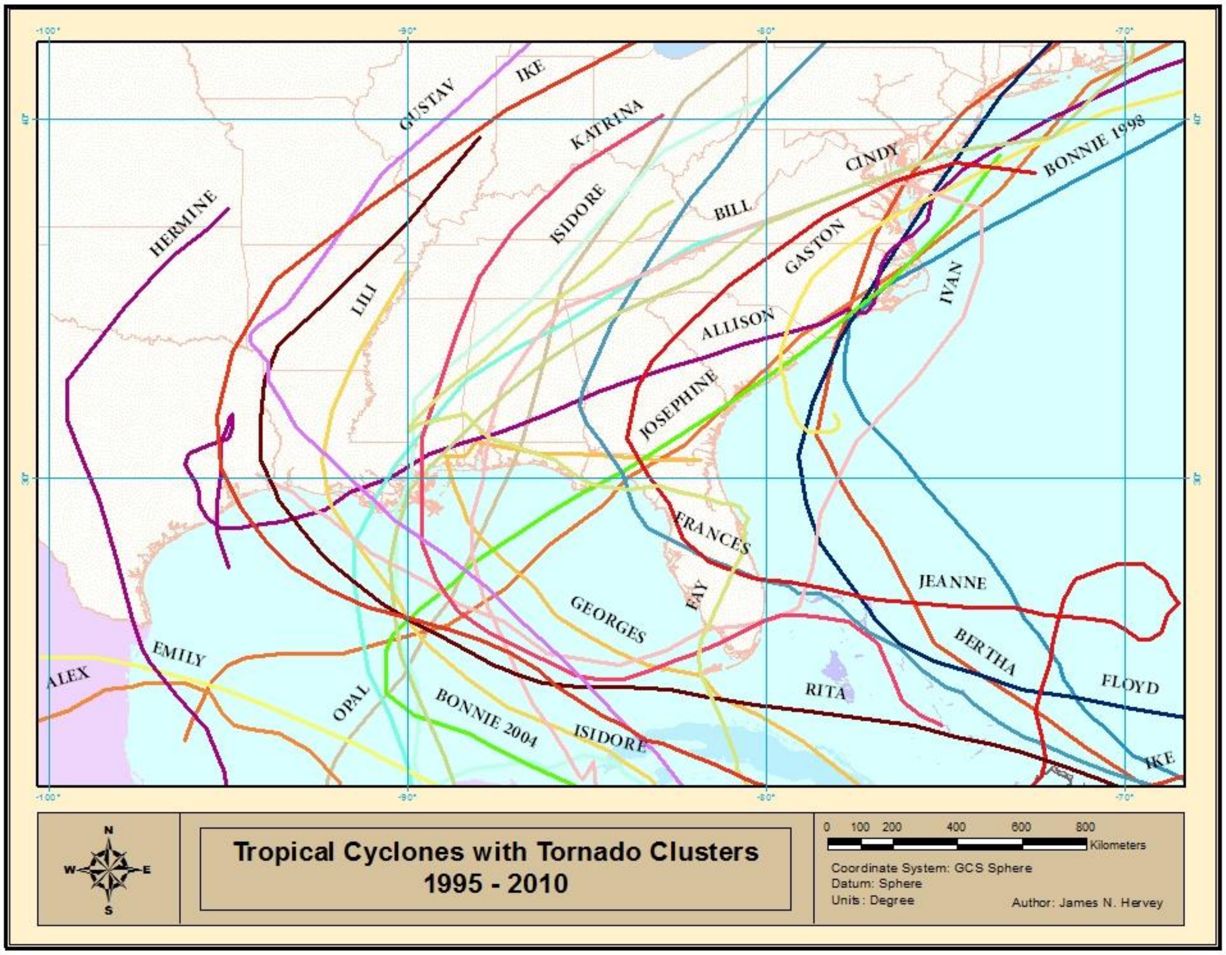

Table 4. Measures of central tendency

Parameter	M	Median	10%	90%
Height				
Surface	87.87	20.00	11.00	256.20
1000hPa	100.97	102.00	59.30	150.00
925hPa	760.24	766.00	671.00	819.40
850hPa	1490.18	1495.00	1399.00	1547.40
700hPa	3126.96	3132.00	3041.80	3176.20
500hPa	5842.78	5850.00	5775.00	5890.00
400hPa	7564.00	7570.00	7510.00	7610.00
300hPa	9682.26	9690.00	9640.00	9730.00
Temperature				
Surface	24.57	25.00	21.12	27.88
1000hPa	24.91	24.90	22.06	27.78
925hPa	21.18	21.14	19.44	23.08
850hPa	17.20	17.40	15.80	18.80
700hPa	8.83	9.20	6.52	11.36
500hPa	-5.34	-5.30	-7.60	-3.00
400hPa	-15.05	-14.70	-17.30	-12.90
300hPa	-29.39	-29.10	-32.70	-26.10
Dew Point				
Surface	22.79	23.10	19.86	24.94
1000hPa	23.05	23.56	20.02	25.24
925hPa	19.44	20.20	16.80	21.56
850hPa	15.00	15.70	10.48	17.64
700hPa	5.05	5.80	-0.20	9.64
500hPa	-10.59	-8.20	-21.60	-4.70
400hPa	-21.29	-18.50	-31.10	-14.86
300hPa	-36.76	-34.10	-53.90	-29.44
North/South Wind[a]				
Surface	-7.04	-5.20	-15.00	-0.00
1000hPa	-7.74	-7.88	-16.14	-0.00
925hPa	-16.30	-13.50	-39.64	2.61
850hPa	-11.24	-7.27	-38.76	10.48
700hPa	-4.98	-4.22	-31.32	19.04
500hPa	4.93	7.71	-21.59	28.47
400hPa	7.63	8.34	-20.57	30.98
300hPa	11.51	11.98	-14.63	34.16
East/West Wind[b]				
Surface	4.59	3.83	-4.55	15.00
1000hPa	6.43	5.17	-3.36	19.63
925hPa	22.32	22.65	-1.27	42.73
850hPa	28.54	28.15	6.32	52.80
700hPa	29.98	28.62	10.73	49.73
500hPa	26.43	26.59	4.17	46.61
400hPa	23.32	23.07	2.66	44.19
300hPa	19.75	18.87	4.31	43.25

a. (-) = south wind.
b. (-) = west wind.

Table 5. Measures of variability

Parameter	STDEV	Range	SQR	CV
Height				
Surface	95.87	263.00	163.00	1.09
1000hPa	36.57	148.00	30.25	0.36
925hPa	52.31	208.00	54.00	0.07
850hPa	52.03	209.00	57.00	0.03
700hPa	49.66	234.00	54.00	0.02
500hPa	46.27	270.00	50.00	0.01
400hPa	42.54	270.00	50.00	0.01
300hPa	42.81	260.00	50.00	0.00
Temperature				
Surface	2.80	16.80	2.80	0.11
1000hPa	2.07	9.20	2.45	0.08
925hPa	2.04	13.2	2.20	0.10
850hPa	1.42	8.40	1.40	0.08
700hPa	1.87	8.40	2.40	0.21
500hPa	1.82	9.20	2.30	-0.34
400hPa	1.80	7.20	2.60	-0.12
300hPa	2.53	14.00	3.10	-0.09
Dew Point				
Surface	2.23	14.40	2.30	0.01
1000hPa	1.95	9.40	2.53	0.08
925hPa	2.45	12.2	3.10	0.13
850hPa	2.82	15.60	3.20	0.19
700hPa	4.23	20.60	4.70	0.84
500hPa	6.73	32.90	7.45	-0.64
400hPa	8.32	46.80	6.10	-0.39
300hPa	9.82	43.10	6.80	-0.39
North/South Wind				
Surface	6.69	35.45	7.76	-0.95
1000hPa	5.83	23.07	5.56	-0.75
925hPa	16.12	76.01	9.84	-0.99
850hPa	20.04	99.77	31.23	-1.78
700hPa	20.56	103.92	31.93	-4.13
500hPa	19.55	90.53	26.55	3.96
400hPa	20.14	100.76	28.65	2.64
300hPa	18.07	92.57	19.19	1.57
East/West Wind				
Surface	8.50	44.62	6.89	1.85
1000hPa	8.40	29.72	8.20	1.31
925hPa	18.98	103.38	13.72	0.85
850hPa	17.96	98.05	24.46	0.63
700hPa	16.42	72.59	25.16	0.55
500hPa	16.36	69.43	23.81	0.62
400hPa	16.10	76.90	24.60	0.69
300hPa	15.65	76.18	18.78	0.79

Note: STDEV = standard deviation; SQR = semi-interquartile range; CV = coefficient of variation.

Table 6. Goodness of fit to the normal distribution

Parameter	Skew	Kurtosis	K-S z score	*P*-value
Height				
Surface	0.91	-0.79	0.27	<0.01
1000hPa	-0.10	-0.65	0.09	0.20
925hPa	-0.79	0.19	0.15	<0.01
850hPa	-0.81	0.17	0.15	<0.01
700hPa	-0.98	0.75	0.14	0.01
500hPa	-1.39	3.54	0.17	<0.01
400hPa	-1.46	5.33	0.12	0.05
300hPa	-1.67	6.48	0.14	0.01
Temperature				
Surface	-0.96	2.91	0.10	0.20
1000hPa	0.20	0.10	0.10	0.20
925hPa	-2.23	9.10	0.17	<0.01
850hPa	-1.47	4.85	0.14	0.01
700hPa	-0.57	0.45	0.12	0.05
500hPa	-0.39	0.47	0.07	0.20
400hPa	-0.99	-0.80	0.14	0.01
300hPa	-0.32	1.04	0.08	0.20
Dew Point				
Surface	-1.55	5.13	0.13	0.03
1000hPa	-0.81	1.11	0.12	0.20
925hPa	-1.68	3.42	0.18	<0.01
850hPa	-1.60	3.75	0.16	<0.01
700hPa	-1.37	2.44	0.12	0.05
500hPa	-1.62	2.94	0.19	<0.01
400hPa	-2.62	8.77	0.23	<0.01
300hPa	-2.27	4.76	0.26	<0.01
North/South Wind				
Surface	-1.91	5.73	0.15	<0.01
1000hPa	-0.20	-0.62	0.91	0.20
925hPa	-0.72	0.29	0.10	0.20
850hPa	-0.66	0.46	0.10	0.20
700hPa	-0.58	0.55	0.07	0.20
500hPa	-0.72	0.46	0.09	0.20
400hPa	-0.97	1.44	0.08	0.20
300hPa	-0.88	1.47	0.13	0.02
East/West Wind				
Surface	0.02	0.69	0.87	0.20
1000hPa	0.49	-0.80	0.11	0.20
925hPa	-0.51	0.98	0.09	0.20
850hPa	0.02	0.30	0.06	0.20
700hPa	-0.32	-0.29	0.09	0.20
500hPa	-0.34	-0.37	0.09	0.20
400hPa	-0.41	-0.03	0.10	0.20
300hPa	0.71	0.45	0.10	0.20

Note: K-S = Kolmogorov-Smirnov

Table 7. Final cluster centers for TCTOR outbreaks

Parameter	Cluster 1	Cluster 2	Cluster 3
Height			
925hPa	799.78	743.00	667.75
850hPa	1528.96	1474.46	1393.25
700hPa	3162.87	3114.83	3027.00
500hPa	5870.87	5837.92	5747.50
400hPa	7583.91	7563.75	74.82.50
300hPa	9690.43	9686.58	9617.50
Temperature			
925hPa	21.12	21.68	18.80
850hPa	17.08	17.57	16.05
700hPa	8.22	9.39	9.10
500hPa	-6.34	-4.81	-4.05
400hPa	-16.32	-14.13	-13.00
300hPa	-31.00	-28.43	-26.40
Dew Point			
925hPa	18.09	20.83	18.08
850hPa	13.18	16.58	15.43
700hPa	2.20	6.14	7.43
500hPa	-12.00	-9.77	-6.65
400hPa	-22.09	-21.88	-15.90
300hPa	-34.24	-37.54	-32.00
North/South Wind[a]			
925hPa	-12.39	-14.19	-43.70
850hPa	-8.80	-5.98	-48.57
700hPa	-2.86	1.28	-43.25
500hPa	7.96	8.49	-25.60
400hPa	12.68	10.41	-27.87
300hPa	15.10	13.48	-21.00
East/West Wind[b]			
925hPa	12.36	32.91	2.85
850hPa	17.60	40.03	13.37
700hPa	19.35	41.26	20.08
500hPa	16.75	37.26	14.54
400hPa	14.00	32.40	18.85
300hPa	13.05	25.36	24.58
Number of Outbreaks	23	24	4

Note: TCTOR = tropical cyclone tornado.

Table 8. Statistically significant parameter mean difference among clusters

Parameter	C1-C2	C1-C3	C2-C3
Height			
925hPa	X	X	X
850hPa	X	X	X
700hPa	X	X	X
500hPa	X		
400hPa			
300hPa			
Temperature			
925hPa			
850hPa			
700hPa	X		
500hPa	X	X	
400hPa			
300hPa	X		
Dew Point			
925hPa	X		
850hPa	X		
700hPa	X		
500hPa	X	X	
400hPa			
300hPa			
North/South Wind			
925hPa		X	X
850hPa		X	X
700hPa		X	X
500hPa		X	X
400hPa		X	X
300hPa		X	X
East/West Wind			
925hPa	X		X
850hPa	X		
700hPa	X		X
500hPa	X		X
400hPa	X		
300hPa	X		

Note: α = 0.05

Table 9. Principal components of RAOB parameters with percent of variance

PC1 – 19.505%	PC2 – 19.327%	PC3 – 16.240%	PC4 – 13.300%	PC5 – 10.231%	PC6 – 5.950%
North/South Wind 700, 850 400, 925 300	Height 500, 700 400, 850 925, 300	Temperature 850, 925 700, 400 500, 300	East/West Wind 500, 400 700, 300 850, 925	Dew Point 700, 850 500	Dew Point 400, 300