Hurricane Properties for KSC and Mid-Florida Coastal Sites

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Hurricane information and climatologies are needed at Kennedy Space Center (KSC) Florida for launch operational planning purposes during the late summer and early fall Atlantic hurricane season. Also these results are needed to be used in estimating the potential magnitudes of hurricane and tropical storm impact on coastal Florida sites when passing within 50, 100 and 400 nm of that site. Roll-backs of the Space Shuttle and other launch vehicles, on pad, are very costly when a tropical storm approaches. A decision for the vehicle to roll-back or ride-out needs to be made. Therefore the historical Atlantic basin hurricane climatological properties were generated to be used for operational planning purposes and in the estimation of potential damage to launch vehicles, supporting equipment, buildings, etc.. The historical 1885-1998 Atlantic basin hurricane data were compiled and analyzed with respect to the coastal Florida site of KSC. Statistical information generated includes hurricane and tropical storm probabilities for path, maximum wind, and lowest pressure, presented for the areas within 50, 100 and 400 nm of KSC. These statistics are then compared to similar parametric statistics for the entire Atlantic basin.

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6.5 HURRICANE PROPERTIES FOR KSC AND MID-FLORIDA COASTAL SITES (AMS 8/30/00)

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1. INTRODUCTION

This paper presents the characterization and climatology of Atlantic basin hurricane and tropical storm properties regarding their effect on the Kennedy Space Center (KSC) FL, and for mid-Florida eastern coastal sites. Each Florida hurricane season (May-November) presents a challenge not only to Florida residents but also to the National Aeronautics and Space Administration (NASA) Space Shuttle mission managers and KSC launch directors to work launch schedules around any potential hurricane advance. A vehicle rollback due to hurricane or tropical storm approach can be costly. This paper resulted from an update to the KSC hurricane statistics contained within NASA TM-4511. Therefore the paper can give managers guidance in terms of expressing the traits and climatology of hurricane and tropical storm passage near the Cape Canaveral/KSC area. A tropical cyclone is defined in this paper as either a tropical storm or a hurricane. Much of the work presented is based on the 1871 through 1999 Atlantic basin hurricane data base, plus a summary of what others have published prior for this eastern Florida area.

2. BACKGROUND

The year 1999 produced a number of hurricane threats to the KSC area with four major storms passing within 278 km (150 nm) of KSC between late August and mid October. These were hurricanes Dennis, Floyd and Irene, and tropical storm Harvey. The five year period starting in 1995 has produced twenty major Atlantic basin hurricanes and may be ushering in a new regime of enhanced storminess (Elsner 2000, Wilson 1999). This again focuses attention upon the threat of hurricanes to space vehicle exposure, i.e., should NASA managers roll back a vehicle on the pad or ride out a storm. Of the thirteen Space Shuttle rollbacks to date, four have been due to tropical storm or hurricane approach and occurred over a 6-year period from October 1990 through September 1996. Two of these rollbacks occurred during one hurricane season (in 1996).

Potential structural damage can occur to many components on the Space Shuttle vehicle while on pad due to hurricane effects of wind and wind loading as well as wind debris impact. One sub-system affected are the Thermal Protection System (TPS) tiles which are extremely vulnerable to hurricane force wind, rain and debris impact. In Figure 1, Barneburg (unpublished) presents curves of drop diameter versus impact velocity in terms of potential TPS tile damage due to hurricane driven rains. NASA announced on June 12, 2000 that modifications to the KSC Vehicle Assembly Building (VAB) to be completed by September 2000 will allow the entire Shuttle fleet of four vehicles to be housed in the eight-acre building during storms. The VAB is designed to withstand 56 m/s (125 mph) winds.

Prior to the 1990's there was a NASA KSC hurricane preparedness plan in place. But since direct hurricane strikes on KSC are relatively rare, managers had not been able to create an exact data base of past rollback decisions and the criterion upon which those decisions were based. A study addressing the KSC hurricane risk assessment for either rollback or ride out was published in 1993 (Wohlman 1993) that addressed a 48 hour lead time (i.e., 48 hours in advance of the onset of the critical winds). KSC has since established a more comprehensive "Kennedy Space Center Hurricane Plan" which is summarized in "NASA Facts On Line", dated July 8, 1996.

The Naval Meteorology & Oceanography Command (NM&OC) publishes a "Hurricane Havens Handbook for the North Atlantic Ocean" (Turpin 1982), which presents hurricane plans and preparations for the Port Canaveral Florida site. The NM&OC report is periodically updated (1999) and a thorough Port Canaveral hurricane study with summary statistics are also presented in their report. Since their period of hurricane record for the Port Canaveral site (1886-1997) is similar to that used in this paper, some of their storm statistics are presented in this paper. There have been various other earlier hurricane studies involving the Cape Canaveral area (Neumann 1968 and Crutcher 1971). Crutcher published two NASA reports in 1971 presenting Atlantic tropical cyclone statistics (POR 1899-1969) and "strike probabilities" for various NASA sites of interest. Strike probability being defined as the probability that the center of an existing tropical cyclone will be within a selected area after a specified time interval (12 to 96 hours). These probabilities are based on the bivariate normal distribution model, and

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can be used to obtain various KSC storm probabilities for specific months.

The literature search revealed that much has been done in terms of hurricane research and forecasting for the Atlantic basin region. Therefore, no hurricane forecasting models or analyses were examined during preparation of this paper. Other investigators (Jarrell 1981, Sheets 1984, Hendrikson 1986, Darling 1991, Neumann 1991) have covered this area extensively. Likewise, no El Nino (Wilson 1999) or Global Warming effects on tropical cyclone development are presented here. Therefore, the main purpose of this paper is to generate and assemble Atlantic hurricane and tropical storm facts that can give Space Shuttle managers some statistical hurricane guidelines that apply to the KSC hurricane season.

3. DATA BASE

This task was initiated by updating two tables within Section 12 of NASA TM-4511 (Johnson 1983), representing the number of tropical cyclones that occurred within 185- and 741-km (100- and 400-nm) of KSC Florida. MSFC obtained the standard 1886-1999 Atlantic basin hurricane data base and added the 1871-1885 hurricane track-only information (Neumann 1978) which contains no wind speeds or pressures. Therefore, the entire 1871-1999 tropical storm and hurricane file containing a 129 year period of record (POR) was utilized for this expanded study. The probabilities of the number of total tropical cyclone storm paths (tropical storm plus hurricane) within various radial distances from KSC were calculated for 185, 333, 556, 741 and 926-km (100, 180, 300, 400 and 500-nm) from Port Canaveral. Hurricane statistics for the actual KSC site were obtained from various sources (Hope 1968, Ho 1975/1987, Batts 1980, Elsner 1997) including the NM&OC (Turpin 1999) study.

4. BREVARD COUNTY/KSC AREA HURRICANE STATISTICS

Table 1 presents estimated tropical cyclone physical and atmospheric related parameters that apply to the KSC coastal area. Included are storm central pressure, radius of maximum winds, fastest mile winds, storm forward speed, probability of hurricane force winds, storm return periods, and landfall and exit statistics (Batts 1980, Ho 1975, Hope 1968). Some Table 1 parameters were interpolated for the KSC area (using mile post site #1650). Elsner (1997) has derived annual probabilities for each Florida County experiencing hurricane force winds, along with hurricane landfall, hurricane return period and wait period statistics. These are all based on a hurricane data base from 1900 through 1996 and values are presented in Table 1. The annual probability of Brevard County experiencing hurricane force winds is 10%. Hurricane landfall climatology for Brevard County indicates that 11 hurricanes (none greater than category 2) made landfall on Brevard County over this 97 year POR (with all occurring between 1921 and 1995 – a 75 year period). Two hurricane landfalls occurred in 1933. Of these 11 landfalls, 8 occurred over a 29 year POR between 1921 and 1949. Since 1949 only 3 landfalls have occurred in Brevard County, i.e., 1964, 1979 and 1995. The hurricane return period (defined as the average number of years between landfalls) for Brevard Co. is 10 years. The Brevard County hurricane wait period (defined as being the number of years until the probability of a landfall exceeds a probability of 50 percent) is 6 years.

A study of observed and calculated "critical" winds (defined as a KSC 1-min average wind speed ≥18 m/s (35 kts) observed at 10m height) for KSC from hurricane and tropical storm climatology (POR 1886-1966) was published in 1968 (Hope 1968), and selected results are presented in Table 1. There is a 37% chance for a storm producing at least one critical wind condition per year at KSC. Probabilities of storms producing critical KSC winds as a function of time and storm direction are also presented in this reference.

The NM&OC figure presented here in Figure 2 illustrates all the path segments of the 26 tropical cyclones that caused sustained winds of at least 11.3 m/s (22 kts) at one or more of five sites near Port Canaveral during the 52-year period, 1945-1996. Ten of these storms produced sustained winds near Port Canaveral of at least 17.5 m/s (34 kts). Of these ten cases, four occurred in September, four in October, while two occurred in August. No sustained winds of at least 17.5 m/s (34 kts) have been recorded at KSC from November through July. By including the 1997-1999 hurricane seasons, hurricane Floyd (in September 1999) gave sustained measured winds at KSC of 66 mph (57 kts) with a peak of 91mph (79 kts), while Patrick AFB recorded 80 mph (70 kts) winds. Likewise, hurricane Irene (in October 1999) gave sustained winds at KSC of 69 mph (60 kts) and a peak gust of 83 mph (72 kts). Therefore ten of the twelve highest measured sustained wind cases (or 83%) observed at KSC over the last 55 years occurred in the mid- to late- hurricane season. This means that there is only a 0.06% chance of encountering sustained winds at KSC of ≥17.5 m/s (34 kts) during any day throughout the year. During the hurricane season the probability rises to 0.10%, and during Aug-Sept-Oct it is 0.24%. Table 2 presents these extreme wind probabilities and wind measurements at KSC.

5. PORT CANAVERAL/KSC HURRICANE THREAT PROPERTIES

When a tropical cyclone is developing out in either the Atlantic or Gulf, it poses a problem to all concerned as to will it come ashore or stay away and pass harmlessly by. To help answer this question the

hurricane analysis of NM&OC (Turpin 1999) did an in-depth study of tropical cyclone passages near Port Canaveral Florida (POR 1886-1997). Some of the information presented here, including the average monthly storm speed at closest point of approach (CPA), was taken from this reference. Figure 3 shows that 92.2% of the storm directions come from the sectors southwest through east. With only 7.8% coming from the sectors west clockwise through northeast. The annual average storm speed is 7.2 m/s (14kts).

To characterize the potential threat to the Florida coast, the number of hurricanes and tropical storms from 1871-1999 that moved within a specified radius of Port Canaveral by month and season were determined. Storms were classified based on the predominant month for all of the 6-hourly observations. For example, if there are 14 observations in August for a particular storm within 400 nautical miles and 15 in September, the storm is classified as occurring in September. The months were combined as follows. May/June, July/August, September, and October/December to match the NM&OC seasonal grouping. Over the 129 year POR there have been 1076 total tropical cyclonic storms in the Atlantic basin, with September offering the greatest number of storms with 387 (36%), and May-June offering the least (75). The three months of August through October tallied a total of 856 storms (79.6%).

Table 3a contains the number and percent probability values of tropical cyclones reaching the various radial distances from Port Canaveral/KSC. Although September gives the maximum number of storms produced in the Atlantic basin, the monthly percent of tropical cyclones penetrating within the various radial circles is lowest in September and highest in May-June/Oct-Dec. Only 38% of all September tropical cyclones ever enter the 500-nm distance from Port Canaveral, and this reduces to only ~6% within 100-nm. Even though both tropical cyclone maximum wind speed (Table 3b) and minimum pressure (Table 3c) are the highest and lowest, respectively, in September (an indication of strong storms) for all 5 radial distances from Port Canaveral, the percentage occurrence of strong storms in September is the lowest of all the monthly groupings. In more detail, the September tropical cyclone maximum wind speed suddenly decreases (for both the median and 95th percentile value) as September tropical cyclone's penetrate the 180- and 100-nm distance. Likewise September storm minimum pressure also increases within 180-nm. Therefore, this indicates that the more intense September tropical cyclones statistically tend to bypass the Florida and KSC areas.

The storm occurrence maximum percent probability value, for all monthly categories (except for September), when tropical cyclones are within 100-nm of Port Canaveral is only 10 to 11% (Table 3a). Empirical quartiles for minimum sea level pressure (SLP) and maximum wind speed (WS) were computed from the available historical 6-hourly observations within the specified search radius for the 1886-1999 period of record. Observations for the quartiles are classified based on the month in which they occurred, regardless of the remaining storm observations. For example, a single wind speed observation in October, in a storm with the remaining observations in September, would be included in the array of values in September.

All monthly categories of tropical cyclones show a general decrease in maximum winds over the 5 distance categories as the storms approach Port Canaveral (Table 3b). And generally throughout the hurricane season the tropical cyclone atmospheric pressures tend to increase or stay the same as storms approach KSC, except for perhaps the May-June time frame when a slight decrease in pressure versus closer distance is noted.

Conditional probabilities (Table 4) were also developed based on the totals for each radial distance given in Table 3a. For example, P (100|500) indicates the probability that a storm will reach within 100 nautical miles, given that it initially moves to within 500 nautical miles, all based on the historical numbers given in Table 3a. These conditional probabilities indicate similar values and trends as compared to those given in Table 3a, as discussed above. September conditional probabilities are again the lowest of the four monthly groupings. i.e., P (100/500) = 16.2 % in September.

6. TROPICAL CYCLONE PATH, SPEED, AND TIME OF ARRIVAL

Hope (1968) presented the average path location of storm center distribution centroids for specific periods prior to, initially at, and after producing critical winds at KSC. His analysis resulted in formulating two distinct paths representing the Atlantic mid-season storms (15 July-15 October) and the late season Western Caribbean and Gulf storms (15 September-31 October). Results also incorporated storm speed with distance away from KSC.

The NM&OC (Turpin 1999) re-analyzed more hurricane data and presented up-dated average storm path results with storm speed and timing, by month. Some of these selected results are presented in Figure 4 and Table 5. Table 5 clearly indicates the inverse relationship between storm speed and the warning boundary distance (A, B or C) from KSC. Managers need to keep in mind that the values presented here represent only "average" tropical cyclone conditions affecting KSC, whereas many storms move faster or slower and traverse different paths. The general trend shown in Figure 4 indicates that Gulf/Caribbean storms dominate in early (May-June) and in late (October-December) season; whereas storms from out of the southeast Atlantic tend to dominate during mid-season (July through September).

7. CONCLUSION

This paper presents a brief synopsis of hurricane and tropical storm climatology for the Cape Canaveral (KSC/Port Canaveral) Florida area. It can aid NASA personnel, mission managers and launch directors by defining tropical cyclone characteristics, climatology and storm trends that have previously affected the KSC area. This information is statistically useful in the mission planning of summer and fall KSC launch attempts, and in considering vehicle roll back.

Key conclusions from this study include the following. In the coastal areas near KSC, there is a 10% annual probability of experiencing hurricane force winds (>64 kts), with a >10 yr return period of hurricane landfall near KSC. Limited wind measurements taken directly at KSC indicate that there is a daily empirical probability of 0.6% of obtaining winds of > 22 kts at KSC. Although September offers the most in number and most intense Atlantic basin tropical cyclones, their impact on the KSC area is smallest of any monthly grouping (probability is only ~6%). Finally the tracks of early and late hurricane season tropical cyclones toward KSC are generally of Gulf origin and relatively slower moving storms of less intensity. Whereas in mid season months, the storms which originate in the southeast Atlantic, are more intense and relatively fast moving.

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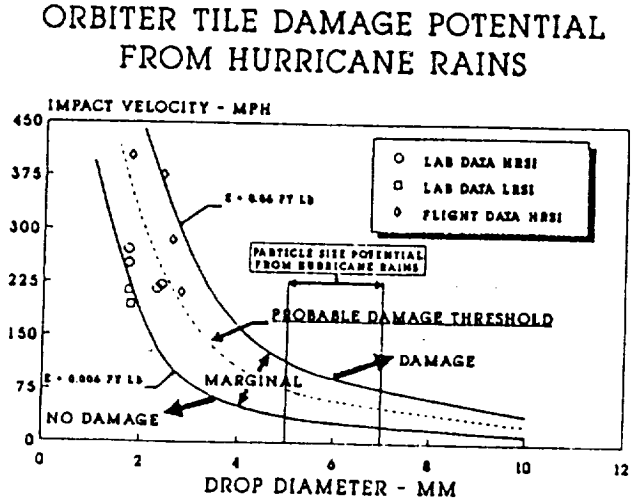

Figure 1. Shuttle Orbiter tile damage potential from hurricane driven rains (Barneburg).

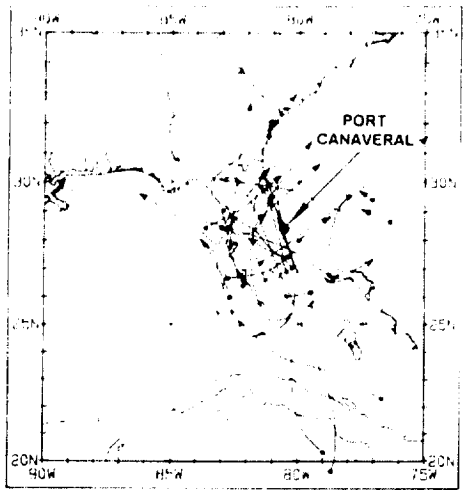

Figure 2. 26 tropical cyclone track segments causing sustained winds ≥ 22 kts at one or more of five sites near Port Canaveral during the 52-yr period 1945-1996 (Turpin 1999).

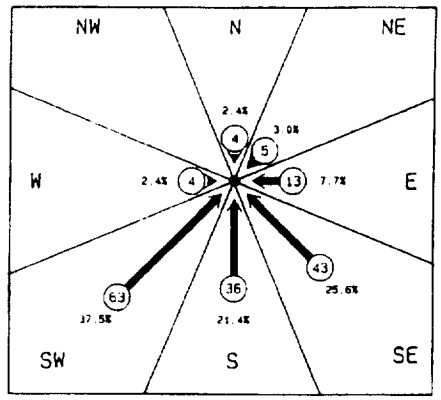

Figure 3. Directions of approach for 168 cyclones passing within 180 nm of Port Canaveral from 1886-1997 (Turpin 1999)

Figure 4. Primary Tropical Cyclone Threat Axis (Average Path) for Storms Passing Within 180 nm of KSC. With Average Storm Area Boundary Lines when Storms Are Within Various Days of KSC.

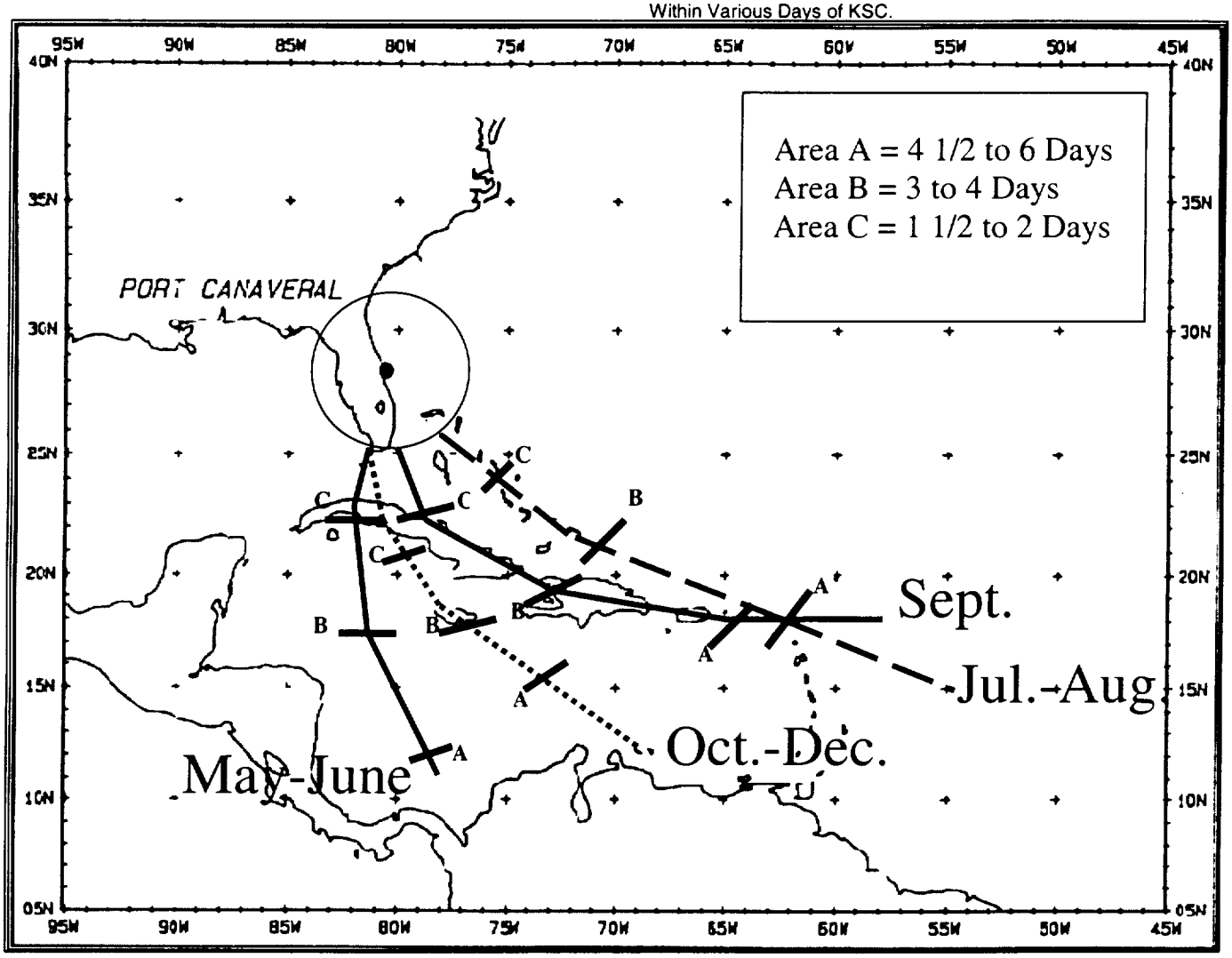

Table 1. Estimated KSC Area Tropical Cyclone Parametric Description/Statistics.

Atmospheric Parameter	At Coastal KSC Annual CPF(%) 5%	med	95%	Other
Atmospheric Pressure [1] (mb)	935	981	999	
Radius of Max Winds [1] (nm)	6	19	37	
Landfall Storm Forward Speed [1] (kt)	4	~10	16	
Fastest Mile Wind Speed [2] (kt)				(with a 10 yr RP) = 57 kt (with a 25 yr RP) = 74 kt
% Frequency of Critical KSC Surface Winds ≥35kt [5] (%)				Worst Mo. = 37 % Annual = 13.6 %
Brevard County [3]:				
• Annual Probability of Hurricane Force Winds (> 64kt/74mph) (%)				= 10 %
• RP Between Landfalls (yr)				= 10 yr
• Wait Period (WP)[4] (yr)				= 6 yr
• # landfalling storms/100yr/10nm of coast [2]				= 0.8
• # exiting storms/100yr/10nm of coast [2]				= 2.0

[1] Ho 1975/1987, (POR=1871-1973/1984); [2] Batts1980, (POR=1871-1973); [3] Elsner 1997, (POR=1900-1996); [4] WP defined as number of yrs until the probability of landfall exceeds a probability of 50%; [5] Hope 1968 (POR=1886-1966).

Table 2. KSC Area Sustained and Extreme Ground-level Measured Winds.

KSC Tropical Cyclone Induced Sustained Winds, over a 55 yr POR (1945-1999).[1,2]	KSC Sustained Winds **Daily Probability (%)**			**1999 Tropical Cyclone Generated Extreme Winds measured at KSC.**
Wind Category #Trop.Cycl.	Annual	Season	Aug-Oct[3]	Sustained WS(kts) Peak WS(kts)
≥22 kts 28	0.14%	0.24%	0.55%	60 kts (Irene) 79 kts(Floyd)
≥34 kts 12	0.06%	0.10%	0.24%	

1 Turpin 1999.

2 Note that thunderstorm peak winds can also be extreme and cause damage. The KSC squall-line thunderstorm of 3/29/97 produced sustained wind speeds of 80 kts recorded at Tower #110 (50 foot level), while an 85 kts peak wind was recorded (204 foot level). Pad 39 recorded a peak wind of 60 kts at the camera site 6 NW pad light pole, while the SLF (ctr) recorded a peak wind gust of 57 kts with sustained winds of 30 kts.

3 83% of all KSC induced tropical cyclone extreme winds occur from August through September.

Table 3a. Number, Probability and Return Periods for Tropical Cyclones within Specified Radial Distances (nm) away from KSC (Port Canaveral), 1871-1999.

Month	Tot. # Atl Cyc.	≤500 nm #	RP #/yr	RP yr	RP P%	≤400 nm #	RP #/yr	RP yr	RP P%	≤300 nm #	RP #/yr	RP yr	RP P%	≤180 nm #	RP #/yr	RP yr	RP P%	≤100 nm #	RP #/yr	RP yr	RP P%
May-June	75	46	0.4	2.8	61	38	0.3	3.4	51	32	0.2	4.0	43	19	0.1	6.8	25	8	0.06	16.1	11
July-Aug	307	139	1.1	0.9	45	111	0.9	1.2	36	89	0.7	1.5	29	55	0.4	2.4	18	32	0.25	4.0	10
Sept	**387**	148	1.2	0.9	**38**	120	0.9	1.1	**31**	91	0.7	1.4	**23**	52	0.4	2.5	**13**	24	0.19	5.4	**6**
Oct-Dec	300	174	1.3	0.7	58	147	1.1	0.9	49	115	0.9	1.1	38	71	0.6	1.8	24	34	0.26	3.8	11
Annual	1069	507	3.9	0.3	47	416			39	327			31	197			18	98	0.76	1.3	9

Table 3b. Number, Percentiles and standard deviation of Tropical Cyclone Wind Speeds (kts), by Monthly Groupings, Within Specified Distances (nm) from KSC.

Month	≤500 nm # obs	med	95%	sd	≤400 nm # obs	med	95%	sd	≤300 nm # obs	med	95%	sd	≤180 nm # obs	med	95%	sd	≤100 nm # obs	med	95%	sd
May-June	471	45	85	16	332	45	85	17	185	45	85	17	58	50	75	14	21	50	65	10
July-Aug	1406	65	105	25	985	63	105	25	642	65	105	25	227	50	105	25	80	50	105	24
Sept	1529	**70**	**120**	**29**	1012	**70**	**120**	**30**	579	**70**	**120**	**31**	196	55	**120**	**31**	58	**55**	**110**	**27**
Oct-Dec	1497	55	105	22	975	55	105	22	551	60	100	21	201	58	95	20	64	50	93	18
Annual	4903				3304				1957				682				223			

Table 3c. Number, Percentiles and Standard Deviation of Tropical Cyclone Pressures (mb), by Monthly Groupings, Within Specified Distances (nm) from KSC.

Month	≤500 nm # obs	med	95%	sd	≤400 nm # obs	med	95%	sd	≤300 nm # obs	med	95%	sd	≤180 nm # obs	med	95%	sd	≤100 nm # obs	med	95%	sd
May-June	155	1002	980	11	119	1002	978	11	89	1004	975	13	28	1009	975	12	7	999	-	29
July-Aug	588	1004	959	20	391	1004	959	20	243	1003	962	19	80	1003	967	19	27	1005	968	16
Sept	503	**986**	**936**	**24**	327	**982**	**935**	**25**	201	**975**	**934**	**25**	90	994	**935**	**22**	36	**987**	**946**	19
Oct-Dec	394	993	964	16	274	992	965	17	170	991	968	17	66	991	967	18	22	993	965	14
Annual	1640				1111				703				264				92			

Table 4. Conditional Probability of Occurrence (%) of Tropical Cyclones within Specified Radial Distances (nm) From Port Canaveral (1871-1999).

MONTHLY GROUPING	P(400/500)	P(300/500)	p(180/500)	p(100/500)
May-Jun	82.6	69.6	41.3	17.4=P(100/500)
May-Jun		84.2	50.0	21.1=P(100/400)
May-Jun			59.4	25.0=P(100/300)
May-Jun				42.1=P(100/180)
Jul-Aug	79.9	64.0	39.6	23.0
Jul-Aug		80.2	49.5	28.8
Jul-Aug			61.8	36.0
Jul-Aug				58.2
Sep	81.1	61.5	35.1	16.2
Sep		75.8	43.3	20.0
Sep			57.1	26.4
Sep				46.2
Oct-Dec	84.5	66.1	40.8	19.5
Oct-Dec		78.2	48.3	23.1
Oct-Dec			61.7	29.6
Oct-Dec				47.9

Table 5. Average Tropical Cyclone Speeds, Distances and Days away from KSC for all Storms passing within 180 nm of Port Canaveral, by Monthly Groupings. (POR = 1886-1997, Turpin 1999.)

Area	Avg. Days Storm at Area Boundary is away from KSC	**May-June** Avg. Storm Speed (kts)	Avg. Distance of Area Boundary from KSC (nm)	**July-August** Avg. Storm Speed (kts)	Avg. Distance of Area Boundary from KSC (nm)	**September** Avg. Storm Speed (kts)	Avg. Distance of Area Boundary from KSC (nm)	**October-December** Avg. Storm Speed (kts)	Avg. Distance of Area Boundary from KSC (nm)
A	4 1/2 – 6	8 kts	370nm	12 kts	360nm	11 kts	370nm	5 kts	460nm
B	3 – 4	7 kts	627nm	8 kts	670nm	7 kts	670nm	5 kts	645nm
C	1 1/2 – 2	9 kts	952nm	8 kts	1132nm	10 kts	1038nm	11 kts	838nm