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Frequency and Duration of Thunderstorms in the Cape Kennedy Area

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ESSA

FREQUENCY AND DURATION OF THUNDERSTORMS IN THE CAPE KENNEDY AREA

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Abstract

This report presents a detailed statistical analysis of thunderstorm occurrence at or in the immediate vicinity of Cape Kennedy, Florida based on 13 years of record through the year 1967. Empirical thunderstorm probabilities are derived for any given time of the day, for any day of the year for time periods ranging up to seven days duration. Presented also are data on multiple thunderstorm occurrence on single days, probability of thunderstorm non-occurrence, thunderstorm duration, "runs" of thunderstorm days and conditional thunderstorm probabilities.

Introduction

The ESSA Weather Bureau's Spaceflight Meteorology Group (SMG), through funds transferred from the NASA Office of Manned Spaceflight provides the primary meteorological support for the NASA manned spaceflight program. This particular study, actually Part I of a larger scale study, was undertaken by SMG, Miami in order to make available to the operational forecaster and also to the mission planner detailed statistical information relative to the annual thunderstorm cycle at Cape Kennedy. Part II of this study is currently in preparation. The main purpose of Part II will be to enable the weather forecaster to determine meaningful thunderstorm probabilities for a given time or over an extended time period based largely on the observed 3000-ft wind speed and direction at Cape Kennedy.

The Florida Thunderstorm Maximum

Portions of peninsular Florida observe more seasonal thunderstorm activity than any other site over the United States [1]; moreover, the area is one of the major thunderstorm genesis areas over the earth [2]. It generally is agreed that the reason for this condition is related to the presence of rather unique physical-environmental conditions. There is virtually an inexhaustible supply of low-level moisture with attendant conditional instability. Furthermore, the land mass is large enough to allow vigorous afternoon convection with further lifting action supplied by the sea-breeze convergence [3] and in some cases by transitory synoptic or sub-synoptic scale phenomena.

There are, of course, marked temporal and spatial variations to the thunderstorm maximum. In general, the greater part of the activity occurs over the interior sections of the peninsula on summer afternoons.

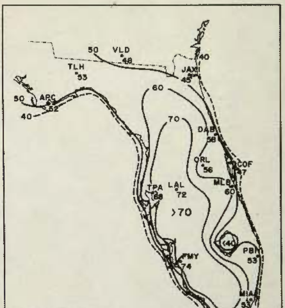

Figure 1
Percent of Days Reporting Thunderstorms July & August

Figure 1 shows the relationship of Cape Kennedy to the rest of the area insofar as the spatial maximum is concerned during the peak two-month period July and August. The isolines on the figure are based on long period records for the stations concerned [4].

Although Figure 1 depicts a relative thunderstorm maximum over interior sections, synoptic forecasting experience has shown that the longitudinal position of the maximum during any given afternoon is a function of the existing low tropospheric wind distribution. In general, with a substantial easterly wind component, the maximum occurs farther westward while with the opposite wind component, the thunderstorm maximum occurs farther eastward. Based on radar data alone, Frank, Moore, and Fisher[5] have documented this condition. The authors have shown further that light and variable winds tend to produce a double thunderstorm maximum, that is, one just inland from both coasts. A westerly component wind regime or a light and variable wind regime normally will result in thunderstorms being advected into or building near Cape Kennedy. Only on rare occasions, apparently as a consequence of large-scale divergence as evidenced by mid-tropospheric dryness, do summertime thunderstorms fail to materialize over the Florida peninsula. Indeed, then, the summertime forecast problem at Cape Kennedy is primarily one of forecasting the velocity of the low-tropospheric wind field.

Purpose of Study

In the foregoing brief introduction, some of the basic factors relating to the Florida thunderstorm maximum were discussed. However, the main purpose of this report is to present a definitive reference on certain climatological parameters dealing with the duration and frequency of thunderstorms at Cape Kennedy itself. Standard available climatological summaries are deficient in several respects. In the first place, most operational problems require statistical information relating to the normal frequency of thunderstorms over an extended period, say three or six hours rather than at a spot time as given in standardized summaries. Secondly, use of the summaries requires the normally invalid assumption that conditions at mid-month are representative of the month as a whole, giving an unrealistic stepwise frequency distribution. Any attempt at simple interpolation between the mid-periods of adjacent months may lead to errors because of non-linearity of the data distribution. Another shortcoming of standardized summaries of non-continuous parameters such as "observations with thunderstorms" is that they do not sample all the data. About 11% of the thunderstorm occurrences at Cape Kennedy begin and end between hourly observations and thus are not recorded on the hourly observations upon which the summaries are based.

Data Available for Analysis

Copies of the original WBAN Form 10A and 10B (weather observation log sheet) for Cape Kennedy are available at SMG, Miami for the eleven-year period 1957 through 1967. In addition, microfilm records were obtained for the preceding years back to May 1950. During this earlier period, however, records were not always maintained for the complete 24-hour period and only 1951 and 1952 were complete in this respect. Accordingly, then, a total of thirteen years (1951, 1952, and 1957 through 1967) were utilized.

The actual location of the observation site is about a mile inland from the easternmost point of Cape Kennedy. During the earlier years, the site was a mile or so farther south and somewhat closer to the ocean. This slight shift in the observation site is believed to be insignificant insofar as overall thunderstorm frequency statistics are concerned.

Procedure

Initially, master data sheets were compiled from the WBAN 10A forms listing the beginning and ending time of all observations of thunder (T, TR, or TRW) at Cape Kennedy during the thirteen-year period of record. In all, 1223 separate thunderstorm (see footnote 1) occurrences were recorded on 912 (see footnote 2) calendar days with a total duration of 2071.8 hours. These data were transferred to computer data cards and all data computations were done on the University of Miami IBM 7040 computer. On a monthly and annual basis, these data were initially summarized in three ways: (1) the number of individual thunderstorm occurrences, (2) the number of days with at least one thunderstorm, and (3) the total time with thunderstorms. The annual thunderstorm cycle at Cape Kennedy appears somewhat different depending whether one selects 1, 2, or 3 for further analysis. This can be seen by a study of Tables 1, 2, and 3.

Table 1. Number of individual thunderstorm occurrences.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1951	0	0	0	4	9	17	19	15	17	8	3	1	81
1952	0	1	3	3	14	12	18	17	16	2	0	1	87
1957	0	0	7	1	15	16	25	26	18	4	1	4	117
1958	2	1	6	3	9	11	11	20	10	1	1	0	75
1959	1	3	3	8	10	15	16	15	16	9	0	0	95
1960	0	2	10	3	8	28	27	15	17	9	0	0	119
1961	1	0	4	3	8	22	15	16	10	2	1	1	84
1962	0	3	6	4	4	27	29	27	14	4	1	0	119
1963	1	3	2	4	11	14	23	20	5	6	2	0	91
1964	0	1	1	6	2	7	9	25	7	1	5	4	68
1965	2	1	8	4	4	18	23	16	5	2	1	0	84
1966	0	1	2	1	19	12	14	18	29	2	0	0	98
1967	0	1	0	0	3	33	32	13	7	2	0	3	94
Total	7	17	52	44	117	232	261	243	171	50	15	14	1223
Mean	0.5	1.3	4.0	3.4	9.0	17.8	20.1	18.7	13.2	3.8	1.2	1.1	94.1

Table 2. Number of "Days with Thunderstorms"

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1951	0	0	0	5	6	14	14	12	12	4	2	1	70
1952	0	1	3	3	11	10	11	16	11	2	0	1	69
1957	0	0	4	1	12	12	17	18	11	3	1	3	82
1958	1	1	4	3	8	10	9	14	9	1	1	0	59
1959	1	2	2	6	10	10	10	12	12	7	0	0	72
1960	0	2	4	4	7	17	21	11	12	6	0	0	84
1961	1	0	4	3	7	13	9	15	9	2	1	1	65
1962	0	3	5	4	4	17	19	23	10	3	1	0	89
1963	1	2	2	2	8	12	15	15	5	3	1	0	66
1964	0	1	1	5	2	7	8	17	6	1	3	2	53
1965	1	1	5	3	3	13	21	13	4	2	1	0	67
1966	0	1	1	1	14	9	12	12	17	1	0	0	68
1967	0	1	0	0	2	22	23	10	7	1	0	2	68
Total	5	15	35	40	92	156	189	189	125	36	11	10	912
Mean	0.4	1.2	2.7	3.1	7.1	12.0	14.5	14.5	9.6	2.8	0.9	0.8	70.2
% of days	1.3	4.1	8.7	10.3	22.8	42.6	45.9	46.7	32.1	8.9	2.8	2.5	19.2

Table 3. Total time with thunderstorms (hours).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1951	0.0	0.0	0.0	15.8	11.2	31.1	38.3	24.4	24.4	7.4	18.5	1.5	172.7
1952	0.0	0.5	4.7	5.7	26.7	19.2	28.8	33.1	15.4	7.4	0.0	0.7	143.2
1957	0.0	0.0	5.9	2.1	34.3	20.9	45.4	33.2	23.1	4.1	*	1.8	170.8
1958	0.8	0.7	6.1	2.5	11.4	20.4	17.7	22.3	16.0	0.9	0.3	0.0	89.0
1959	0.8	1.7	1.8	10.2	20.7	17.7	27.7	16.0	23.0	11.0	0.0	0.0	129.4
1960	0.0	2.4	30.7	7.0	7.6	41.8	60.1	25.7	27.5	10.3	0.0	0.0	213.9
1961	*	0.0	8.6	2.5	10.8	42.0	40.9	47.3	19.3	4.2	0.2	1.2	177.1
1962	0.0	7.9	2.9	5.8	6.8	40.9	60.6	64.1	28.1	2.9	0.8	0.0	220.7
1963	0.9	5.7	2.0	2.1	14.1	21.9	43.6	30.5	6.7	6.1	3.5	0.0	136.9
1964	0.0	0.1	2.8	6.6	6.1	13.6	30.5	49.5	5.9	0.2	9.8	7.6	132.5
1965	1.0	1.7	14.4	2.5	5.5	43.0	37.2	29.0	3.5	2.6	0.4	0.0	140.8
1966	0.0	0.6	2.8	0.2	46.3	16.4	23.7	33.8	44.8	1.5	0.0	0.0	169.9
1967	0.0	0.8	0.0	0.0	4.2	45.9	76.5	21.3	13.9	2.7	0.0	0.8	166.1
Total	3.5	22.0	52.7	63.0	206.7	374.7	531.6	430.0	250.6	61.0	33.2	13.6	2071.8
Mean	0.3	1.7	6.4	4.8	15.8	28.8	40.9	33.1	19.3	4.7	2.6	1.0	159.4

(* less than 0.05 hours)

1 According to standard observational procedure, a thunderstorm is considered ended when at least 15 minutes passes without thunder. An individual thunderstorm occurrence may consist of thunder from one or more individual cells.

2 The total 912 includes 13 days which were considered thunderstorm days only because a thunderstorm which started on the previous day continued past midnight and no further thunder was recorded on these 13 days. This is standard observational practice.

Table 1 presents monthly and annual data based on the mean number of individual thunderstorm occurrences. Note that a distinct maximum occurs in mid-July with a secondary maximum in late March. Table 2 presents monthly and annual data on the number of days with at least one thunderstorm. Note that the means of Table 2 are less than those of Figure 1, due, of course, to the fact that more than one thunderstorm can occur on any given day. It is interesting to note that although more individual thunderstorms are observed in March than April (Table 1), a greater number of "days with thunderstorms" occur in the latter month. The annual summertime maximum appears from Table 2 to occur about 1 August. Table 3 presents data on the total time with thunderstorms, (see footnote 3). In this summary, a well-defined maximum appears to occur around the third week of July. A well-defined secondary maximum occurs in March.

Tables 1, 2, and 3 have presented simple statistics on the monthly frequency of thunderstorms without regard to diurnal variation. The method of presenting further data depends on the specific operational problem for which these data may be used. For most spaceflight applications, information relative to the occurrence or non-occurrence of a thunderstorm during a given time span is a more meaningful statistic than the mean number of individual occurrences of the mean duration of thunderstorms. Furthermore, in forecasting practice, no attempt is made to specify whether a single or multiple thunderstorm occurrence is expected nor is the duration of a thunderstorm specified. Rather, the forecast will specify something like "probability of thunderstorms at launch time, 10%", or "probability of thunderstorms during the last 3 hours of countdown, 40%." For this reason, it was decided to investigate thunderstorm occurrence on a probability scale at fixed times and over extended time intervals.

Data Smoothing Procedures

In order to establish the trend of the annual thunderstorm cycle, a 15-day moving average of "days with thunderstorm" was computed for each of the 365 days according to formula (1):

3 Fifteen minutes were subtracted from the ending time of all thunderstorms - see footnote 1. Thus, a thunderstorm which started at, say 1600E and ended at 1620E produced audible thunder at the observing site from 1600E to 1605E. Accordingly, in this case, only 5 minutes would be recorded in Table 3.

$$F_n = 1/N \sum_{k=n-7}^{n+7} T_k \qquad (1)$$

where F_n is the moving average on day number n, T_k is the frequency of one or more thunderstorms on day k and N is the total number of days over the period of record. For example, suppose it is desired to determine the average frequency of at least one thunderstorm on July 19 (day number 200). The following data are required by formula (1):

Day	Day No.	Date	Number of Occurrences of at Least One TSTM
T(n-7)	193	July 12	5
T(n-6)	194	July 13	6
T(n-5)	195	July 14	4
T(n-4)	196	July 15	5
T(n-3)	197	July 16	4
T(n-2)	198	July 17	7
T(n-1)	199	July 18	7
T(n+0)	200	July 19	6
T(n+1)	201	July 20	4
T(n+2)	202	July 21	6
T(n+3)	203	July 22	6
T(n+4)	204	July 23	4
T(n+5)	205	July 24	8
T(n+6)	206	July 25	7
T(n+7)	207	July 26	5
		Total	84

According to formula (1), F(200) = 84/13x15 = 0.431 = 43.1%

The decision to use a 15-day smoothing period was made after an analysis of computer generated plots of the daily "thunderstorm-day" averages smoothed over several smoothing periods. The results of this smoothing are shown in Figure 2. The 1-day values on Figure 2 are simply the number of thunderstorm days out of the 13 possible thunderstorm days expressed on a percentage basis. The remaining panels show the smoothing over periods of 5-day, 15-day and 31-days. The 5-day smoothing still shows too much scatter; the 31-day smoothing period seems excessive in that some of the real seasonal variations (notably the mid-July minimum) are filtered out. The 15-day smoothing period does not show excessive scatter and is still short enough to preserve cyclical variations explainable by known atmospheric processes. Accordingly, the 15-day period was selected and was used for all subsequent data summaries contained within this report.

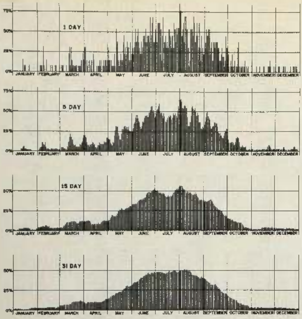

Figure 2. Plots of daily probability (%) values of "thunderstorm-days" smoothed over 1, 5, 15, and 31 days.

The Annual Thunderstorm Cycle

The upper part of Figure 3 shows a computer plot of the 15-day moving average of the number of "days with thunderstorm" compiled according to formula (1). Since there is a relatively long period of record effectively increased by the moving average technique, the ordinate of this figure has been labeled in probability rather than in frequency. However, it should be borne in mind that this is an estimate of the true probability. By ignoring the slight day-to-day variations, the general trend of the annual thunderstorm cycle plainly is discernable and, in general, can be subdivided into eight periods:

Period 1

(November through early March). Thunderstorms are observed only about once per month and are confined, for the most part, to instability or convergence associated with synoptic-scale disturbances.

Period 2

(Early March through early April.) There is a marked increase in thunderstorm activity associated primarily with pre-frontal squall lines.

Period 3

(Mid-April.) Slight decline in thunderstorm activity due to cessation of frontal activity and still insufficient diurnal heating.

Period 4

(Late April through June.) Almost linear increase in thunderstorm activity associated with increasing solar heating and attendant instability.

Period 5

(First half of July.) There is a slight decline in thunderstorm activity. See Period 6 for explanation.

Period 6

(Latter half of July through early August.) There is a secondary increase in thunderstorm activity. The reason for the mid-July slump in thunderstorm activity is probably related to the fact that the mid-tropospheric ridge line is frequently directly over central Florida in July. This results in warmer mid-tropospheric temperatures with attendant stability. By late July or early August, the mid-tropospheric ridge line retreats southward but the low-level ridge line continues to drift northward. This latter condition is a mechanism for greater instability.

Period 7

(Early August through the first third of September.) Gradual decline in afternoon thunderstorm activity with decreasing solar heating. The rate of decline is relatively slow during this period due to the fact that nocturnal and early morning thunderstorm occurrence reaches a maximum at this time.

Period 8

(Latter two-thirds of September through October.) There is a rapid decline in thunderstorm activity. The primary reason for this rapid decline is, of course, associated with the decrease in solar radiation. Other contributing factors are the rapid decline of nocturnal activity and the occasional presence of a recurving tropical cyclone off the coast of Florida. This latter condition results in large scale divergence over Florida and oftentimes the intrusion of cooler and drier air.

Diurnal Variation of Thunderstorms

While the annual thunderstorm cycle is described adequately in the top panel of Figure 3, little has been said concerning the diurnal variation of thunderstorms. In order to define the diurnal variation, overlapping frequency distributions were compiled for 15-day periods centered every five days starting on January 3rd. The January 3rd summary includes data for the 15-day period December 27 through January 10; the January 8th summary contains data for the 15-day period January 1 through January 15, etc. By ignoring February 29 (which date occurred three times in the period of record under consideration) this moving average technique conveniently contains exactly 73 15-day overlapping periods. The seventy-third period itself is centered on December 29 and includes data from December 22 through January 5.

The diurnal frequency distributions were computed over nine different time periods ranging from instantaneous occurrences to occurrences over eight-hour periods. The lower panel of Figure 3, and Figures 4, 5, 6, and 7 show computer print-outs for the various time periods. An isoline analysis was performed directly onto the print-out for values of every 4%. Where the gradient was slight, this was increased to every 2%. A shading was used on the figures in the areas where the frequency was equal to or less than 2%.

Certain controls were used in making the analysis. In the first place, care was taken to insure that each isoline on a particular figure encompassed a greater area than on the preceding figure representing the next lower time interval. Also, the analysis was performed with consideration given to tenths of a percent rather than to the whole percent as printed out on the figures. This was completely insignificant when dealing with the larger percentages but was quite important in the case of the small percentages. It is for the above two reasons that the analysis of the shading may, in some cases, seem to violate the printed data. A third control was that the centers of maximum and minimum activity on Figures 3 (bottom) through 7 were positioned with cognizance of the positions of these centers as precisely defined in Figure 3 (top). Finally, some slight smoothing of the data was accomplished where it seemed appropriate. Actually, very little smoothing was required and the data, for the most part, was analyzed exactly as indicated by the computer print-out. The isolines can be considered to be good estimates of the true probability because of the relatively large amount of data included, because of the moving-average technique, and because of the controls used in making the analysis.

Figures 3 through 7 point out some rather significant features of the thunderstorm pattern at Cape Kennedy. Some of these are listed below:

a. There is a rather well-defined double peak to the seasonal thunderstorm cycle. On the average, the first peak occurs on June 30th and the second peak on August 3rd.

b. Another small maximum occurs between early March and early April.

c. Thunderstorms can be expected on over 25% of the days between May 16 and September 22. This period can be considered as the main convective thunderstorm season.

d. Over the 13-year period of record, no thunderstorms ever occurred between December 28 and January 12.

e. Most night and early morning thunderstorms occur mid-August through mid-September.

One or More Thunderstorm Occurrences Over Extended Time Periods

Figures 3 through 7 each presented data pertaining to the probability of thunderstorm occurrence on a particular day or over a time period of up to 8 hours duration. Occasionally it becomes necessary to estimate the thunderstorm probability over a more extended time period. It may be required, for example, to estimate the probability of at least one thunderstorm occurring over a three-day consecutive period. Or, more specifically, it may be necessary to estimate the probability of at least one afternoon thunderstorm during the 7-day period, starting say, July 22.

The method used to estimate these extended probabilities was similar to the method used to determine the 24-hour probabilities specified on Figure 2a as computed by formula (1). The formula can be restated using a slightly different subscript notation:

$$F_{n(j)} = 1/N \sum_{k=n-7}^{n+7} T_{k(j)} \qquad (2)$$

where $F_{n(j)}$ refers to the 15-day moving average over a j-day period starting on day n, $T_{k(j)}$ is the frequency of one or more thunderstorms over a set of j-consecutive days starting on day k and N is the total number of j-day sets. For example, suppose it is desired to determine the average frequency of at least one thunderstorm over the 3-day period starting on July 19 (day number 200). The following data are required by formula (2):

Day	Day Numbers	Dates (July)	No. of Occ. of at least One TSTM
$T_{n-7(3)}$	193,194,195	12,13,14	9
$T_{n-6(3)}$	194,195,196	13,14,15	8
$T_{n-5(3)}$	195,196,197	14,15,16	6
$T_{n-4(3)}$	196,197,198	15,16,17	7
$T_{n-3(3)}$	197,198,199	16,17,18	9
$T_{n-2(3)}$	198,199,200	17,18,19	9
$T_{n-1(3)}$	199,200,201	18,19,20	8
$T_{n-0(3)}$	200,201,202	19,20,21	10
$T_{n+1(3)}$	201,202,203	20,21,22	8
$T_{n+2(3)}$	202,203,204	21,22,23	8
$T_{n+3(3)}$	203,204,205	22,23,24	9
$T_{n+4(3)}$	204,205,206	23,24,25	9
$T_{n+5(3)}$	205,206,207	24,25,26	10
$T_{n+6(3)}$	206,207,208	25,26,27	10
$T_{n+7(3)}$	207,208,209	26,27,28	10
		Total	130

According to formula (2),
$F_{200(3)} = 130/195 = 0.667 = 66.7\%$.

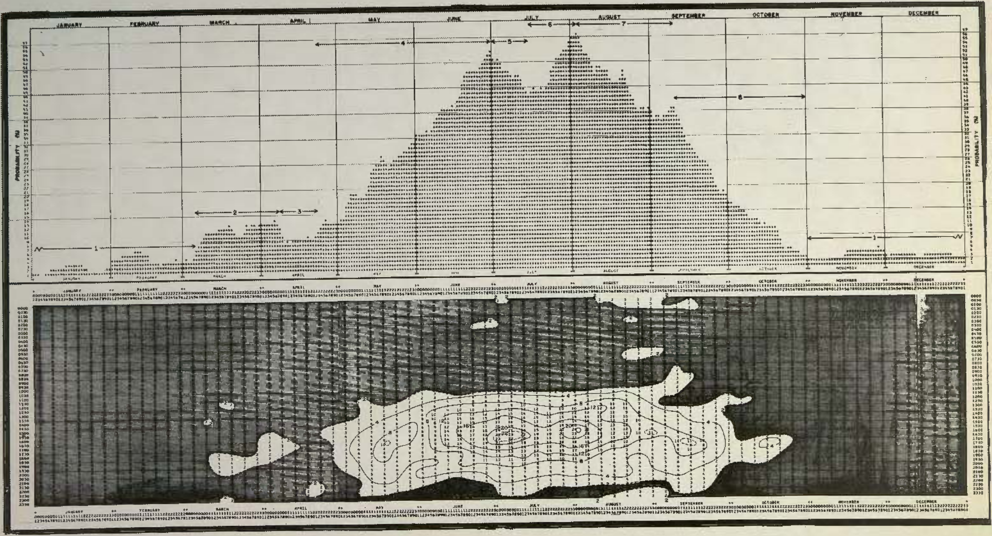

Figure 3: (TOP) Identifiable periods in the annual thunderstorm cycle. (BOTTOM) Probability (%) of a thunderstorm being in progress or in the immediate vicinity of Cape Kennedy at any given time (EST) on any given day.

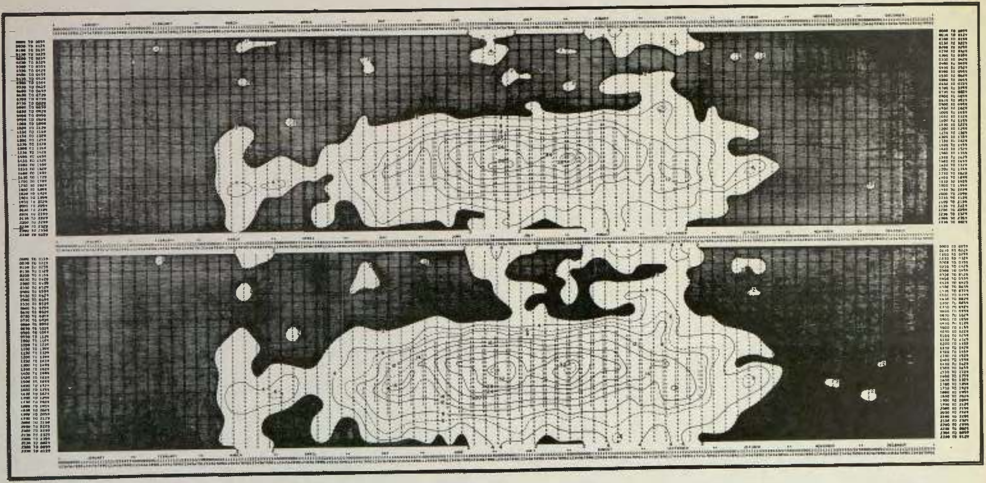

Figure 4: Probability (%) of at least one thunderstorm at or in the immediate vicinity of Cape Kennedy on any given day over a time span of (TOP) 1 hour, and (BOTTOM) 2 hours (EST).

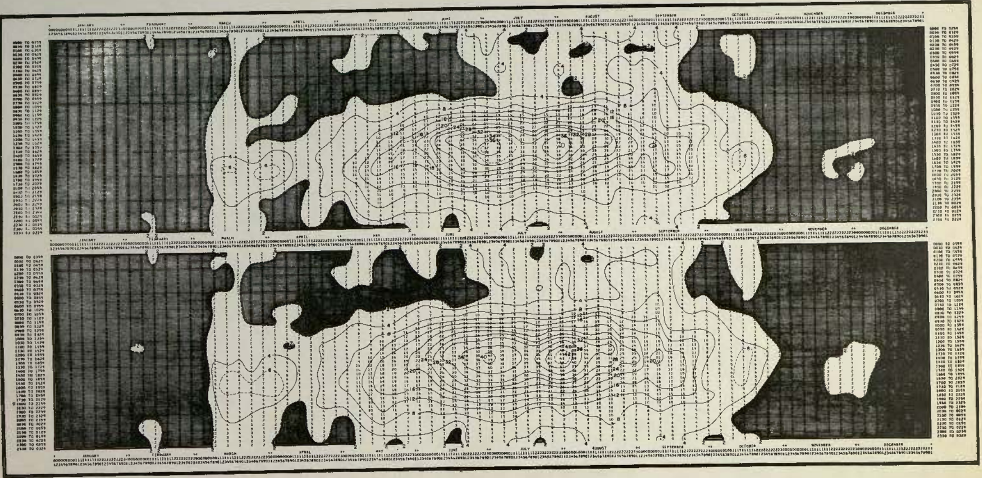

Figure 5: Probability (%) of at least one thunderstorm at or in the immediate vicinity of Cape Kennedy on any given day over a time span of (TOP) 3 hours, and (BOTTOM) 4 hours (EST).

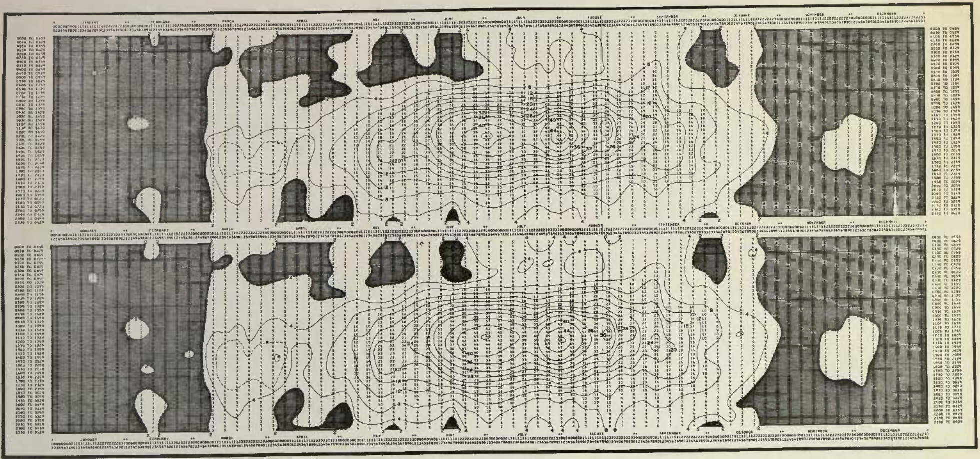

Figure 6: Probability (%) of at least one thunderstorm at or in the immediate vicinity of Cape Kennedy on any given day over a time span of (TOP) 5 hours, and (BOTTOM) 6 hours (EST).

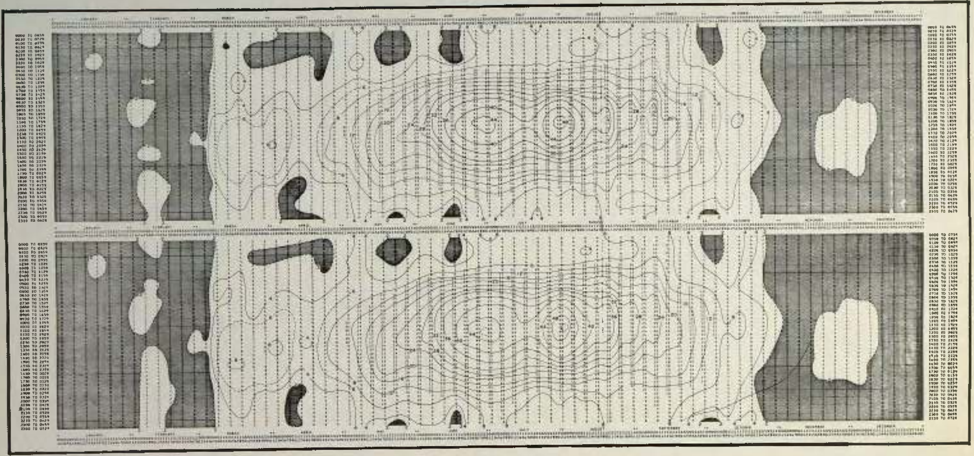

Figure 7: Probability (%) of at least one thunderstorm at or in the immediate vicinity of Cape Kennedy on any given day over a time span of (TOP) 7 hours, and (BOTTOM) 8 hours (EST).

The same technique was used to estimate the probability of at least one thunderstorm on 2, 3, 4, 5, 6, and 7 days for any day of the year. Figure 8 is a computer plot of these data. Also included on Figure 8, for comparative purposes are the single day probabilities that appeared on Figure 2a.

Formula (2) was also used to estimate the probability of at least one <u>afternoon type</u> thunderstorm on j-consecutive days. To do this, the computer program was modified to filter out all non-afternoon type thunderstorms; an afternoon type thunderstorm being defined as one which occurred between 1000EST and 2200EST. A plot of these data are shown in Figure 9. The data included in Figures 8 and 9 are considered to be good estimates of the true probabilities and accordingly the ordinate is labeled as probability.

Multiple Thunderstorm Occurrences on Single Days

Standard observational procedure requires that a thunderstorm be considered to have ended when at least 15 minutes passes without thunder. For this reason, more than one "thunderstorm" can occur on a single day. Of the 899 days upon which 1223 "thunderstorms" began, 638 (71.0%) of the days had single occurrences; 204 (22.7%) of the days had two occurrences; 51 (5.7%) of the days had three occurrences and the remainder, 6 (0.6%) had four occurrences. There were no cases of 5 or more occurrences in a single 0000-2400EST day. For a particular month, July, the breakdown is shown in Table 4. Included also in Table 4 are the number of days without any occurrence.

Table 4. Actual and Theoretical Number of Thunderstorm Occurrences on Single Days for the Month of July

	number of occurrences (x)					
	0	1	2	3	4	5
Actual	214	130	47	11	1	0
Theoretical	210.4	136.6	44.7	9.7	1.2	0.4

Total number of "thunderstorm days" = 189
Total number of occurrences = 261
Total number of days = 403
Mean of x = 261/403 = 0.65

Shown also in the table are the theoretical number of occurrences computed according to the Poisson distribution function:

$$F(x) = e^{-m}m^{x}/x! \qquad (3)$$

where F(x) is the probability distribution function, x is the number of occurrences, e is the base of natural logarithms and m is the expected (mean) value of x. The excellent agreement between the fitted and actual values indicates that the distribution is closely approximated by the Poisson distribution function.

Days Without Thunderstorms

Figures 3 through 9 presented data on the probability (p) of at least one thunderstorm over various time intervals. The probability of non-occurrence (q) is given by:

$$q = (100-p) \qquad (4)$$

where both q and p are expressed in percent. For example, from Figure 8, the probability of at least one thunderstorm over the seven-day period July 19 through 25 is read as 89%. From formula (4) the probability of non-occurrence of thunderstorms between the period July 19 through July 25 is computed to be 11%.

Duration of Thunderstorms

Table 4 presents data on thunderstorm duration.

Table 4. Mean Thunderstorm Duration Over Period of Record (Hours)

Jan	0.5	Jul	2.0
Feb	1.3	Aug	1.8
Mar	1.6	Sep	1.5
Apr	1.4	Oct	1.2
May	1.8	Nov	2.2
Jun	1.6	Dec	1.0
		ANN	1.7

With the exception of the month of November, the general trend is for summer thunderstorms to last longer than those of winter and, according to Table 4, the average duration of July storms is four times greater than those of January. The 2.2 hour average duration of November storms seems excessive when compared to the adjacent months and is due to the fact that on one occasion continuous thunder was recorded for 11 hours 10 minutes, and only 15 thunderstorms were recorded this month during the 13-year period of record.

Figure 10 presents the cumulative percentage frequency distribution of the duration of all 1223 thunderstorms. The mean duration is 1.7 hours. The median duration is considerably shorter, 1.3 hours, while the poorly defined modal duration is only about 36 minutes. The maximum duration of 11 hours 10 minutes occurred November 15-16 1951, in advance of a strong cold front approaching Cape Kennedy from the northwest.

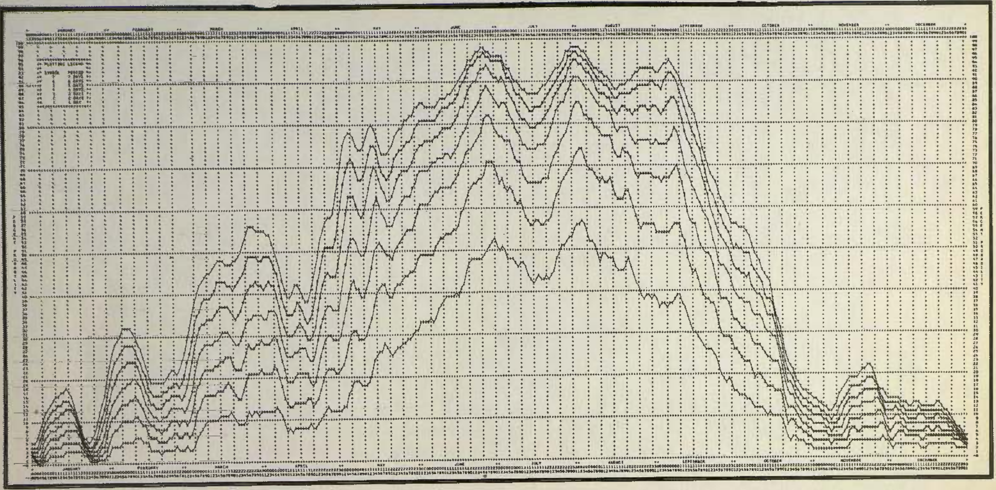

Figure 8: Probability (%) of at least one thunderstorm at or in the immediate vicinity of Cape Kennedy over periods ranging from 1 to 7 consecutive days (EST) starting on day listed along abscissa.

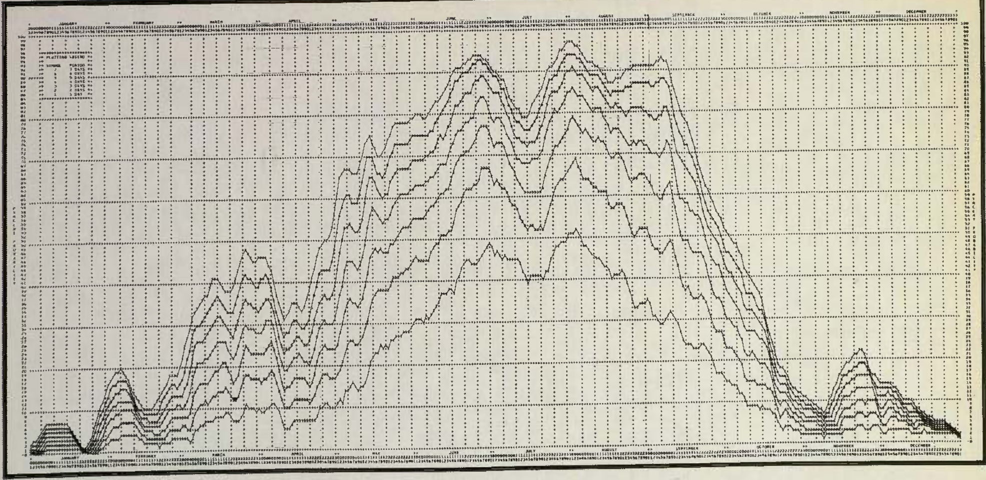

Figure 9: Probability (%) of at least one afternoon-type (1000EST-2200EST) thunderstorm at or in the immediate vicinity of Cape Kennedy over periods ranging from 1 to 7 consecutive days (EST) starting on day listed along abscissa.

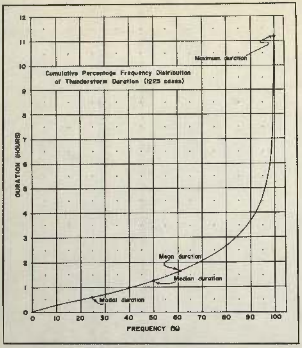

Figure 10. Cumulative percentage frequency distribution of thunderstorm duration.

As mentioned in footnote 1, a thunderstorm is considered ended when at least 15 minutes passes without thunder being heard by the weather observer. For operational requirements, a much longer period of waiting would normally be required between individual thunderstorms before resuming normal out-of-doors activity. A thunderstorm which ended say, 1500 and resumed again at 1520 would probably have the same effect on scheduling outside activity as would one which continued uninterrupted between 1500 and 1520. With this restriction in mind, the average thunderstorm duration was recomputed for a 75-minute break and for a 135-minute break before a thunderstorm was considered ended. This would have no effect on the single thunderstorm occurrences but would tend to merge certain of the multi-occurrences of thunderstorms on single days. The effect, as expected, was to lengthen the average duration the order of 15 or 20%. Specific values are shown on Figure 11. If, for example, two hours between individual thunderstorms is required, the average duration is about 2.1 hours.

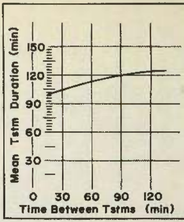

Figure 11. Average duration of thunderstorms at Cape Kennedy as a function of the time between individual thunderstorms.

Runs of Consecutive Days with Thunderstorms and Conditional Probabilities

Forecasting experience in Florida has shown that summertime daytime thunderstorms (as well as many other meteorological parameters) tend to be persistent from one day to the next. the following sequence, where Y represents a thunderstorm occurrence day and N represents a non-occurrence day is more or less typical of mid-summer:

N Y Y Y Y Y N N N Y Y Y Y Y Y N Y N N Y

Y Y N N N N N N.

In this sequence, there are four "runs" of thunderstorm occurrence where a "run" is defined as an unbroken sequence of a particular event. In order or occurrence, these runs were of absolute duration, 5, 6, 1, and 3 days. Also, a run of say, 5 days contains two 4-day runs, three 3-day runs, four 2-day runs and five 1-day runs. For lack of any other qualifying information, the forecaster would have done quite well with a simple persistence forecast. He would, in fact, have verified 11 out of 15 "yes" forecasts and 8 out of 12 "no" forecasts.

A 15-day moving average of the observed frequency of runs of afternoon thunderstorms from one to ten days duration was computed for each day of the year. These data are too lengthy to be included in this report but can be found in reference 7. Selected run data, however, are shown in Figure 12. This figure depicts, for two different dates, 1 May and 1 August, the probability of specific-length runs of afternoon thunderstorm days. Also included on the figure are the probability of at least one afternoon thunderstorm over time periods ranging from two through ten days duration. These latter data are derived from Figure 9.

Attention is directed to the fact that these run data are cumulative. On 1 August, for example, the probability of runs of at least one-day duration is 50.8% while the probability of runs of at least two days duration is 35.4%. The probability of duration exactly one day is therefore 50.8-35.4% or only 15.4%. The cumulative nature of these run data facilitates the computation of conditional probabilities. In the precise mathematical sense, a conditional probability can be stated as:

$$P(A_2 | A_1) = P(A_1 A_2)/P(A_1) \qquad P(A_1) > 0 \qquad (5)$$

That is to say, the probability of A_2 occurring under the condition that A_1 has already occurred (conditional probability) is equal to the probability of the joint occurrence of both A_2 and A_1 divided by the probability of A_1 alone. Formula (5) can be restated as:

$$P_c(k + j, k) = P(k + j)/P(k) \qquad P(k) > 0 \qquad (6)$$

where $P_c(k + j, k)$ is the probability of a run lasting j-additional days under the condition of having already lasted k-days, $P(k + j)$ is the cumulative probability on day k + j, and $P(k)$ is the cumulative probability on day k, the latter having already occurred. Properly used, these conditional probabilities can be quite useful to the operational forecaster. For most operational forecasting requirements, j will equal 1. That is, thunderstorms will have occurred the last k afternoons and the forecaster needs to know the probability of at least one additional occurrence. Formula (6) then becomes:

$$P_c(k + 1, k) = P(k + 1)/P(k) \qquad P(k) > 0 \qquad (7)$$

For convenience, these "one-additional-day" probabilities have been computed for the months May through September. Again, these data are too lengthy to be included in this report but can be found in reference 7. Selected data, however, are shown in Figure 13. This figure shows the increase in probability of afternoon thunderstorm occurrence one would expect on the second day once an afternoon thunderstorm has initially occurred on the first day. The figure suggests that, once a thunderstorm has initially occurred, a simple persistence forecast of re-occurrence on the second day would work more than half the time from late May through late August and again (for some apparent synoptic-scale reason) in late September.

There are, of course, many types of conditional probabilities which might be calculated depending on a particular operational requirement. One might need to know, for example, the probability of thunderstorms occurring on both August 5 and August 6 if they have occurred each afternoon of August 2, 3rd, and 4th. These specific conditional probabilities can be calculated from data given in reference 7.

Summary

It is recommended that the thunderstorm data contained within this report be used for planning purposes for all spaceflight missions at Cape Kennedy for prognostic periods of beyond 5 days. For shorter range periods, forecasts of the low-tropospheric wind flow at launch time should enable the forecaster to refine the probabilities. In general, with westerly or with light and variable low-tropospheric winds higher probabilities should be forecast whereas, with easterly winds, lower values should be forecast. Such a probability study based on the 3000-ft. winds is currently being prepared and will be issued as a subsequent part of this study.

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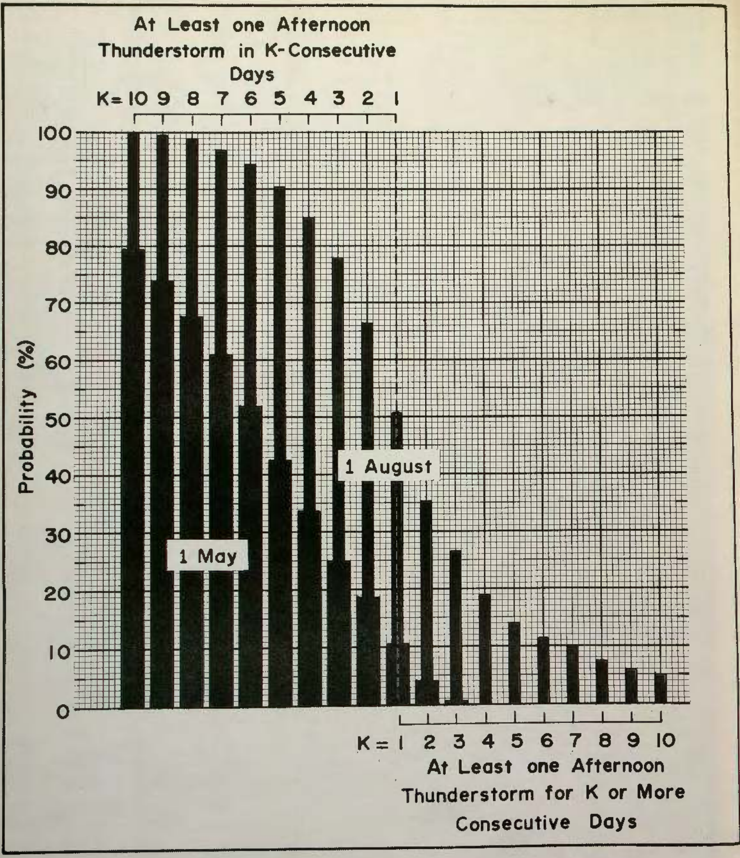

Figure 12: Probability (%) of "runs" of thunderstorm days of specified duration for 1 May and 1 August.

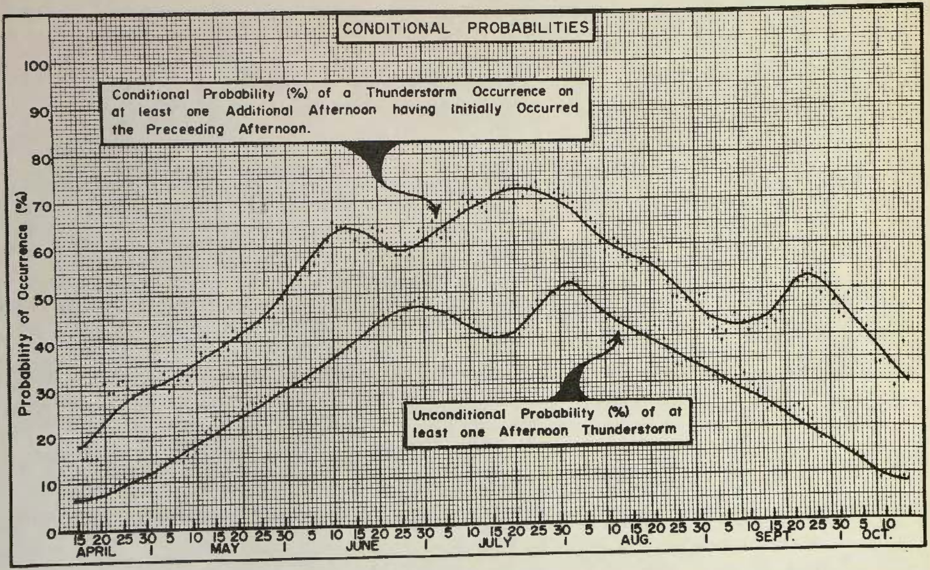

Figure 13: Probability (%) of at least one additional afternoon thunderstorm day having initially occurred preceding afternoon.