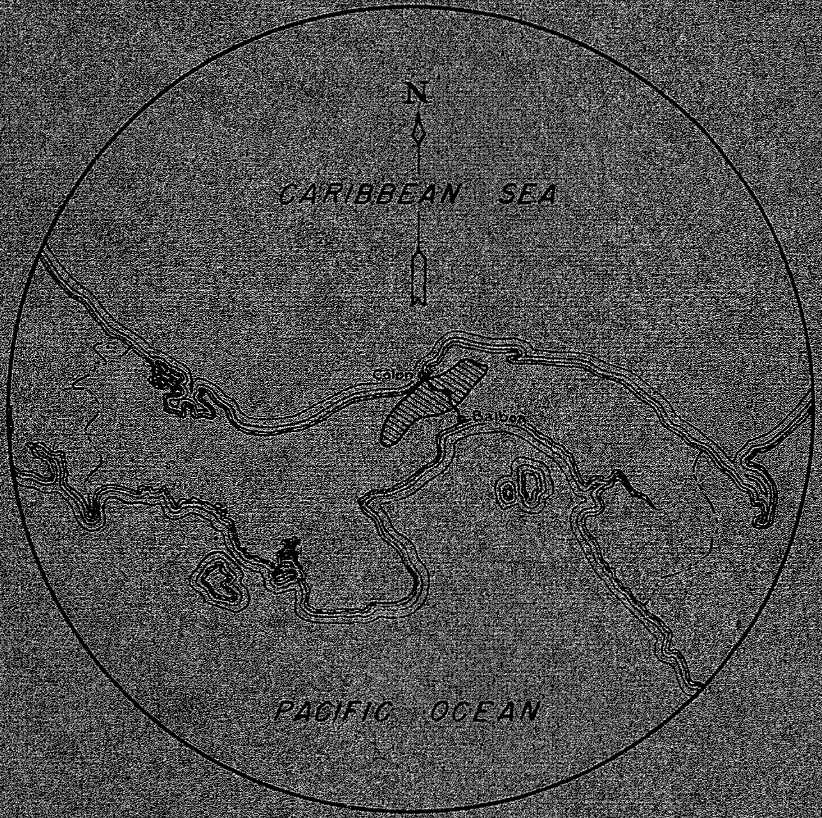
DEPARTMENT OF COMMERCE
WEATHER BUREAU
HYDROMETEOROLOGICAL SECTION

WAR DEPARTMENT
CORPS OF ENGINEERS
ENGINEER DEPARTMENT

HYDROMETEOROLOGICAL REPORT NO. 4



MAXIMUM POSSIBLE PRECIPITATION OVER THE PANAMA CANAL BASIN

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MAXIMUM POSSIBLE PRECIPITATION
OVER THE PANAMA CANAL BASIN

A Study of Meteorological Causes of Record Storms and Quantitative Estimates of Critical Precipitation Rates

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Submitted by the Hydrometeorological Section
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INTRODUCTION

1. Authorization. In a letter dated December 22, 1941, from the Office of the Chief of Engineers, War Department, the cooperation of the U. S. Weather Bureau was requested in making a meteorological study of the Panama Canal region to determine, insofar as possible, the limiting storm conditions. The study was assigned to the Hydrometeorological Section of the Weather Bureau, operating under special transfer of funds from the War Department.

2. The Panama Hydrology Report. A report, entitled "Hydrology of the Panama Canal: Part I - Flood Control," had already been submitted by the Hydraulic Section of the Special Engineering Division, Department of Operation and Maintenance, The Panama Canal. The report was prepared by Howard W. Brod, Associate Hydraulic Engineer, and will hereinafter be referred to as the Panama Hydrology Report. For this report the physiography of the Panama Canal region was thoroughly studied both by field observation and by review of recorded data. Available meteorologic and hydrographic records were collected and analyzed. Interpretations of past storms were made by means of isohyetal maps adjusted for the influences of topography, exposure, geographic location, storm direction, etc. The design storm was developed on the basis of a probability analysis of point rainfall; the areal and time distribution

of rainfall during past storms; and certain fundamental concepts of air-mass analysis. In effect, a so-called 500-year storm was adopted as the limiting or design storm. The meteorological analysis to be made by the Hydrometeorological Section was to act as a check on the values of the hypothetical storm thus derived.

3. The Hydrometeorological Method. The general method pursued by the Hydrometeorological Section in the derivation of the maximum possible storm over any given area is based on an investigation of all the measurable meteorologic characteristics and antecedents of the storms which have in the past produced heavy rainfall over or near the designated region. Every effort is made to determine the characteristic or variable distribution of rainfall in area and in time within each of the major storms. Synoptic analyses of the storms -- both at the surface and, when possible, aloft -- are made to determine the factors which are responsible for the intensity, duration and distribution of the rainfall. When these factors are revealed, it becomes necessary to study their intensities and variations within the particular storm period and then to evaluate, either theoretically or empirically from such data as may be available, their maximum possible values and associated durations. From the physical upper limits determined for the controlling meteorological phenomena, both individually and in combination, the maximum possible storm is derived.

4. Sometimes it is possible to isolate the factors but impossible to evaluate them other than qualitatively because of poverty of storm data. On the other hand, it may be possible to obtain quantitative values for the factors during the storm period but impossible to make

adequate measurement of persistence of maximum values because of shortness or incompleteness of total record. In the derivation of the maximum possible storm over the Panama Canal Basin, all these impediments caused by lack or insufficiency of fundamental data were encountered. In the end only the properly measurable factors could be used, and their range and persistence evaluated from the data that were both most appropriate and extensive.

5. Acknowledgments. The progress of this report would have been definitely impeded had not the information ably gathered and summarized in the Panama Hydrology Report been available. Credit is also due, for assistance in obtaining meteorological records, to the U. S. Engineer Department and to the Special Engineering Division, Department of Operation and Maintenance, The Panama Canal.

6. The report was prepared by the Hydrometeorological Section, under the general supervision of Merrill Bernard, Hydrologic Director. Collaborating in the assignment were:

A. K. Showalter,	Meteorologist in Charge
G. N. Brancato,	Associate Meteorologist
P. Light,	Associate Hydrologic Engineer
M. A. Garstens,	Assistant Meteorologist
H. K. Gold,	Assistant Meteorologist
P. R. Jones,	Assistant Meteorologist
A. L. Shands,	Assistant Meteorologist

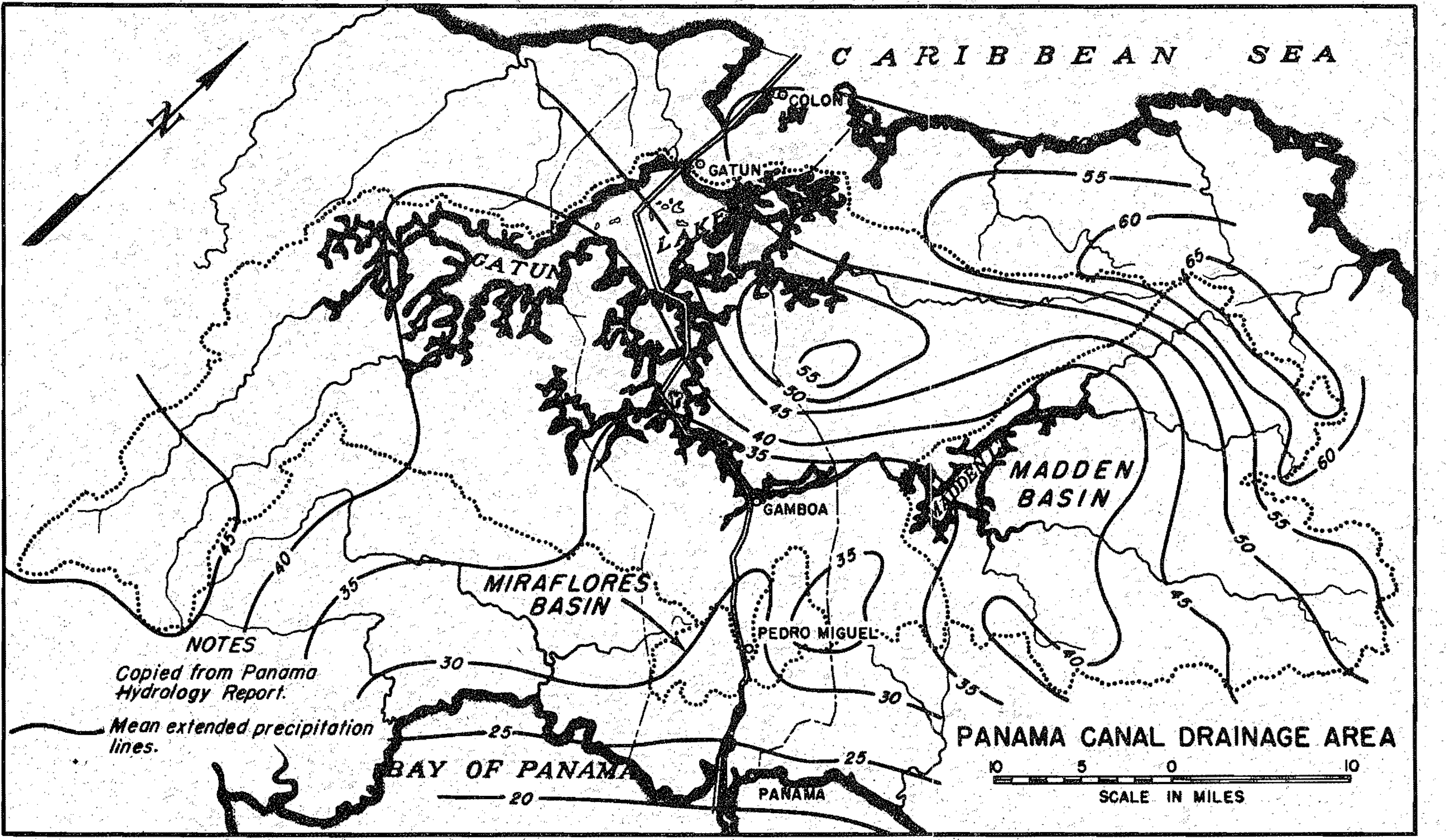
CARIBBEAN SEA
N
COLON
GATUN
GATUN LAKE
MADDEN
MADDEN BASIN
GAMBOA
MIRAFLORES BASIN
PEDRO MIGUEL
BAY OF PANAMA
PANAMA
NOTES
Copied from Panama Hydrology Report.
Mean extended precipitation lines.
PANAMA CANAL DRAINAGE AREA
10
5
0
10
SCALE IN MILES
65
60
55
50
45
40
35
30
25
20

Figure 1

CHAPTER I

HYDROLOGY

7. Rainfall Characteristics. The seasonal and areal distribution of rainfall in the region of the Canal Zone has an important bearing on the characteristics of the critical flood-producing storm. The meteorological conditions responsible for the rainfall variation will be discussed in succeeding chapters. In general, a distinctly dry season lasts through the four months from January to April, while the remainder of the year comprises the rainy season. Within the rainy season, the major storms producing widespread rainfall over the Isthmus are mostly confined to the months of October, November and December. Only a comparatively small proportion of the total rainfall occurring during these major storm periods is of the local convective type although, as will be shown, convection is responsible for the short-period peak intensities. Most of the prolonged rainfall can be ascribed primarily to orographic effects -- and, since these effects result from the invariant topography of the region, the mean extended precipitation map, shown in Figure 1, embodies the characteristic pattern of the large-scale type of rainstorm. The mean extended precipitation map was developed in the Panama Hydrology Report and shows the isohyets of long-period mean rainfall for October, November and December.

8. The typical areal distribution of the rainfall results from the effect of the basin's topography upon the air flow characteristic of the storm period. Because that flow is most often from a northerly direction, the heaviest rain is precipitated along the north or windward side of the San Blas Range forming the northern border of the basin. As the air flows out of the basin it is again lifted, this time over the Continental Divide where additional moisture is precipitated. In both cases there is some precipitation carried over to the leeward side. Thus, the two mountain ranges and the prevailing storm-wind direction account for the sharp rainfall gradient in the north-south direction.

9. To study the character of short-period rainfall an investigation was made of comparative rainfall intensity and frequency at Panama and in the United States. The results are expressed in Figures 2 and 3. The duration-depth curve of 100-year-frequency rainfall for Alhajuela,

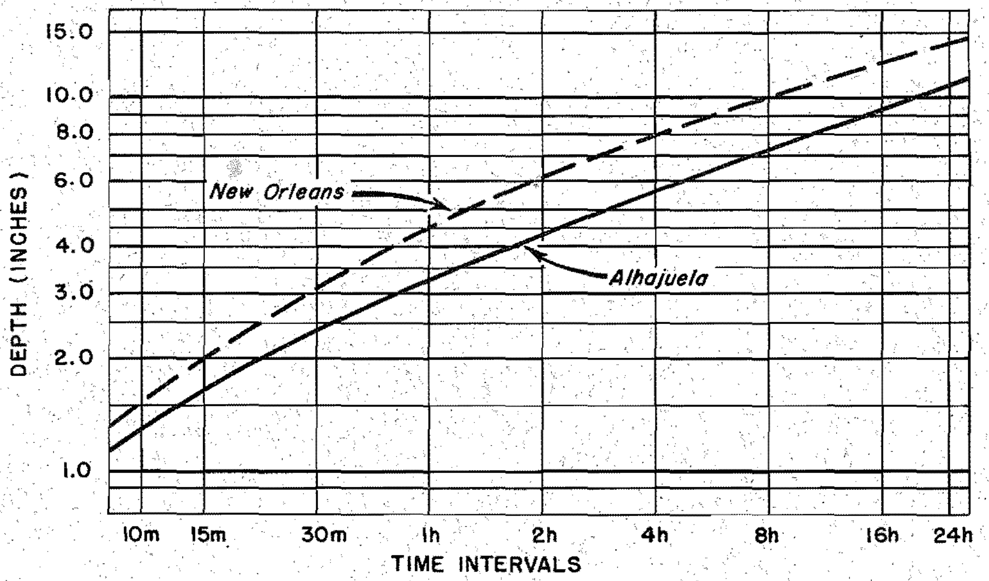

Figure 2

Comparison of 100-year rainfall at New Orleans and Alhajuela a representative station in the basin, was derived from data contained in the Panama Hydrology Report. The curve approaches values obtained from Yarnell(1) for corresponding 100-year rainfall at New Orleans. This indicates a comparatively high point-rainfall intensity for Panama. Figure 3 also indicates that Panama has a steadier rainfall regime than continental United States. As a general rule, within a particular season as well as from year to year, there is a greater regularity of storm occurrence and greater uniformity of storm intensity in tropical as compared to temperate regions. The figure shows that rainfall increases at a lesser rate with frequency at Alhajuela than it does anywhere in the United States(2). For further

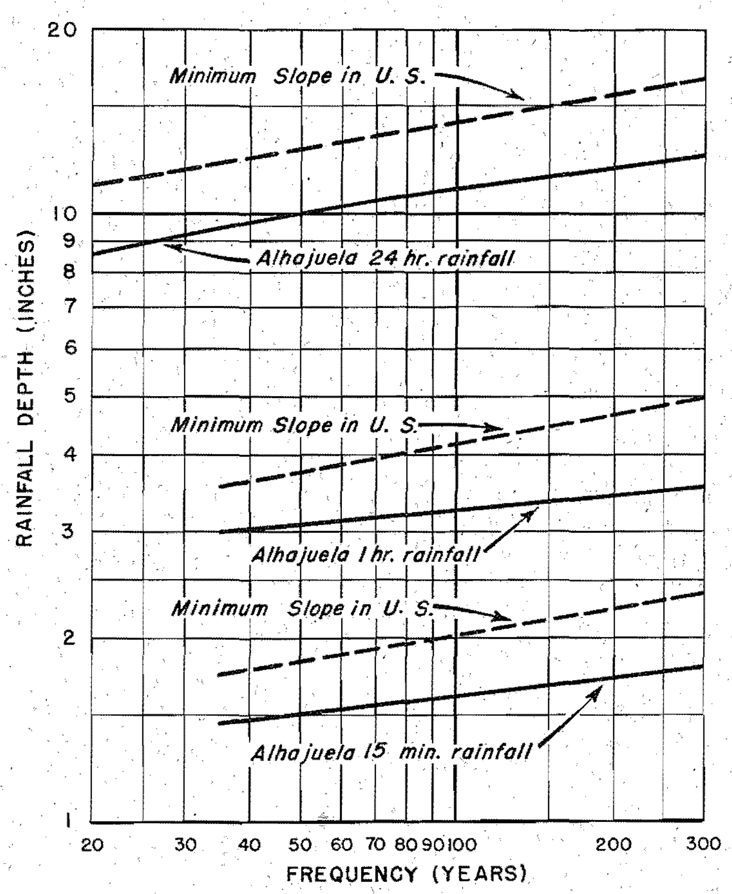

Figure 3

Comparison of slopes of rainfall frequency curves in the United States and Panama

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(1) Rainfall Intensity-Frequency Data, Dept. of Agriculture Misc. Pub. No. 204, Aug. 1935.

(2) Low Dams, National Resources Committee, 1938.

confirmation of the rainfall stability at Panama, a statistical analysis was made of annual rainfall at selected stations with long periods of record. The results are presented in Table 1, which shows that annual rainfall at Cristobal is less variable than at two coastal stations in the United States: San Francisco and New Orleans. No definite conclusions can be drawn regarding physical upper limits of precipitation from such an analysis. However, the available statistical evidence suggests that enveloping values derived from the storms of record at Panama are less likely to be exceeded than similar enveloping values for most of the regions previously studied by the Hydrometeorological Section.

TABLE 1

VARIABILITY OF ANNUAL RAINFALL

	Period of Record (Years)	Rainfall			Range	Range	Standard Deviation	Coefficient of Variation
		Average in Inches	Maximum in Inches	Minimum in Inches	in Inches	per-cent		
Cristobal	69	129.8	177.4	84.2	93.2	72	20.8	0.16
New Orleans	95	57.5	85.7	31.1	54.6	95	11.3	0.20
San Francisco	92	22.0	38.8	9.0	29.8	136	5.6	0.25

10. Hydrologic Characteristics. The hydrology of the Panama Canal drainage system has been treated thoroughly in the Panama Hydrology Report. The report states that the runoff characteristics of the basin and the problems of reservoir control require that the duration-depth curves for the maximum storm be extended to at least six days. It further states that the critical time-position for the most intense rain

would be the sixth day. For purposes of peak-runoff determinations, this maximum period should be presented as a time sequence of rainfall in half-hour increments.

11. Because reservoir levels are likely to be at or near maximum during the period October through December, the time of occurrence of the maximum storm is restricted to the period of mean extended precipitation. The detailed analysis of past storms was likewise restricted to types that can occur during the same period.

12. The problem areas outlined by the Panama Hydrology Report are as follows:

	Area (Square Miles)
Miraflores Basin	37
Madden Basin	393
Gatun Basin (Excluding Madden Basin)	892
Total Basin	1322

13. <u>Storm-Rainfall Analysis</u>. The nine major storms analyzed are listed below:

December 1-3, 1906
November 15-19, 1909
December 25-30, 1909
October 21-24, 1923
November 6-9, 1931
November 26-29, 1932
November 14-19, 1935
December 2-4, 1937
November 1-7, 1939

These storms produced major flood peaks during the period of adequate rainfall data. Only one storm during a period of approximately 100 years shows evidence of greater intensity on the basis of estimated discharge at Alhajuela: the November 1879 storm for which rainfall data are extremely limited.

14. The available precipitation data consisted of daily rainfall amounts for all stations for the total period of record in the Panama Canal Basin and its vicinity. In addition, five-minute amounts at tipping-bucket gages and reproductions of recorder charts from weighing-type gages were available for the storm periods. Isohyetal maps for significant periods of the storms were also on hand. These maps were based on station-rainfall values as well as considerations of runoff and the mean extended precipitation pattern.

15. With the storm-isohyetal maps and station-rainfall amounts for various intervals of time as basic data, the specific problem was to arrive at satisfactory values of areal rainfall for durations as short as 30 minutes. It was decided to eliminate non-recording stations as a factor in determining short-period rainfall. The area is well served by automatic stations and in most storms more than 50% of the gages were of the automatic type. On the other hand, the non-recording data are of poor caliber. Observation times are missing in many cases, and no times of beginnings or endings of rainfall are given. Under the circumstances, it was felt that no important additional information could be obtained by the construction of mass curves for non-recording stations. It should be emphasized, however, that all the available data were utilized in the original construction of isohyetal maps.

16. The method previously used by the Section for obtaining short-period rainfall amounts was to weight the stations within the area according to a Thiessen network. The weighted rainfall values were then combined and an adjustment factor applied uniformly to each increment so as to bring the total value into agreement with the average depth obtained from the isohyetal map(1). In the Panama Canal Basin the rainfall stations are concentrated chiefly along the Canal Zone and there are few stations immediately outside the basin boundary. An individual Thiessen block, therefore, encloses an area of varied topographic features and irregular rainfall pattern.

17. A more reasonable method of weighting assigns homogeneous rainfall areas to each station. The method is illustrated in the schematic diagram of Figure 4. A curve was derived from the isohyetal map for the period concerned, expressing the percentage of area encompassed within a given isohyet as a function of the value of the isohyet. Horizontal lines, representing rainfall depths at each station, were extended and blocks thus formed whose areas represented the contribution of each gage to the total volume of rainfall over the basin area. In the figure, a hypothetical

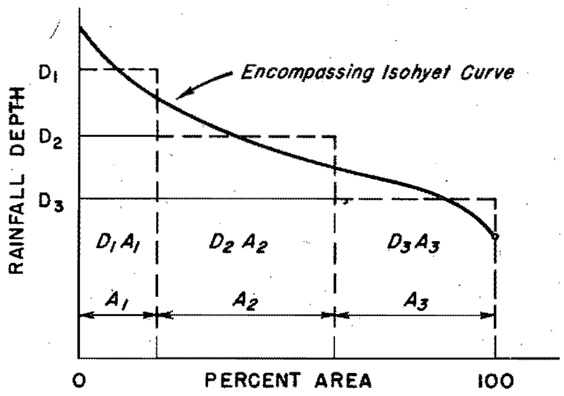

Figure 4

Method of assigning weights to rainfall stations

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(1) Hydrometeorological Report No. 3: "Maximum Possible Precipitation over the Sacramento Basin of California."

network of 3 rainfall stations, designated as 1, 2 and 3, is assumed. The rainfall depths are D_1, D_2 and D_3 and the corresponding weights determined by this process are A_1, A_2 and A_3. The area underneath the encompassing-isohyet curve is equal to the average depth of rainfall over the drainage area. On the other hand, the sum of the block areas is equal to the weighted total rainfall. Hence, the adjustment factor referred to previously is equal to the ratio $\frac{\text{Area under Curve}}{D_1A_1 + D_2A_2 + D_3A_3}$. It can be seen that the adjustment factor approaches unity as the number of stations increases and hence greater dependability may be expected for the larger areas with this method.

18. The results of the storm-rainfall analysis are presented in the form of six-hour increments for each major storm for Miraflores, Madden, Gatun, and the total basin in Figures 5 to 13, inclusive. Periods of intense rainfall within these storms were selected for detailed breakdown into 30-minute increments. The over-all results are plotted as duration-depth values on log-log paper in Figures 14 through 17.

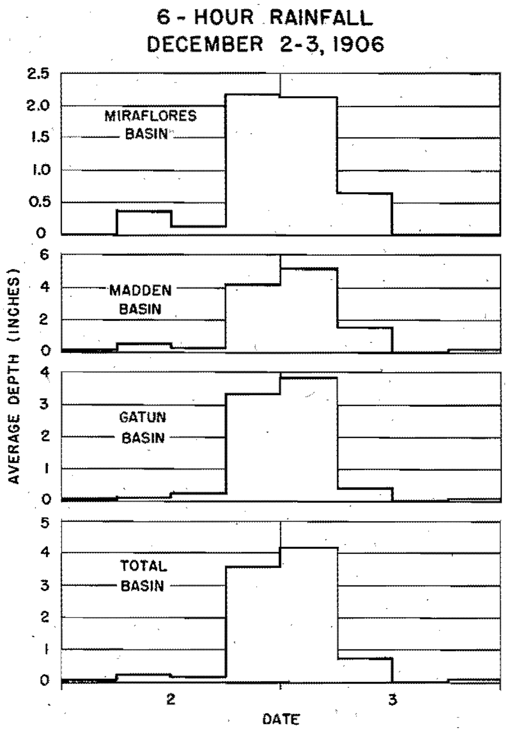


Figure 5

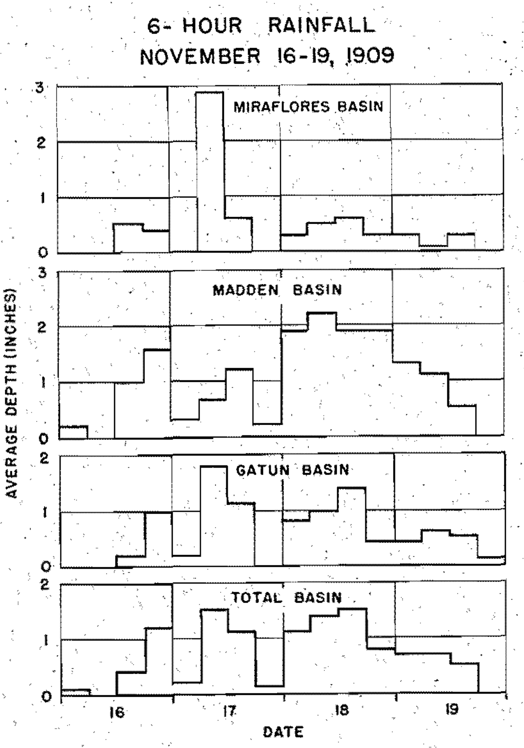


Figure 6

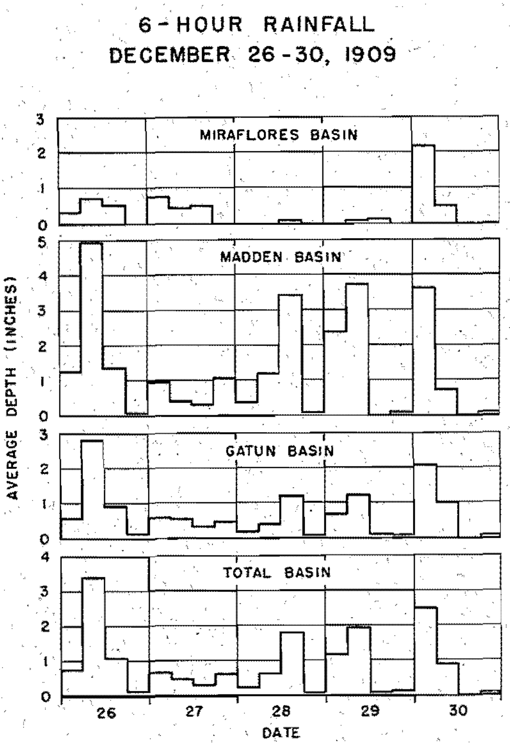


Figure 7

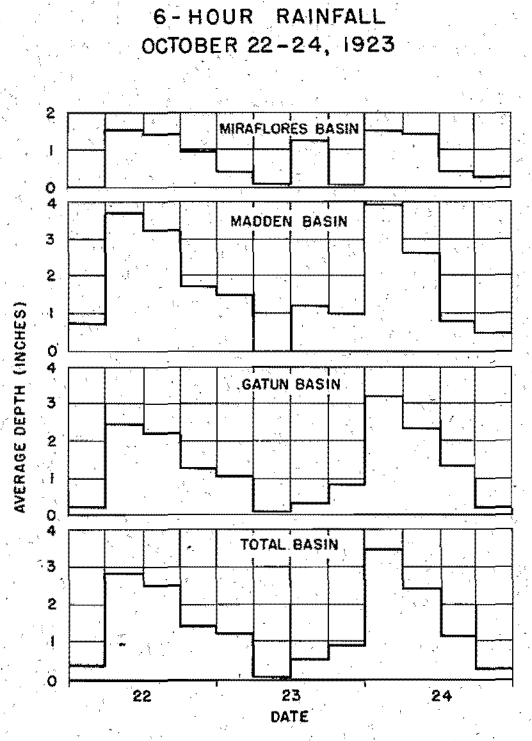


Figure 8

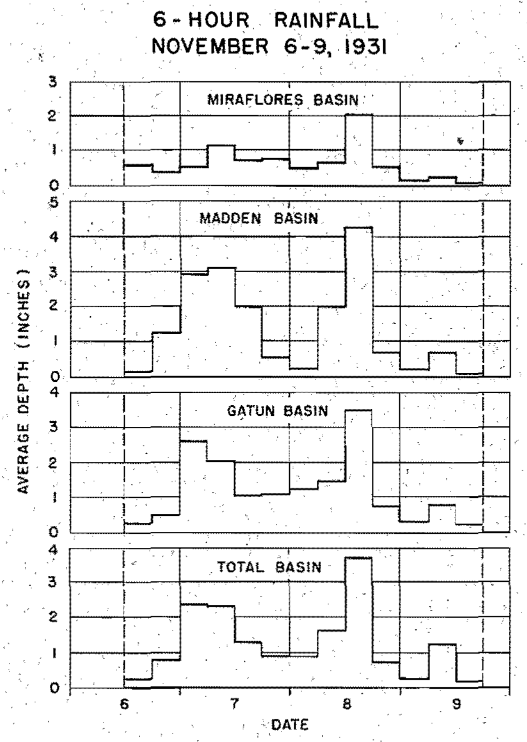


Figure 9

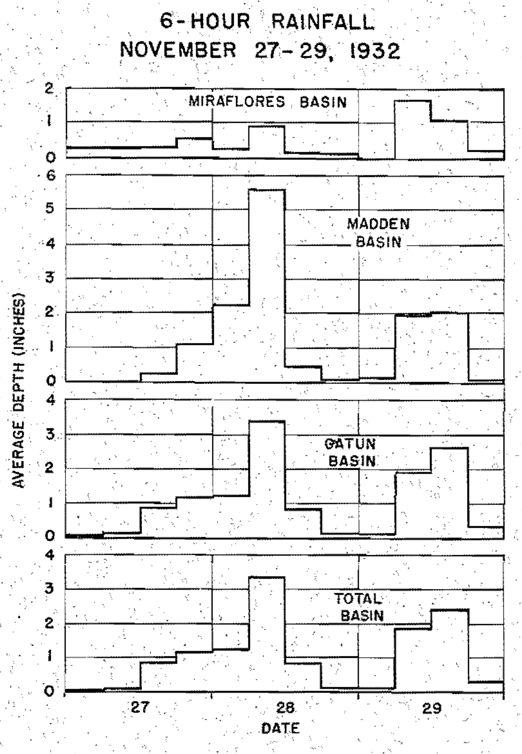


Figure 10

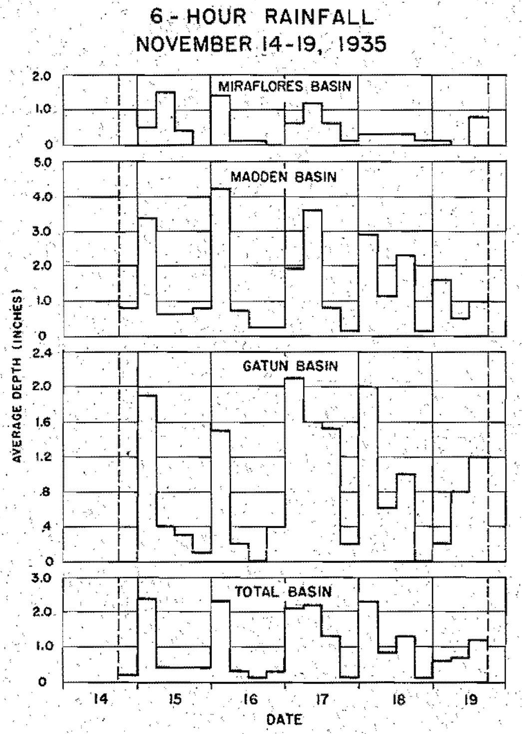


Figure 11

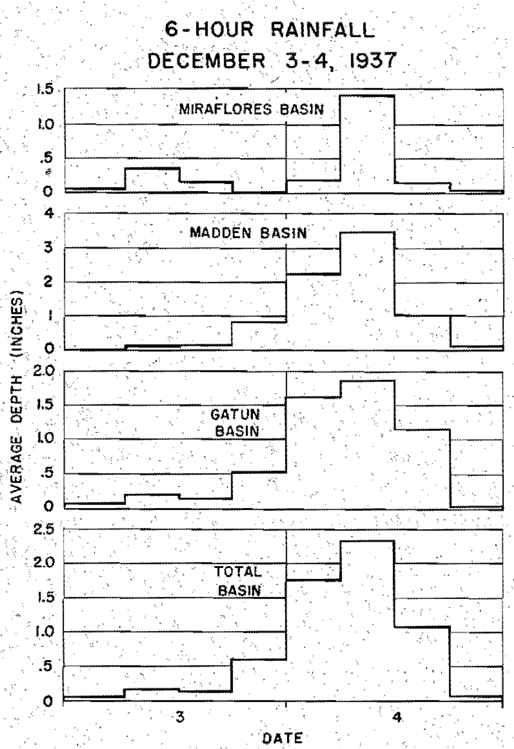


Figure 12

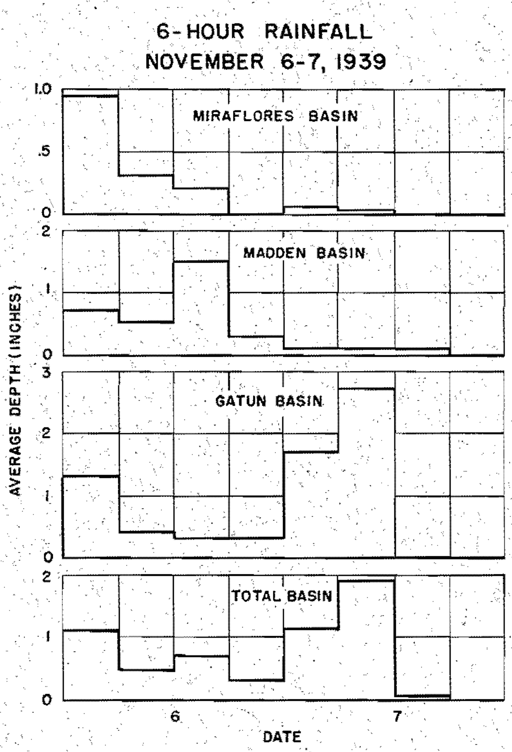


Figure 13

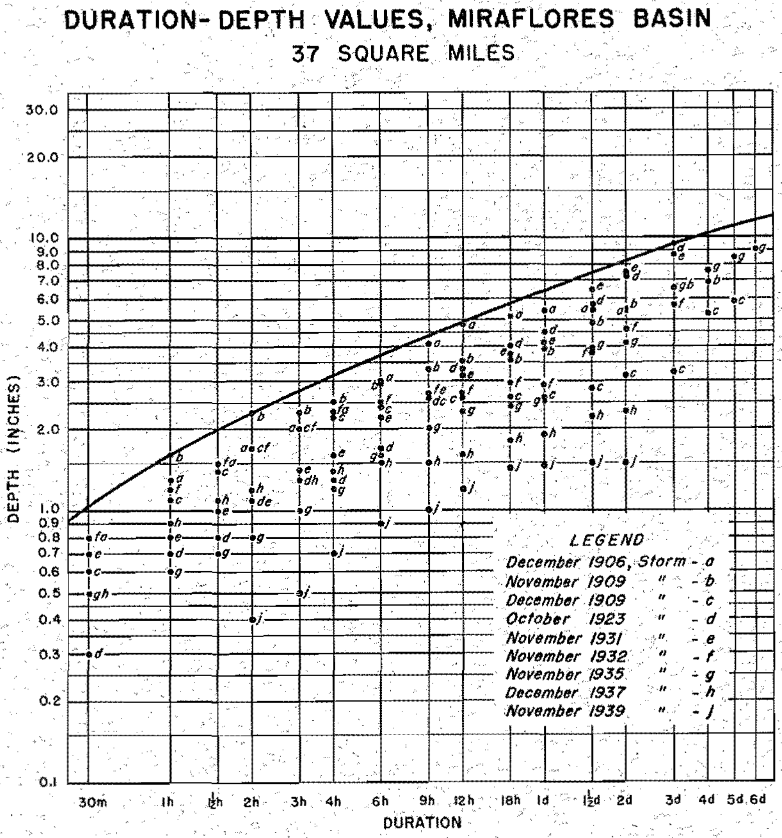


Figure 14

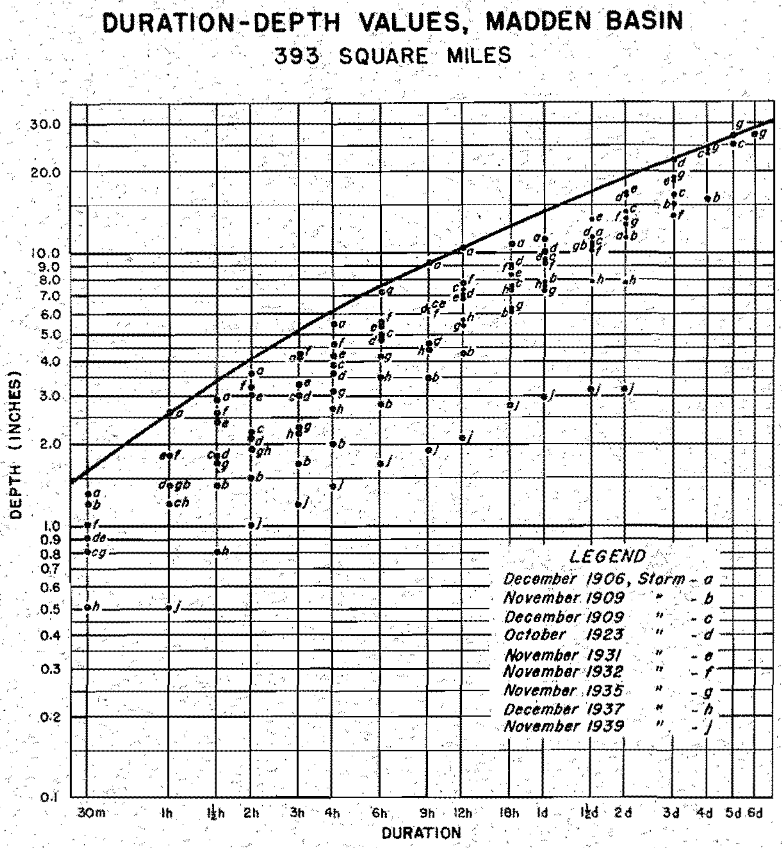


Figure 15

DURATION-DEPTH VALUES, GATUN BASIN
892 SQUARE MILES

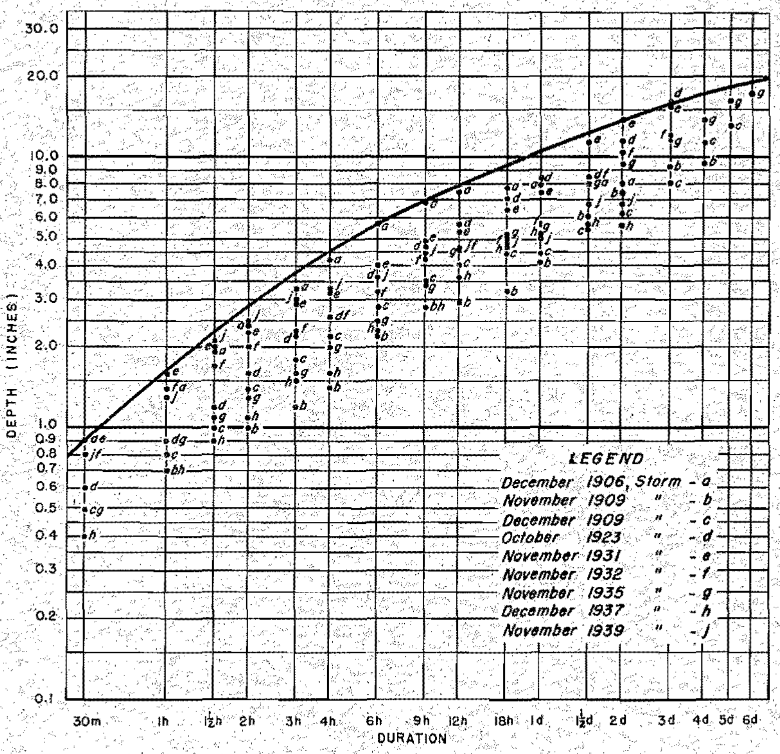


Figure 16

DURATION-DEPTH VALUES, TOTAL BASIN
1322 SQUARE MILES

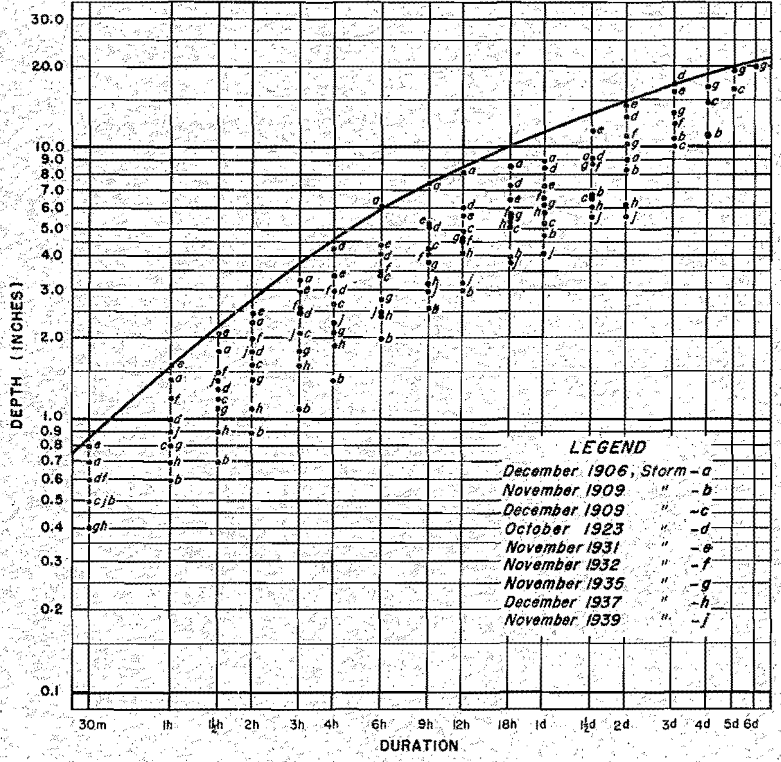


Figure 17

CHAPTER II

DYNAMIC CLIMATOLOGY

19. Available Data. Daily morning synoptic observations were available from Mexico, Central America and the West Indies for all storms except that of 1906. Daily evening observations became available from Central America and the West Indies in 1923, and from Mexico in 1939. Hourly or bi-hourly observations were received from two or three stations within the Canal Zone for most of the storm periods. For more recent storms synoptic data from northern South America were available but were almost entirely lacking for the earlier periods. The west coast of Colombia was not represented by any observations. Ship reports from the Gulf of Mexico and the Caribbean were numerous but in the earlier storms there were few Greenwich midnight observations reported. In the Pacific area weather observations were scanty and those available were mostly concentrated along the ship lanes from the Canal northwestward.

20. Upper-air data were definitely scarce. At Coco Solo pilot-balloon observations were begun in 1920. For storm periods since 1935 winds aloft were available from Albrook Field and France Field. For varying lengths of time since 1935 there were similar observations available from David, Panama; Turbo and Baranquilla, Colombia; Maracaibo,

Venezuela; Managua, Nicaragua; and Tapachula, Mexico. That is also true of other stations in the Caribbean and West Indies region with the exceptions of Guantanamo Bay, Port au Prince and Santo Domingo where records were available for the 1932 storm. Upper-air soundings by means of airplane meteorograph were available at Coco Solo since 1936 and by means of radiosonde at Swan Island during the 1939 storm. Both pilot-balloon and airplane soundings are so much dependent on favorable weather that, more often than not, they were missing during critical storm periods.

21. Adequate climatological summaries of the meteorological elements were available in various publications, but considerable work had to be done in summarizing upper-air data. It was also necessary to secure monthly resultant-wind data from the vast store of ship weather observations and in this task the services of the Statistics Division of the Weather Bureau were enlisted.

22. The Climatological Approach. In higher latitudes, where secondary circulations predominate and fluctuations in weather elements are extreme, the climatological means may serve to mask rather than reveal the actual weather sequences. In tropical regions, however, where the range through which the meteorological elements fluctuate is narrow, climatological means can be considered much more representative of the daily weather. This is fortunate because observations in those regions are sparse and, where meteorological services are poorly organized, neither representative nor entirely reliable. The character of such land observations plus the poor distribution of ship observations precludes a unique analysis of the individual synoptic chart. However,

if it can be assumed that the individual pattern is not too unlike the mean, then the network of observations is both enlarged and improved.

23. This is not to say that conditions are constant throughout the year, although of some elements such as pressure, it is essentially true. Within each month and even within each season the relative constancy is easily observed. However, the change in meteorological conditions from dry to wet or wet to dry season is well-defined. It is logical, therefore, to preface the analysis of the major Panama storms with a consideration of the mean or general atmospheric circulation over the region and its effects upon the annual variations of the meteorological elements.

24. The General Circulation. Situated at about longitude 80°W. and latitude 9°N., the Canal Zone lies in an area primarily dominated by the southern limits of the circulation around the Atlantic cell of the high pressure belt that girdles the globe along latitude 30°N. Following the annual march of solar altitude, the belt of high pressure moves southward in the winter and northward in the summer of the Northern Hemisphere. Accompanying the movement in the winter is a weakening of the oceanic high-pressure centers and a strengthening of continental high pressure. In the summer, on the other hand, the oceanic anticyclone, then farther north, is strengthened while the continental Highs disappear to be replaced by comparative low pressure. A counterpart of this shifting circulation exists in the Southern Hemisphere with direction of circulation and latitudinal displacement reversed.

25. On the equatorial sides of both hemispheric high-pressure belts there are the trades, broad bands of easterly winds, southeasterly

in the Southern and northeasterly in the Northern Hemisphere. Between the two trade-wind belts, particularly over the oceans, there is an area of ill-defined low pressure and light, variable winds. This is the zone of doldrums. Its width, latitudinal position and exact boundaries vary greatly, but in the vicinity of the Western Caribbean it is entirely within the Northern Hemisphere and its northern boundary may extend as far north as 11 to 12°N. latitude. Its mean position oscillates seasonally with the subtropical anticyclones that bound it.

26. On April 13 the zenith position of the sun moves northward across Cristobal-Colon, to be followed by the northward displacement of the Atlantic anticyclone and the northeast trades. By May the trades have moved far enough northward so that the Canal Zone lies south of them, in the region of the doldrums. On August 29 the zenith position of the sun recrosses Cristobal-Colon, to be followed by the southward displacement of the doldrums, trades and oceanic anticyclones. By November the Canal Zone is again the meeting-place of trades and doldrums, and by December the regression southward is sufficient to bring the region again entirely within the trade-wind belt, where it remains until April-May.

27. By mid-autumn, the polar front, which hovers near the Canadian border in the summertime, begins to appear more and more often in the lower latitudes. Following it is the continental anticyclone of polar air which builds up over the cooling land of fall and winter. By October the outbreaks of polar air bring the polar front occasionally to the latitude of the Canal Zone, and the outbreaks increase in frequency and in southward displacement throughout the following months, reaching

a maximum in February and then diminishing through spring and practically vanishing in the summer when the continental High is replaced by the continental Low resulting from the increased heating of the land surface.

28. <u>Annual Variation of the Elements</u>. The effect on its rainfall regime of the Canal Zone's position within the general circulation is well-marked. Figure 18 shows the annual variation in mean monthly rainfall for 23 stations in and near the Canal Zone. The combined mean values for the 23 stations are presented by the histogram in the lower right-hand corner of the figure. The latter values can be accepted as approximate, mean monthly rainfall depths for the basin. The dry season, which can be defined as the period from December 15 to May 1, occurs when the region is definitely within the trade-wind belt. During the rest of the year -- the rainy season -- the region is within the doldrum

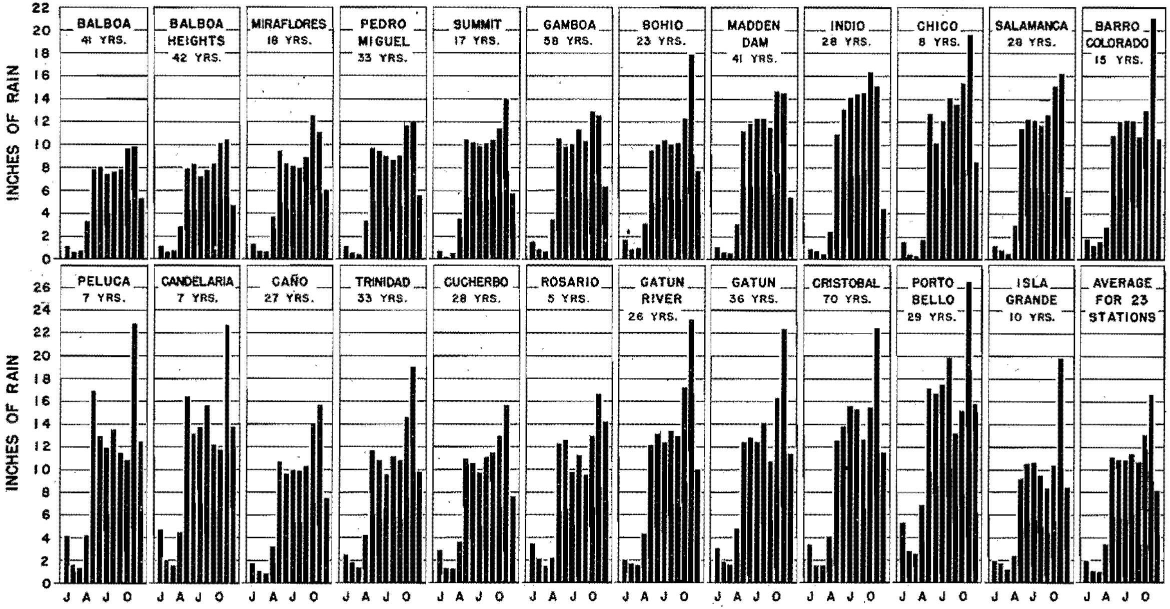


Figure 18

Mean monthly rainfall at stations in and near Panama Canal Zone for years of record through 1940 belt. The regional nature of the wet and dry seasons is well-illustrated by their noticeable appearance at all the 23 stations. The repetition of the marked rainfall maximum centered in November is also notable.

29. In Figure 19 the annual variation in other meteorological elements, as well as rainfall, is shown for Cristobal, Madden Dam (Alhajuela) and Balboa Heights. The marked change in values during April-May and November-December is noticeable for all the elements. These are the months during which the season changes from dry to wet and wet to dry, respectively. In elements such as dew point, relative humidity and percentage of cloudiness, the higher values are natural concomitants of the rainy season and the lower values of the dry. The variation in wind speed is of an opposite kind, the higher values being characteristic of the dry season and the lower of the wet. The higher speeds are in the trade winds and the lower a doldrum phenomenon. The slackening of the wind, when added to the variability of direction, in fact defines the doldrums. Not shown in the figure, the variation in constancy of wind direction is such that during the months January, February and March north or northeast winds prevail at Cristobal more than 90% of the time while from May to November, inclusive, the percentage of occurrence of north or northeast winds falls well below 50. During October, the percentage actually falls to nine. In that month, it can be seen from the section of Figure 19 showing the mean monthly position of the edge of the doldrums, the Canal Zone is deepest within the doldrums.

30. The surface temperature has an anomalous variation, the maximum value occurring in April and the minimum in November. The

THE EFFECT OF THE MIGRATION OF THE DOLDRUMS ON THE CLIMATIC ELEMENTS
PANAMA CANAL ZONE

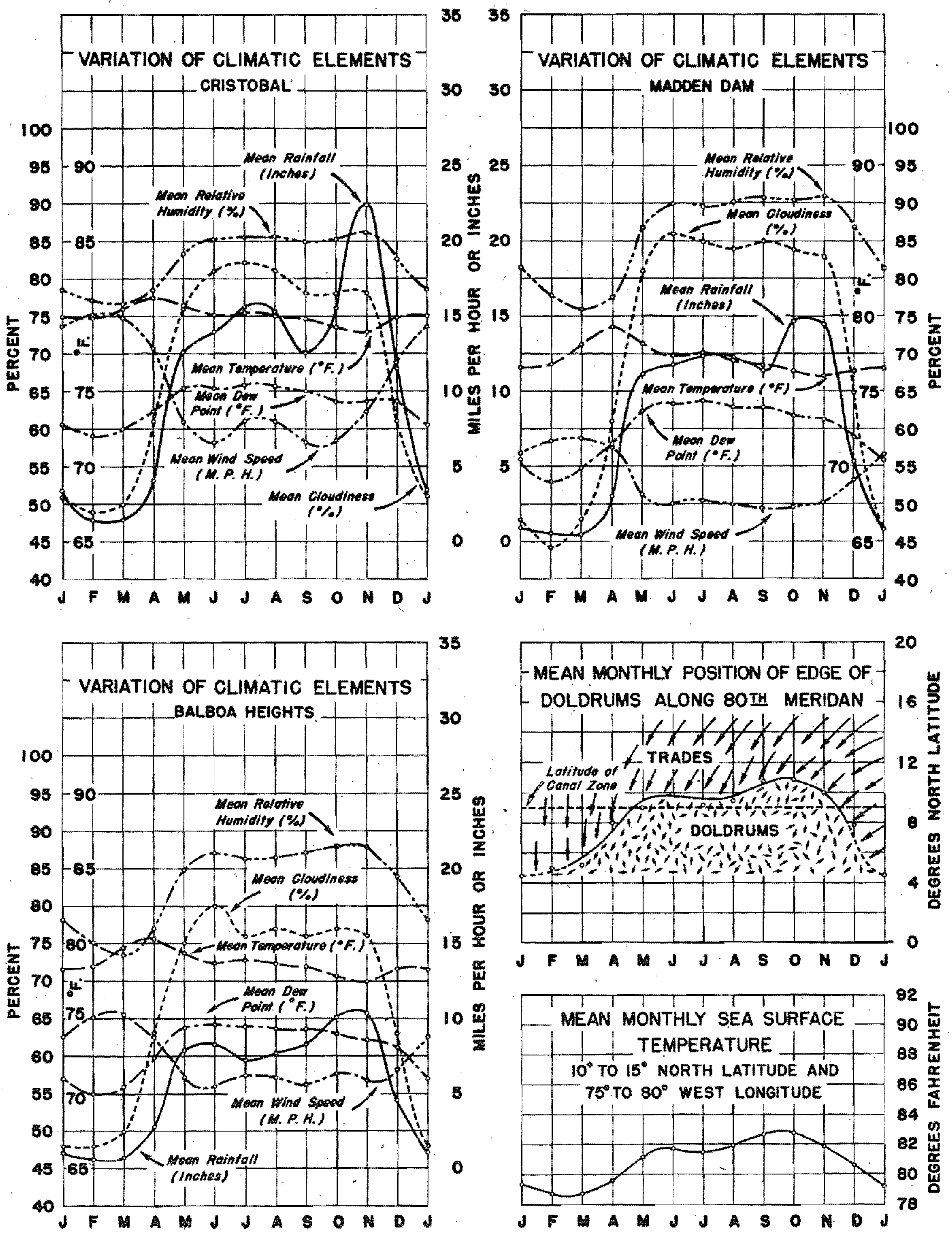


Figure 19

explanation of the difference, as well as of the other better-correlated variations, also lies in the variation of the position of the doldrum edge in the vicinity of Panama. In the figure this is satisfactorily illustrated by plotting the monthly latitudinal position of this boundary at longitude 80°W. and using 9°N. as the mean latitude of the Canal Zone. The curve thus represents the northern edge of the doldrums and the horizontal broken line the approximate position of the Canal Zone with respect to it. The arrows are a schematic representation of the accompanying wind regime. During April, it can be seen, the doldrum edge is at Panama at approximately the time of the zenith position of the sun, but after August 29 the retreat southward of the doldrum edge lags about two months behind the sun's zenith -- crossing Panama in late November. It is apparent that both April and November are critical in the same sense -- during those months the Canal Zone is at the doldrum edge.

31. The moderately high surface temperatures of the dry season, an effect of the greater insolation due to the comparatively clear sky of the period, rise to a peak in April when the receipt of solar energy is at a maximum. As the rains and cloudiness increase, the temperatures fall steadily through the rainy season, reaching a minimum in November when the rains are heaviest and most prolonged. The maximum monthly temperature thus coincides with the northward passage of the doldrum edge over Panama and the minimum with the southward passage. It is also of interest to note that the mean sea-surface temperature to the north and northeast of Panama follows a curve of variation closely resembling the curve of the mean doldrum-edge position. This is shown in the lower

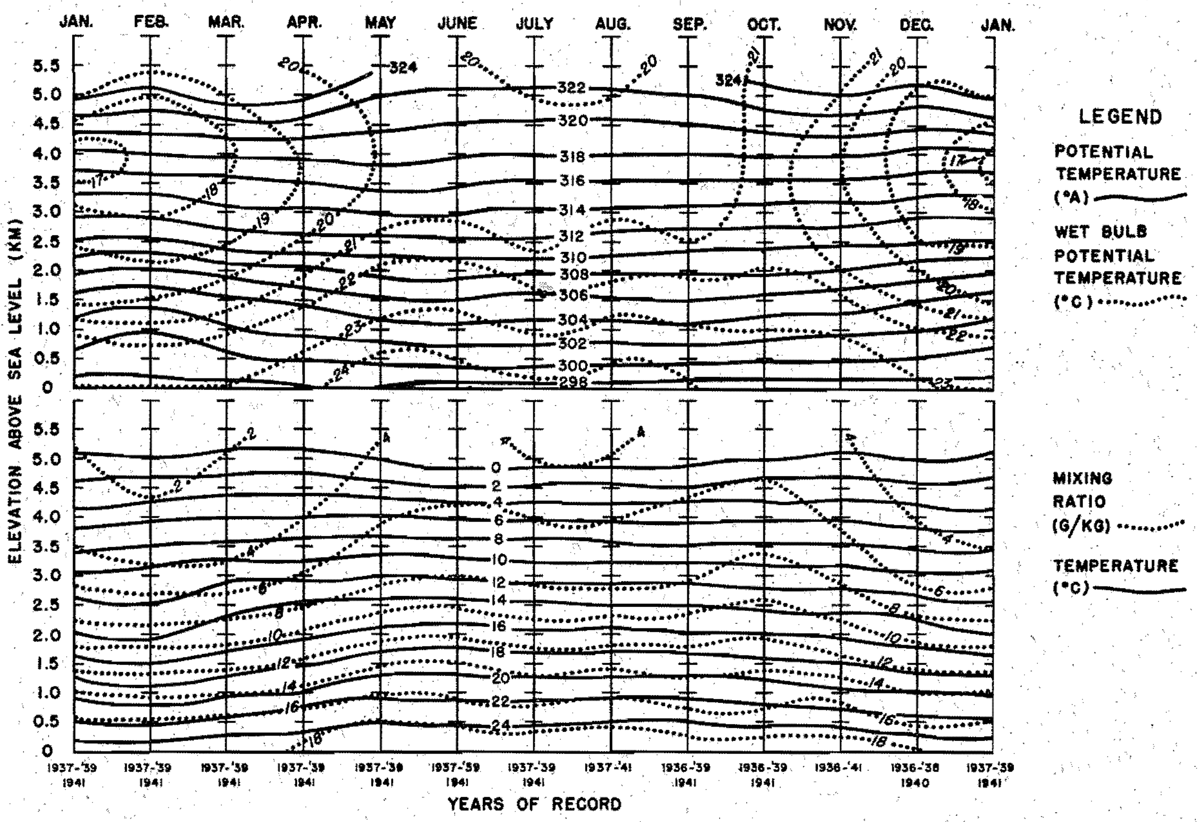


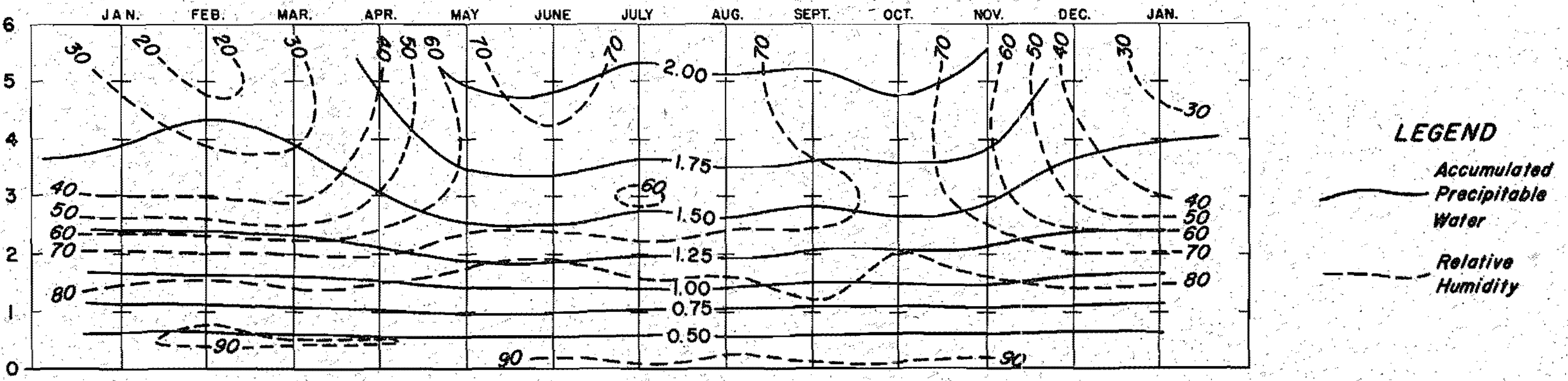
Figure 20

Weighted means of apob data by months -- Coco Solo, Canal Zone

right-hand corner of Figure 19.

32. Aloft the patterns of the annual variation of the elements also show a similarity to the movement of the doldrum edge. Of particular interest in Figure 20, illustrating some of these variations, is the evidence of the comparative dryness aloft during the winter months. This is also shown in the upper half of Figure 21, where an important distinction between the variation of precipitable-water content and the variation in relative humidity can be observed. If the five-kilometer levels in June and February, for example, are compared, it can be seen that whereas the mean precipitable water in a column that deep is only

MONTHLY MEAN PRECIPITABLE WATER AND RELATIVE HUMIDITY AT COCO SOLO, CANAL ZONE



NORMAL DEPTH OF LAYER CAPABLE OF PENETRATING THE 5 KM SURFACE

(ASSUMING THE NECESSARY INITIAL LIFT TO PRODUCE SATURATION)

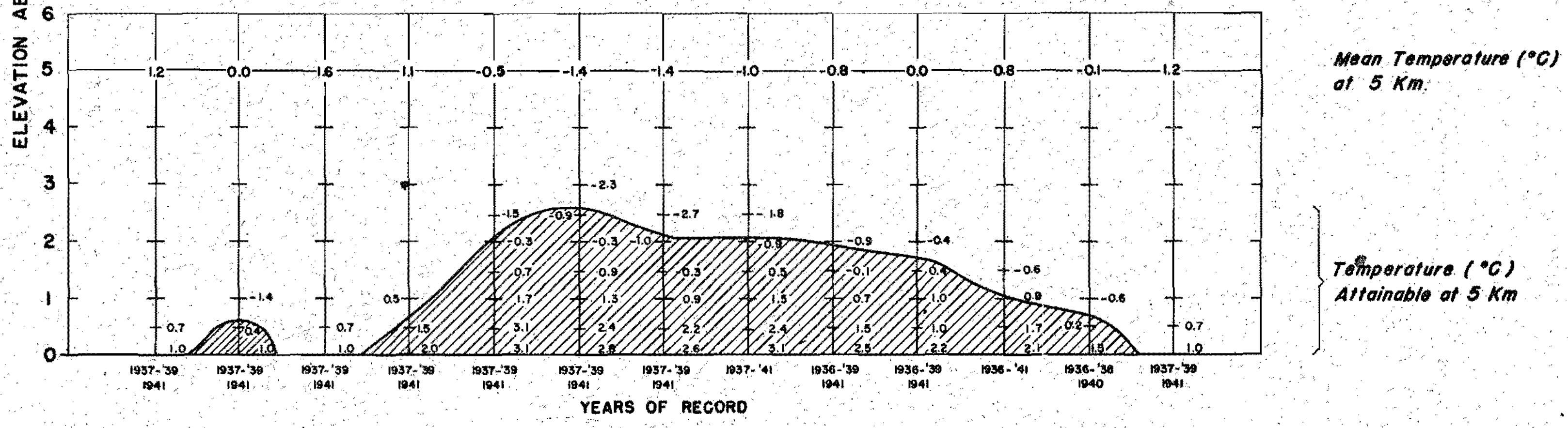


Figure 21

one-fourth less in February than in June, the relative humidity at that level is about two-thirds less in February than in June. In the dry season, then, the air aloft is quite far from a saturated condition.

33. <u>The Wet and Dry Seasons</u>. The dryness of the air aloft over Panama during the dry season is an effect of the continuous subsiding tendency existing in warm, subtropical anticyclones. The air sinking from high levels within the trade-wind belt warms dry-adiabatically in the process, producing higher temperatures and therefore lower relative humidities. The result is the trade inversion which, over Coco Solo, is more often discernible as a sharp decrease in humidity but sometimes also as an abrupt increase in temperature at an elevation of approximately 2000 meters. All the airplane observations made at Coco Solo during the years 1937 to 1940, inclusive, were analyzed, and the percentage of observations per month on which a trade inversion was noted is given in the following table:

TABLE 2

MONTHLY FREQUENCY OF TRADE INVERSION AT COCO SOLO

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
%	67	82	75	46	21	23	25	34	16	22	16	38

The high frequency of the occurrence of the inversion in the dry season is notable. The frequency for the other months is overestimated in the table because airplane observations are often cancelled during rainy weather when the trade inversion is usually missing. The effect of the inversion aloft is to place an effective ceiling on convection and to dissipate (because of the dryness above) such cloudiness as may occasionally penetrate the inversion.

34. Further examination of Figures 20 and 21 reveals the difference in the stability of the air during the wet and dry seasons. An air mass is convectively unstable -- that is, it will become actually unstable after being cooled to saturation by lifting -- if the wet-bulb potential temperatures decrease with height. The upper half of Figure 20 shows the wet-bulb potential temperature θ_w decreasing with height throughout the five kilometers during the rainy doldrum period but becoming constant or increasing with height above 3500 meters during the dry trade-wind regime. In the lowest layers the convective instability (measured by the rate of decrease of θ_w with height) is actually greater during the dry season. The lapse rate of θ_w is 2 C in the first 1500 meters in July-August but 3 C for the same layer in January. During the winter the instability can seldom be realized because of the inversion-cap on convection. Even the thermal instability, shown by the lapse rate of temperature, is greater in the lower layers in the dry season. The comparative crowding of the isotherms in winter in the lower half of Figure 20 demonstrates this. Such a condition is to be expected in modified polar air undergoing heating from below as it approaches Panama. But again the instability -- conditional, in this case -- cannot be attained because of the dry inversion above.

35. Using the mean monthly data obtained from the Coco Solo airplane soundings, mean monthly lapse-rate curves, with humidities indicated, were plotted on pseudo-adiabatic charts and analyzed. The lower half of Figure 21 shows some of the results. Assuming that the necessary lift to saturate the lower layers can be attained -- and the

orographic barrier present in the basin is generally sufficient to provide this -- the only air that will penetrate the five-kilometer level will be air that reaches that level at a higher temperature than its surroundings. In the figure the temperatures shown at five kilometers are the mean temperatures at that height. At the lower levels, the temperatures shown are those which air, originally at the indicated level, will attain if lifted pseudo-adiabatically to five kilometers. The curve, then, divides the attainable temperatures which exceed the actual five-kilometer temperatures from those which do not. Only the depth of air below the dividing line will succeed in penetrating the five-kilometer surface. The impossibility of convection to such height during the dry season, on the average, is clear. The maximum depth occurs in June. November, it is to be noted, which is the month of maximum rainfall, shows a much smaller normal depth capable of such convective altitude. The five-kilometer level is important for more than its height. At or near that height over Panama the zero or freezing isotherm is located and modern theories of condensation indicate that heavy precipitation cannot occur unless condensation extends to a level where there is co-existence of ice and water droplets. Otherwise, according to the theory, there is little possibility for the formation of droplets large enough to fall to the surface before evaporating.(1)

36. Convection, however, is not the only assignable cause of rainfall over the Canal Zone, although it must always be involved in appreciable falls. The basin's topography presents an orographic

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(1) G. C. Simpson: "On the Formation of Cloud and Rain," Quarterly Journal of Royal Meteorological Society, April, 1941.

barrier to prevailing winds which must be surmounted, the resulting lift causing saturation and at times producing the lapse rate required for convective action. Air crossing the basin from the northwest, for instance, will undergo a mean lift of about 1400 feet. If the surface layer can be saturated by that much lift, it can then realize its potential instability -- if conditions aloft allow. However, examination of the mean monthly soundings shows that in February, on the average, a lift of 1500 feet is required for saturation of the surface layer while in November a 900-foot lift is sufficient.

37. Although the purely orographic effect is mechanical, it has dynamic effects which can be used as an index of the orographic intensity. Because it is a heightened frictional effect, fundamentally, it manifests itself in a disturbance of wind flow. The frictional effect on wind direction is to deflect it across the isobars toward lower pressure. The turning of northeast winds to north and northwest on the north coast of the Panama Isthmus is such an effect. Another is the diminution of surface wind velocity as the air flows across the barrier. Since the frictional or orographic effect introduces a vertical component in the air movement, it is obvious that the horizontal velocity on the leeward side of the barrier will be less than on the windward side. Such a wind difference can also be considered as a manifestation of surface convergence -- the phenomenon of net inflow of air over a given region. Frontal passages and local convection, as well as divergence aloft, will also intensify the surface convergence field, but the orographic effect, if present, will always contribute.

38. To obtain the mean monthly convergence patterns over Panama,

the monthly resultant wind vectors (based on a.m. synoptic observations) were plotted for the region of the Caribbean and Pacific surrounding Panama and the convergence computed in units of square miles of air converging upon a two-degree square. In Figure 22 the convergence values interpolated from these charts for the Canal Zone region are superposed on the mean rainfall values for the 23 stations of Figure 18. The qualitative resemblance between the variations is good, although the dip in convergence values for September and October is not readily explicable. In those months the Canal Zone is deepest in the doldrums and the winds, as has been shown, are lightest and most variable. Among the variable winds will be some with no component normal to the high barriers of the basin. The result would be lower convergence values due to the orographic effect. Furthermore, the mean monthly values of convergence include divergence values. It would be possible to have heavy rainfall resulting from convergence during a month even though divergence predominated. Despite this, the high values of rainfall and convergence are, in general, well-related. In Figures 23 and 24 the resultant-wind patterns and associated

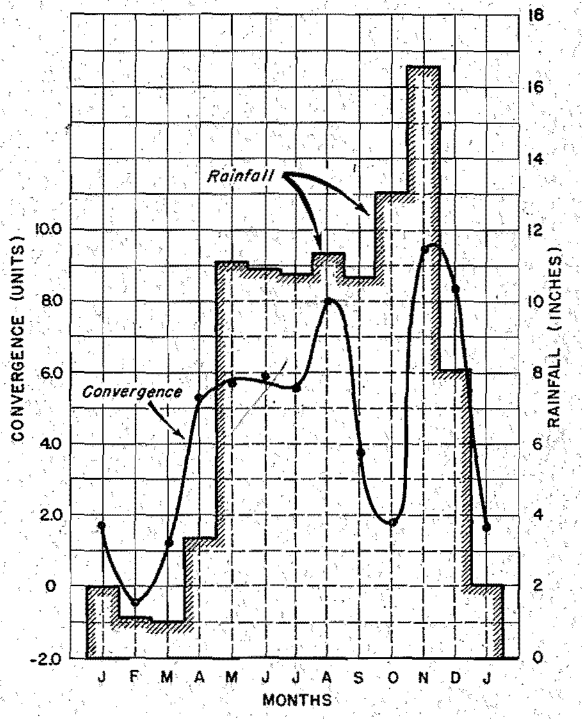
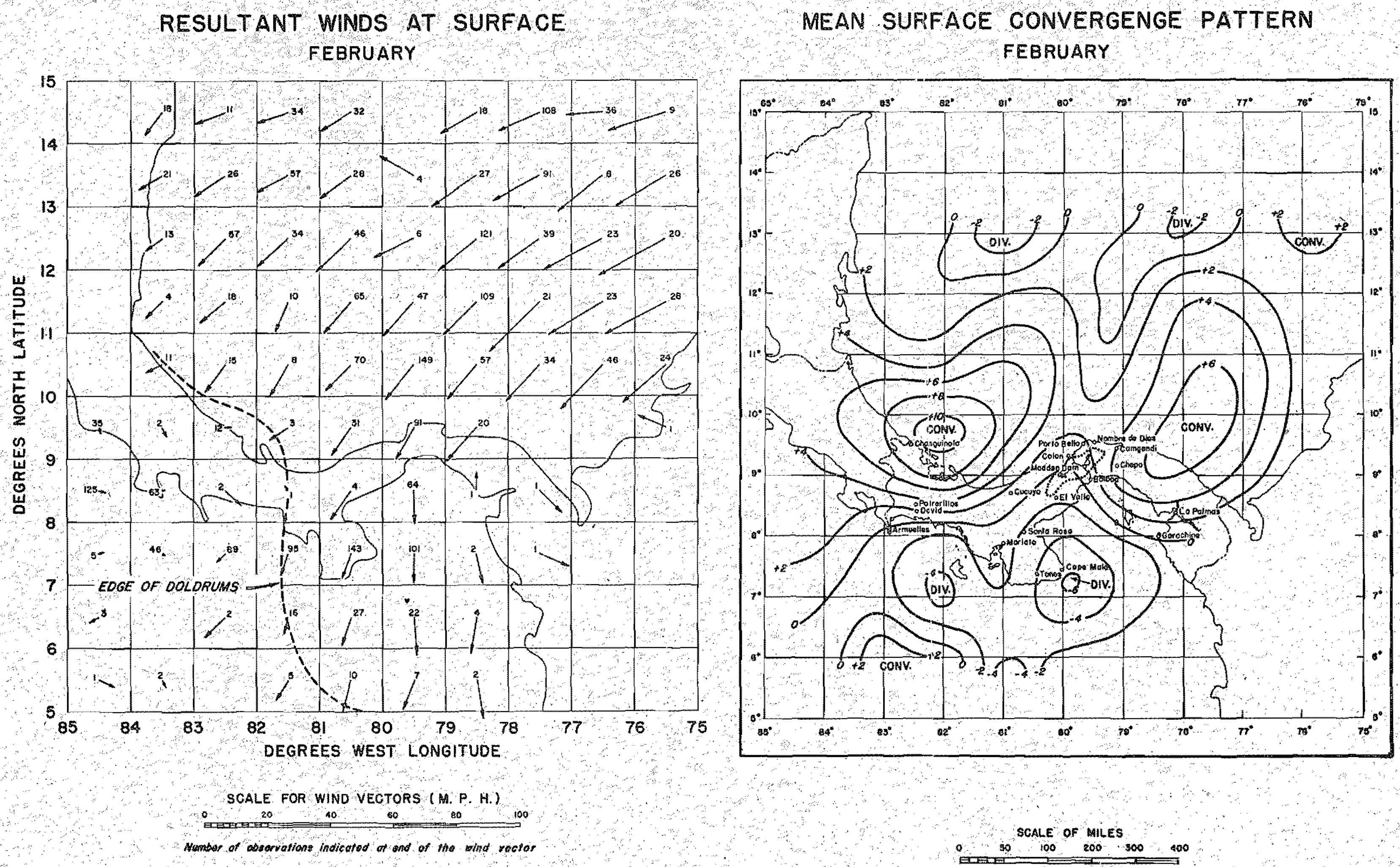


Figure 22

Seasonal variation of rainfall
and surface convergence over
the Canal Zone region


RESULTANT WINDS AT SURFACE
FEBRUARY

MEAN SURFACE CONVERGENCE PATTERN
FEBRUARY

Figure 23

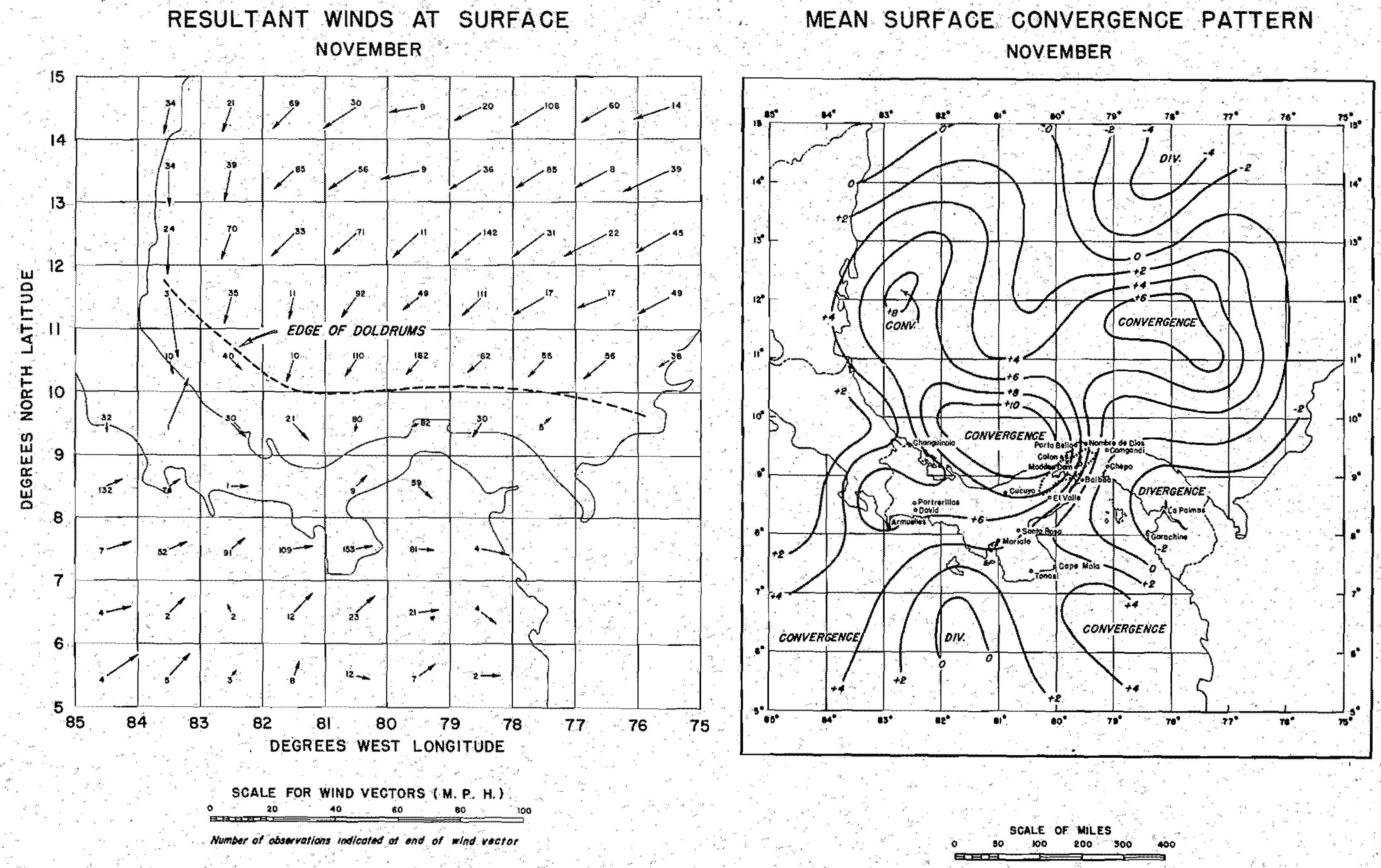

RESULTANT WINDS AT SURFACE
NOVEMBER
DEGREES NORTH LATITUDE
DEGREES WEST LONGITUDE
EDGE OF DOLDRUMS
SCALE FOR WIND VECTORS (M. P. H.)
0 20 40 60 80 100
Number of observations indicated at end of wind vector
MEAN SURFACE CONVERGENCE PATTERN
NOVEMBER
CONVERGENCE
DIVERGENCE
DIV.
CONV.
Changuinola
Porto Bello
Nombre de Dios
Colon
Madden Dam
Balboa
Chepo
Cucuyo
El Valle
Portrerillos
David
Armuelles
Santa Rosa
Mariato
Cape Mala
Tonosi
La Palmas
Garachine
SCALE OF MILES
0 50 100 200 300 400

Figure 24

convergence fields are shown for February and November, the minimum and maximum points on the convergence curve of Figure 22.

39. In summary, the dry season at Panama results from the establishment of the trade-wind regime over the region. Although modified polar incursions bring convectively unstable air into the region during the period, the instability does not extend to high levels and the trade inversion acts as a ceiling on both the convective and orographic effects. As a result, surface convergence diminishes during that season, with February actually showing divergence. During the rainy season, however, the Canal Zone is in the belt of doldrums, with convective instability existing to the icing level and beyond and with only occasional appearances of the trade inversion. Although convergence values climb during this period, the light and variable character of the wind in the doldrums indicates that the purely orographic effect is probably less, the major contribution being from convection of the local type. The November maximum in rainfall, partly due to the persistence of phenomena described above but which is definitely associated with the major-storm period in the Canal Zone, still remains to be explained.

40. The November Maximum. The mean structure of the air aloft during the months of May to September, inclusive, shows evidence, as do the monthly convergence charts, of strong convective action. It is well-known that this is the period of local rather than general storms, of high intensities of rainfall but short durations. The forces instigating the rains are confined to the belt of light and variable winds, the doldrums.

41. In November, however, when the general and major storms of

Panama occur with the greatest frequency, the region is on the edge of, rather than within, the doldrums. While the local convective activity of the previous months lingers on, an external agent is now added. It is the occasional surge of polar air, often designated as the norther, from the cooling continent. Preceded by a cold front, polar air passes through the trade-wind belt and enters the doldrums. Beneath the trades themselves only minor rains develop -- for reasons outlined in previous paragraphs -- but at the boundary of the trades and the doldrums the major storm of Panama ensues.

42. It would appear, then, that the major Panama storm is simply a norther. The originally cold and dry air mass surging southward over the warm waters of the Gulf of Mexico and Western Caribbean must naturally acquire heat and moisture that will develop extreme convective instability. In most northers, however, the strong winds rather than the heavy rains are the predominant features over the water. When the Isthmus is reached, the orographic effect induces convective rains not realizable over the water. The intensity of the orographic effect becomes a direct function of the speed of the wind normal to the mean highest barrier. Other facts, however, do not support the conclusion that the norther is the sole explanation of the Panama storm. October, November and December -- which are the months of greatest frequency of major Panama storms -- are also the months in which the first cold outbreaks from the north appear in the vicinity of Panama. The outbreaks become more frequent and also more intense in the following months of January and February. In these latter months the surface modification of the polar air still goes on, the orographic effect of the Isthmus

remains, but the major storms of Panama have ceased and, in fact, the dry season has begun. The ceiling on convection, already demonstrated, which exists at that time is one of the dampening effects.

43. The norther, then, cannot be the sole cause of the major Panama storm although it is obviously an essential factor. The norther accompanies most of the storms but storms do not accompany most of the northers. The norther serves to set off a storm only when certain conditions exist. The conditions prerequisite to the norther's effectiveness as a rainfall producer are a seasonal feature of the Panama region, and that feature is the presence of the boundary between the trades and the doldrums. Sometimes called the intertropical front, data are insufficient to establish with certainty its vertical characteristics in the Panama region. Its surface position, however, is usually easily identified and its surface character usually that of a quasi-stationary front with undulations of slight amplitude. In most of the storms studied the meeting of the polar and intertropical front is equally well-marked.

44. In the Meteorological Magazine for March 1926, C. E. P. Brooks, in a study of Pacific islands at the edge of the doldrums, said: "...the greatest source of rain is to be found in the occurrence of winds of conflicting direction. The occurrence of varying directions probably indicates eddy-motion, and the edge of the doldrums may be taken as the line along which the solid current of the trade winds breaks up into eddies." The incursion of the norther intensifies the perturbation tendency already present along the intertropical front and the result is the occasional peak of convective rain added to the prolonged,

partly orographic convection of the Panama major storm.

45. April is the other month when the doldrum edge passes over Panama, this time northward. There is, however, no convective tendency lingering on from other months, such as there is in November. Furthermore, anticyclonic activity over the United States is diminishing, with cold thrusts becoming fewer and less intense. The rainy season usually begins in late April and the first important rains are usually the consequence of a last vigorous cold thrust from the continental source. The rains that follow, however, are of the local convective type until the norther season begins again in autumn.

46. Between the rainy season and the major-storm season, then, the following distinctions can be made: The convective activity resulting from the intensification of perturbation tendencies of the intertropical front is on a larger scale than the local convective activity of the summer months. The wind-component normal to the highest basin barriers is stronger and of greater duration during the storm season than during the within-doldrum period. The November maximum in rainfall results from a combination of these effects.

47. The Hurricane Possibility. At least one other important theory extant explains the phenomenon of large-scale convection in terms of other elements. Rodewald's Dreimasseneck (1) is a point at which three currents of air meet and at which, as a result, cyclogenesis, sometimes of hurricane intensity, has been known to occur. If it is agreed to call the doldrum air the southwest monsoon -- that is, air

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(1) E. Scofield: "On the Origin of Tropical Cyclones," Bulletin, American Meteorological Society, June 1938.

originally the southeast trades of the Southern Hemisphere deflected northeastward in its passage across the equator -- then the region of the Canal Zone during a major storm may be at the juncture of the three air masses which should meet at the "triple point." The other two are the air of the northeast trades and the modified polar air of the norther.

48. It is true that, although cyclonic flow is obviously present, the surface evidence of cyclogenesis over Panama during such a period is never very great. The pressure fall is slight. However, there is abundant evidence in most of the storms studied, and on monthly charts, of marked convergence over the region of the Canal Zone. This tendency, natural in any cyclogenetic process, is intensified over the Canal Zone by the lesser rightward deflection of wind at such latitudes, by the doldrum-edge effect in itself, by the shift from the frictional influence of the sea surface to the greater roughness of the land surface, and finally by the topography of the basin. The result is that the pressure fall characteristic of cyclogenesis is neutralized by the pressure rise due to horizontal convergence. And the horizontal convergence induced by the cyclogenetic perturbations along the norther-intertropical front produces the peak of convection of the Panama storm.

49. Mention of the Dreimassenecк of Rodewald naturally suggests the possibility of the hurricane-type storm in the Canal Zone. There is, however, no record of any hurricane ever having occurred over the region, and qualified synoptic meteorologists are agreed that no hurricane will ever cross the Isthmus.

50. The mechanism of the formation of the tropical cyclone or

hurricane is still to be solved but it has often been noted that the region of the doldrums -- whether called the doldrum edge, the intertropical front or the habitat of the Dreimasseneck -- is the place of origin. Of special interest in the current study is the following from C. L. Mitchell: "Over the western third of the Caribbean Sea, especially in the region a short distance north of the Isthmus of Panama, a belt of doldrums appears at times.... This, quite likely, is the extreme eastern end of the Pacific belt of doldrums, which is usually just south of the Isthmus of Panama ... and which has shifted northward beyond latitude 10° N. Thus conditions in the western Caribbean Sea at these times become as favorable for the development of a cyclonic disturbance as they are in the region south of the Cape Verde Islands in the months of August and September."(1) Figure 25, based mostly on data gathered by Mitchell and Tannehill(2), shows the tracks of tropical storms which have originated as close to the Canal Zone as the theory calls for. Their points of origin are the points where their development was first observed. None had hurricane intensity then and some never developed such intensity. While these observations still agree with the fact that no hurricanes have ever occurred over the Canal Zone, it also becomes apparent that the Canal Zone is at times in a region where these storms can theoretically develop (the doldrums) and also very close (approximately half a degree of latitude) to a region where tropical storms, some of which have later achieved hurricane

(1) "West Indian Hurricanes and Other Tropical Cyclones of the North Atlantic Ocean," Monthly Weather Review, Supplement No. 24, 1924.

(2) "Hurricanes," Princeton University Press, 1938.

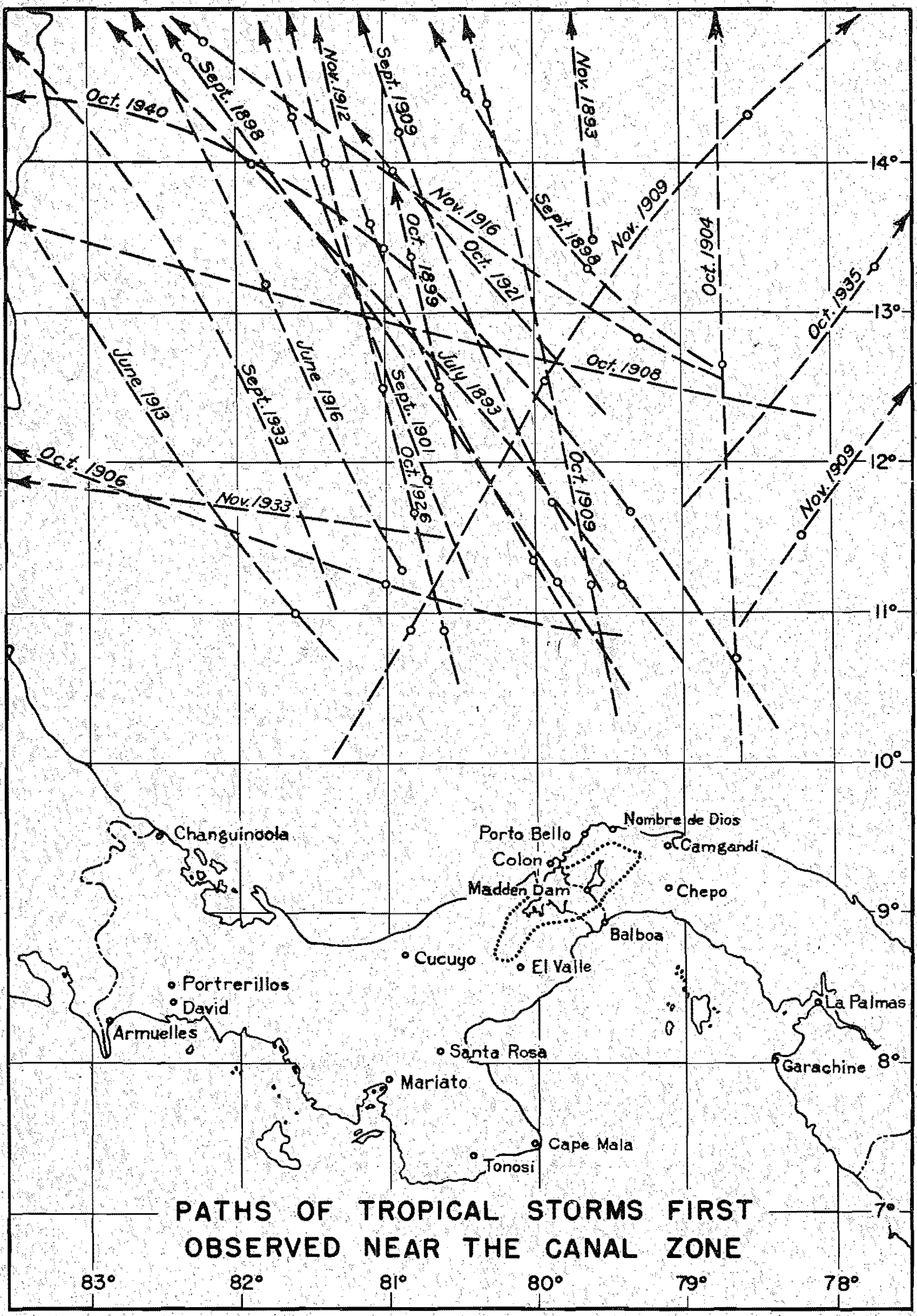
PATHS OF TROPICAL STORMS FIRST OBSERVED NEAR THE CANAL ZONE
Oct. 1940
Sept. 1898
Nov. 1912
Sept. 1909
Nov. 1893
Nov. 1916
Oct. 1899
Oct. 1921
Sept. 1898
Nov. 1909
Oct. 1904
Oct. 1935
Oct. 1908
June 1913
Sept. 1933
June 1916
Sept. 1901
July 1893
Oct. 1926
Oct. 1909
Nov. 1909
Oct. 1906
Nov. 1933
Changuinoola
Porto Bello
Nombre de Dios
Camgandi
Colon
Madden Dam
Chepo
Balboa
Cucuyo
El Valle
Portrerillos
David
Armuelles
La Palmas
Santa Rosa
Garachine
Mariato
Cape Mala
Tonosi
14°
13°
12°
11°
10°
9°
8°
7°
83°
82°
81°
80°
79°
78°

Figure 25

intensity, have been first observed.

51. There is evidence that the Canal Zone can be definitely within the influence of these storms, sometimes even before the storm is first spotted as an entity in the Western Caribbean. In connection with a discussion of the hurricane of October 20-25, 1921, Bowie quotes the following from a letter from the Chief Hydrographer, Panama Canal: "Reference is made to the cabled predictions of the West Indian Hurricane of October 21-25.... As usual we were not detrimentally affected here locally. However, we did have a noticeable effect from it, considerably more than usual. I inclose barometric record, October 12 to 26 (not reproduced). You will note that our barometer, disregarding diurnal fluctuations, was steadily declining from October 12 to 18, preceding the birth of the hurricane. This period was accompanied by heavy daily rains, noticeably on the Pacific half of the Canal Zone; winds prevailing from northward.... Ships tell us of stormy voyages from San Francisco to Nicaragua contemporaneously with the passage of the Caribbean storm."(1) Bowie adds: "We infer from the foregoing that there had taken place previously to the birth of the cyclone fundamental changes in the primary wind regime of the Tropics."

52. Mitchell's statement that no hurricanes in the Atlantic or Caribbean are ever in evidence south of 9° N. latitude can be said to mean that, although they have been known to develop at approximately that latitude, their subsequent movement is never southward. The tracks of Figure 25 show that to be the case. Consideration of the land and

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(1) "The Hurricane of October 25, 1921, at Tampa, Florida," Monthly Weather Review, V. 49, October 1921.

water distribution in the vicinity of Panama gives rise to the following corollary ideas. Any path that had a southward or no northward component would carry the storm over a land mass in its early stages and result in its dissipation. Furthermore, any storm that first developed over the region of the Canal Zone would never appear even as an incipient hurricane in the Western Caribbean unless it were free to travel in some northward direction.

53. It has already been noted that one of the characteristic features of the circulation in a Panama general storm is the huge anticyclone spreading from the continent through the Gulf of Mexico, causing the surface winds to shift to northward over Panama and even east of the Isthmus. Aloft, the wind flow over the region is then from the east or northeast. One of the rules that has been accepted concerning the tropical storm is that it moves in the direction of the wind at the 3-4 kilometer level, with the anticyclone to the right of its path. It is therefore possible to say that the Panama storm may be an incipient hurricane whose further development is prevented, first, because it is imbedded in a circulation compelling it to move in a westward direction; and, second, because the ruggedness of the Panama terrain and of the region toward which the storm is forced to move is not conducive to the establishment of an intense cyclonic circulation. How dampening those effects can be is evidenced by the fact that the minimum sea-level pressure observed in the Canal Zone (through 1940) is 29.61 inches at Balboa. When in the doldrums, the area is apparently sufficiently maritime to allow incipient cyclonic formation but it is also sufficiently continental to prevent the cyclonic development. It is interesting to

note that a large majority of the tropical storms originating near the Canal Zone occur in October and November (see Figure 25), the months of greatest frequency of the major Panama storms.

54. In the eastern two-thirds of the Caribbean there usually are no doldrums. Mitchell emphasizes that "tropical cyclones never [develop] over the portions of the Caribbean Sea east of about longitude 78° W." On the northeastern side of South America hurricanes have been known to develop as far south as about 10° N. latitude. On September 8, 1921, one formed unusually far south, southeastward of the Windward Islands, about due east of the Island of Trinidad. It moved west-northwestward and recurved near Turks Island. Similar hurricanes, according to F. G. Tingley, occurred in June 1831 and October 1892, both pursuing "a course somewhat north of west, the former striking the Yucatan Peninsula, the latter the coast of Honduras."(1) It is obvious that a movement toward the Canal Zone would have to be along a direction somewhat south of west, which would involve the storm's crossing about 15° of the South American land mass. At so early a stage in the storm development the frictional effects of such a path would cause the storm to fill beyond recognition. On the western, Pacific side of Central America no eastward moving hurricanes have ever been observed nor, for that matter, a circulation aloft that would permit them.

55. The evidence thus supports the generally accepted view that a fully-developed hurricane cannot occur over the Panama Canal Zone.

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(1) "Additional Notes on the Hurricanes of September 1921," Monthly Weather Review, V. 49, 1921.

CHAPTER III

SYNOPTIC METEOROLOGY

56. The Panama Storm Type. The nine storms, chosen on the basis of hydrologic significance and all confined to the months of October, November and December, were studied in detail, using all available surface and upper-air observations. In addition, the synoptic charts for a very large number of lesser storms, occurring at all seasons and presenting varied rainfall patterns over Panama, were subjected to a less rigorous analysis. Table 3 lists the latter group of storms and gives significant rainfall values at stations in the Canal Zone. The rainfall analyses of the nine major storms were presented in Chapter I, and the meteorological features of the storms will be discussed in this chapter.

57. The synoptic studies reveal certain large-scale features which are common to all periods of widespread, heavy rain over the Panama Canal Basin. Chief of these is the thrust of polar air from western Canada down to and past the latitude of the Canal Zone. On the surface such a thrust shows a synoptic pattern dominated by a cold high pressure area of great expanse, often extending from the Mississippi Valley to and beyond the Atlantic Coast and stretching southward toward the Isthmus. Preceding the anticyclonic circulation is the trough containing the cold front, vigorously active in its northern portion off

TABLE 3

ADDITIONAL STORMS STUDIED

Year	Month	Station	Dates, with rainfall in inches for period indicated		
		A. General Seasonal Storms:			
1934	Nov.		16	16-17	15-17
		Colon	7.54	11.37	13.54
	Nov.		15	15-16	15-17
		Alhajuela	4.11	8.14	11.76
	Nov.		17	16-17	16-18
		Balboa	3.92	6.30	7.07
1933	Nov.		27	26-27	22-27
		Colon	6.68	9.02	21.92
	Nov.		26	26-27	23-28
		Alhajuela	2.04	3.19	6.86
	Nov.		27	27-28	25-30
		Balboa	1.84	1.96	4.03
1928	Nov.		20	20-21	19-24
		Colon	2.34	3.60	5.32
	Nov.		20	20-21	19-24
		Alhajuela	3.99	4.00	4.95
	Nov.		19	18-19	14-19
		Balboa	1.48	1.93	4.26
1924	Nov.		6	6-7	2-7
		Colon	1.28	1.46	3.16
	Nov.		5	4-5	2-5
		Alhajuela	2.07	3.30	5.05
	Nov.		4	3-4	2-7
		Balboa	3.35	3.78	4.08

(Continued on next page)

TABLE 3 (continued)

Year	Month	Station	Dates, with rainfall in inches for period indicated		
1917	Nov.	Colon	19 4.08	18-19 5.84	16-21 9.64
	Nov.	Alhajuela	23 3.29	23-24 4.75	20-25 11.22
	Nov.	Balboa	20 1.78	20-21 3.19	
1912	Nov.	Colon	4 2.94	4-5 3.31	2-7 7.35
	Nov.	Alhajuela	6 1.15	6-7 1.32	2-7 1.95
	Nov.	Balboa	4 1.35	4-5 1.87	2-7 2.96
1910	Dec.	Colon	4 2.51	3-4 3.42	1-6 5.86
	Dec.	Alhajuela	6 2.63	5-6 2.77	1-6 10.28
	Dec.	Balboa	3 1.28	2-3 2.43	1-6 3.45
1909	Nov.	Cristobal	11 6.13	11-12 8.47	11-13 10.52
	Nov.	Alhajuela	11 3.55	11-12 5.93	
1906	Nov.	Cristobal	16 4.68	15-16 5.96	14-17 8.02
	Nov.	Alhajuela	16 5.22	16-17 9.34	
	Nov.	Balboa	17 7.31	16-17 8.17	15-17 9.70

(Continued on next page)

TABLE 3 (continued)

Year	Month	Station	Dates, with rainfall in inches for period indicated		
B. Seasonal Storms Producing Heavy Rainfall at Cristobal-Colon Only:					
1939	Nov.		16	15-16	13-16
		Colon	7.70	8.38	12.30
1937	Nov.		3	2-3	Oct. 30-Nov. 3
		Colon	4.72	7.33	13.78
1935	Nov.		3	2-3	2-5
		Colon	4.32	5.73	9.56
1935	Dec.		2	2-3	Nov. 30-Dec. 5
		Colon	4.63	5.86	12.48
1932	Nov.		23	23-24	21-24
		Colon	6.23	9.53	13.56
1930	Nov.		28	28-29	28-30
		Colon	4.12	7.06	9.71
1927	Nov.		12	11-12	10-12
		Colon	4.05	5.69	7.14
1925	Nov.		23	23-24	23-27
		Colon	6.89	9.04	14.06
1924	Nov.		23	22-23	17-23
		Colon	4.32	6.95	14.53
1923	Nov.		26	26-27	
		Colon	3.69	6.82	
1920	Nov.		21	20-21	17-21
		Colon	4.34	5.17	7.36
1919	Oct.		10	9-10	7-10
		Colon	3.21	5.57	9.60
1918	Oct.		17	16-17	15-19
		Colon	5.47	7.78	13.41
1913	Nov.		10	9-10	8-12
		Colon	2.66	3.91	9.28

(Continued on next page)

TABLE 3 (continued)

Year	Month	Station	Dates, with rainfall in inches for period indicated		
1910	Nov.		30	Nov. 30-Dec. 1	Nov. 29-Dec. 4
		Colon	3.65	5.79	11.51
1909	Dec.		6	5-6	5-10
		Cristobal	3.56	6.28	14.58
1908	Nov.		16	16-17	16-20
		Cristobal	3.42	6.76	12.69

C. Late Seasonal Storms Producing Heavy Rainfall at Cristobal-Colon Only:

1915	Feb.		10	10-11	9-11
		Colon	7.12	8.81	10.27
1902	Jan.		9	9-10	8-10
		Cristobal	5.86	9.66	10.70

D. Non-Seasonal Storms Producing Heavy Rainfall at Cristobal-Colon Only:

1937	June		10	9-10	7-12
		Colon	8.47	9.86	17.82
1935	May		3	2-3	
		Colon	3.32	4.74	
1931	May		16	16-17	14-17
		Colon	4.76	8.29	13.00
1927	Aug.		26	26-27	24-29
		Colon	5.25	7.10	18.01
1926	May		25	25-26	25-29
		Colon	4.05	5.22	11.00
1926	June		22	21-22	18-22
		Colon	4.24	5.44	10.17
1923	May		10	10-11	10-12
		Colon	3.69	6.82	8.04
1914	May		7	7-8	7-9
		Colon	4.91	5.00	7.25

(Continued on next page)

TABLE 3 (continued)

Year	Month	Station	Dates, with rainfall in inches for period indicated		
1914	May		22	21-22	21-23
		Colon	3.63	5.22	6.26
	May		21	21-22	
		Alhajuela	2.29	2.63	
	May		22	21-22	
		Balboa	1.39	2.45	
1913	May		21	20-21	20-24
		Colon	4.74	5.07	10.14

E. Storms Producing Heavy Rainfall at Alhajuela and/or Balboa with Fairly Light Amounts at Cristobal-Colon:

1920	Oct.		20	20-21	18-21
		Alhajuela	2.06	4.01	7.03
1919	Oct.		22	22-23	22-24
		Alhajuela	3.48	4.19	7.26
	Oct.		24		
		Colon	3.51		
	Oct.		24		
		Balboa	1.25		
1916	May		25	25-26	
		Alhajuela	3.23	5.61	
		Balboa	26	25-26	
			5.42	5.82	
1912	May		12	11-12	
		Balboa	7.00	7.40	
1911	Oct.		25	24-25	
		Alhajuela	7.05	8.83	

(Continued on next page)

TABLE 3 (continued)

Year	Month	Station	Dates, with rainfall in inches for period indicated		
1911	Oct.		24	23-24	
		Colon	2.73	4.49	
1909	Dec.		3	3-4	1-6
		Alhajuela	8.19	8.33	9.36
1903	Aug.		29	28-29	26-31
		Balboa	2.75	4.64	8.00

F. Storms Earlier in the Rainfall Season:

Year	Month	Station	Dates, with rainfall in inches for period indicated		
1934	Sept.		4	4-5	
		Colon	4.39	7.51	
	Sept.		5	5-6	4-7
		Alhajuela	2.79	3.32	3.44
	Sept.		5		
		Balboa	3.76		
1929	Aug.		4	4-5	3-7
		Colon	1.90	3.42	8.04
	Aug.		3	3-4	3-5
		Alhajuela	1.71	2.08	3.50
	Aug.		5	5-6	
		Balboa	1.63	3.16	
1921	Oct.		12	12-13	12-15
		Alhajuela	3.66	5.59	7.64
	Oct.		16		
		Colon	3.77		
	Oct.		14	13-14	
		Balboa	3.42	5.21	
1914	Oct.		14	14-15	10-14
		Cristobal	3.99	4.77	10.15

(Concluded on next page)

Year	Month	Station	Dates, with rainfall in inches for period indicated		
1914	Oct.	Alhajuela	17 3.29	17-18 5.07	15-18 7.00
1912	Oct.	Colon	27 2.36	27-28 3.60	
	Oct.	Alhajuela	27 1.50	27-28 2.46	26-31 4.95
	Oct.	Balboa	26 2.39	26-27 2.73	26-31 5.08

the Atlantic Coast but becoming quasi-stationary in the vicinity of Panama. In a majority of cases, the cold front crosses the Florida Peninsula oriented northeast-southwest and its progress is marked by definite shifts of wind and falling temperatures at stations in western Cuba, Yucatan and on the Mexican Gulf Coast. Often, too, the front can be traced as a surface phenomenon beyond Cape Gracias and Pacific Coast stations such as Salina Cruz and Tapachula. This gives rise to the norther, known locally as the "Tehuantepecer" or, in Costa Rica, as the "Papagayo." Occasionally the cold front can be traced southward to the Isthmus of Panama, but the meager data available do not suffice to establish definitely its progress much beyond the Isthmus. On the maps studied, what was most clearly evident in the vicinity of the Isthmus was an increase of pressure gradient, producing surface winds in excess of normal for the rainy season. On most days with heavy, widespread rain within the basin, those winds were from the northwest over the Western Caribbean and at stations on the North Coast of the Isthmus.

Characteristic also was the presence over or near the basin of an area of horizontal convergence.

58. Northwesterly winds may also occur over the Isthmus of Panama when a tropical disturbance is present in the Western Caribbean. This condition may prevail without a pronounced anticyclone over the Gulf of Mexico and, if so, the northwesterly winds are not particularly significant since rainfall periods of hydrologic importance do not then ensue.

59. It has already been pointed out that the edge of the doldrum belt or, in other words, the demarcation between the steady northeast trades and the region of calms and light, variable winds, is to be found in the vicinity of the Isthmus of Panama during the autumn months. Particularly is this true in November. As the cold front, followed by modified polar air, overtakes and becomes coincident with a portion of the edge of the doldrums (or intertropical front), the result is, in effect, an occlusion. This follows from the consideration that the air mass in the belt of doldrums (equatorial air) is cooler than the air in the region of the northeast trades (tropical air). That this is true can only be assumed from a very small number of upper-air soundings which have been made in the equatorial air. Without sufficient evidence, based on meteorograph soundings and pilot-balloon ascents, it is impossible to do more than surmise that the conjunction of the polar and intertropical fronts results in an occlusion. But, whether the result is an occlusion, with the warm-sector air mass (tropical air) lifted above the surface, or whether the conjunction of the fronts results in a simple cold front between modified polar air and the equatorial air, is a problem primarily of academic interest. Practically, the effect on

the rainfall pattern would be similar in the two cases.

60. The slope of the polar frontal surface diminishes as it moves into more southerly latitudes, so that any active lifting of the warm, moist air mass by a wedge of cold air seems to be of only minor significance. However, the horizontal convergence associated with the frontal zone results in a vertical displacement of the low-level air and a release of the convective instability inherent in the tropical and equatorial air masses. This occurs whenever the combined polar-intertropical front passes over the Isthmus. Waves along this front, occasionally cresting over the basin, produce the greater peaks in convergence and therefore in rainfall intensity, in a manner similar to the wave action along the quasi-stationary fronts of middle latitudes. As the north or northwest winds behind the front continue, the air is lifted up the topographic slopes of the basin, resulting in the prolonged orographic rainfall which persists without benefit of any intense convective activity. The Panama storm type can, in fact, be said to consist of prolonged orographic activity, mildly aided by convection and punctuated by short durations of intense convection.

61. The orographic rain falls from the modified polar air which, on its long trajectory over the warm waters of the Gulf of Mexico and Western Caribbean, has absorbed both heat and moisture in the lower layers. In the upper levels of the modified polar air, however, there occurs the characteristic subsidence associated with anticyclonic pressure distribution. The effect of the subsidence, as explained in the previous chapter, is to produce an inversion at intermediate levels which serves to damp out convective activity. Little rain can thus fall

out of the convectively unstable lower layers until the air strikes the orographic barrier, and even then the rainfall intensity is limited by the inhibiting effect of the inversion aloft. That the prolonged periods of widespread rain over Panama occur when there is a stable layer at intermediate levels in the atmosphere is borne out by descriptions of clouds given by unofficial observers, as well as by records of meteorological stations in the area. During the period of the so-called "November rains," persistent stratiform clouds often replace the transient, cumuliform type.

62. An excellent example of a cold front reaching Panama and merging with the intertropical front was found in the storm period of November 1-7, 1939. This storm period seems to have run the gamut of variations in synoptic patterns for Panama storms. The large number of surface and upper-air reports available, the length of the period covered and the presence within the region of interest of both a tropical disturbance and a pronounced continental anticyclone make this storm best-suited for demonstrating the typical-storm analysis. Hence weather maps for this storm only have been reproduced, and discussion of the meteorology of Panama storms will be confined principally to a discussion of the storm of November 1-7, 1939.

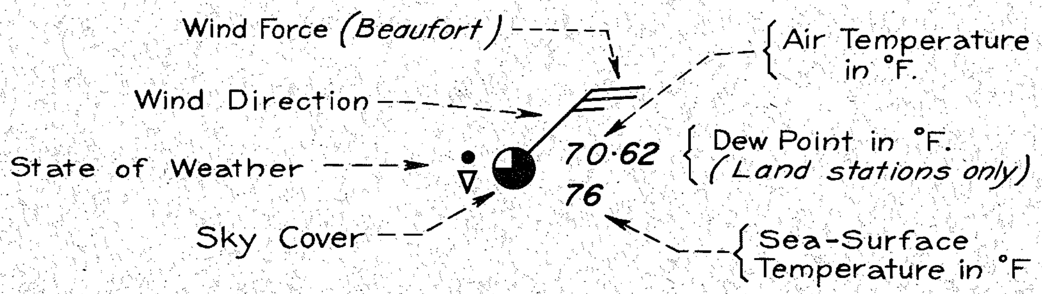
63. <u>Storm of November 1-7, 1939</u>. The synoptic chart for the morning of November 1 showed the characteristic outbreak of polar air east of the Mississippi River, with the continental High extending southward into the Gulf. The cold front preceding it extended from a position east of Cape Cod southwestward to Bluefields, Nicaragua and then westward into the Pacific. In the vicinity of eastern Cuba the

front had been dissolved by a tropical disturbance. The edge of the doldrums or intertropical front lay immediately north of the Panama Isthmus extending as a flat but sinuous curve eastward from Costa Rica to the Island of Trinidad. Figure 26, the 7:30 p.m. weather map of November 1, showed the frontal pattern farther advanced. During the afternoon the polar front had merged with a portion of the intertropical front and by evening the combined or occluded system had passed beyond the stations on the North Coast of Panama. Under the influence of the strong northwest winds and the convergence which resulted, vertical motions were induced which were sufficient to release the potential instability of the air masses involved. For a period of about 36 hours moderately heavy rains occurred over the basin but analyses of the automatic rainfall records showed the precipitation to be generally of an intensity which could be ascribed to orographic origin, interspersed with convective outbursts lasting no more than a few hours.

64. By 7:30 a.m. of November 2 (Figure 27), the combined polar-intertropical front had passed the Isthmus. The tropical cyclone had seemingly begun to fill but the introduction of new cold air into the system rejuvenated it so that by 7:30 a.m. of November 3 (map not shown) there was considerable deepening. Thereafter its intensity decreased but the cyclonic circulation expanded to include the Western Caribbean and the Isthmus of Panama. The result was to produce a wave on the quasi-stationary front which brought it temporarily north of the Isthmus, as shown on the 7:30 a.m. map of November 4 (Figure 28). The almost complete absence of rain in Panama from noon of the 3rd to the early morning of the 5th coincides with this period. Within the doldrums,

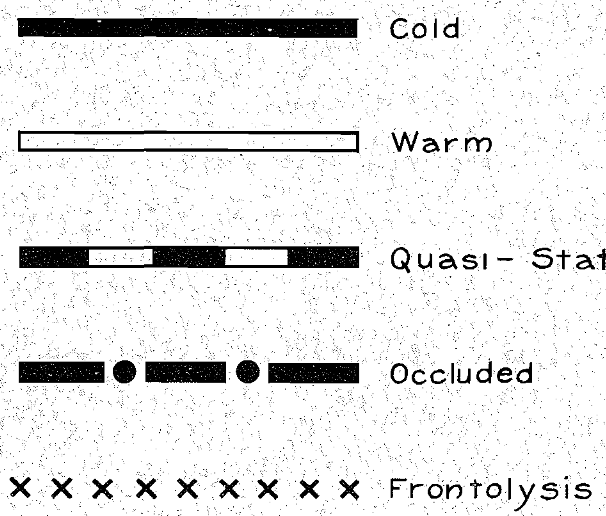
SYMBOLS USED ON SYNOPTIC CHARTS

STATION MODEL (SPECIMEN OBSERVATIONS)



International symbols used for State of Weather and Sky Cover

SURFACE FRONTS



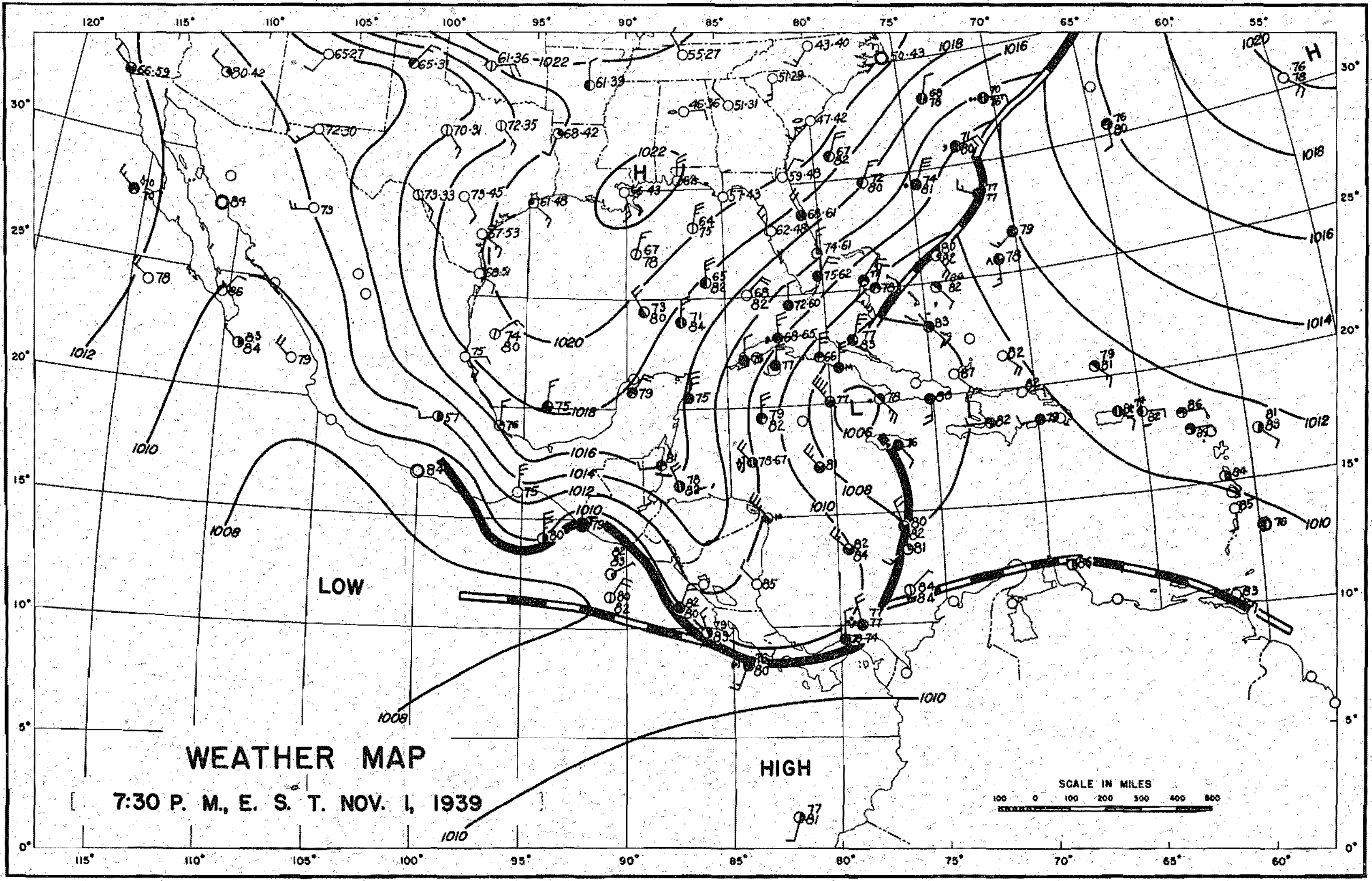
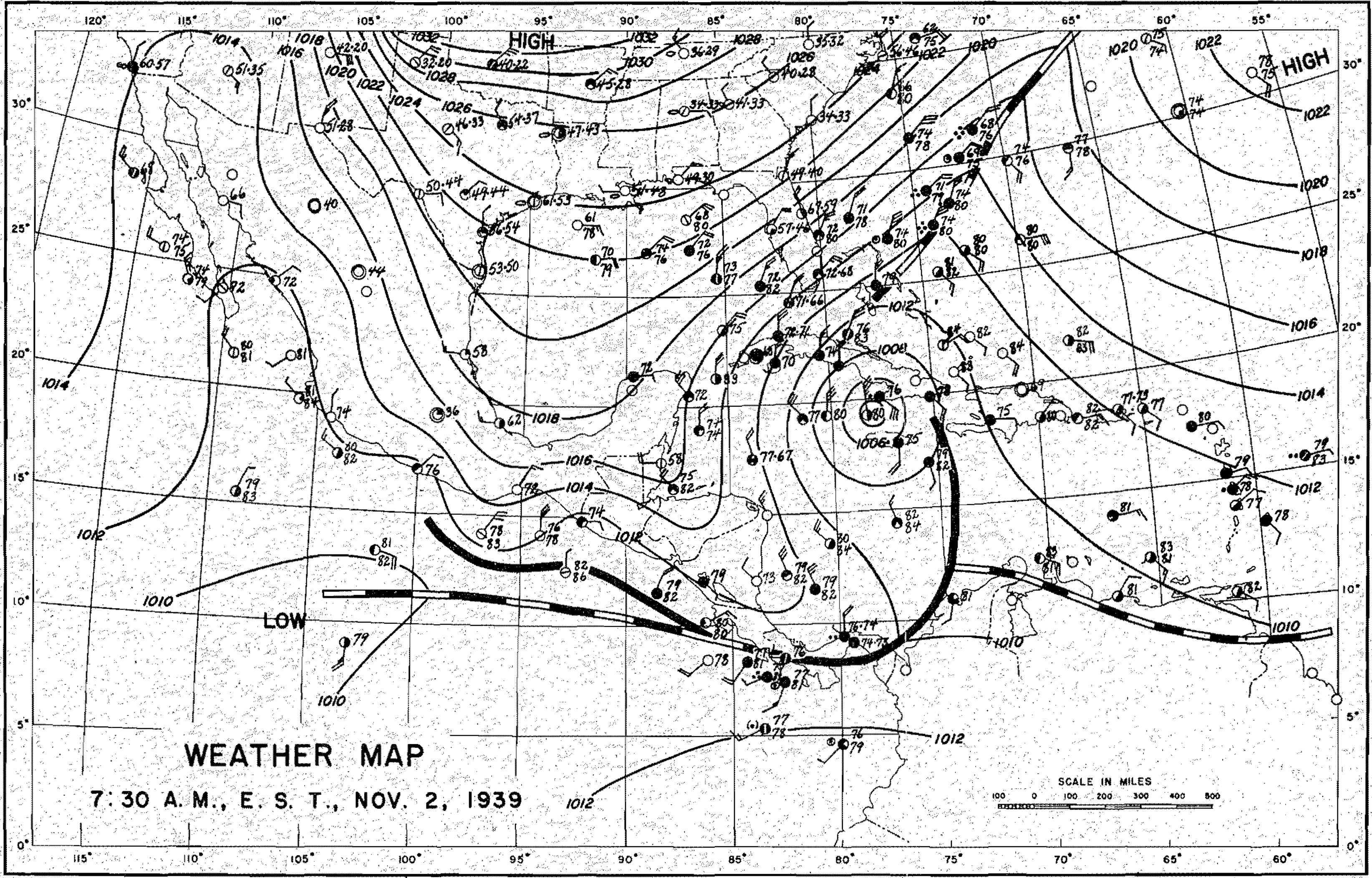

WEATHER MAP
7:30 P. M., E. S. T. NOV. 1, 1939
LOW
HIGH
H
L
H
SCALE IN MILES
100 0 100 200 300 400 500
1022
1020
1018
1016
1014
1012
1010
1008
1006
120° 115° 110° 105° 100° 95° 90° 85° 80° 75° 70° 65° 60° 55°
30° 25° 20° 15° 10° 5° 0°

Figure 26



WEATHER MAP

7:30 A.M., E.S.T., NOV. 2, 1939

Figure 27

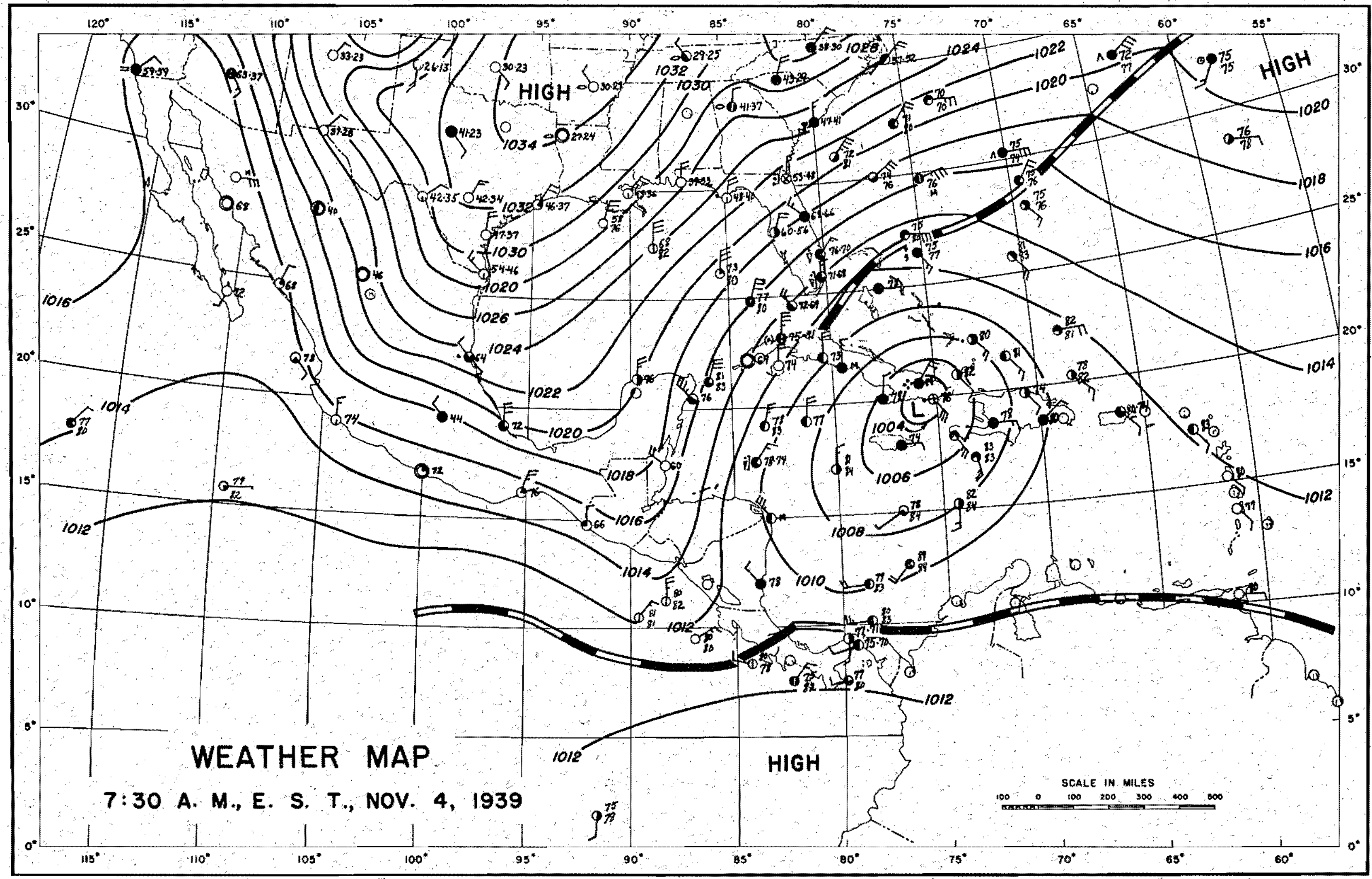

WEATHER MAP
7:30 A. M., E. S. T., NOV. 4, 1939
HIGH
HIGH
HIGH
L
1034
1032
1030
1028
1026
1024
1022
1020
1018
1016
1014
1012
1010
1008
1006
1004
SCALE IN MILES
100 0 100 200 300 400 500
120°
115°
110°
105°
100°
95°
90°
85°
80°
75°
70°
65°
60°
55°
30°
25°
20°
15°
10°
5°
0°

Figure 28

then overspreading Panama again, the surface winds were too light to produce an appreciable orographic effect while above the doldrums the dry air spreading out from the subsiding portions of the continental anticyclone extended farther south than at the surface. Northwesterly winds were observed at 10,000 feet and above at Coco Solo, while the airplane sounding of the 4th at the same station showed an inversion at about 9-10,000 feet, above which the relative humidity decreased rapidly to 11% at about 14,000 feet, which was the maximum altitude attained by the flight.

65. Rain began again during the early morning of November 5. A wave on the polar-intertropical front was again passing over the Isthmus on the 7:30 a.m. map (Figure 29). It is, however, enlightening to examine the structure of the air aloft at this time, for it had been an inhibiting influence on the 4th. Unfortunately, no data were available from Coco Solo but critical examination of the Swan Island radiosonde record reveals the probable changes. At that station, the inversion found above Coco Solo on the 4th was observed on the 1st and 2nd. By November 3 it was completely destroyed at intermediate levels and a marked increase of moisture content was noted to 20,000 feet. Study of the pilot balloon observations from all stations in the West Indies, the Gulf of Mexico and the Caribbean area showed that the cyclonic circulation of the rejuvenated tropical disturbance extended well above 10,000 feet and even at that level, as at the surface, had expanded to include the Isthmus. The circulation carried the warm moist air from the Caribbean region northward and westward around the cyclonic center and then southward across Panama. The velocities of the persistent northerly

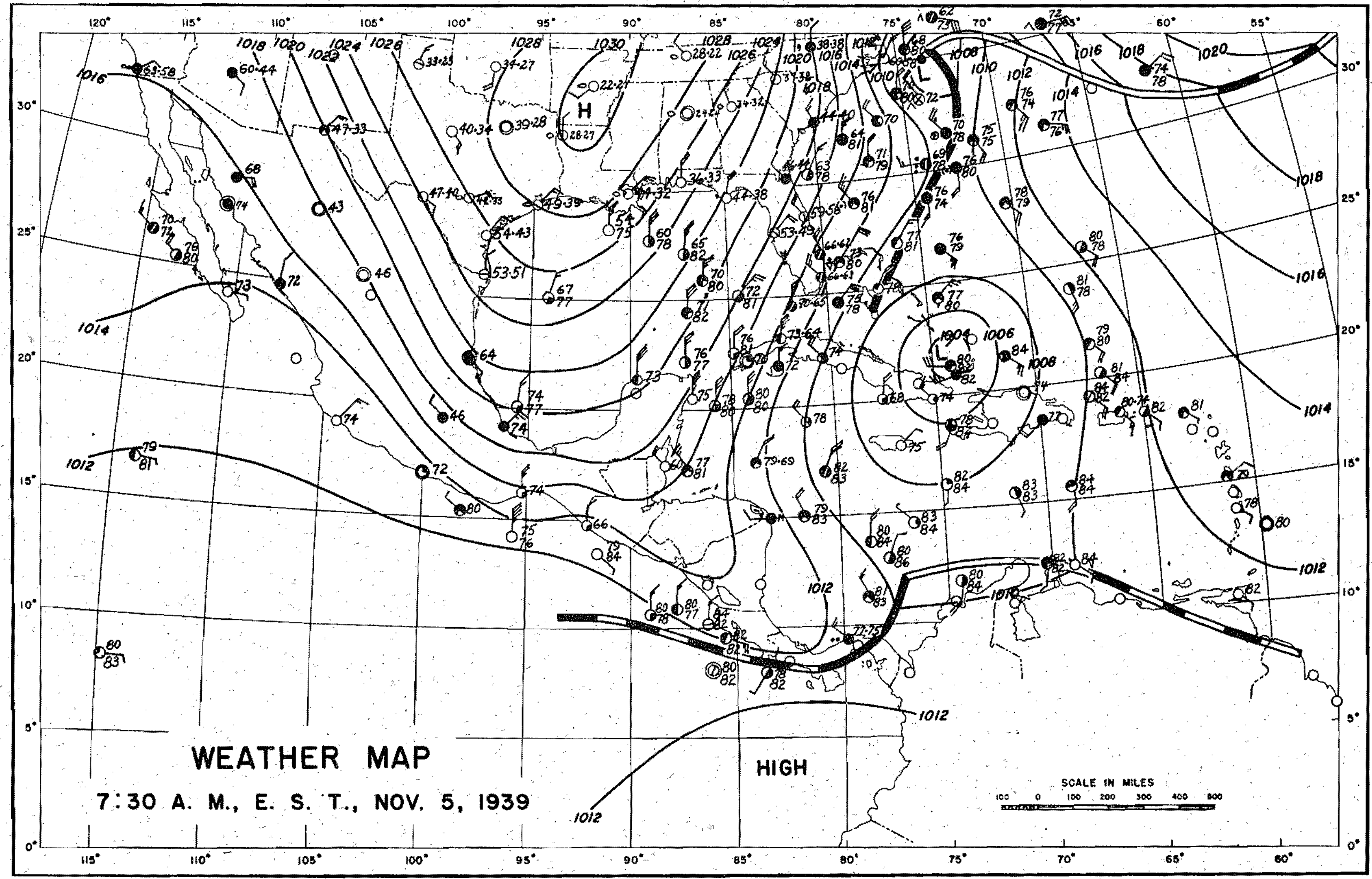

WEATHER MAP
7:30 A. M., E. S. T., NOV. 5, 1939
HIGH
H
L
SCALE IN MILES
100 0 100 200 300 400 500
1004
1006
1008
1010
1012
1014
1016
1018
1020
1022
1024
1026
1028
1030

Figure 29

winds in the Western Caribbean were sufficient to bring the moist air to Panama between the 3rd and the 5th. When it reached Panama, the perturbation of the front, cresting over the region, was there to provide the necessary convergent impulse. The rainfall, however, was relatively light and became intermittent during the afternoon and evening as the stable wave moved rapidly eastward.

66. Aloft the moist current from the northwest persisted and, with the passage of another wave early on the 6th, heavy rains set in again. The high intensity, convective rains were as usual short-lived but at a number of stations the rate of fall exceeded one inch per hour for an hour or two. The wave was unstable and showed signs of occluding, as indicated on the 7:30 a.m. map of November 6, Figure 30. As the occlusion process proceeded, steady light to moderate rains continued under the influence of the persistent northwesterly winds.

67. The final burst of heavy rains, exceeding any previous downpour during the entire storm period, came during the morning of November 7. The maximum six-hour, one-hour and half-hour rains all occurred within the period from 6 a.m. to noon. The 7:30 a.m. map of November 7 (Figure 31) showed the presence of a trough extending onto the Isthmus of Panama from the occluded cyclone which formed on the unstable wave previously mentioned. The basin was so situated with respect to this trough as to be in a region of marked convergence. The rate of movement of the pressure system was slow, and consequently its influence over Panama was quite pronounced for a period of about 12 hours.

68. While the wave activity was causing rains over Panama, the rejuvenated tropical disturbance moved to a position northeast of Cuba

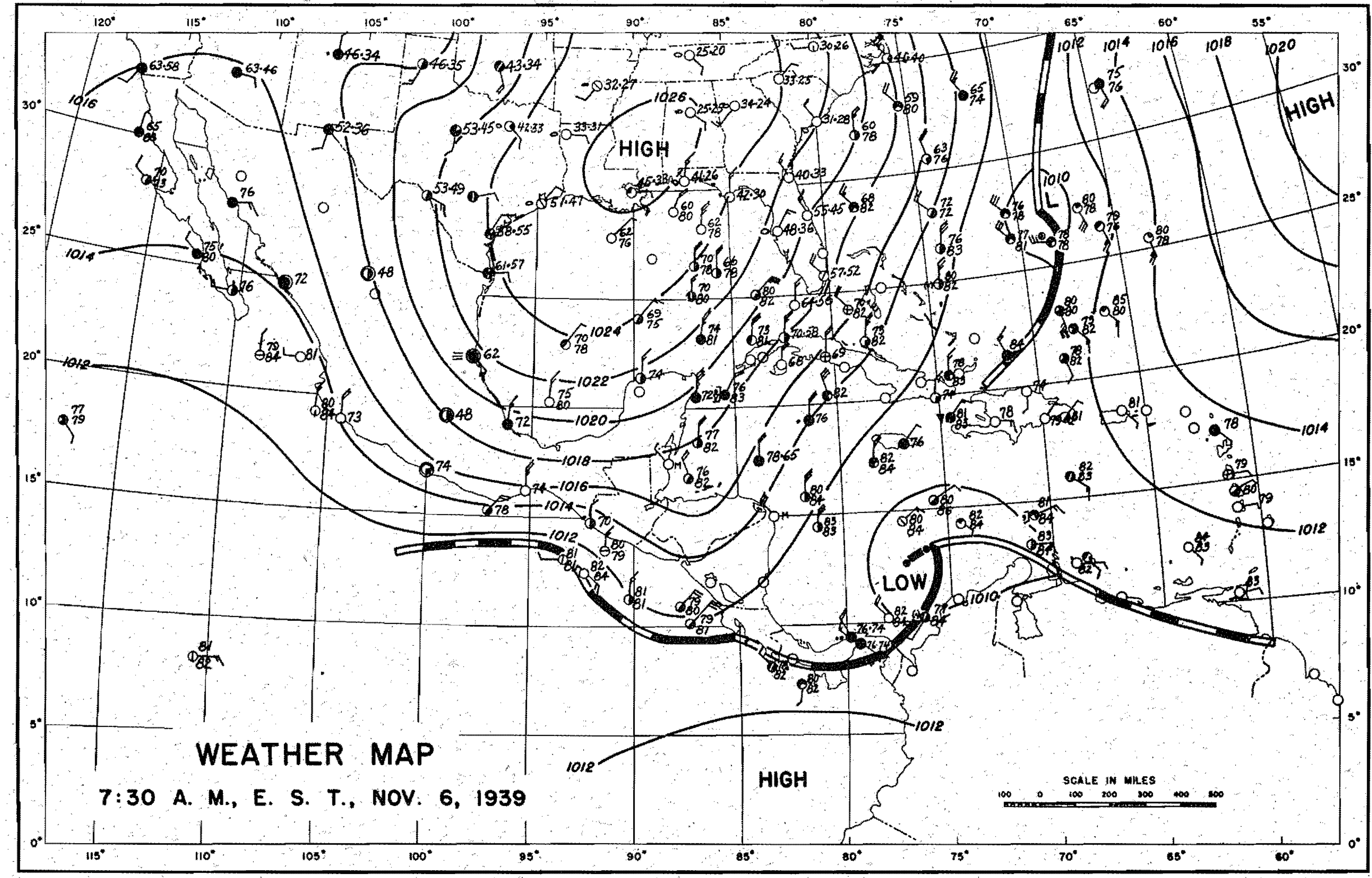

WEATHER MAP
7:30 A. M., E. S. T., NOV. 6, 1939
HIGH
HIGH
HIGH
LOW
L
1026
1024
1022
1020
1018
1016
1014
1012
1010
SCALE IN MILES
100 0 100 200 300 400 500

Figure 30

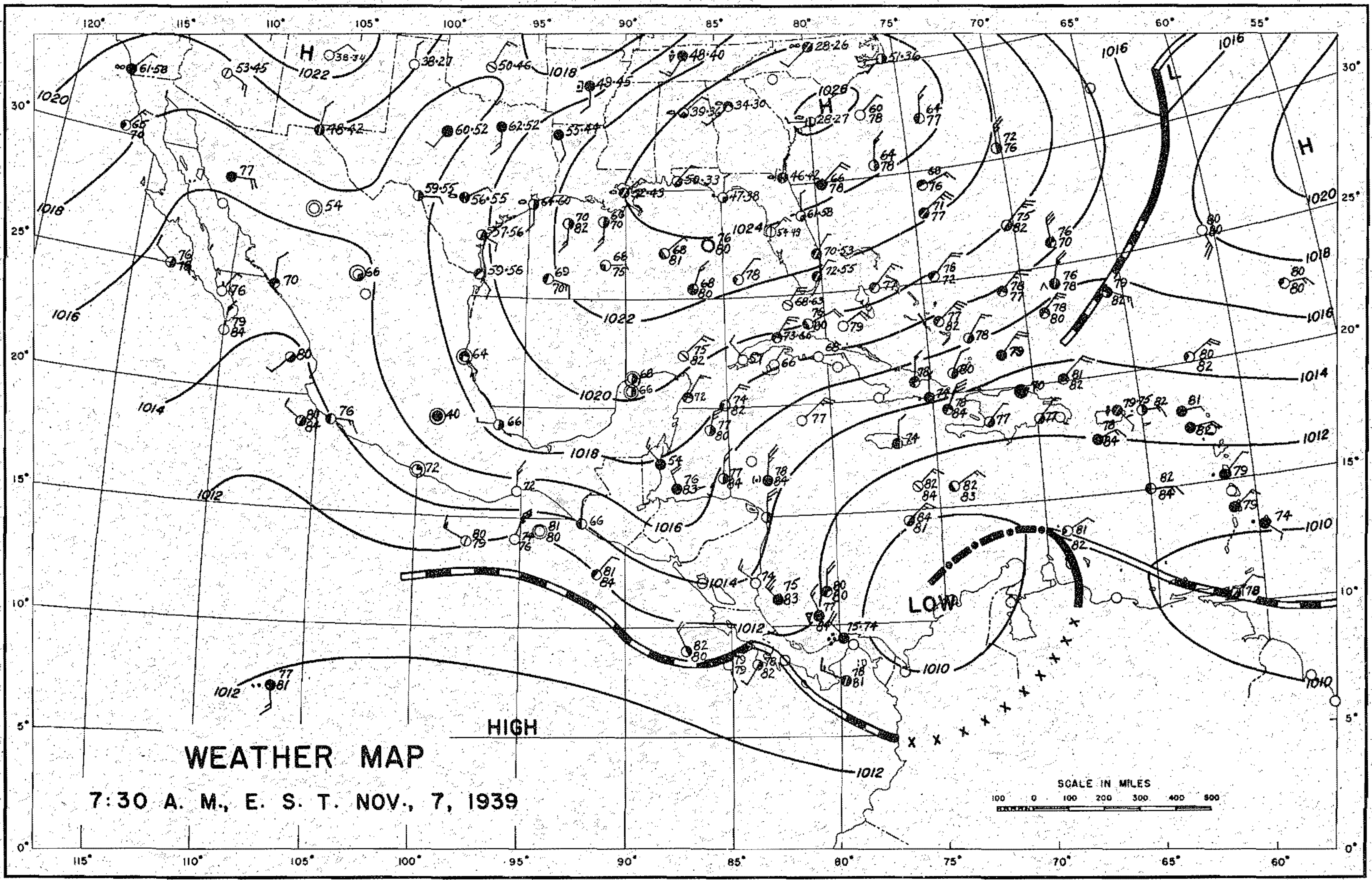

WEATHER MAP
7:30 A. M., E. S. T. NOV., 7, 1939
HIGH
LOW
H
L
1026
1024
1022
1020
1018
1016
1014
1012
1010
SCALE IN MILES
100 0 100 200 300 400 500
120°
115°
110°
105°
100°
95°
90°
85°
80°
75°
70°
65°
60°
55°
30°
25°
20°
15°
10°
5°
0°

Figure 31

by the morning of November 5 (Figure 29). The moist current being carried around it ceased flowing over the Western Caribbean and Panama as the cyclone progressed farther northward. Pressures rose in its wake and, by the 7th, anticyclonic circulation dominated the region of the Greater Antilles. Finally, as the occluded wave over the Caribbean filled, the pressure gradient in the vicinity of Panama weakened and a return to more normal pressure distribution followed, ending the major storm.

69. Storm of December 2-4, 1937. With the tropical disturbance absent from the picture, the synoptic pattern of the December 1937 storm bears a close resemblance to the November 1939 storm. On the first day of the indicated period, a cold front from a Low centered off southeastern United States extended south-southwestward into the Western Caribbean. With no tropical storm to retard it, the front pushed southward and eastward through the region ahead of the characteristic, huge anticyclone which covered all of the eastern United States and the Gulf of Mexico. During the late forenoon of December 3, the polar front passed Panama. Wind shifts accompanying the frontal passage were negligible because northerly winds already prevailed over the Isthmus, with the intertropical front a short distance south of the region. There the merging of the fronts occurred. Although observational evidence of the occurrence is rather scant, the resulting field of convergence is well-indicated. Also, the airplane sounding of that date at Coco Solo establishes the presence of the deep layer of convectively unstable air which was acted upon by the alternating wave-convection and orographic effect that normally follow the merging of the fronts south of the Canal Zone.

Rain was light until the evening of the 3rd when the first of three distinct convective outbursts began. By the evening of the next day, rains had practically ceased. The short duration of the storm can be attributed to the steady southeastward movement of the continental anticyclone which inhibited the effects of the wave action along the combined front by bringing in without cessation the subsiding anticyclonic air sooner than, for instance, in the 1939 storm. Furthermore, there was no tropical cyclone to induce an oscillation of the intertropical front north of the Isthmus during the period, nor to bring in new, deep, moist unstable air from the north.

70. Storm of November 14-19, 1935. Although the characteristic pressure pattern of the Panama storm was present in this storm -- that is, the pressure trough off the east coast of the United States followed by the expansive anticyclone moving slowly southward and eastward -- there was an important difference. Indications were that a polar front had merged with the intertropical front before the 14th, which is the first day of the storm as discussed. On the morning of that day the combined front still lay just north of the Isthmus, but farther north, from the Florida Straits to the northern tip of Yucatan, a fresh polar front was in evidence and behind it a vigorous anticyclone whose chief movement was eastward across the northeastern states and the Maritime Provinces. The movement southward was extremely slow. The result was that the quasi-stationary front already observed persisted in the vicinity of the basin until the 19th.

71. On the 15th and 16th stable waves along the front passed eastward across Panama, each accompanied by a brief period of rain.

On the 17th an unstable wave passed over the region and finally occluded off the north coast of Colombia. Like the occluding wave that ended the 1939 storm, it stagnated and produced a prolonged period of surface convergence at Panama. Over the basin the resulting heavy rain lasted for about 18 hours. Around the deepening center of the occlusion the pressure gradient increased, bringing stronger west to northwest winds over the basin and prolonging moderate rainfall, now largely orographic in origin, through the 18th and 19th. By the evening of the 19th, though, the anticyclone, whose slow progress southward had resulted in a maintenance of the quasi-stationary wave pattern over the Isthmus, was in a position to contribute the effects of its subsidence to the upper air of Panama, resulting in diminution of the rainfall.

72. Storm of November 26-29, 1932. Although resembling it closely in synoptic pattern, this storm exceeded that of December 1937 both in duration and intensity of rainfall. These differences can be attributed to the slower rate of eastward movement of the frontal system off the east coast of the United States. Waves traveling northeastward from the Caribbean along this front were responsible for the retardation.

73. Again, as in the December 1937 storm, the merging of the polar and intertropical fronts took place south of the Isthmus of Panama. Following the passage of the polar front there was a marked increase in wind velocity at Cristobal with the result that the maximum 24-hour wind movement of all storms studied occurred between 1 p.m. of November 27 and 1 p.m. of November 28. This period coincided with the maximum 24-hour rainfall of the storm. The relatively intense orographic rain was augmented by a heavy burst of convective rain between 6 a.m. and noon of

the 28th as a wave on the frontal system moved rapidly eastward immediately south of the Isthmus.

74. Another wave passed eastward south of Panama on November 29, causing a final 12-hour period of relatively intense rainfall. Thereafter the drier air from the subsiding portion of the anticyclone, which had been moving steadily southward, apparently arrived aloft over Panama to cause cessation of rain.

75. Storm of November 6-9, 1931. The large-scale synoptic pattern of this storm is the typical one. The significant rainfall of the storm began after the merger of the polar and intertropical fronts which occurred the night of November 6-7. After the 7:30 a.m. map of November 7, the combined front passed the Isthmus. Marked cyclogenesis occurred at the Dreimasseneck which had formed northeast of the Canal Zone with the conjunction of the fronts. The resulting Low center remained nearly stationary as it deepened, its minor fluctuations in position causing winds at Cristobal to vary between southwest and northwest. On November 8 the pressure gradient in the southwest quadrant of the cyclone reached a maximum, accompanied by the greatest one-hour wind movement (33 miles) from the northwest at Cristobal of any of the storms studied. It is significant that the maximum one-hour average depth over the basin occurred during the same six-hour period.

76. Storm of October 21-24, 1923. Of the nine storms chosen for detailed study, this was the only one to occur in October. This storm is also of special interest because it produced a maximum 24-hour point rainfall in the basin (12.25 inches at Gatun from about

7 p.m. October 23 to 7 p.m. October 24)(1) and a three-day average depth over the basin (October 22-24, inclusive) that determined a value on the enveloping duration-depth curve of Figure 17.

77. During October the edge of the doldrums is generally well north of the Isthmus and outbreaks of polar air from the continent have not yet reached their late-autumn and winter intensities. The displacement south of the Isthmus of a combined polar-intertropical front is thus unlikely. In the storm under consideration, the intertropical front hovered in the vicinity of the basin, generally north of it, and underwent only minor displacements southward as a result of weak and occasional intrusions of modified polar air. The usual huge anticyclone dominated the continent, centered somewhat farther north than in other Panama storms and, as in November 1935, tended to expand eastward along the Canadian border rather than southward. Its southern extension, however, was in the form of an attenuated anticyclonic wedge over Central America, from which the smaller modified polar offshoots broke off occasionally to provide temporary intensifications of perturbations on the intertropical front.

78. The first merger of the fronts occurred on the 21st, resulting in a movement of the frontal system beyond the Isthmus. The rainfall accompanying its passage was relatively light and the combined front remained in its new position but a short time. Dominating the scene to an unusual extent was a cyclonic disturbance centered between Swan Island and Jamaica. Like the disturbance -- farther eastward then --

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(1) Exceeded on October 12-13, 1941 at Candelaria (12.38 inches).

that affected the storm of November 1939, it seems to have been a weak tropical cyclone in which, as in 1939, the pressure fell accompanied by an expansion of the cyclonic circulation westward and southwestward following the introduction into the system of cooler air from the continent. From October 22 to October 24 the cyclonic system continued to dominate, inducing at the surface small outbreaks of modified polar air toward Panama from the anticyclonic wedge but all the while maintaining aloft, above the polar air, a northerly current of tropical air coming around the Low center. The frontal zone, now most apparent as a trough line between northwesterly and southwesterly winds, remained over Panama throughout the three days. At Cristobal-Colon, for example, the wind varied between southwest and northwest as the trough line swayed. Above the trough, though, there was no intrusion of anticyclonic subsiding air. The result was that the only appreciable cessation of rain occurred between 6 a.m. and noon of the 23rd. At all other times the deep tropical air flowing around the cyclone maintained the convective potentialities of the air above the basin. Late on October 24, the anticyclonic circulation replaced the cyclonic at Panama both at the surface and aloft. The rains rapidly diminished but the establishment of the inversion aloft could only be surmised because no upper-air data were available.

79. Storm of December 25-30, 1909. Synoptic data for this and earlier storms are scant but the main features of the Panama storm type are nevertheless discernible. The synoptic pattern immediately preceding December 25, 1909 resembled more closely the last day of other storms, but what followed was the usual course of events. At the

beginning of the storm a cold front moving rapidly eastward passed east of Bermuda before it reached the region of Panama and the intertropical front. By the time the merger of the fronts occurred, a new cold front with its attendant cold anticyclone was moving southward. It was when the latter front merged with the already existing one on the morning of December 26 that the major storm began. After a lull on the 27th, the outbursts of rainfall, occurring about 12 hours apart during the next three days, were clearly the result of wave action along the front, although the synoptic data were insufficient to establish the exact position of the perturbations.

80. Storm of November 15-19, 1909. Characterized by a sequence of events very similar to December 25-30, 1909, this storm differs from the latter mainly in the fact that some of the storm rainfall can be attributed to the first merger of fronts. When the second anticyclone pushed southward on November 18 to reinforce the first polar outbreak, the pressure gradient was also increased and the resulting increase in wind speed brought about the heavier rainfall of the 18th and 19th. By the evening of the 19th anticyclonic circulation dominated the Canal region and appreciable rains ended.

81. Storm of December 2-3, 1906. The sequence during December 2-3, 1906 displayed the double cold-front structure of the 1909 storms but differed in one important respect. Moving with extreme rapidity, the second cold front was followed quickly by the continental anticyclone bringing with it the characteristic subsiding air aloft. The result was that only one wave could form on the combined polar-intertropical front and almost all of the storm rainfall was thus confined to about 12 hours.

CHAPTER IV

THE MAXIMUM POSSIBLE RAINFALL

82. The Basic Method. The Hydrometeorological Section has developed certain techniques for the computation of maximum possible precipitation which have been adapted to individual basins, notably the Ohio tributaries above Pittsburgh(1) and the Sacramento Basin(2). Basic to the methods is the major premise that the volume of precipitation over an area in a given time is not greater than the product of the total number of unit columns of moisture-laden air entering the area, and the amount of moisture which can be precipitated out of each column. Assuming that all of the air crossing a given line normal to the direction of inflow will move across the area, the average depth of precipitation $\bar{R}$ can be expressed by $\bar{R} \leq \frac{xvW_E t}{A}$ where x is the length of the line normal to the inflow direction, v the velocity of inflow, W_E the effective precipitable water, t time and A area.

83. It is obvious that the purely geometric portion of the equation, x/A, which may be called the basin constant, has considerable

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(1) Hydrometeorological Report No. 2: "Maximum Possible Precipitation, Ohio River above Pittsburgh," June 1941.

(2) Hydrometeorological Report No. 3: "Maximum Possible Precipitation over the Sacramento Basin of California," May 1942.

importance. Its magnitude varies with the direction of inflow and is largest when x, the inflow border, is longest. However, the longest axis of the basin cannot be chosen as x unless it happens to be normal to the direction of the most favorable wind and moisture source. Consideration must also be given to the basin length parallel to the direction of inflow, for that must be great enough to allow sufficient time and space for the complete precipitation process to occur. Although there remains some doubt as to the minimum value of such a length, the dimensions of the Pittsburgh and Sacramento Basins far exceeded any conceivable minimum.

84. The maximum wind values and their durations can be determined either theoretically or statistically, or both. They must be consistent with the direction of inflow that has been climatologically and synoptically predetermined as most critical. And, finally, they must be representative of both the width and depth of the inflow layer assumed for the maximum storm.

85. The value W_E, the effective precipitable water, is the maximum difference in the moisture content of the air column before and after the rain-producing process. The process of maximum efficiency due to convergence is schematically illustrated in Figure 32. In a saturated air mass with a pseudo-adiabatic lapse rate both the initial moisture content and the height of convection can be determined from the surface dew point. The latter value -- which can be reduced for comparative purposes to a pressure of 1000 mb -- thus becomes the measure of W_E. Since the assumption of saturation and a pseudo-adiabatic lapse rate is reasonable in the maximum storm, it becomes necessary to establish the

EFFECT OF MOISTURE CHARGE ON THE STRUCTURE OF A CONVECTIVE CELL

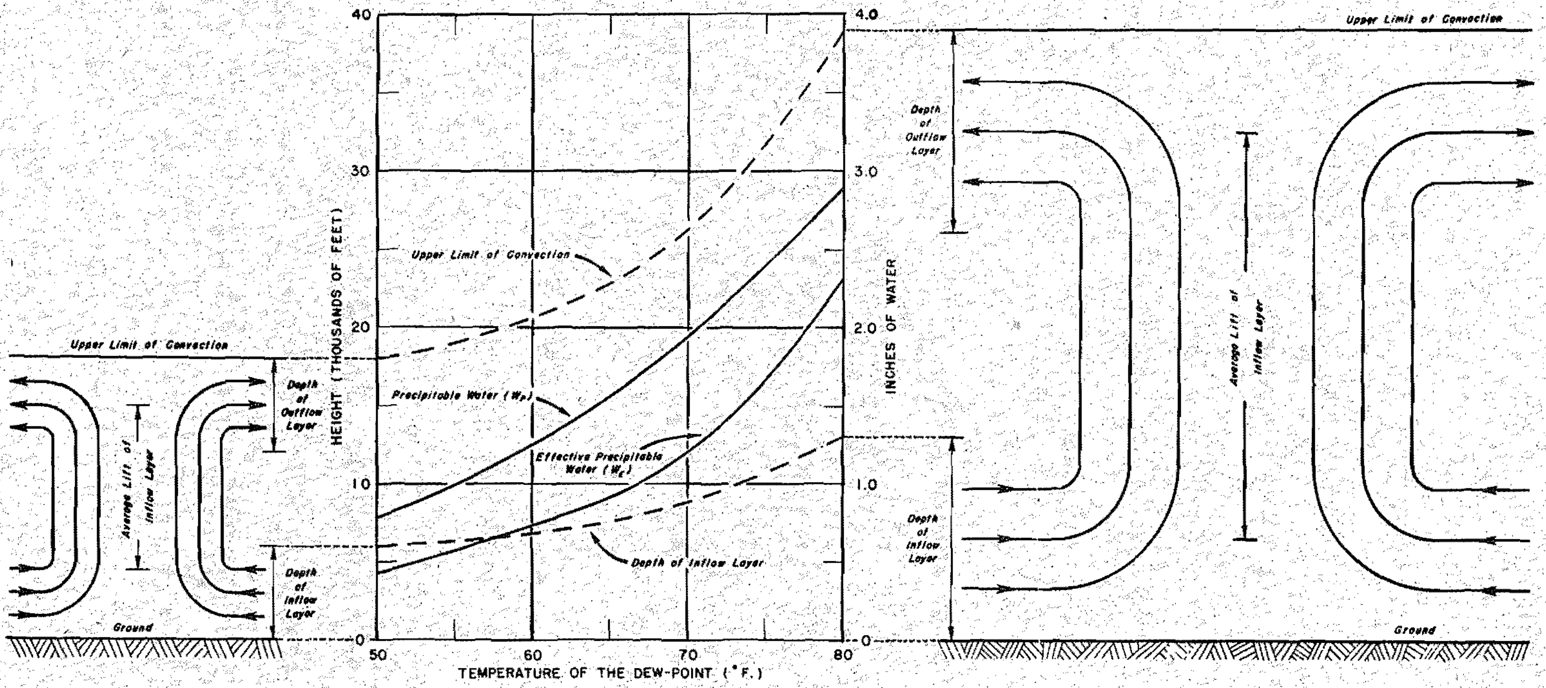

Figure 32

maximum possible dew point and its duration, appropriate to the season and the region. With sufficient length of record available, this can be done by statistical investigation of the regional values and then checked against the ultimate values at the source of moisture, which is the ocean(1). Figure 32 also illustrates the variation in W_p (the total moisture content), W_E and convective height with dew point. Figure 33 is a working chart for the computation of W_p in a saturated column with pseudo-adiabatic lapse rate and can also be used to compute the difference in W_p after the column has undergone a particular lift.

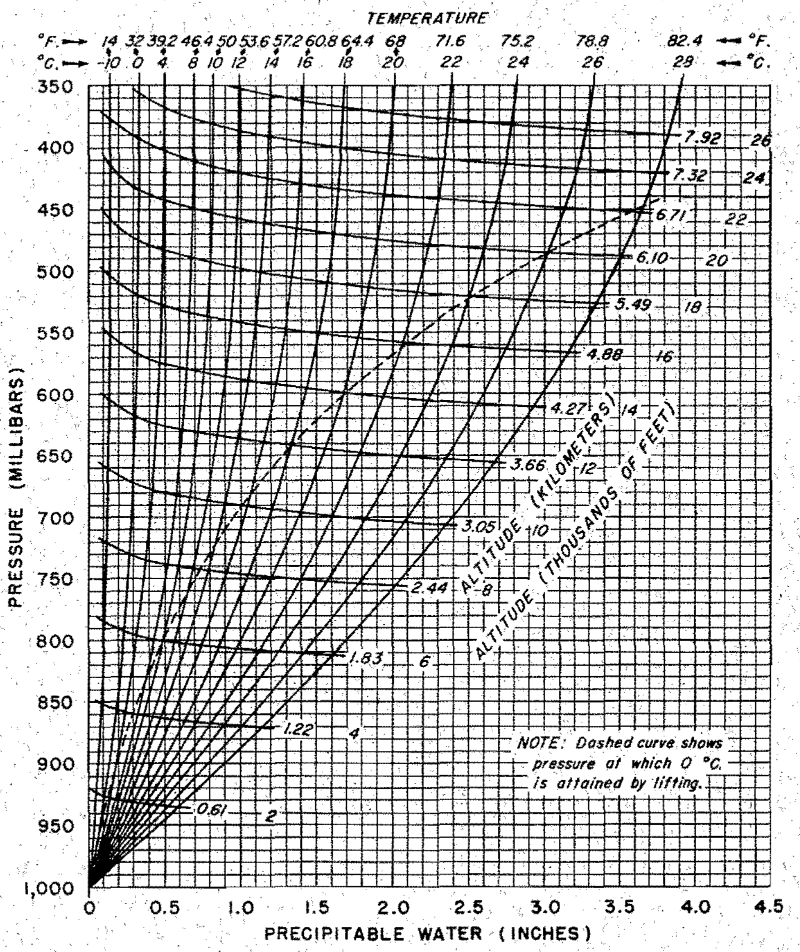

Figure 33

Depths of precipitable water in a column of air of given height above 1000 millibars assuming saturation with a pseudo-adiabatic lapse rate for the indicated surface temperatures

(1) Hydrometeorological Report No. 1: "Maximum Possible Precipitation over the Ompompanoosuc Basin above Union Village, Vermont," March 1940.

86. The time t to be used in the equation is determined from a hydrologic study of the drainage characteristics of the basin. Duration-intensity characteristics of the maximum values of wind and moisture through the chosen time period may make it necessary to rewrite the equation in differential form, with the result obtainable only after integration between the maximum possible values over the designated period. With the equation in final form, for the computation of the maximum possible rainfall the inequality sign may be dropped.

87. The Problem at Panama. It became apparent, after preliminary reconnaissance and trial efforts in the early part of the study, that the solution of the problem of the maximum possible rainfall over the Panama Canal Basin required still further adaptation of the Hydrometeorological Section's basic technique. Three factors were of paramount importance in influencing the modifications of the method. They were the size of the basin, the meteorological limitations on intensity of circulation, and the paucity or inaccessibility of available data.

88. While the areas of the Sacramento and Pittsburgh Basins are 25,200 and 19,117 square miles, respectively, the Panama Canal Basin is only 1322 square miles. The axes finally chosen as normal to the optimum moisture inflow were approximately 215, 100 and 60 miles, respectively, which made the average basin length parallel to inflow of the order of 117, 200, and 22 miles, respectively. In the Panama Canal Basin study, then, consideration had to be given to the possibility that the full convective process could not be expected, on the average, to occur within 22 miles or during the time that it would take to cover that distance.

89. The chapters on the climatology of the region and the meteorology of the Panama major storms have already demonstrated the comparative weakness of both the general and secondary circulation over the region, when contrasted with the known cyclonic intensities farther north and particularly in the United States. The dynamic effects of the great temperature contrasts observed or possible over, for instance, Texas cannot be observed over the Panama region simply because the temperature contrasts cannot be achieved. While temperatures equally high can be attained in both regions, the extreme low temperature observed at three kilometers, for instance, over Swan Island is 3.9 C and over Coco Solo 5.6 C as compared with -14.6 C over San Antonio. The driving mechanism, then, which could maintain a large-scale and prolonged convective action of maximum efficiency could not be assumed in the solution of the Panama problem.

90. The inadequacy of data has already been discussed in the chapter on the climatology. The absence of long, continuous records of upper-air winds, temperatures or pressures at enough stations to encompass the total range of values over large enough a region made it impossible either to calculate with assurance the geostrophic wind aloft for example, in the manner of the Pittsburgh Report, or to secure the index stations that proved so successful in the Sacramento Report.

91. The storms studied synoptically revealed a characteristic large-scale circulation pattern over most of the United States and the adjacent waters to the south and east, but in the vicinity of Panama conjecture had to play a large part in the analysis. A predominating direction of surface wind over the Isthmus during storm periods was

revealed -- but it did not completely characterize all the great storms nor all the heavy rainfalls. Aloft the flow pattern during the storm period could be one of two or even three kinds. Most secure was the maximum possible value of the moisture content of the air. A maximum dew point of 79 F was determined by the temperatures of the adjoining sea-surfaces. That fixed the height of the ideal convective cell at 39,000 feet or 12 kilometers (Figure 32) and furthermore fixed the maximum W_E which could enter the basin. In addition, although the basin's topography was not as effective in compelling complete convection as the Sacramento's, its definite importance as a factor was established by the conformity of the areal distribution of the total-storm rainfall values to the pattern of the mean extended isohyets for the season of the major storms.

92. Any solution of the Panama problem had to be consistent with the facts and limitations outlined above. It is thought worthwhile to describe briefly the methods of computation tried and discarded, as well as the method finally adopted. They are of both theoretical and practical interest, and are not necessarily invalidated by their lack of success in the Canal Zone solution.

93. The Convergence Method. The monthly mean convergence values discussed in Chapter II showed a fair qualitative correlation with the mean monthly rainfall (Figure 22). Convergence charts synoptic with the surface maps of the individual storms showed a similar correlation. In general, the highest values were associated with periods of heavy rainfall, although the measurement was of an instantaneous value at 12-hour intervals, and it was unreasonable to assume that such a value could be

representative of more than one or two hours during a process of probably continuously changing intensity.

94. It was thought that if convergence charts for the storm periods were drawn for all of the ocean area adjacent to the Isthmus, it would be possible to find extreme values of convergence that could be transposed to the basin. However, the high convergence values were usually concentrated over the vicinity of the basin, no significantly higher values occurring far from the basin at any time. Still another insurmountable objection was that both over Panama and elsewhere there are no data on the variation of the intensity of convergence through time.

95. The Wind-Difference Method. In most of the storms studied wind data were available from Cristobal-Colon on the northwest side of the Isthmus and from Balboa Heights on the southeast side. When the synoptic convergence charts were examined it was noted that high values of convergence were often characterized by north to northwest winds at both stations, with a higher velocity at Colon than at Balboa. Particularly striking was the recurrence of a north or northwest wind of Beaufort force four or five at Colon and a wind of similar direction but of only force three or less at Balboa. In general, such a down-wind decrease in wind speed rather than radial inflow was the type of convergence observed over Panama as well as over the Western Caribbean.

96. Hourly wind directions and velocities at the two stations were available for all of the major storms except December 1906. Three assumptions were prerequisite to the utilization of these data as measures of convergence:

a. The surface winds at Colon and Balboa were representative of the winds aloft.

b. The surface winds at Colon and Balboa were representative of inflow and outflow velocities, respectively.

c. The inflow or outflow from the northeast and southwest ends of the basin was negligible.

The assumptions were not meteorologically unreasonable and, at any rate, necessary to the utilization of the available wind data. It was possible to examine the relations within the storms themselves to discover the validity of the assumption and, perhaps, a coefficient which could be applied to correct for non-representativeness. When such a coefficient was found and its variation within the selected storms determined, it was possible to reproduce the actual rainfall depth by calculation. But to exceed the usual graphical envelopment of actual storm depths, as shown in Figure 17 of Chapter I, it was necessary to have a maximum possible wind-difference intensity-duration curve. No such data were available.

97. The Inflow-Wind Method. There still remained one other type of computation using wind flow. This was the inflow-wind method, essentially as used in the Pittsburgh Report. Basically, the method assumes the wind at its maximum on the inflow side of the basin and simultaneous maximum efficiency of the convective system for precipitating the moisture from the inflowing air. The record at only one station was required for the wind intensity-duration in this case, and such a record was fortunately available at Cristobal-Colon.

98. The optimum conditions for the production of the maximum rainfall over the Panama Canal Basin can now be restated as follows:

a. Flow from the northwest across the long side of the basin.

b. Maximum speed of flow of air into the basin at all levels.

c. Presence of the maximum amount of effective precipitable water in the inflowing air.

d. Complete delivery of precipitated water into the basin, i.e., no loss from premature precipitation on the windward side and no loss due to carry-over on the leeward side.

While it cannot be implied that a combination of circumstances a, b and c always produces the maximum rainfall, it is however true that the maximum rain must occur during such a combination.

99. The Basin Constant. Assumption of flow from the northwest is consistent with the most characteristic synoptic pattern of the major storms studied. The sea-surface temperatures (which determine the maximum possible dew point) are also higher on the northwest side of the Isthmus. The basin axis normal to inflow from the northwest is the longest. The basin constant thus becomes the maximum possible:

$$\frac{X}{A} = \frac{60}{1322} = \frac{1}{22} \quad \frac{mi}{sq\,mi} = mi^{-1}$$

This means that the basin length along flow is 22 mi.

100. The Maximum Wind. The more rapidly the wind blows through the convective cell, the more rapidly does rain fall from it. In Table 4 are listed the average rates of precipitation for the whole basin for various inflow-wind velocities and a unit W_E of 1.00 inch, using the maximum basin constant previously defined.

101. The maximum intensity-duration curve of wind speed was based on the following Cristobal-Colon records:

a. The maximum 5-minute surface velocity of 48 miles per hour on November 25, 1927.

b. The maximum 24-hour wind movement of 22.5 miles per hour during any storm period (November 27-28, 1932).

TABLE 4

PRECIPITATION AMOUNTS DUE TO CONVECTIVE ACTIVITY

v	R_1	R_{12}	R_{24}
.5	.02	.28	.56
1	.05	.56	1.1
2	.09	1.1	2.2
3	.14	1.7	3.4
4	.19	2.2	4.5
5	.23	2.8	5.6
6	.28	3.4	6.7
7	.33	4.0	7.8
8	.37	4.5	9.0
9	.42	5.0	10.1
10	.47	5.6	11.2
15	.70	8.4	16.8
20	.93	11.2	22.4
25	1.16	14.0	28.0
30	1.40	16.8	33.6
35	1.63	19.6	39.2
40	1.86	22.4	44.8
45	2.10	25.2	50.4
50	2.33	28.0	56.0

(v in miles per hour; R in inches, numeral subscripts refer to duration in hours; $W_E = 1.00$ inch.)

c. The maximum monthly wind movement of 15.1 miles per hour in December 1918.

The values a and b were rounded off to 50 and 23, respectively, before straight-line interpolation on log-log paper. For one hour, twelve hours and six days the maximum average wind thus becomes 35, 25 and 18 miles per hour, respectively. In the actual storms studied the maximum one-hour wind movement was 33 miles on November 8, 1931, and the maximum six-day wind movement 12.7 miles per hour during the period November 14-19, 1935.

102. It is still necessary to prove that the maximum surface wind is representative of maximum possible flow aloft, since to obtain the maximum transport of air over the basin the flow at all levels must be considered. The convective nature of the heaviest rainfall over Panama implies lesser wind velocities aloft and also a variation of wind direction with height. The available upper-air data during the storm period corroborate both types of variation. In Table 5 the maximum observed winds above Coco Solo are listed for all standard levels and all months from 1920 to 1941, inclusive. The average maximum wind speed up to four kilometers is 36.5, 36.3 and 30.9 for October, November and December, respectively. Since very few of these winds blew from the northwest, the transport of air over the basin was much less than would be obtained in the maximum case. It can also be seen that the maximum average winds aloft do not exceed the maximum surface wind used and, furthermore, that during the rainy season the maximum surface wind used is exceeded only once at any level. For all these reasons, the maximum surface wind was accepted as representative of the maximum possible transport of the

TABLE 5

MAXIMUM OBSERVED WINDS ALOFT AT COCO SOLO
(Elevations in meters above sea level, velocities in m.p.h.)

Elev.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average
250	NNE 42.5 NE 42.5	NNE 42.5	NNE 54.8	N 42.5	N 38.0	NNE 47.0	N 31.3	NNE 26.8	SSE 29.1	SSE 35.8	NNE 40.3	NNE 44.7	39.6
500	N 47.0	NNE 44.7	NNE 47.0	N 42.5	SSE 35.6	NNE 42.5	SSE 33.6	ENE 29.3	NE 26.8	S 40.5	S 44.1	NE 38.0	39.2
750	NNE 42.5	NNE 40.3	NNE 51.4	NNE 44.7	S 34.0	SSE 31.3	NE 29.3	NNW 29.1	SSE 24.6 NE 24.6	S 41.2	S 45.4	NNE 38.0	37.6
1000	NE 40.0	NNE 40.3	NNE 37.6	NNE 38.0	S 35.1	NNE 24.6	S 26.8	NE 26.8 SE 26.8	NE 26.2	SSW 46.5	S 42.5	ENE 47.0	35.9
1500	NNE 49.2	NNE 40.3	NNE 33.6	NNE 29.1	SW 28.5	ENE 22.6	E 23.3	E 29.1	NE 24.8	SSW 29.1	WSW 36.0	NE 40.3	32.1
2000	NE 37.8	NNE 36.5	NNE 30.0	NNE 33.6	SW 27.7	ENE 29.1	ESE 29.1	E 26.8	WSW 25.7	SW 28.8	WSW 32.1	NE 42.5	31.6
2500	NNE 33.6	NNE 32.9	ENE 23.9	NNE 22.6	SW 31.1	E 34.0	ESE 33.6	E 31.3	WSW 28.6	WSW 32.7	SW 36.0	ENE 27.3	30.6
3000	SE 31.3 NNE 31.3	NNE 28.4	NNE 22.4	E 40.3	E 31.3	ESE 22.4 E 22.4	ESE 33.6	ENE 33.6	E 34.4	WSW 41.2	WSW 38.0	ENE 27.3	32.0
3500	ESE 37.8	ENE 25.0	NW 29.1	E 67.1	SW 33.3	ESE 29.1	ESE 38.0	ENE 38.0	ESE 32.0	SW 53.7	W 37.6	E 28.0	34.2
4000	E 36.0	ENE 30.4	ENE 23.5	NE 30.6	SW 30.4	ESE 28.0	ENE 33.6	SSW 30.6	W 30.6	W 27.1	WSW 35.3	ENE 30.4	30.5
4500	NE 40.3	ENE 23.9	ENE 27.3	NE 38.5	SW 24.6	ESE 30.2	SE 26.8	ENE 27.7	S 31.3	E 40.3	NNW 26.8	E 38.0	31.3
5000	E 29.1	NE 29.3	ENE 24.6	ENE 25.3	SW 28.8	ESE 31.3	SE 33.6	E 29.5	SSE 29.1	E 27.3	E 30.2	ESE 30.9	

(Concluded on next page)

TABLE 5 (Continued)

Elev.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average
6000	ENE 26.8	SE 22.4		WNW 15.6	ESE 15.6		SE 17.9	E 24.6	SW 24.6	SE 17.9	W 11.2	ENE 15.6	
7000	ENE 55.9	NNE 24.6		WNW 22.4	ESE 29.1					E 32.4	ENE 17.9	ENE 6.7	
8000										E 13.4	NNE 20.1		
9000											NNE 33.6		

inflowing air.

103. The Maximum Moisture. As has been pointed out in the section on the general method, the water vapor content of a saturated column of air can be calculated from the dew point at the ground, if a pseudo-adiabatic lapse rate is assumed. The highest dew point observed during any flood-producing storm over the Canal Zone was 79 F. The highest dew point obtained from three years of airplane soundings at Coco Solo was also 79 F. Considering these temperatures as well as those of the adjoining sea surface, a maximum dew point of 79 F is a safe upper limit at Panama. Using Figure 32, such a dew point indicates:

a. A convective cell approximately 12 kilometers deep.

b. An inflow layer approximately four kilometers deep.

c. An effective precipitable water W_E of 2.2 inches.

104. Before the saturated air mass can enter the basin it must pass over the inflow barrier. The lifting undergone in this passage will naturally deplete the W_E within the inflowing column. The mean height of the inflow barrier is one thousand feet and the orographic

depletion can be computed from Figure 33 as 0.3 inch. This leaves the maximum W_E for the basin, for inflow from the northwest, as 1.9 inches, the effective precipitable water in a convective process of maximum efficiency over the Panama Canal Basin.

105. Actually the maximum efficiency is seldom observed over the Isthmus. Neither the driving mechanism of an intense circulation nor the extreme topography which can maintain a large-scale and prolonged convective action at maximum efficiency is present. This results in a weakening of the process by breakdown into cellular units of more local character, separated by the counterpart of the cell in which lifting is occurring, i.e., an adjoining unit in which the necessary sinking to complete the continuity must occur. In the convective cell model of Figure 32 only the up-flow currents are illustrated. The equivalent downward currents which must occur elsewhere are obviously rain-inhibiting. They can also be rain-depleting. The precipitation formed in the rising current of the cell can fall through the sinking current and be evaporated into the descending air. Instead of being adiabatically warmed and dried (with respect to relative humidity) as occurs in the usual down-slope or foehn process, the descending air will be cooled by the evaporating rainfall and reach the surface saturated. In the case of convectively unstable air, the wet-bulb temperature in the new air at the surface will be lower than any observed in the previous surface air(1). Wet-bulb temperatures lower than could have resulted

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(1) G. N. Brancato: "The Meteorological Behavior and Characteristics of Thunderstorms," Hydrometeorological Section, U. S. Weather Bureau, April 1942.

from advection have been observed in most of the Panama major storms studied.

106. The dew point at the surface of the saturated air in the downward current thus becomes the measure of the negative W_E or the precipitable water absorbed during the reversible-convective or sinking process. The moisture absorbed by evaporation during the sinking process is numerically equal to the amount which could be released by lifting, using the new dew point as a base. Hence the difference (ΔW_E) between the W_{E_1} in the rising air and the W_{E_2} in the falling air is the precipitation resulting from the completed process. A schematic outline of a complete unit in the cellular pattern is shown in Figure 34, where T_1 and T_2 are the surface dew points which determine the W_E values of the opposing currents.

107. The greatest dew-point range in any one of the major Panama storms was 7 F, for all the storms studied the over-all range 10 F. A survey was made of the extreme values of moisture content of the air

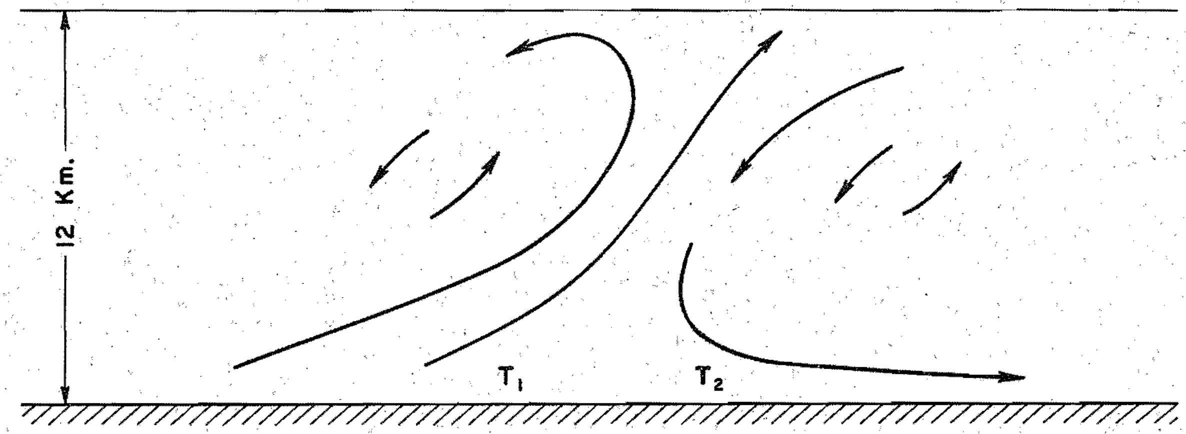
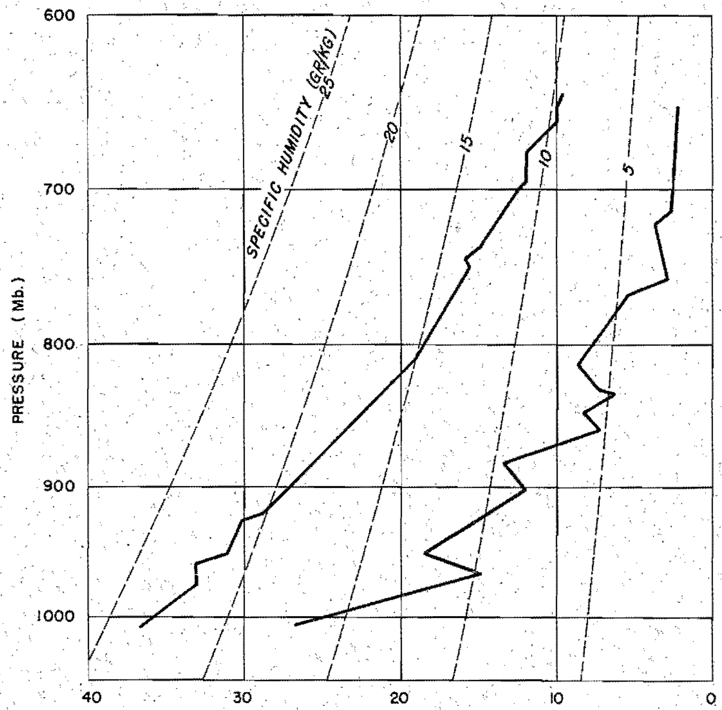


Figure 34

Schematic diagram of a çellular convective pattern over Coco Solo up to a height of four kilometers (the inflow layer) for the months of August to November, inclusive. Figure 35 indicates these extremes. The difference in water content is 0.98 inch, while the ΔW_E for a dew-point difference of 9 F between 79 and 70 F is 1.0 inch, which was therefore considered to be the maximum average W_E for a sustained convective process over the Panama Canal Basin.



NOTE
Maximum up to 650 Mb. = 2.231 inches
Minimum up to 650 Mb. = 1.256 "
Difference up to 650 Mb. = 0.98 "

Figure 35

Extremes of moisture content over Coco Solo for months of August, September, October and November, Years 1937, 1938 and 1940

108. Not more than a total duration of six to eight hours of rainfall whose intensity is such that it must be attributed to convection involving the maximum average W_E of 1.0 inch has ever been observed in any total storm period over the Panama Canal Basin. Most of the rainfall can be attributed chiefly to the orographic effect, an influence confirmed by the similarity of the storm isohyetal pattern to the mean extended precipitation pattern. The maximum possible W_E which can be attributed to the lifting of saturated air across the

Continental Divide (mean height 1,400 feet) is 0.4 inch. (See Figure 33.) This is equivalent to stating that all of the moisture originally below 1,400 feet is precipitated by the orographic process. This maximum possible value for the orographic process is based on the following assumptions:

a. The total effect of the barrier is to produce horizontal convergence down wind (see Chapter II).

b. The saturated air is potentially unstable and the excess mass of air coming in below 1,400 feet is subjected to vertical impulses that are finally damped out at very high levels.

c. Compensating outflow of mass takes place at very high levels by lateral motion of air parallel to the long axis of the basin.

d. This lateral outflow of air occurs in regions of low W_p and therefore robs the system of a negligible amount of moisture.

e. The northwest-southeast components above the barrier are equal, level for level, to those on the North Coast of the Isthmus and, therefore, inflow of moisture above 1,400 feet is approximately equal to outflow above 1,400 feet.

Hence, the extreme possibility is that all moisture flowing in below 1,400 feet is finally precipitated.

109. The observed distribution of orographic rainfall over the Isthmus is such that the percentage, in proportion to distance in the northwest-southeast direction, decreases from the Atlantic to the Pacific side. Rainfall measurements outside the basin are too sparse for any accuracy to be gained by considering the actual quantitative distribution and apportioning the theoretical rainfall accordingly. However, since the ratio of basin length to Isthmus length (along direction of inflow) is about 0.5, the orographic rain was distributed

according to that ratio, which is the same as reducing the original orographic W_E of 0.4 to 0.2 inch.

110. The Maximum Rainfall. For the final computation an intense convective period of 12 hours was assumed concurrent with the maximum 12-hour wind period. The W_E values vary so that the highest values coincide with the maximum winds. The five-minute value of W_E is 1.9 inches and the average for the 12-hour period is the 1.0 inch which was previously determined to be the maximum average value during sustained convection over the Panama Canal Basin. By the end of the maximum 24 hours, the W_E value has waned to 0.2 inch, the orographic value, which was used for the remainder of the six-day period.

111. Using the maximum-wind and W_E averages indicated, Table 6 presents the computed average depths of maximum rainfall for the total basin for the designated periods. These values, plotted on a duration-depth chart, were then enveloped by a smooth curve (Figure 36, next chapter) drawn parallel to the enveloping duration-depth curve obtained from the rainfall analysis of Chapter I. This procedure adjusts the computed values slightly upward in the longer durations. Computed and

TABLE 6

THEORETICAL MAXIMUM POSSIBLE DURATION-DEPTH
VALUES OVER PANAMA CANAL BASIN

Duration	Average v (mph)	Average W_E (inches)	Average R (inches) (Computed)	Average R (inches) (Adjusted)
5 minutes	50	1.9	0.4	0.4
1 hour	35	1.8	2.9	2.9
12 hours	25	1.0	13.6	14.0
144 hours	18	0.28	33.0	33.2

adjusted values are included in the table. The latter are the values of the maximum possible storm.

112. The validity of the computation formula is corroborated by comparison of the observed and maximum possible six-day values. The maximum observed six-day average wind intensity in any of the storms studied was about 13 miles per hour. The maximum possible wind for the same period is 18 miles per hour, a 40% increase. The maximum possible average depth of rainfall for the same duration is 33.2 inches, approximately 50% higher than the maximum observed average depth of 21.0 inches.

113. Reliability Factor. The Hydrometeorological Section does not consider it necessary to make any further upward adjustment of the maximum possible rainfall values for reliability. The individual maximum values used in the computation have been chosen to include such a factor, so that the final result contains a progressive integration of the necessary adjustments.

CHAPTER V

THE MAXIMUM POSSIBLE STORM

114. Comparative Duration-Depths. In Figure 36 the two solid lines are enveloping duration-depth curves. The lower one is a reproduction of the curve from Figure 17 of Chapter I, representing an envelopment of the maximum depths of recorded rainfall over the basin for durations from 30 minutes to six days. The values were obtained from the rainfall analysis of the nine storms, as explained in Chapter I. It is obvious that the basin might actually have experienced rainfall in excess of the amounts shown, for two reasons. Storms occurring previous to the period of adequate

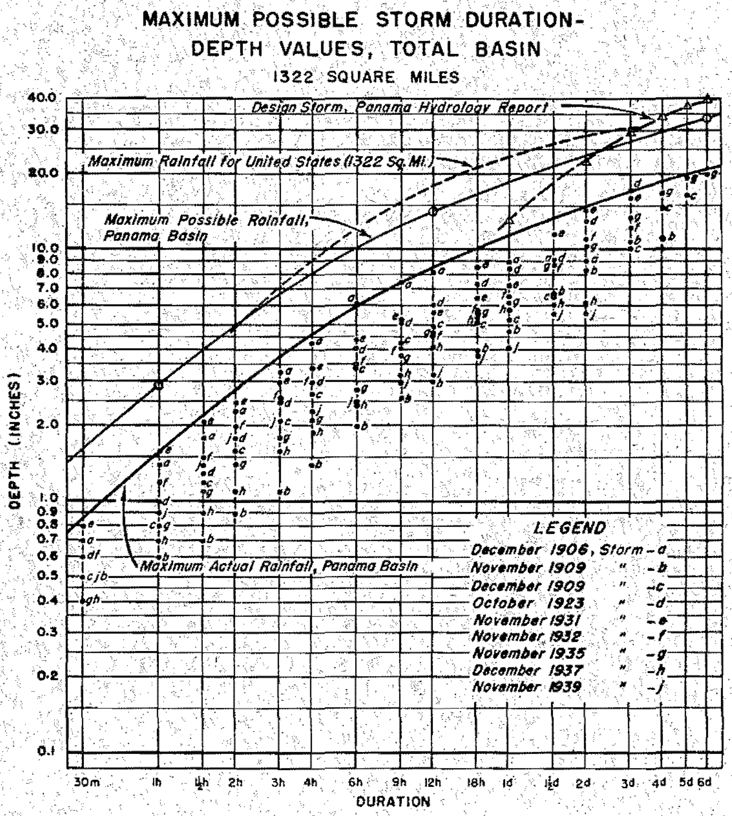


Figure 36

rainfall records might have produced greater amounts. In addition, the values obtained by analysis of the nine storms can be in error, particularly for the short durations. Were the curve enveloping these values to be used in estimating limiting rates of rainfall, it would be necessary to apply a liberal factor of safety. On the other hand the duration-depth curve of the maximum possible rainfall, also shown in Figure 36, is based on a computation involving the maximum possible values of the principal factors which combine to produce rainfall, each value already including a safe margin for possible error as well as for inadequacy in fundamental data.

115. For purposes of comparison, two other duration-depth curves are presented in the same figure. One envelops the maximum rainfall depths recorded over areas of 1322 square miles in continental United States. The values were obtained from the rainfall analysis of major United States storms and it has already been pointed out in Chapters II and IV why such values should be higher than at Panama. The other comparative curve on the chart presents the maximum rainfall amounts of the design storm for the Panama Canal Basin as developed in the Panama Hydrology Report. For durations of one and two days those values are exceeded by the Hydrometeorological Section's maximum storm, but for durations of three to six days the Panama Hydrology Report's values exceed those of the Section. Values from the Panama Hydrology Report for durations less than 24 hours are not shown on the chart because over-all figures for the entire basin for those durations are not presented in that report. However, on the basis of the maximum 24-hour isohyetal map and the intensity-duration curves for the maximum day of

the Panama Hydrology Report's design storm, it is believed that comparable values for 30 minutes and one hour are in excess of the Section's values for those periods.

116. Distribution of the Maximum Rainfall. The maximum possible rainfall as represented by the duration-depth curve can occur in a variety of sequences. The most critical duration and sequence is determined by the hydrologic characteristics of the basin. Before presenting the final results in a form that would facilitate computations of volume and peak runoff in the maximum possible flood, it is necessary to consider the meteorological plausibility of the sequence.

117. The six-day duration has already been noted in the major Panama storms, November 1935 for example. The length of the period of maximum possible convection was decided after considering the maximum durations of such intensities in all the storms. The prolongation of the predominantly orographic rain has also been observed. It is important to note that although the latter becomes predominant in the longer durations, the maximum storm never postulates any period of rain of the stable orographic type. Potential instability is realized throughout the storm, but at a diminishing rate as duration increases. The mounting intensities of the maximum storm, climaxed by a maximum 24-hour period on the last day, have also been previously observed, notably in the November 1939 storm.

118. Table 7 lists the maximum possible accumulated values of rainfall depth as taken from the duration-depth curve of Figure 36. In Table 8 these values are tabulated in terms of successive increments, first for 24-hour periods for the six days, then for 6-hour periods

TABLE 7

TABULATED VALUES FROM DURATION-DEPTH CURVE FOR MAXIMUM POSSIBLE STORM, PANAMA CANAL BASIN (1322 SQUARE MILES)

Duration (Hours)	Depth (Inches)	× 1.33 = Madden	× 25.4 = mm
1/2	1.6	2.1	53
1	2.9	3.9	99
1-1/2	4.0	5.3	135
2	5.0	6.7	170
2-1/2	5.9	7.9	208
3	6.7	8.9	226
3-1/2	7.4	9.8	248
4	8.0	10.6	269
4-1/2	8.6	11.4	290
5	9.2	12.2	310
5-1/2	9.7	12.9	329
6	10.1	13.4	340
12	14.0	18.6	452
18	16.8	22.4	568
24	18.6	24.8	630
48	23.6	31.4	796
72	26.9	35.8	906
96	29.2	38.8	985
120	31.3	41.6	1060
144	33.2	44.2	1120

TABLE 8

SUGGESTED CRITICAL ARRANGEMENT OF STORM INCREMENTS FOR TOTAL BASIN

Total Storm (24-hour Increments)	Maximum 24 Hours (6-hour Increments)	Maximum 6 Hours (1/2-hour Increments)
1.9	1.8	0.5
2.1	2.8	0.6
2.3	10.1	0.7
3.3	3.9	0.9
5.0		1.1
18.6		1.6
		1.3
		1.0
		0.8
		0.6
		0.6
		0.4

during the maximum 24-hour period of the storm, and lastly for 30-minute increments of the maximum 6-hour rainfall. The 24-hour periods are not subject to any restrictions and hence are arranged in critical hydrologic order, that is, increasing steadily from a minimum on the first day to a maximum on the sixth. This conforms to the time pattern presented in the Panama Hydrology Report.

119. The maximum 6-hour rainfall is placed in the third 6-hour interval of the final 24 hours of the maximum possible storm. This is during the period characterized by the maximum convection which lasts a total of 12 hours. In presenting the 30-minute increments of rainfall

during this period of maximum convection, it is not intended to place any restrictions on their arrangement. They may be regrouped in any manner whatsoever, subject only to the limiting conditions of the duration-depth curve.

120. In the breakdown of the total rainfall for the subsidiary areas of the basin, consideration was given to the areal distribution as shown by the duration-depth curves of actual rainfall for each of the sub-basins (Figures 14, 15 and 16). A fairly uniform ratio of values was attained for periods of one to six days. This uniformity is in agreement with the concept that orographic features control the distribution of the storm rainfall over the Panama Canal Basin and that, therefore, a fixed proportion of the total rainfall is deposited within each sub-area. If the average depth of rainfall over the total basin is considered as unity, then the coefficients to obtain average depths over Gatun, Madden and Miraflores Basins are 0.87, 1.33 and 0.53, respectively. When compared to the mean extended precipitation, these figures provide an abnormal concentration of rainfall for the Madden area. The mean extended precipitation pattern is affected by the contributions from very localized storms which, because they are not entirely dependent on orographic features, tend to produce a more uniform precipitation pattern over the basin.

121. In Figures 37 and 38 the time increments of rainfall, for the six-day period and for the maximum one-day period, are shown for the total basin and also for the subsidiary basins after applying the coefficients defined above. Within the maximum 6-hour period the 30-minute increments over the sub-basins were computed in the same manner. The

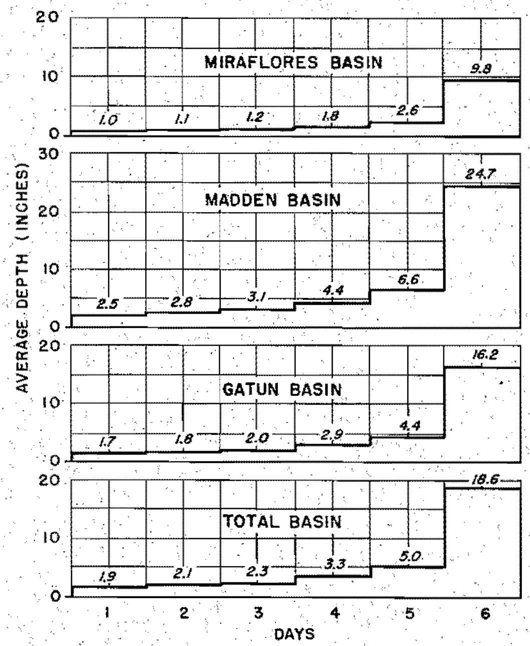


Figure 37

Critical arrangement of maximum possible storm, 24-hour increments

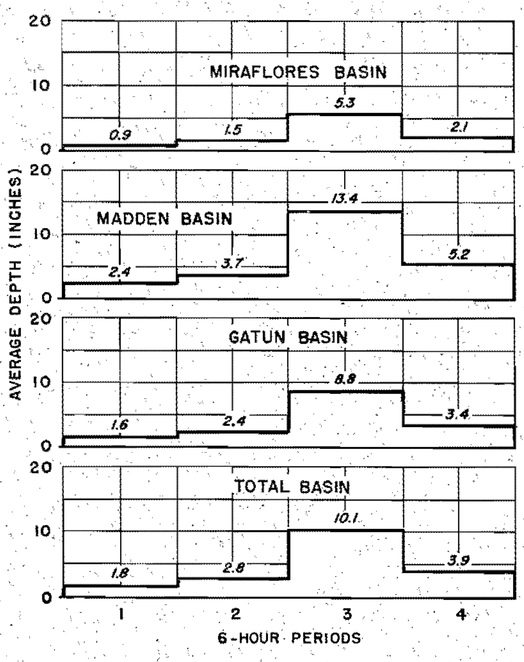


Figure 38

Critical arrangement of maximum possible storm, 6-hour increments of maximum 24-hour period

values are given in Table 9. A study of the short-period rainfall in the major storms indicates the possibility of considerable time lag in the peaks of rainfall within a 6-hour period. The November 1939 storm (see Figure 9) illustrates such a lag between the sub-basins in the 6-hour rainfall increment. It is therefore possible to stagger the peak increments between the three sub-areas. Hence, no block diagram is shown for the maximum 6-hour period, but the tabulated values may be arranged in any order governed by critical-runoff considerations.

TABLE 9

POSSIBLE ARRANGEMENT OF HALF-HOUR INCREMENTS OF RAINFALL WITHIN THE MAXIMUM 6-HOUR PERIOD OF THE MAXIMUM POSSIBLE STORM

TOTAL BASIN	GATUN BASIN (Total Basin x 0.87)	MADDEN BASIN (Total Basin x 1.33)	MIRAFLORES BASIN (Total Basin x 0.53)
0.5	0.4	0.6	0.3
0.6	0.5	0.8	0.3
0.7	0.6	0.9	0.4
0.9	0.8	1.2	0.5
1.1	1.0	1.5	0.6
1.6	1.4	2.1	0.8
1.3	1.1	1.7	0.7
1.0	0.9	1.3	0.5
0.8	0.7	1.1	0.4
0.6	0.5	0.8	0.3
0.6	0.5	0.8	0.3
0.4	0.4	0.5	0.2
SIX-HOUR TOTALS			
10.1	8.8	13.4	5.3

GLOSSARY

GLOSSARY

Adiabatic Chart. A thermodynamic diagram in which temperature is plotted against pressure (log p or $p^{0.288}$), and on which dry adiabats have been constructed. It is used for the evaluation of an aerological sounding.

Adiabatic or Dry Adiabatic Lapse Rate. The rate of change of temperature of an unsaturated air particle as it is adiabatically raised or lowered in the atmosphere -- equal to approximately 1 C per 100 meters.

Adiabatic Process. Atmospheric process in which changes in volume, pressure and temperature occur without the loss or gain of heat.

Air Mass. An extensive body of air approximating horizontal homogeneity in its source region.

Anticyclone. In the Northern Hemisphere, a clockwise circulation around relatively high pressure at the center. Counterclockwise in the Southern Hemisphere.

Cold Anticyclone. Anticyclone of chiefly thermal origin, with anticyclonic circulation confined to lower troposphere.

Cold Front. Front at which relatively cold air displaces warmer air.

Conditional Instability. Thermodynamic state which is unstable for saturated air but stable for dry or unsaturated air.

Convective Instability. Thermodynamic state of a layer of air which will become unstable after sufficient lift.

Convective Process. Process, mechanical or thermal, causing the upward or downward movement of a limited portion of the atmosphere.

Cumulus type clouds are indicative of the occurrence of convective processes.

Convergence. Generally refers to the condition that exists when the wind distribution within a given area causes a net horizontal inflow into the region. Horizontal convergence is usually accompanied by vertical divergence, which is referred to as stretching. A net horizontal outflow is known as divergence and is generally accompanied by vertical convergence, which is referred to as shrinking.

Cyclone. In the Northern Hemisphere, a counterclockwise circulation around relatively low pressure at the center. Clockwise in the Southern Hemisphere.

Cyclogenesis. Process which creates or develops a new cyclone, or which produces an intensification of an existing one.

Deepening. Decreasing pressure at the center of a pressure system.

Dew Point Temperature. The temperature, at constant pressure, at which saturation occurs in a cooling mass of air.

Divergence. See Convergence.

Duration-Depth Curve. Maximum depths of rainfall plotted against the duration required for their accumulation over a selected area in a particular storm or group of storms.

Effective Precipitable Water. The greatest amount of precipitable water which can be removed from an atmospheric column by convective action.

Filling. Increasing pressure at the center of a pressure system.

Foehn. A warm dry wind, dynamically heated in descent down mountain slopes.

Front. The line of intersection with the earth of an inclined surface of discontinuity separating two different air masses. When the surface of discontinuity is forced over a third homogeneous air mass, the line of intersection is called an upper front.

Frontogenesis. The process which creates a front or intensifies an existing front.

Frontolysis. The process which tends to weaken or destroy an existing front.

Geostrophic Wind. The wind resulting from the balance of the force due to the pressure gradient and the apparent deflecting force of the earth's rotation, neglecting friction and curvature of path.

Gradient Wind. The wind resulting from a balance (neglecting friction) between the force due to the pressure gradient, the apparent deflecting force of the earth's rotation, and the centrifugal force due to the curvature of path.

Instability. Thermodynamic state in which vertical displacements are favored.

Inversion. An increase of temperature with height.

Isentropic Chart. Synoptic chart of data plotted at a surface of constant potential temperature, which is also a surface of constant entropy for unsaturated air.

Isopleth. A line connecting equal values on a chart.

k-type Air Mass. An air mass colder than the surface over which it is passing, with stability consequently decreasing in the lower layers.

Lapse Rate. Rate of decrease of temperature in the atmosphere with height.

Mass Curve. Curve representing cumulative values distributed through time.

Mixing Ratio. Ratio of the weight of water vapor to the weight of dry air in a given sample of atmosphere.

Occluded Front. The type of front resulting when a cold front overtakes a warm front, forcing aloft the air in the warm sector.

Occlusion. Process of formation of an occluded front, or a system which has undergone the process.

Orographic Rainfall. Rainfall caused by deflection upwards of moisture-laden winds by mountain slopes.

Polar Front. The line of intersection with the earth of a surface of discontinuity separating air masses of polar origin from those of tropical origin, the line being more or less continuous within each hemisphere.

Potential Temperature. Temperature of air after expansion or compression dry adiabatically to a standard pressure of 1,000 mb.

Precipitable Water. Total water vapor contained in an atmospheric column of unit cross-section area, expressed in terms of a column of liquid water of the same cross-section area.

Pressure Gradient. Decrease in barometric pressure per unit horizontal distance in a direction normal to the isobars.

Pseudo-Adiabatic Chart. The adiabatic chart to which saturation adiabats and lines of constant mixing ratio have been added.

Pseudo-Adiabatic Lapse Rate. The rate at which an ascending body of saturated air will cool during adiabatic expansion. Its value is not constant but approaches the dry adiabatic rate asymptotically as the water vapor content decreases toward zero.

Quasi-Stationary Front. Front along which displacement of warm by cold air, or vice versa, is small and accomplished by minor wave action.

Reduced Dew Point (as used in this report). Dew point reduced pseudo-adiabatically to 1,000 mb.

Specific Humidity. Ratio of the weight of water vapor to that of moist air in a given sample.

Stability. Thermodynamic state in which vertical displacements are resisted.

Strength (of Cyclones and Anticyclones). Steepness of pressure gradient. Synonymous with intensity.

Stretching. See Convergence.

Subsidence. A sinking of air within an air mass.

Synoptic Chart. A chart, such as the ordinary weather map, which shows the distribution of meteorological conditions at a given moment.

Thermal Equator. Line of highest temperatures, near the geographical equator, but displaced to either side of it according to season.

Thiessen Polygon. Geometrical figure drawn by plotting perpendicular bisectors between adjacent precipitation stations. These bisectors bound closed areas around each station and together form a network of contiguous Thiessen polygons, for each of which the enclosed station's rainfall is considered representative.

Tongue. The projecting portion of a large-scale eddy of dry or moist air, as revealed on an isentropic surface.

Trades or Trade Winds. Two belts of winds, one on either side of the equatorial doldrums, in which the winds blow almost constantly from easterly quadrants.

Trough. An elongated area of relatively low barometric pressure.

Warm Anticyclone. Anticyclone of primarily dynamic origin, with anticyclonic circulation extending to high levels.

Warm Front. Front at which relatively warm air displaces colder air.

Warm Sector. The air bounded by the cold and warm fronts of a cyclone.

Wave. A localized deformation of a front, which travels along the front as a wave-shaped formation, and which may develop into an intense cyclone.

Wet-Bulb Temperature. Lowest temperature to which air can be cooled by evaporating water into the air at constant pressure.

Wet-Bulb Potential Temperature. Wet-bulb temperature reduced pseudo-adiabatically to 1,000 mb.