The Structure and Evolution of Tropical Cyclones in the North Atlantic Ocean Basin

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1. Introduction

Tropical cyclones are a diverse phenomenon coming in many shapes, sizes and strengths. From an operational standpoint, when a tropical cyclone threatens an area, a thorough understanding of a tropical cyclone's windfield is necessary for the safe evacuation of people and movable property (e.g. Barry and Guinn, 2012). Our research is aimed at analyzing tropical cyclone structure and its structural variation in the North Atlantic Ocean. Using the Extended Best Track (EBT) dataset we have documented the size, shape, and seasonal and geographical variation of the wind field associated with tropical cyclones. Wind fields associated with speeds greater than 17 ms^{-1} (tropical storm force), 25 ms^{-1} (Gale force), and 33 ms^{-1} (hurricane force) were examined.

2. Method

Version 2.01 - Feb 2012 of the EBT was used for our study. Prior to conducting any analysis, quality control (QC) was performed on this data set. Inconsistent data such as records containing observations of the pressure of the outer closed isobar being less than the minimum central pressure were eliminated. Records with observations over land were also eliminated. The raw EBT file contained 10860 records (6-hourly observations) of which 9742 remained after QC.

Using Microsoft Excel and MATLAB (Matrix Laboratory) statistical analyses were conducted on the areal extent of the wind fields associated with tropical storm force winds, gale force winds and hurricane force winds. These statistics included the distribution with quartiles and the average and median values. This was done for the entire dataset. In addition these statistics were derived on a monthly basis and for selected geographic areas. See Figure 1 for the geographic regions.

The area of the relevant wind field of a tropical cyclone was approximated by the sum of the areas of the four quarter circles (See Appendix Equation 1). Unlike in Kimball and Mulekar (2004) where the outer-wind radii for each quadrant of the storm was averaged to obtain a single value to represent storm size, we have calculated areas by quadrant and summed those values to obtain a representative size. In addition, a normalization technique was incorporated for the representation of storm size. For normalization, the area of the storm was divided by the area of 1^{o} X 1^{o} latitude-longitude grid box centered at the 15^{o} latitude. This yields a dimensionless depiction of area in terms of a latitude-longitude grid box.

Using the four wind radii, we were able to derive a dimensionless quantity to understand the symmetry of the windfield structure of the tropical cyclone as well. The asymmetry index was obtained by calculating the standard deviation between the 4 estimates of the windfield radius for each quadrant of the storm and then dividing by the average radius of the storm. The result of the asymmetry calculation is a value between 0 and 2. Zero implies a symmetric windfield structure and, two implies an asymmetric windfield structure (See Appendix Equation 2). The storm asymmetry was calculated for all three wind field estimates (i.e., 17, 25 and, 33 ms^{-1} winds).

3. Results

Table 1 shows the statistical distribution of storm area for the entire dataset over water in the North Atlantic Ocean. The results show a wide distribution of storm sizes similar to previously

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conducted research (Merrill 1984). Specifically, the wind field associated with tropical storm force winds range from 763485.6 Km^2 down to 157.1 Km^2; three orders of magnitude difference. For the wind field associated with hurricane force winds, the range is 74534.3 Km^2 to 78.5 Km^2; also three orders of magnitude difference. These results are also shown graphically in Figure 2.

Table 2 lists the 5 largest and smallest tropical cyclones recorded in the data set. For this analysis, only the observation showing the maximum tropical storm force wind area during each storm's recorded existence was considered. Based on the tropical storm force winds, the largest storm recorded was Tropical Storm Rafael (2012) with an estimated storm force wind area of 763485.6 km^2 and smallest storm recorded was Tropical Storm Karl (2010) with an estimated storm force wind area of 157 km^2. It is interesting to note that all storms in this table lie between 2001-2012 and, all but 1 tropical cyclone lie between 2007-2012. This may be attributed to the recent improvements in observing technology such as QuikSCAT and ASCAT aiding in early recognition of tropical cyclones and overall size determination. However, this may also be due to an increase in range of tropical cyclone size over the years.

Table 3 shows the statistical distribution of the tropical cyclone areal windfield by month from June to November. The month of September displays maximum storm activity (i.e., the greatest number of tropical cyclone events). However, based on median size, the largest storms occur in November. This however is likely due to earlier extratropical transition of the tropical cyclones due to the southward movement of the baroclinic environment during the winter months. A secondary maximum occurs in September coincident with the month of maximum activity. We also observe a significant decrease in the values for area of hurricane force winds in November when compared to September. These results are also shown graphically in Figure 3a, 3b and 3c.

Table 4 show the statistical distribution of the tropical cyclone areal windfield by geographical area. Tropical cyclones are significantly larger in the North Atlantic sector and smallest in the Caribbean sector. This is probably due to extratropical transition acting on the storm system as it moves northward into a baroclinic region.

Table 5 indicates that most tropical cyclones display a symmetric structure for each wind field with the median values of the asymmetry index being 0.31, 0.28 and 0.13 for the 17, 25 and 33 ms^{-1} wind fields respectively. It is interesting to note that in the analysis of the entire data set, the 17 ms^{-1} windfield indicates the most asymmetry however, in the analysis of the subset containing tropical cyclones with wind speeds greater than 33 ms^{-1} (presented in Table 6), the 17 ms^{-1} windfield is more symmetrical that the 33 ms^{-1} windfield. This tells us that the windfield structure for the tropical storm force winds tends to be symmetric for a hurricane. These results are also shown graphically in Figure 5 and Figure 6.

Table 7 shows the statistical distribution of the tropical cyclone windfield asymmetry by month. We observe that the median storm symmetry for the tropical storm force winds increases as we approach the month of maximum storm activity and then decreases. We also observe an increase in the median hurricane wind field asymmetry for the month of July and maximum symmetry for the month of November. This is of interest since we are aware that a baroclinic environment results in higher storm asymmetry.

Table 8 show the statistical distribution of the tropical cyclone windfield asymmetry by geographical area. The median value of storm asymmetry is highest in the North Atlantic sector and least in the South Atlantic sector. This is likely due to the low shear barotropic environment necessary for tropical cyclogenesis in the southern hemisphere and, extra tropical transition near the mid-latitudes leading to higher windfield asymmetry in the northern hemisphere. When we study the average storm asymmetry, we observe that tropical storm force winds are significantly more symmetric in the South Atlantic Sector.

4. Summary and Conclusions

Though the EBT is a relatively coarse data set, we were able to understand many aspects regarding the structure and evolution of tropical cyclones. We show that tropical cyclones show a broad range in size constant with other studies of this nature. Storms are largest in the month of November; however, we see a secondary maximum during September coincident with the month of maximum storm activity.

The data available in the EBT contains a wealth of information from a research standpoint (e.g. we have derived many parameters such as storm position velocity). Since this project stemmed from the necessity to understand the tropical cyclone wind field structure and behavior of tropical cyclones for forecasting and evacuation of people and movable property prior to landfall (Barry, 2008), we plan to conduct multiple individual storm analyses to further our understanding of tropical cyclone wind field structure and storm track.

5. Acknowledgment

I would like to thank my research advisor Dr. Randell J. Barry for his perpetual support through the duration of this project, Dr. Christopher G. Herbster for invaluable programing assistance and recommendations and, Dr. Thomas A. Guinn for the many thought-provoking comments that greatly improved the depth of this research. Gratitude is extended to The Embry-Riddle Honors program and, Office of Undergraduate Research (IGNITE) for their support and financial assistance for this project.

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Table 1: Statistics of the areal wind field for the 17 ms^{-1}, 25 ms^{-1}, 33 ms^{-1} winds for the entire dataset.

Statistics on Storm Area						
	Values in Sq. Km and 1o X 1o Lat-Lon grid box					
	17 m/s		25 m/s		33 m/s	
MAXIMUM	763485.6	61.85	345025.4	27.95	74534.3	6.04
90th Percentile	117342.4	9.51	42301.5	3.43	16081.0	1.30
75th Percentile	61850.1	5.01	19635.0	1.59	8344.9	0.68
MEDIAN	29452.4	2.39	8580.5	0.70	2827.4	0.23
25th Percentile	12900.2	1.05	3936.8	0.32	1433.4	0.12
10th Percentile	6041.7	0.49	1649.3	0.13	785.4	0.06
MINIMUM	157.1	0.01	39.3	0.00	78.5	0.01
MEAN	51330.7	4.16	16664.8	1.35	6351.1	0.51
STD. DEV	65975.7	5.35	21763.2	1.76	7848.3	0.64
NO. OF RECORDS	6628		4198		2631	

Table 2: List of the 5 smallest and largest unique tropical storm records.

Storm Name	Area of 17 m/s windfield Values in Sq.Km	
RAFAEL (20-OCT-2012 00Z)	763485.6	*Largest Storm Record.*
OLGA (25-NOV-2001 18Z)	479249.9	
SANDY (30-OCT2012 00Z)	506581.8	
IGOR (23-SEP-2010 00Z)	587949.0	
NOEL (03-NOV-2007 12Z)	591012.1	
MARCO (07-OCT-2008 12Z)	2827.3	*Smallest Storm Record.*
GASTON (01-SEP-2010 18Z)	3848.3	
ALBERTO (20-MAY-2012 18Z)	5105.0	
PATTY (12-OCT-2012 00Z)	5497.7	
HELENE (17-AUG-2012 18Z)	1413.7	

Table 3: Statistical Analysis of Storm Force Wind Area by Month (June through November)

Statistics on Tropical Cyclone Area for the 17, 25 and, 33 m/s windfields from June to November (1988-2012)																		
Storm Area (Sq. Km)																		
	Jun			**Jul**			**Aug**			**Sep**			**Oct**			**Nov**		
	17 m/s	25 m/s	33 m/s	17 m/s	25 m/s	33 m/s	17 m/s	25 m/s	33 m/s	17 m/s	25 m/s	33 m/s	17 m/s	25 m/s	33 m/s	17 m/s	25 m/s	33 m/s
MAXIMUM	191912	20833	4163	182605	74122	28471	331831	73140	28451	506582	172473	74534	763486	105950	43118	591012	345025	28981
90th Percentile	63617	15237	3138	67741	19615	13106	87376	35323	12763	135968	51051	20126	133219	38312	14854	165326	49904	14176
75th Percentile	37306	7854	2464	35343	11712	4099	49087	19478	6715	78049	24544	10161	56725	17671	6676	81485	17671	5027
MEDIAN	19635	5655	1473	19635	6646	1954	22619	8168	2827	38327	11300	3848	25447	6794	2278	45082	8836	2042
25th Percentile	10603	2985	726	9817	2611	1021	9817	3907	1610	17671	5027	1963	12763	2513	1021	22619	3534	1257
10th Percentile	6912	785	511	5486	1414	628	5027	1414	962	7854	1963	982	5832	1319	628	8490	2278	628
MINIMUM	2042	314	511	1257	491	314	353	177	79	157	157	157	236	39	79	314	334	314
MEAN	30127	6368	1724	29347	10781	4547	37424	14236	5200	59817	19532	7604	56770	13627	5170	75232	22032	4895
STD. DEV	32343	5046	1247	30022	13746	6421	42862	15200	5180	65147	22319	9064	86926	17394	7144	98553	44975	6347
Count	151	53	10	485	266	124	1607	980	638	2743	1942	1343	1089	677	386	383	215	106

Table 4: Statistical Analysis of Storm Force Wind Area by Month (June through November)

Statistics of Tropical Cyclone Area by Geographical Area															
	GULF OF MEXICO			**CARABIAN SECTOR**			**EAST COAST**			**NORTH ATLANTIC**			**SOUTH ATLANTIC**		
	STORM AREA														
	17 m/s	**25 m/s**	**33 m/s**	**17 m/s**	**25 m/s**	**33 m/s**	**17 m/s**	**25 m/s**	**33 m/s**	**17 m/s**	**25 m/s**	**33 m/s**	**17 m/s**	**25 m/s**	**33 m/s**
MAXIMUM	208621	98175	40252	178678	98175	40252	541296	149717	43118	763486	172473	74534	591012	345025	37365
90th Percentile	97342	37591	20273	68644	27650	11891	122954	51510	22070	374918	118202	74534	110961	33379	12763
75th Percentile	53034	20062	12468	43266	16081	6440	76576	35323	14137	229022	73140	21461	54664	16621	5478
MEDIAN	28471	11104	5360	21108	6372	2611	35343	13862	8306	135717	40998	13254	28274	7854	2827
25th Percentile	12763	3848	1900	9817	2042	982	15188	5341	2729	67402	23091	9763	12763	4251	1414
10th Percentile	5400	1455	982	5027	982	511	6597	2121	1257	36600	9052	4178	6362	1963	844
MINIMUM	707	314	177	157	39	79	491	177	157	3004	314	982	353	177	79
MEAN	40548	16212	8699	30438	10921	4825	56835	22335	9864	169380	52320	22844	47747	14084	5002
STD. DEV	38379	17496	8993	28264	12422	6015	64589	22141	8989	133916	39213	24758	59643	20041	6124
NO. OF RECORDS	393	238	136	987	628	405	1258	825	535	265	144	29	3725	2363	1526

Table 5: Degree of Asymmetry within the 17, 25, 33 ms^{-1} windfields for the entire data set.

Statistics on Storm Asymmetry			
	17 m/s	**25 m/s**	**33 m/s**
MAXIMUM	2	2	2
90th Percentile	1.155	1.155	1.155
75th Percentile	0.667	0.667	0.603
MEDIAN	0.315	0.286	0.231
25th Percentile	0.167	0.128	0.000
10th Percentile	0.056	0.000	0.000
MINIMUM	0.000	0.000	0.000
MEAN	0.465	0.471	0.407
STD. DEV	0.445	0.522	0.493
NO. OF RECORDS	6968	4358	2709

Table 6: Degree of Asymmetry within the 17, 25, 33 ms^{-1} windfields for the subset of the records containing a windfield greater than 33 ms^{-1}.

Statistics on Storm Asymmetry (Winds greater than 33 m/s)			
	17 m/s	**25 m/s**	**33 m/s**
MAXIMUM	0.861	2	2
90th Percentile	0.409	0.524	1.154
75th Percentile	0.303	0.348	0.577
MEDIAN	0.220	0.225	0.230
25th Percentile	0.133	0.104	0
10th Percentile	0.057	0	0
MINIMUM	0	0	0
MEAN	0.229	0.254	0.398
STD. DEV	0.143	0.241	0.485
NO. OF RECORDS	2631	2631	2631

Table 7: Statistical Analysis of Storm Force Wind Asymmetry by Month (June through November)

Statistics on Tropical Cyclone Asymmetry for the 17, 25 and, 33 m/s windfields from June to November (1988-2012)																		
Storm Asymmetry																		
	Jun			**Jul**			**Aug**			**Sep**			**Oct**			**Nov**		
	17 m/s	25 m/s	33 m/s	17 m/s	25 m/s	33 m/s	17 m/s	25 m/s	33 m/s	17 m/s	25 m/s	33 m/s	17 m/s	25 m/s	33 m/s	17 m/s	25 m/s	33 m/s
MAXIMUM	2.000	2.000	0.673	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
90th Percentile	1.200	2.000	0.610	1.155	1.171	1.165	1.155	1.200	1.155	1.155	1.155	1.155	1.155	1.169	1.155	1.157	1.155	1.155
75th Percentile	1.155	1.225	0.371	0.747	0.750	1.155	0.667	0.622	0.542	0.462	0.410	0.389	0.667	0.743	0.845	0.667	0.622	0.667
MEDIAN	0.634	1.155	0.231	0.408	0.457	0.506	0.299	0.287	0.231	0.235	0.231	0.215	0.360	0.353	0.231	0.360	0.289	0.053
25th Percentile	0.385	0.444	0.041	0.245	0.223	0.286	0.171	0.133	0.000	0.136	0.080	0.000	0.202	0.154	0.000	0.219	0.105	0.000
10th Percentile	0.231	0.190	0.000	0.136	0.095	0.105	0.000	0.000	0.000	0.000	0.000	0.000	0.087	0.000	0.000	0.065	0.000	0.000
MINIMUM	0.000	0.128	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MEAN	0.740	0.978	0.262	0.546	0.614	0.669	0.467	0.498	0.386	0.380	0.379	0.350	0.486	0.542	0.487	0.513	0.409	0.374
STD. DEV	0.492	0.639	0.241	0.428	0.524	0.510	0.453	0.557	0.455	0.397	0.463	0.455	0.426	0.544	0.558	0.468	0.424	0.521
Count	151	53	10	485	266	124	1607	980	638	2743	1942	1343	1089	677	386	383	215	106

Table 8: Statistical Analysis of Storm Force Wind Asymmetry by Month (June through November)

Statistics of Tropical Cyclone Asymmetry by Geographical Area															
	GULF OF MEXICO			CARABIAN SECTOR			EAST COAST			NORTH ATLANTIC			SOUTH ATLANTIC		
	STORM ASYMMETRY														
	17 m/s	**25 m/s**	**33 m/s**	**17 m/s**	**25 m/s**	**33 m/s**	**17 m/s**	**25 m/s**	**33 m/s**	**17 m/s**	**25 m/s**	**33 m/s**	**17 m/s**	**25 m/s**	**33 m/s**
MAXIMUM	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
90th Percentile	1.178	1.225	1.155	1.155	1.245	1.155	1.155	1.164	1.164	1.155	2.000	1.185	1.155	1.155	1.155
75th Percentile	0.766	0.719	0.667	0.731	0.883	0.667	0.688	0.727	0.777	0.756	1.165	1.155	0.495	0.467	0.354
MEDIAN	0.410	0.373	0.360	0.385	0.339	0.250	0.339	0.348	0.385	0.427	0.445	0.667	0.266	0.231	0.163
25th Percentile	0.225	0.230	0.222	0.222	0.182	0.128	0.196	0.185	0.210	0.240	0.269	0.264	0.133	0.000	0.000
10th Percentile	0.164	0.133	0.131	0.105	0.000	0.000	0.115	0.080	0.088	0.164	0.168	0.206	0.000	0.000	0.000
MINIMUM	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.192	0.000	0.000	0.000
MEAN	0.551	0.589	0.501	0.534	0.568	0.451	0.502	0.537	0.567	0.559	0.759	0.697	0.393	0.377	0.311
STD. DEV	0.429	0.540	0.411	0.458	0.569	0.504	0.460	0.509	0.508	0.458	0.603	0.474	0.406	0.477	0.457
NO. OF RECORDS	393	238	136	987	628	405	1258	825	535	265	144	29	3725	2363	1526

Figure 1 Map depicting the division of areas for the geographical analysis of tropical cyclones in the Atlantic basin.

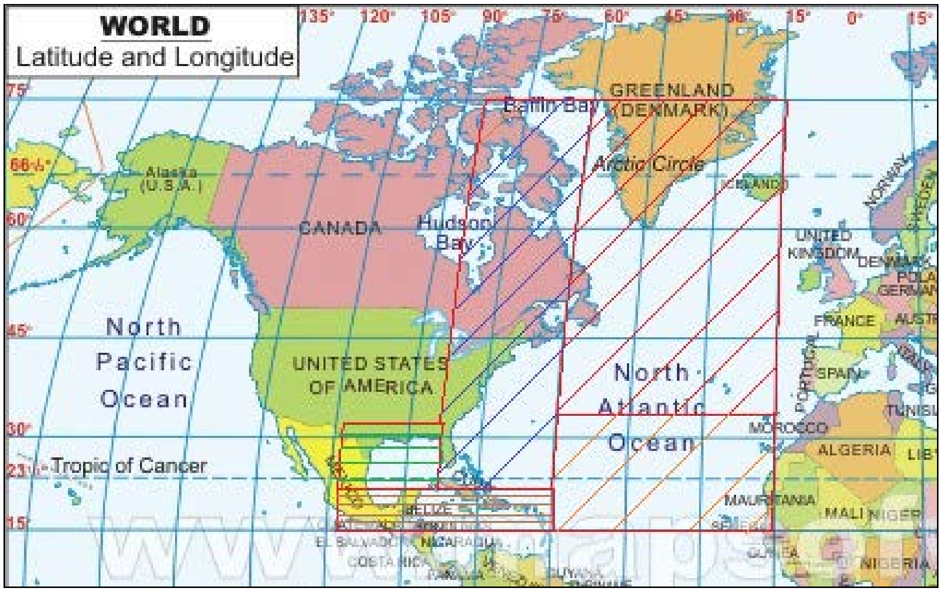


Figure 2: Statistics of the areal wind field for the 17 ms^{-1}, 25 ms^{-1}, 33 ms^{-1} winds for the entire dataset.

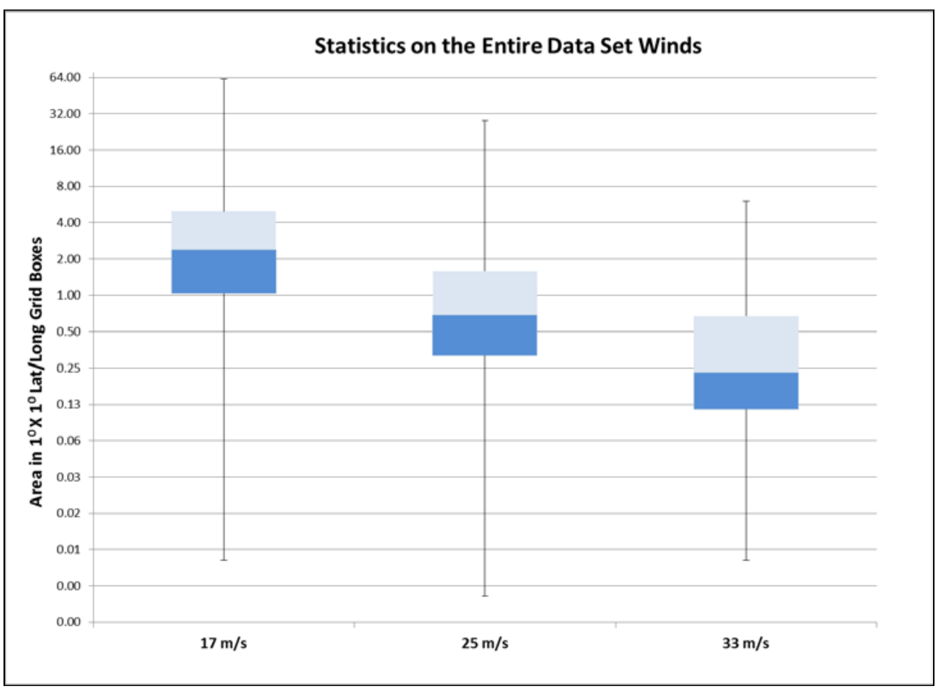


Figure 3 a, b and c Seasonal variation of storm area

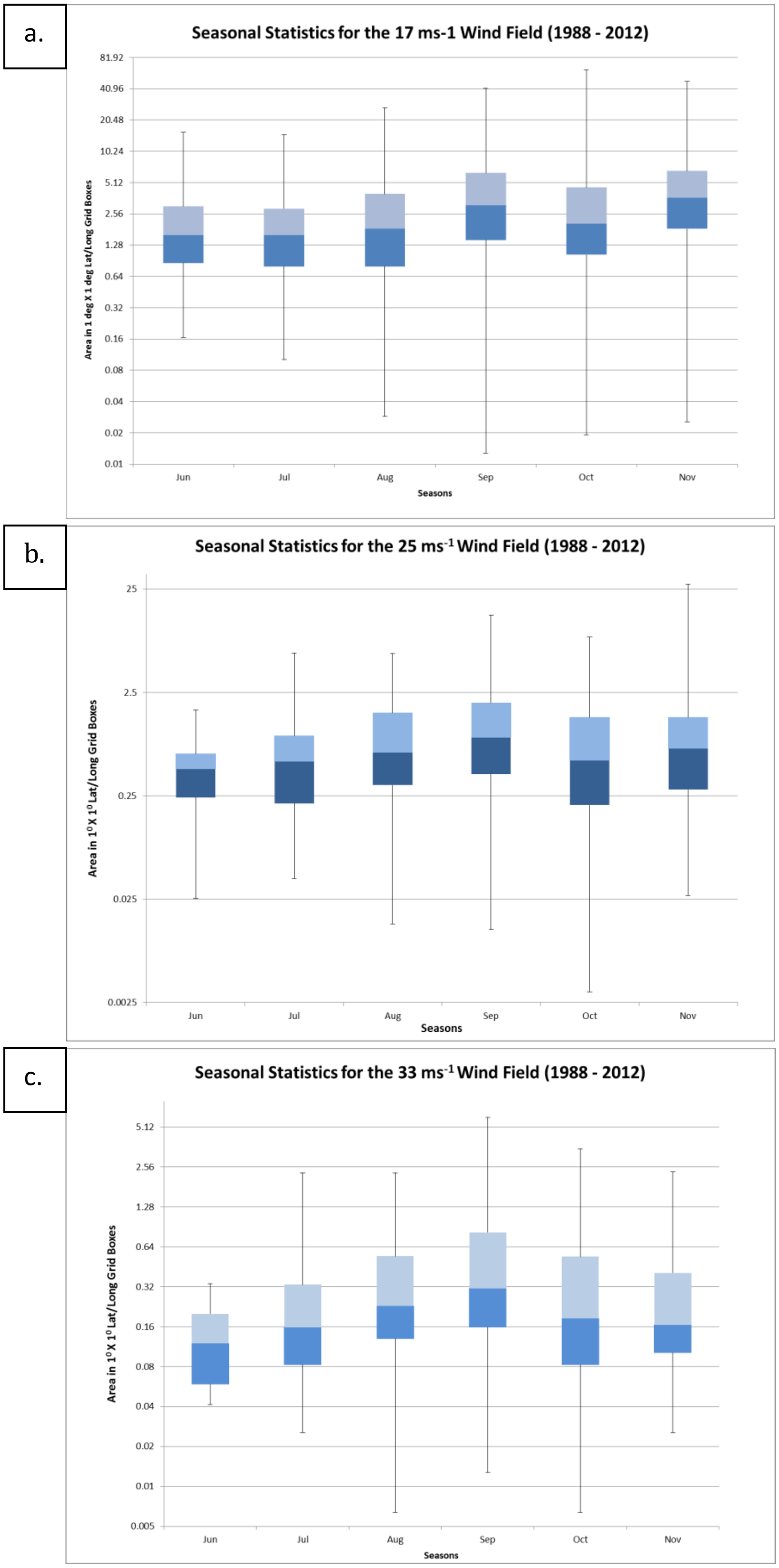


Figure 4: Asymmetry counts within the 17, 25, 33 ms^{-1} windfields for the entire data set.

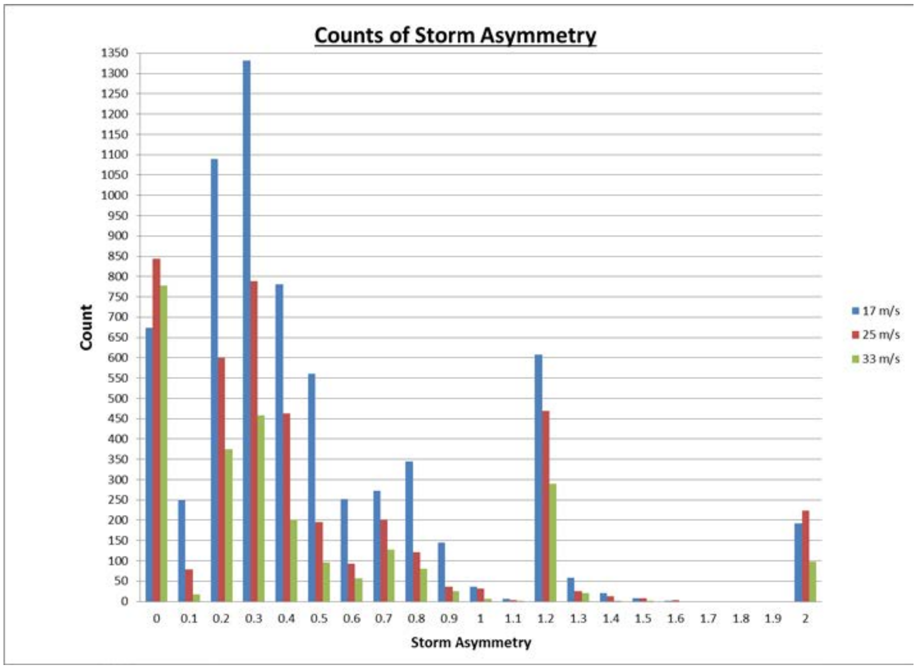
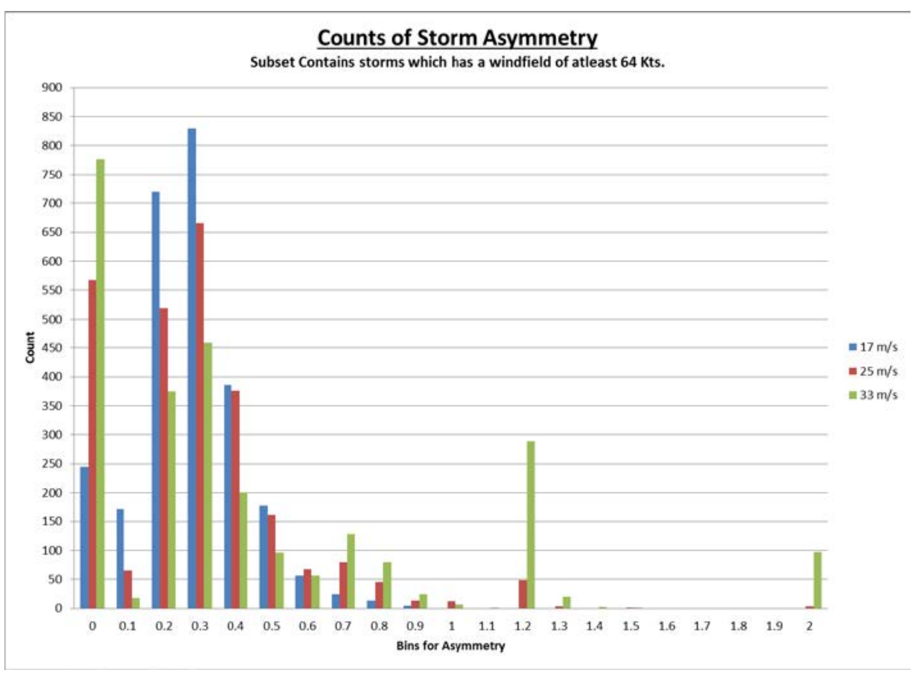


Figure 5: Asymmetry counts within the 17, 25, 33 ms^{-1} windfields for the subset of the records containing a windfield greater than 33 ms^{-1}.



APPENDEX

The following technique was used to calculate the area and asymmetry of a wind field for a tropical cyclone.

Example: Area and asymmetry for the 17 ms^{-1} wind field is given by

1. $Area_{17\ m/s} = \frac{\pi(NE_{17}^2+SE_{17}^2+SW_{17}^2+NW_{17}^2)}{4}$

2. $Asymmetry_{17\ m/s} = \frac{Standard\ Deviation(NE_{17},SE_{17},SW_{17},NW_{17})}{Avergae(NE_{17},SE_{17},SW_{17},NW_{17})}$