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SECTION 12

OCCURRENCES OF TORNADOES AND HURRICANES

12.1 Introduction. Severe weather may adversely affect the design, transportation, test, and operation of aerospace vehicles. This section contains a discussion of such atmospheric phenomena. (The reader is referred to section 9 for a discussion of lightning and thunderstorm activity and to section 5 for information regarding severe worldwide weather conditions, including tornado, waterspout, dust devil, and hurricane extreme winds. Hail criteria is presented in section 7.)

12.2 Tornadoes. A tornado is a violently rotating column of air in contact with the ground which can be seen when it contains either surface dust and debris or condensation. Water spouts are tornadoes occurring on a water surface, and a funnel cloud occurs when the air column does not reach the ground. Although tornadoes are regarded as the most destructive wind force, most tornadoes (62 percent) are weak tornadoes. Weak tornadoes have wind speeds close to or below 100 miles per hour (mi/h), while strong tornado speeds may be in excess of 200 mi/h (ref. 12.1). Due to differential pressures created by tornadoes, buildings have been known to literally explode. Tornadoes are sometimes observed in association with hurricanes in Florida and along the coastal states. A subsection is presented here on this topic. Fortunately, the aerial extent of tornadoes is small compared with hurricanes. Tornado paths are predominately from the southwest direction (59 percent), with 72 percent of all F5 scale tornadoes being from the southwest (ref. 12.2). Figure 12.1 is a United States contour map showing the average annual tornado incidence per 10,000 mi^2 between 1953 and 1980. On this map, the months of peak tornado activity and average number of annual occurrences are given for each state (ref. 12.1). The three main centers of highest tornado incidence occur around Florida, Oklahoma, and Indiana.

The Fujita tornado intensity scale (F-scale) was introduced by Fujita (ref. 12.2) in 1971. Table 12.1 describes some characteristics of this six-point scale. The five most deadly (loss of life) individual tornadoes that have occurred over a 40-year time span in the U.S. since 1950 are shown in table 12.2 (ref. 12.3). Note that the associated F-scale is given, whereby indicating that loss of life is indeed more frequent in violent tornadic storms. The most individual tornadoes to occur on a single tornado day (i.e., tornado outbreak) is 144 on April 3, 1974, with path lengths totaling 2,452 miles (ref. 12.2). Tornado length, width, and area characteristics are presented in table 12.3 (ref. 12.4) for various states of interest to NASA. Fujita calculated what the maximum tornadic wind speeds would be with a 10^{-7} or 1/10,000,000 per year probability of occurrence. These windspeed categories are presented in fig. 12.2 for the continental United States. The highest windspeed of 308 mi/h with a 10^{-7} per year probability was found to be located in both central Oklahoma and northern Alabama. Wind speeds of 320 mi/h appear to be a reasonable maximum speed for tornadoes east of 105° longitude (eastern and central U.S.); while 180 mi/h maximum is reasonable west of 105° longitude (ref. 12.4).

Based on Thom's analysis of the number of tornado occurrences (ref. 12.5), table 12.4 has been prepared giving tornado statistics for stations of interest. The statistics included in table 12.4 are based upon an area (A_2) of a 1° square of latitude and longitude on the Earth's surface. The period of record is 1954 to 1983 (ref. 12.3). The probability of one or more tornadoes in N years in an area (A_1) is given by[1]

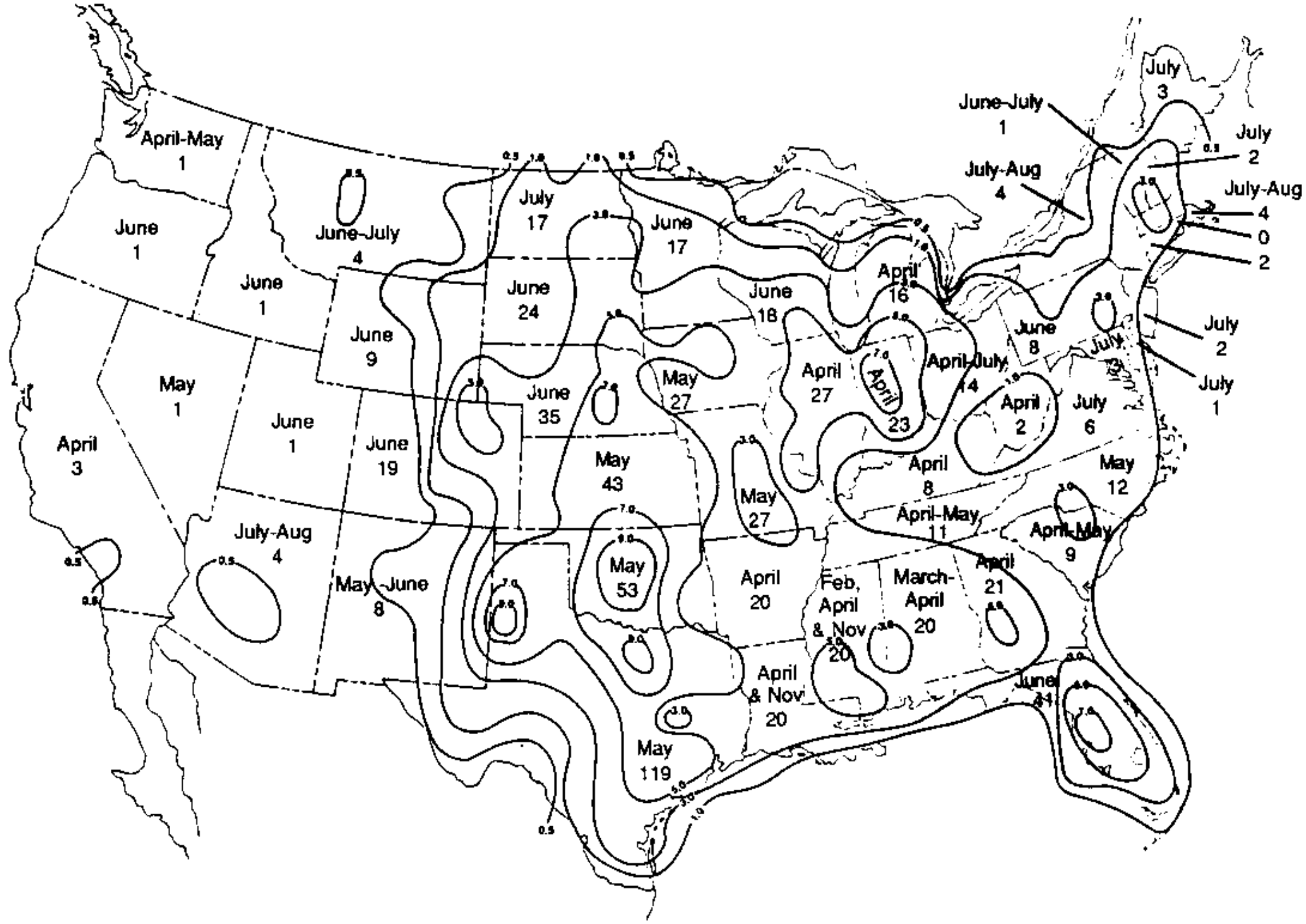
$$P(A_1;N) = 1 - \exp[(-\bar{x} * A_1 * N)/A_2] \ , \qquad (12.1)$$

where $\bar{x}$ is the mean number of tornadoes per year in a 1° square. The area size for A_1 was chosen as 7.3 km^2 (2.8 mi^2) because Thom (ref. 12.5) reports that 7.2572 km^2 (2.8209 mi^2) is the average ground area covered by tornadoes in Iowa, and the vital industrial complexes for most locations are of this general size. Thus defining A_1 as 7.3 km^2 (2.8 mi^2) and 2.59 km^2 (1.0 mi^2) and evaluating equation 12.1 for the values of $\bar{x}$ and A_2 for the stations given in table 12.4 yields the data in table 12.5. Table 12.5 gives the probability of one of more tornadoes in 7.3 km^2 and 2.59 km^2 areas in one year, 10 years, and 100 years for the indicated eight locations. It is noted that for $A_1 << A_2$ and N < 100, equation (12.1) can be approximated by

$$P(A_1;N) = (\bar{x} * A_1 * N)/A_2 \ . \qquad (12.2)$$

An interpretation of the statistics in table 12.5 is given using Kennedy Space Center (KSC) as an example. There is a 13.2 percent chance that at least one tornado will "hit" within a 7.3 km^2 (2.8 mi^2) area at KSC in 100 years. For a 2.59 km^2 (1 mi^2) area at KSC, the chance of at least one tornado hit in 100 years is 4.6 percent. If several structures within a 7.3 km^2 area at KSC are vital to a space mission and these structures are not designed to withstand the wind and internal pressure forces of a tornado, then there is a 13.2 percent chance that one or more of these vital structures will be damaged or destroyed by a tornado in 100 years. If the desired lifetime of these structures (or 7.3 km^2 industrial complex) is 100 years and the risk of destruction by tornadoes is accepted in the design, then the design risk or calculated risk of failure of at least one structure due to tornado occurrences is 13.2 percent. This example serves to point out that the probability of occurrence of an event which is rare in 1 year becomes rather large when taken over many years, and that estimates for the desired lifetime versus design risk for structures discussed in subsection 2.2.10 of section 2 should be made with prudence.

[1] Credit is due Dr. J. Goldman, International Center for the Solution of Environmental Problems, Houston, Texas, for this form of the probability expression.



[1]Month of peak tornado activity given on each state.

[2]Lower figure is average, annual tornadoes for each state.

Figure 12.1 Contours of average annual tornado incidence per 10,000 square miles, 1953–1980[1,2] (ref. 12.1).

TABLE 12.1 F-Scale Tornado Intensities and Corresponding Wind Speed Ranges and Characteristics (Ref. 12.2)

Tornado Intensity	F-Scale	Sustained Damage	Wind speed (mi/h)	F-Scale Percent Occurrence	Mean Path Length (mi)	Path Length Percent Occurrence
Weak	0	Light	40–72	25.5	1.2	7.3
	1	Moderate	73–112	37.3	2.6	22.9
Strong	2	Considerable	113–157	25.6	5.4	32.5
	3	Severe	158–206	9.3	10.0	21.8
Violent	4	Devastating	207–260	2.0	27.2	13.2
	5	Incredible	>261*	0.3	35.5	2.4
*Up to ~318 mph.						

TABLE 12.2 Five Deadliest Individual Tornadoes 1950–1989 (Ref. 12.3).

Date	Place	Deaths	F-Scale
1. June 8, 1953	Flint, MI	116	F5
2. May 11, 1953	Waco, TX	114	F5
3. June 9, 1953	Worcester, MA	90	F4
4. May 25, 1955	Udall, KS	80	F5
5. February 21, 1971	Pugh City, MS	58	F4

TABLE 12.3 Tornado Event Characteristics, 1954–1983 (Ref. 12.4).

		Tornado Length (mi)			Tornado Width (mi)			Tornado Area (mi^2)		
State	No. of Events	Average	F0 95%	F4 95%*	Average	F0 95%	F4 95%	Average	F0 95%	F4 95%
Alabama	685	7.25	42.7	53.5	0.099	0.327	0.677	1.048	8.02	19.1
California	111	1.87	7.55	—	0.059	0.223	—	0.239	0.645	—
Florida	1,328	2.67	8.70	—	0.028	0.074	—	0.137	0.368	—
Louisiana	703	4.56	20.2	36.6	0.055	0.161	1.43	0.379	1.76	17.0
Mississippi	744	8.72	47.8	58.2	0.106	0.341	0.616	1.093	7.39	11.2
New Mexico	250	3.54	15.5	—	0.100	0.483	—	0.291	3.19	—
Texas	4,008	3.42	13.9	44.5	0.063	0.184	1.23	0.453	1.43	26.2
Utah	36	0.89	3.53	—	0.049	0.328	—	0.069	0.629	—
Eastern U.S. Longitude <105°	21,583	4.44	18.5	113.0	0.068	0.224	0.968	0.512	2.08	39.5
Western U.S. Longitude >105°	779	2.29	8.03	—	0.049	0.163	—	0.137	0.514	—

*Assume log-normality distribution.

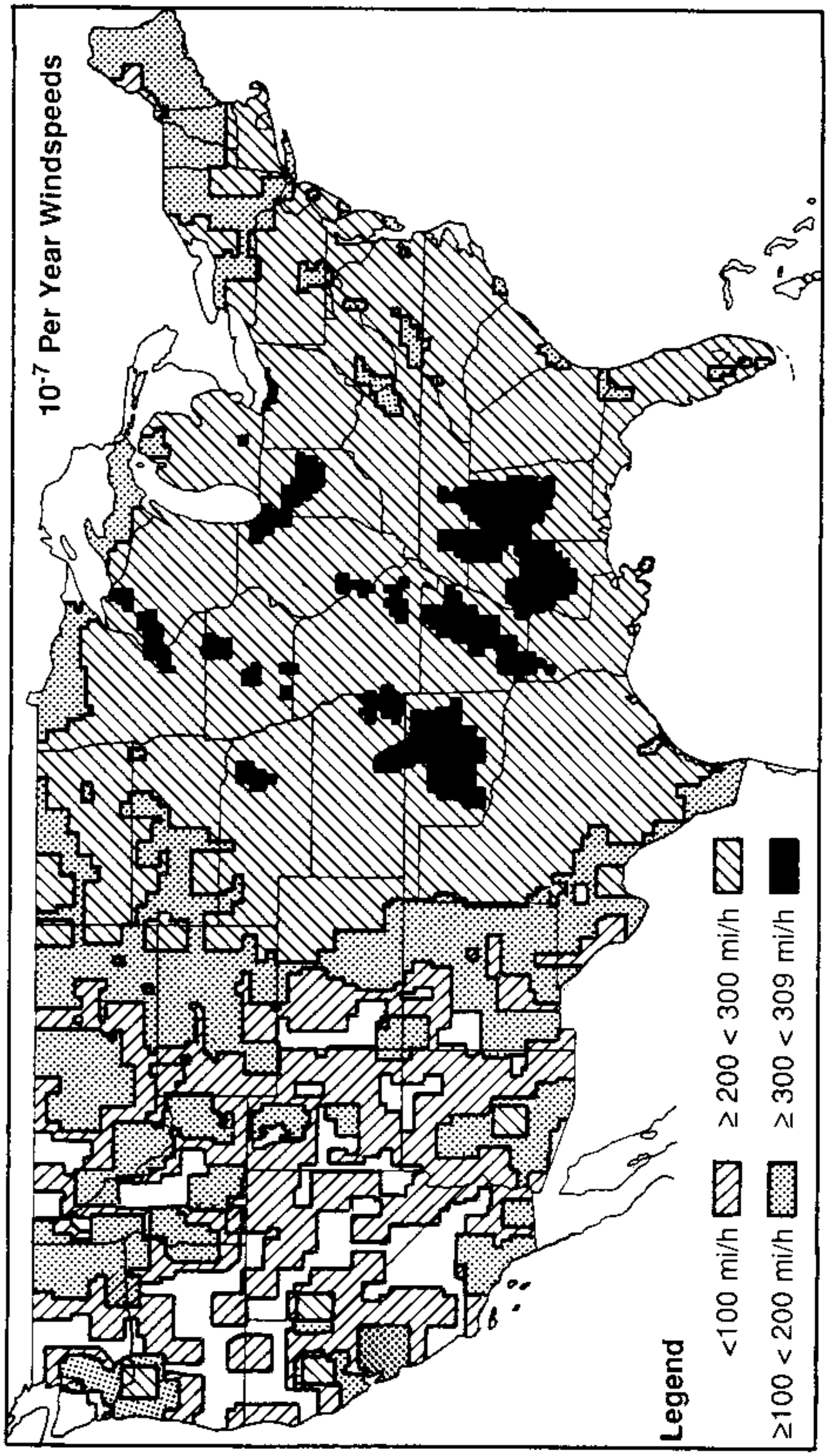


Figure 12.2 Distribution of the maximum windspeeds of tornadoes expected to occur with a 10^{-7} or 1/10,000,000 per year probability which is required for protecting nuclear power plants in the United States (ref. 12.2).

Table 12.4 Tornado statistics for stations specified, 1954–1983.

Station	Number of Tornadoes in 1° Square	Mean ($\bar{x}$) Number of Tornadoes Per Year in 1° Square	Area (A_2) of 1° Square km² (mi²)	Mean (P) Probability of a Tornado Striking a Point in Any Year in 1° Square	Mean (R) Recurrence Internal (yr) for a Tornado Striking a Point in a 1° Square
Huntsville	95	3.17	10,179 (3,930)	0.002275	440
Kennedy Space Center	59	1.97	10,839 (4,185)	0.001328	753
Vandenberg AFB	2	0.07	10,179 (3,930)	0.000050	19,902
Edwards AFB	11	0.37	10,179 (3,930)	0.000266	3,759
New Orleans	75	2.50	10,645 (4,110)	0.001716	583
NSTL, Bay St. Louis	72	2.40	10,645 (4,110)	0.001647	607
Houston	187	6.23	10,736 (4,145)	0.004240	236
White Sands	7	0.23	10,412 (4,020)	0.000161	6,211

$P = 2.8209\ \bar{x}/A_2,\ R = 1/P$

Table 12.5 Probability of one or more tornadoes in a 7.3-km² area and a 2.59-km² area in 1, 10, and 100 years.

Station	Mean ($\bar{x}$) Number of Tornadoes Per Year in 1° Square	$P(A_1;N)$ for A_1 = 7.3 km² (2.8 mi²)			$P(A_1;N)$ for A_1 = 2.59 km² (1.00 mi²)		
		N=1 Year	N=10 Years	N=100 Years	N=1 Year	N=10 Years	N=100 Years
Huntsville	3.17	0.002256	0.022585	0.202164	0.000807	0.008066	0.077494
Kennedy Space Center	1.97	0.001317	0.013180	0.131804	0.000471	0.004707	0.045982
Vandenberg AFB	0.07	0.000050	0.000499	0.004975	0.000018	0.000178	0.001780
Edwards AFB	0.35	0.000249	0.002494	0.024936	0.000089	0.000891	0.008866
New Orleans	2.50	0.001702	0.016887	0.170316	0.000608	0.006083	0.059014
NSTL, Bay St. Louis	2.40	0.001634	0.016217	0.150837	0.000584	0.005839	0.056722
Houston	6.23	0.004199	0.041211	0.343508	0.001503	0.015030	0.139552
White Sands	0.23	0.000160	0.001601	0.015892	0.000057	0.000572	0.005705

$P(A_1;N) = 1 - e^{-\bar{x}(A_1/A_2)N}$

12.3 Tornadoes Generated From Hurricanes. From a study by R. Gentry (ref. 12.6), which used a 22-year data base, it was determined that in nearly all full-intensity hurricanes, whose centers cross the U.S. coastline (south of Long Island, NY, and east of Brownsville, TX), have tornadoes associated with them. Also approximately 60 percent of tropical storms crossing into land develop tornadoes.

Most tornadoes (~20 percent) form near the hurricane core, or form within 100 km (~80 percent) of the hurricane center and frequently northeast and east of the center (between 20° and 120° azimuth) where the tipping and convergence terms of the vorticity equation are the largest. That is where the lower atmospheric layers are slowed by ground friction, but the upper (850-Mb level) winds are still moving at high hurricane speeds, thus creating strong vertical shears in the horizontal wind component. Satellite-observed cloud-top temperatures were also very low in these tornadoes, or the tornado formed in areas of existing strong temperature gradients. Generally the air that goes into and forms a tornado does not travel far from the ocean before genesis. In most cases, the tornadoes formed closer to the water (coastline) than to the hurricane center (with the center being farther inland). Finally, as a hurricane moves farther inland and loses its tropical characteristics, some tornadoes do form, but these do not have the genesis characteristics of the classical hurricane-spawned tornado. Hurricane-generated tornadoes can occur at any local time, but 50 percent were found to occur between 1200 and 1800 l.s.t. Figure 12.3 presents the locations of all hurricane-associated tornadoes, occurring between 1972 and 1980 (ref. 12.6), as a function of distance from the coastline. The hurricane David ground track is plotted in figure 12.3, as a reference for the David tornado occurrences.

12.4 Hurricanes and Tropical Storms. The occurrence of hurricanes at KSC and other locations for the Eastern range is of concern to the space program because of high winds and because the range support for space operations is closed during passage or near approach of a hurricane. This discussion will be restricted to the frequency of tropical storms, hurricanes, and tropical cyclones (tropical storms combined with hurricanes) for annual reference periods and certain monthly groupings, as a function of radial distances from KSC as well as some information about tropical storms in the Gulf Coast area.

TABLE 12.6 Saffir/Simpson Scale of Hurricane Intensity (Ref. 12.7).

Storm Category	Storm Surge (feet)	Mean Wind Speed (knots)
1. Weak	4–5	64–82
2. Moderate	6–8	83–95
3. Strong	9–12	96–112
4. Very Strong	13–18	113–135
5. Devastating	18–?	136–?

By definition, a hurricane is a storm of tropical origin with maximum sustained (1-min mean) surface winds greater than or equal to 34 m/s (65 knots). A tropical storm is a cyclone whose origin is in the tropics with sustained winds equal to or less than 33 m/s (64 knots) but greater than or equal to 18 m/s (35 knots).

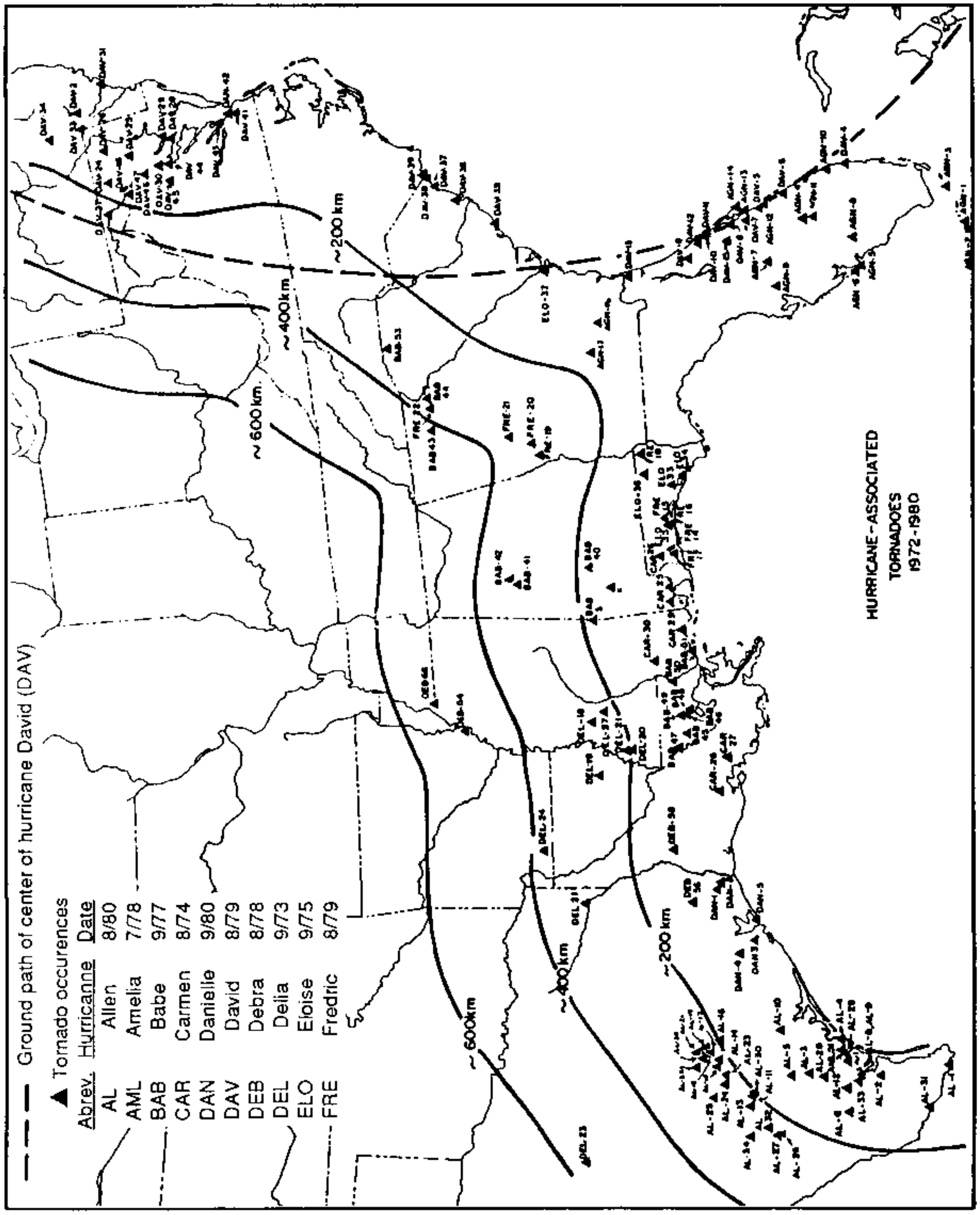


Figure 12.3 Location of tornadoes associated with hurricanes for the period 1972–80 with indications of the distance from the coast (ref. 12.4).

There is an established hurricane intensity scale which categorizes a hurricane's mean wind speed (and surge) versus its severity. It is called the Saffir/Simpson scale of hurricane intensity (ref. 12.7) and is presented in Table 12.6. There is no upper limit for wind speed in hurricanes, but speeds exceeding 90 m/s (175 knots) have been measured. In the United States, maximum hurricane wind speeds of 89.4 m/s (173.9 knots) have been recorded at Matecubme Key, FL, in 1935 and during Hurricane Camille on the Louisiana/Mississippi coast in 1969 (ref. 12.8). Tornadoes have also been observed in association with hurricanes as previously mentioned in subsection 12.3.

Tables 12.7 and 12.8 give a general indication of the frequency of tropical storms and hurricanes by months within 185- and 741-km (100- and 400-nmi) radii of KSC. From table 12.7, it is noted that hurricanes within these radii of KSC have been observed as early as May and as late as November, with highest frequency during August and September. In the 102-year period (1886–1987), there were 34 hurricanes that came within a 185-km (100-nmi) radius of KSC during this period. Although a hurricane path may come within a radius of 185 km (100 nmi), the wind speeds observed at KSC are not always greater than 33 m/s (64 knots). The highest recorded KSC hurricane-associated wind gust speed was 45.5 m/s (88.4 knots) measured atop (96 m) the launch complex 34 service structure during hurricane Dora on September 9, 1964. A simultaneous measurement of 42.4 m/s (82.3 knots) from the 21-m level, blockhouse location, was also recorded (ref. 12.9). Hurricanes at distances greater than 185 km (100 nmi) from KSC can possibly produce hurricane force winds at KSC.

Severe thunderstorms, and hurricanes downgraded to tropical storms, have also produced strong peak winds in the KSC area; i.e., peak speeds of 38.8 m/s at 150 m and 34.2 m/s at 18 m were recorded from downgraded Hurricane Abby in June 1968. Nonhurricane-associated winds at KSC have reached 26.2 m/s at 18 m and 32.6 m/s at 150-m levels (ref. 12.9). In general, hurricanes approaching KSC from the east (from the sea) will produce higher winds than those approaching KSC after crossing the peninsula of Florida (from the land). Hurricane David, September 1979, was the first hurricane to strike the Cape Canaveral area directly since 1926. The eastern edge of the eye passed within an estimated 1.5 mi of the space shuttle runway. Hurricane David's peak speed of 34.5 m/s (measured at 10.4 m) exceeded the design launch peak wind speed profile of the space shuttle natural environment requirements for a 5-percent risk of exceeding a 10-m level peak wind speed of 15.8 m/s (30.8 knots) for the windiest 1-h exposure period (ref. 12.10).

TABLE 12.7 Number of Hurricanes In a 102-Yr Period (1886–1987) Within a 185- and 741-km Radius of KSC.

Month	Number of Hurricanes Within 185-km (100-nmi) Radius	741-km (400-nmi) Radius
January	0	0
February	0	0
March	0	0
April	0	0
May	1	2
June	1	11
July	3	15
August	13	51
September	8	51
October	7	41
November	1	8
December	0	0
Total	34	179

TABLE 12.8 Number Of Tropical Storms in a 117-Yr Period (1871–1987) Within a 185-and 741-km Radius of KSC

Month	Number of Tropical Storms Within 185-km (100-nmi) Radius	741-km (400-nmi) Radius
January	0	0
February	1	1
March	0	0
April	0	0
May	2	4
June	7	31
July	6	29
August	23	69
September	24	112
October	33	103
November	1	17
December	1	1
Total	98	367

12.4.1 Distribution of Hurricane and Tropical Storm Frequencies. Knowing the mean number of tropical storms or hurricanes (events) per year that come within a given radius of KSC, without knowing other information, is of little use. Assuming the distribution of the number of tropical storms or hurricanes is a Poisson-type distribution, the mean number of events per year (or any reference period) can be used to completely define the Poisson distribution function as demonstrated below.

From figure 12.4 the probability of no event, $P(E_0,r)$ where r = radius, for the following can be read: (1) tropical storms and hurricanes for annual reference periods; (2) tropical storms and hurricanes for July-August-September; and (3) tropical storms and hurricanes for July-August-September-October, versus radius, in kilometers, from KSC. To obtain the probability for one or more events, $P(E_1,r)$ from figure 12.4 the reader is required to subtract the $P(E_0,r)$, read from the abscissa, from unity; that is $[1–P(E_0,r)] = P(E_1,r)$. For example, the probability that no hurricane path (eye) will come within 556 km (300 nmi) of KSC in a year is 0.33 $[P(E_0,r=300) = 0.33]$, and the probability that there will be one or more hurricanes within 556 km (300 nmi) of KSC in a year is 0.67 (1–0.33 = 0.67).

Figure 12.5 shows the average number of tropical cyclones entering on land in the Gulf Coast/Atlantic Coast areas per 100 years and per 10 nmi of coast in the time period from 1871 to 1984 (ref. 12.11).

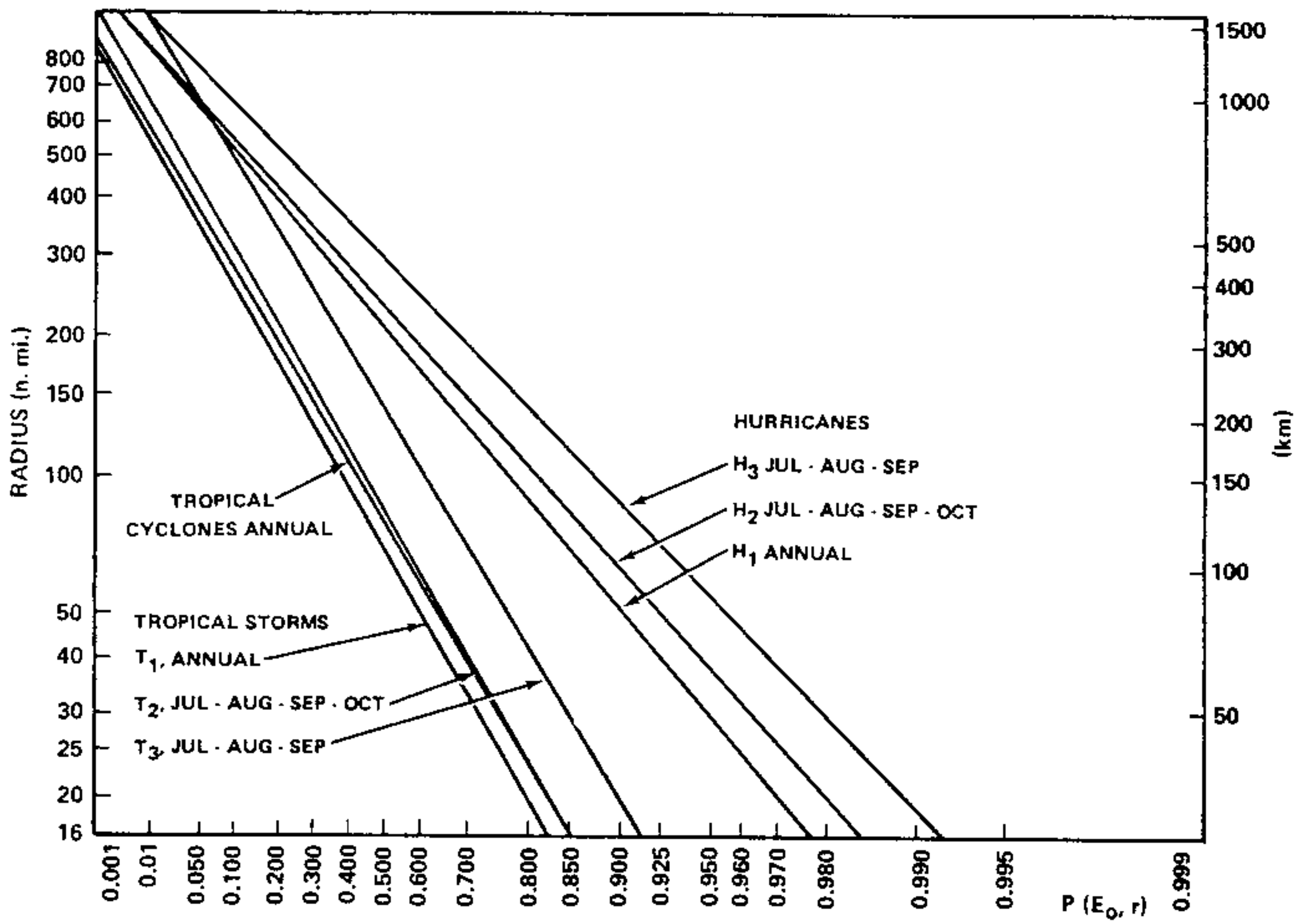


FIGURE 12.4 Probability of No Tropical Storms or Hurricanes for Various Reference Periods Versus Various Radii from KSC.

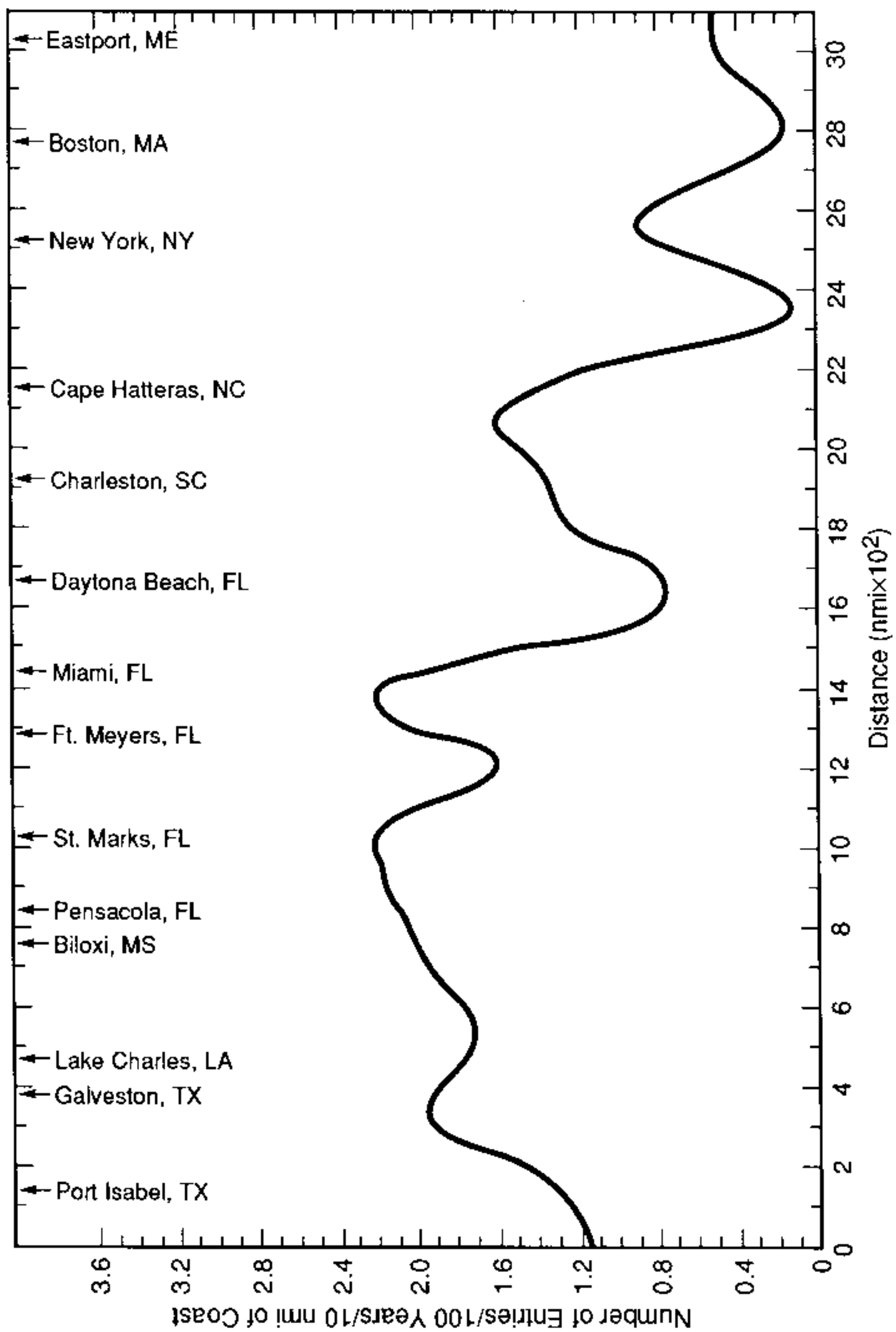


Figure 12.5 Smoothed frequency of landfalling tropical storms and hurricanes (1871–1984) by 50-nmi segments of a smoothed coastline for the Gulf and Atlantic coasts of the United States (ref. 12.9).

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