Probability of Tropical Cyclone Induced Winds at Cape Kennedy

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PROBABILITY OF TROPICAL CYCLONE INDUCED WINDS AT CAPE KENNEDY

John R. Hope and Charles J. Neumann
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Abstract

A statistical technique is developed for estimating the climatological probability that an existing tropical cyclone will produce sustained 35-knot winds at Cape Kennedy. Probabilities are specified for specific times and for various time intervals extending to seven days. The technique is developed initially considering only the storm's location, then expanded to take into account its antecedent path. Two classes of storms are processed separately: (1) Those originating over the Atlantic Ocean or the eastern Caribbean Sea, and (2) those originating over the western Caribbean Sea or the Gulf of Mexico. The technique can be adapted for wind speeds of other threshold values and for other coastal locations which may be affected by tropical cyclones.

Introduction

This study was undertaken in response to a request from NASA, Kennedy Space Center, to provide quantitative estimates of the likelihood of Cape Kennedy experiencing critical winds associated with tropical storms or hurricanes. Since the time required to return the Saturn V-Apollo space vehicle to the Vehicle Assembly Building at certain stages of launch preparation exceeds the period for which forecasts are issued, it is necessary to rely on climatology for periods exceeding 72 hours.

The problem posed to the Spaceflight Meteorology Group was threefold: (1) What is the probability of critical winds at Cape Kennedy during periods of various specified lengths during the hurricane season without regard to the current tropical cyclone situation? (2) What is the probability at a specified time of an existing tropical storm or hurricane producing critical winds at Cape Kennedy, and the total probability of an existing tropical storm or hurricane producing critical winds within a specified period of time? (3) What is the probability of an existing tropical storm or hurricane producing critical winds at Cape Kennedy, considering its antecedent motion?

In this report a critical wind is defined as a 35-knot one-minute average wind at anemometer level (10 meters at the Cape Kennedy Weather Station) produced by a tropical storm or hurricane. Assuming the gust factors usually associated with winds of this magnitude (1.4 or slightly higher), 35-knot one-minute winds would be accompanied by gusts approaching 50 knots. Tropical storms or hurricanes will be referred to jointly in this paper as tropical cyclones or simply as storms.

Procedure

Data on all tropical cyclones occurring in the Atlantic, Gulf of Mexico, or the Caribbean after the year 1885 were computer processed to determine if they were likely to have produced critical winds at Cape Kennedy. The University of Miami IBM 7040 computer was used for this and, wherever feasible, for other computational aspects of this study. Since the period of surface wind records at Cape Kennedy is much shorter than the period of record of tropical cyclones, a procedure was devised for the selection of storms likely to have produced critical winds at this site. The following regression equation was developed and tested on all tropical cyclones passing within 150 miles of Cape Kennedy during the ten years of overlapping period of record of Cape Kennedy surface winds and tropical cyclones, 1957-1966:

\[ R = 0.6 W_{max} + 30 \] (1)

where \( R \) = radius in nautical miles of 35 knot winds

\( W_{max} \) = estimated mean maximum wind in the storm in miles per hour for given day.

Maximum winds in each tropical cyclone were estimated for each day of the storm's existence by the National Weather Records Center for periods subsequent to 31 July 1899. During the 14 years of record prior to that date, maximum winds in storms approaching Cape Kennedy were estimated by the writers according to whether the storms were classified as tropical storms or hurricanes, and whether they approached from the land or the sea.

It is realized that this method of selection of storms affecting Cape Kennedy is somewhat arbitrary. Undoubtedly in some hurricanes sustained winds in excess of 35 knots will extend much farther from the storm center than equation (1) indicates, while in some minimal tropical storms the radius of 35 knot winds would be smaller. It is true also in general that asymmetry in the wind field would be observed in most storms, which in turn is a function of the intensity of the storm, its direction of movement, and the surrounding synoptic features. However, it is believed that in dealing with mean conditions where large numbers of storms are considered, the method outlined above correctly identified most of the storms that have produced 35 knot sustained winds at Cape Kennedy.

Equation (1) yields values for radii of 35 knot winds not greatly different from those obtained from other models, for example, Jelesniski (1966) and Hughes (1952). In any case, it is believed that this method of selection is superior to considering all storms passing within a fixed distance from the station.

18.1.1
The paths of all tropical storms, 1886-1966, which were calculated to have produced critical winds at Cape Kennedy according to the above criteria are shown in Figure 1.

Problem 1: To determine the average frequency of critical winds at Cape Kennedy without regard to the current existence of any tropical cyclones.

Figure 2 shows the computed critical wind frequency at Cape Kennedy 1886-1966. In all, there were 36 such occurrences over the span of 81 years. However, in the years 1887, 1890, 1893, 1928, 1933, and 1964 there were two occurrences each, leaving 30 years without occurrence. During these critical winds were observed at least once. The average frequency of one or more occurrences of the critical wind condition is therefore .37 or 37 per cent of the years.

Figure 3 stratifies the tropical cyclone data into calendar months, while Figure 4 further stratifies the data into calendar weeks (week one, January 1-7, etc.). As expected, both figures show the typical late summer and autumn tropical cyclone maximum but the latter figure suggests the possibility of some minor variations within the season itself. These intra-seasonal variations are depicted in greater detail in Figure 5. The probabilities shown on this latter figure are based on a 3-week moving average of the daily critical wind occurrences at Cape Kennedy over the period of record. For example, the percentage probability of 0.76 on October 16 indicates that between October 6 and October 26, 1886 through 1966 (a total of 1701 days), critical winds were observed at Cape Kennedy on 13 days (.0076 x 1701 = 13).

Between May 18 and November 8, Figure 5 shows that there are four peaks to the tropical cyclone season at Cape Kennedy. A small, almost insignificant maximum occurs in early June, while other, better defined peaks are seen to occur in early August, early September, and finally in mid-October. Minimum values occur during the first two weeks in July, mid-August, and late September.

The early season maximum is produced by storms which originate in the Gulf of Mexico or the western Caribbean and generally approach Cape Kennedy from the south or southwest. A rapid increase in the probability of critical winds can be expected in late July. The reason for the decline to a minimum in mid-August is not clear and may be due simply to the relatively few cases available for analysis. It was noted, however, that most of the storms that comprise the early August maximum originated in the 10-degree latitude-longitude box centered at 15N, 60W, whereas most of the storms that comprise the early September maximum originated either in the 10-degree latitude-longitude box five degrees farther north or traversed the entire Atlantic Ocean from off the coast of Africa. The late season maximum in mid-October has a sound physical basis and, as pointed out by Cry (1955), is produced by tropical cyclones that form over the western Caribbean Sea or Gulf of Mexico during that period.

Problem 2: To determine the probabilities at a given time and the cumulative probabilities of an existing tropical cyclone producing critical winds at Cape Kennedy within specified periods of time.

The location of all tropical cyclone centers calculated to have produced critical winds were plotted at 24-hour intervals beginning with the time of onset of these winds at Cape Kennedy and working backward seven days, or to the origin of the storm if it was existing less than seven days. An analysis of these plotted positions revealed two distinct source regions for storms which eventually affected Cape Kennedy. One source region was the Atlantic and extreme northeastern Caribbean, while the other was the Gulf of Mexico and western Caribbean. It was necessary, therefore, to process these two groups separately. It was found that, excepting one May and one June storm during the 81-year period, all of the eastern group of storms occurred during the period July 15 through October 15 (mid-season, Type B, storms), and all of the western group occurred during the period September 15 through October 31 (late-season, Type B, storms). Tropical cyclones occurring from May 1 through July 15 were designated as early season storms, but since only two have produced critical winds at Cape Kennedy during the period of record, they could not be processed according to the scheme to be outlined below.

After plotting the locations of the mid and late season storms, equi-probability ellipses were computed from the distribution of the storm center locations for each day prior to affecting Cape Kennedy and for each of the two groups of storms, assuming a bivariate normal distribution of the latitude and longitude coordinates. The Kolmogorov-Smirnov one-sample test (Siegel, 1956) was applied to determine that this assumption was reasonable. The difference between the theoretical and actual cumulative probabilities did not indicate that this hypothesis should be rejected.

An example of a computed ellipse is shown in Figure 6. Following convention, storm symbols plotted with open circles are tropical storms while those with darkened circles represent hurricanes. This ellipse depicts the theoretical distribution of storms that might be expected to be producing critical winds at Cape Kennedy in the number of cases. It is observed that 90 per cent of such storms should lie within the .90 contour, 10 per cent within the .10 contour, etc. This procedure is a modification of a technique suggested by Haggard, Crutcher and Whiting (1965). Elsewhere, techniques utilizing probability ellipses applied to a number of meteorological parameters have been described by, among others, Rapp and Insardi (1951), Veigas et al (1959), and Crutcher and Baer (1962).

It was necessary to compute probability ellipses in order to expand the available data. According to the criteria used in this study, only thirty-six storms affected the Cape Kennedy area during the eighty-one year period of record. The number of storms plotted
at 24-hour intervals prior to affecting Cape Kennedy ranged from eight to twenty-three in the Atlantic and from four to eleven in the western Caribbean and the Gulf of Mexico. The ellipses permit redistribution of these storms so that a value can be assigned to each area into which the ellipse is subdivided.

The centroids of the two groups of storms plotted at 24-hour intervals as they approached Cape Kennedy are shown in Figure 7. Note that in the late season group, that is, those originating in the western Caribbean or the Gulf of Mexico, the ellipses were computed for periods extending out to five days (120 hours) only. It was not possible to compute ellipses for six to seven days in that area because too few storms were in existence for that length of time prior to their affecting Cape Kennedy.

The probability ellipses were computed as follows. The variances along the major and minor axes of the distribution were obtained from the formula, given by the National Weather Records Center (1963) and others,

\[
K = \frac{\sigma^2_x + \sigma^2_y + \sqrt{(\sigma^2_x + \sigma^2_y)^2 - 4\sigma^2_x \sigma^2_y (1 - r^2)}}{2}
\]

(2)

where \(\sigma^2_x\) = variance of longitude

\(\sigma^2_y\) = variance of latitude

\(r\) = correlation coefficient between the latitudes and the longitudes of the distribution.

The larger value of \(K\) (\(K_a\)) is the variance along the major axis, while the smaller value (\(K_b\)) is the variance along the minor axis of the distribution.

The probability contours of the ellipse are computed by multiplying the square root of \(K_a\) and \(K_b\), or the standard deviations along the major and minor axes, by a multiplier (C) computed from the formula, Burington and May (1958),

\[
P = 1 - e^{-\frac{1}{2}}
\]

(3)

where P = probability

e = base of natural logarithms.\(^{10}\)

The orientation or angle of rotation, \(\psi\), of the ellipse relative to the latitude parallels and the longitude meridians is given by

\[
\psi = \frac{1}{2} \arctan \left[ \frac{2 \cdot r \sigma_x \sigma_y}{\sigma_x^2 - \sigma_y^2} \right]
\]

(4)

\(\psi\) is positive when measured from the positive X-axis to the positive Y-axis. In the frame of reference used here the X-axis is positive eastward, the Y-axis is positive northward.

The storm distribution indicated by the ellipse was used to determine the probabilities that storms located over particular areas would affect Cape Kennedy at a given time. These probabilities were determined by the following procedure.

It was found that the best resolution of the data could be obtained by dividing the area studied into 2\(\frac{1}{2}\)-degree latitude-longitude boxes. Positions of hurricanes back to the year 1886 as given by Crv et al. (1959) have been punched on computer cards at the National Weather Records Center, Asheville, North Carolina.\(^{11}\) This card deck was brought up to date and computer processed to determine the total number of tropical storms or hurricanes that had been in each 2\(\frac{1}{2}\)-degree latitude-longitude box during the eighty-one years of record. These data, divided into early-season storms, May 1-July 31, mid-season storms, July 15-October 15, and late-season storms, September 15-October 31, are shown respectively in Figures 8, 9 and 10.

Each 2\(\frac{1}{2}\)-degree box, any part of which was contained within a 99 per cent ellipse, was examined to determine the portion of the ellipse, in terms of per cent probability, that it contained. These values are the percentages of storms within the ellipse that would be located in the included boxes at a particular time prior to their reaching Cape Kennedy. These percentages multiplied by the total number of storms from which the ellipse was computed, yield the number of storms that would have been in the individual boxes, assuming a bivariate normal distribution. This adjusted number of storms affecting Cape Kennedy, divided by the total number of storms in the box during the period of record, gives the desired probability of a storm in a given box affecting Cape Kennedy at a specified time.

An example of the results of these computations for the 120-hour Atlantic storms is shown in Figure 11.

Summarizing the above, the probability of an existing storm in a particular box affecting the Cape Kennedy area at a given time is given by

\[
P_1 = \frac{\text{EN}}{N} (\text{5})
\]

where \(P_1\) = probability that an existing storm will affect Cape Kennedy at a specified time

\(N\) = actual number of storms affecting Cape Kennedy from which the ellipse was computed

\(B\) = contribution of a box to 99 per cent ellipse

\(N_t\) = total number of storms passing through a latitude-longitude box during season over entire period of record.

\(\text{EN}\) is the computed number of storms in each box that should have affected Cape Kennedy. The computation of \(B\) is illustrated in the Appendix.

So far all of the probabilities computed refer to the occurrence of critical winds at Cape Kennedy at specified times. There remains to determine an estimate of the total probability that an existing storm will affect Cape Kennedy within a specified period of time.
The probabilities previously computed cannot simply be added to obtain the total probability of Cape Kennedy being affected by an existing storm. In the cumulative process, it is necessary to consider the number of boxes that the storms passed through from one day to the next. When these are counted, a factor is obtained which can be applied to each box within the ellipse, and has the effect of adding storms to each box, because the number of storms passing through each box during a given time span is considered, not merely those storms that were in the box at a specified time. For Atlantic and eastern Caribbean storms, this increased the number in each box affecting Cape Kennedy by an average factor of 3.0, while in the western Caribbean and the Gulf of Mexico they were increased by an average factor of 2.2. The difference here is due to the fact that the average speed of Atlantic storms is greater than those in the Gulf of Mexico and the Caribbean.

A selected example of a total cumulative probability chart is shown in Figure 12. The data presented in this chart were smoothed by averaging the numbers in the boxes at their common intersection, boxes with no entry being counted as zero.

Problem 1: To determine the probability of an existing tropical cyclone producing critical winds at Cape Kennedy considering the storm's antecedent motion.

Figure 12 presented data on the probability of an existing Atlantic or eastern Caribbean tropical cyclone producing critical winds at Cape Kennedy within 168 hours without regard to the storm's direction of motion. For example, the figure indicates that a tropical cyclone located at 22°N, 65°W has a 19% chance of producing critical winds at Cape Kennedy within 168 hours. It is apparent, however, that if a storm is located at this given point and is moving in some direction away from Cape Kennedy, say towards the northeast, the probability would be considerably less than 19%. On the other hand, a storm located at this same site moving toward the WNW or NW would have a higher probability than 19% of producing critical winds at Cape Kennedy. It is desirable, therefore, to stratify further the data of Figure 12 in such a manner that the final cumulative probabilities are dependent on the storm's direction of motion.

A computer program was written to count the number of storms passing through each 2° degree latitude-longitude box from each of the eight directions measured clockwise from north (north through northeast, north through east, etc.). Storm motion was taken as the motion of the storm upon its entry into a given box. The program was run initially for all storms of a given category, regardless of their effect on Cape Kennedy. The program was then run for a second time including only those storms which eventually yielded critical winds for Cape Kennedy.

The data pertaining to the latter category of storms were processed further to determine the variation of storm movement with longitude. Table 1 shows the results of this processing and clearly demonstrates that for longitudes east of 77.5°W, nearly all of the storms which affected Cape Kennedy were moving in a direction from east through southeast but with a few cases from the adjacent directions of east through northeast or southeast through south. Given a larger data sample, it is considered likely that each of the zones would observe at least a few cases in the adjacent boxes. It appears, therefore, that insofar as longitudes east of 77.5°W are concerned, the average direction of movement of storms which eventually bring critical winds to Cape Kennedy is, for all practical purposes, constant. It was permissible, therefore, and in fact, desirable, to combine the longitude zones east of 77.5°W into a single zone. This averaging process has the effect of partially compensating for the limited data sample under consideration. Referring again to Table 1, the two zones west of 77.5°W were retained as separate entities since the directional values within these two latter zones show distinctly the trend for recurvature in these longitudes. The modifications just described are shown in Table 2.

The data from Table 2 provide sufficient additional information to subdivide the cumulative non-directional probabilities obtained from Figures 12 into cumulative directional probabilities. For a given 2° degree latitude-longitude box and for a given cumulative time period, the necessary computations can be expressed as follows:

$$P_d = \frac{P \cdot N_t \cdot F_d}{N_d}$$

where:

- $P_d$ = cumulative probability of a tropical cyclone moving from direction $d$ producing critical winds at Cape Kennedy
- $P$ = cumulative probability of a storm producing critical winds at Cape Kennedy without regard to the storm's movement
- $N_t$ = total number of storms passing through the given 2° degree latitude-longitude box
- $F_d$ = appropriate directional factor (from Table 2)
- $N_d$ = actual count of total number of storms passing through the given 2° degree latitude-longitude box from a direction $d$.

In formula (6), the product $PN_t$ in the numerator equals the number of storms in a given box calculated to have affected Cape Kennedy. This product multiplied by the factor $(F_d)$ yields the number of storms moving from a particular direction which eventually reached Cape Kennedy. Dividing the numerator by $N_d$ gives the desired directional probability. If the numerator and denominator from which each cumulative directional probability is computed are added separately and the quotient of these two sums obtained, the result is the same as for the cumulative non-directional probabilities.
As an example of the computation of a specific cumulative directional probability, suppose it is desired to determine the probability of a storm located in the center of the 2° degree latitude-longitude box located just south of 20° N and just west of 60° W of producing critical winds at Cape Kennedy within 168 hours. The storm is moving from the ESE. In formula (6),

\[ P = 0.16 \text{ (from Figure 12)} \]
\[ N_t = 52 \text{ (from Figure 9)} \]
\[ F_d = 0.966 \text{ (from Table 2)} \]
\[ N_d = 46 \text{ (from computer output; these figures not included in report)} \]
\[ P_{ese} = \frac{0.16 \times 52 \times 0.966}{46} = 0.175 \text{ or 17.5%} \]

Thus, the fact that the storm is moving towards Cape Kennedy increases the probability of this storm producing critical winds at Cape Kennedy from 16% to 17.5%.

A computer program was written to perform the necessary computations for Type B storms for each of the eight directions and for each of the cumulative time periods (168 hours, 144 hours, 120 hours, and 96 hours) and to smooth the data over four adjacent boxes. Selected examples of the results of these computations along with an isoline analysis of the plotted data are shown in Figures 13 through 15.

Conclusions

The probabilities computed in this study are most useful for time scales beyond those for which forecasts are issued. Normally military and NASA installations will have forecasts available for periods extending out to 72 hours. Studies have been made on the accuracy of these forecasts, and some of these use the forecasts themselves to compute storm strike probabilities. Among these are Tracy (1966), Appleman (1963), U.S. Navy Weather Research Facility (1963), and Veigas et al (1959).12,13,14,15 Although climatological probabilities for periods less than 72 hours are presented in this paper, they are not intended to replace those based on the latest available forecasts.

There were insufficient data available to process May, June, or early July storms according to the method outlined. However, if a storm should appear during this period, an estimate of the probability of its affecting Cape Kennedy can be obtained by noting its point of origin. For example, if a May, June, or early July storm originated in the western Caribbean or the Gulf of Mexico, the probabilities computed for the late-season storms would be more appropriate. Similarly, if a storm appears in the Atlantic or eastern Caribbean during the early season, probabilities computed for the mid-season storms would be used. In either case, caution should be used since the computations were not made from early-season data.

Certainly more confidence can be placed in the probabilities computed for mid-season storms, that is, those originating in the Atlantic or the eastern Caribbean, than for late-season storms because there were more data available from which to compute the former. Indeed, it was not possible to stratify the latter group of storms according to antecedent motion due to lack of data.

It is believed that the probabilities computed herein will be of use to planners whose responsibility it is to initiate action in advance of the time of onset of critical winds. Besides giving an estimate of the probability and time of Cape Kennedy being affected by a tropical cyclone, the study clearly shows the areas from which the greatest threats emanate as well as those areas from which there is little likelihood that a storm may reach Cape Kennedy.

The breakdown of tropical storm occurrences in the Atlantic, Gulf of Mexico and the Caribbean into 2° degree latitude-longitude boxes is a refinement of tropical cyclone climatology since previous studies have shown the distribution over 5° degree latitude-longitude boxes.

Acknowledgments

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Special thanks are due to Mr. Dale Martin of the Miami Section of the Spaceflight Meteorology Group for his excellent drafting work on the many figures contained in this report and also for his many helpful suggestions throughout all phases of this study.
Appendix

Computation of $B$ in Formula (2)

$P_1 = B/N_t$

Consider the 120-hour (5-day) ellipses for storms originating in the Atlantic or eastern Caribbean (Figure A).

Now consider the $2\frac{1}{2}$ degree latitude-longitude box bounded by 20N, 62.5W, 17.5N, and 65W.

Portions of the .50-.70, .30-.50, and .10-.30 elliptical rings pass through the box. Each elliptical ring contributes .20 (20 per cent) to the total ellipse.

The contribution of the area in the box to the entire ellipse in terms of probability can be determined by finding the portion of each complete elliptical ring that is included in the box. For this a planimeter or a fine-mesh grid can be used. In this case, the box includes:

- 5.0 per cent of the .50-.70 elliptical ring
- 8.8 per cent of the .30-.50 elliptical ring
- 14.5 per cent of the .10-.30 elliptical ring

To find the portion of the ellipse contained in the box, multiply the portion of each elliptical ring included in the box by the per cent contribution of each elliptical ring to the entire ellipse, and total the products.

\[
\begin{align*}
5.0\% \times 0.20 &= 1.0 \\
8.8\% \times 0.20 &= 1.7 \\
14.5\% \times 0.20 &= 2.9
\end{align*}
\]

Total included in box 5.6%

That is, 5.6% of the storms within the ellipse would have been in this particular box assuming a bivariate normal distribution. Since there were 16 storms from which the ellipse was computed at 120 hours, the total in the box would have been

$B = 5.6\% \times 16 = .89$ storms

References

Table 1: Direction of motion of Type B storms within specified longitude zones prior to producing critical winds at Cape Kennedy

<table>
<thead>
<tr>
<th>Number of Cases Observed Within Long. Zones (°W)</th>
<th>N-NE</th>
<th>NE-E</th>
<th>E-SE</th>
<th>SE-S</th>
<th>SW-W</th>
<th>W-NW</th>
<th>NW-W</th>
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<td>80.0 to 82.5</td>
<td>11</td>
<td>8</td>
<td>5</td>
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<td>77.5 to 80.0</td>
<td>24</td>
<td>7</td>
<td>1</td>
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<td>75.0 to 77.5</td>
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<td>72.5 to 75.0</td>
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<td>70.0 to 72.5</td>
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Table 2: Direction of motion of Type B storms within specified combined longitude zones prior to producing critical winds at Cape Kennedy

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<thead>
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<th>Movement from</th>
<th>Longitude Zones (°W)</th>
<th>80.0 - 82.5</th>
<th>77.5 - 80.0</th>
<th>East of 77.5</th>
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<td>% of total</td>
<td>Cases</td>
<td>% of total</td>
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<td>0</td>
<td>0.0</td>
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<td>24</td>
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Figure 1  Tracks of tropical storms or hurricanes which produced critical winds at Cape Kennedy, 1886-1966.

Figure 2  Occurrences of critical winds at Cape Kennedy by year, 1886-1966.
Figure 3

Percent probability of one or more occurrences of critical wind speed at Cape Kennedy during specified months.

18.1-9
Figure 4 Percent probability of one or more occurrences of critical wind speed at Cape Kennedy during specified weeks.
Figure 5 Percent probability of critical wind speed occurrence at Cape Kennedy on any given date based on 3-week moving average.
Figure 6  Probability ellipse of the distribution of tropical storms or hurricanes, having originated in the eastern Caribbean or Atlantic July 15 - October 15, 1886-1966, which produced critical winds at Cape Kennedy at 120 hours.
Figure 7  Location of storm center distribution centroids at specified periods prior to (X), initially (o), and after (4) producing critical winds at Cape Kennedy.
Figure 8  Number of tropical storms or hurricanes passing through each 2½ degree latitude-longitude box 1 May - 15 July 1886-1966.
Figure 9  Number of tropical storms or hurricanes passing through each 2½ degree latitude-longitude box 15 July - 15 October 1886-1966.
Figure 10  
Number of tropical storms or hurricanes passing through each 2 1/2 degree latitude-longitude box
15 September - 31 October 1886-1966.
Figure 11  Percent probability that tropical storms or hurricanes having originated in the Atlantic or eastern Caribbean July 15 - October 15 will produce critical winds at Cape Kennedy at 120 hours.

Figure 12  Cumulative percent probability of a tropical storm or hurricane located at a given point and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 168 hours.
Figure 13  Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the east through northeast and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 168 hours.
Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the east through southeast and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 168 hours.
Figure 15  Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the southeast through south and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 168 hours.
Figure A  Ellipse used in illustration of the computation of B in formula (5), $P^1 = \frac{BN}{N_t}$