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Electrical Engineering Research Laboratory
The University of Texas

Austin, Texas

RESEARCH IN TROPICAL METEOROLOGY

Final Technical Report

31 July 1963

Sponsored by

U. S. Army Electronics and Development Laboratory
Fort Monmouth, New Jersey

Department of Army Contract No. DA-36-039 SC 89179
Department of the Army Project No. 3A99-27-005

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To develop a detailed plan for a long range research program in the field of tropical meteorology; to survey and extend existing knowledge of tropical mesometeorology concerning the nature of small-scale circulations; to determine the relation of these phenomena to terrain, radiation, and large-scale conditions in the tropical atmosphere.

Department of Army Contract No. DA-36-039 SC 89179

Department of the Army Project No. 3A99-27-005

Prepared by

Wilfried H. Portig
John R. Gerhardt

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PURPOSE

As a continuation of the research conducted under the previous contract, DA-36-039 SC-84937, the general purpose of this current research is the development of a long range program which will further our existing knowledge of those mesometeorological features of tropical weather which are of concern to military operations of a modern field army in the tropics. Efforts are to be made to relate these small scale circulation patterns to terrain, radiation and the larger scale circulations of the atmosphere.

The research was divided into the following three concurrent phases:

1. The continuing review and survey of existing pertinent literature in tropical meteorology with the aim of preparing as complete a subject bibliography as possible. The bibliography is such as to permit the addition of new entries as they become available and supplements a previously published author bibliography.

2. Selected meteorological analyses on both a synoptic and mesoscale of particular weather features in the tropics. These analyses are concerned primarily with the Caribbean area but efforts have been made to determine the extent to which the relationships derived are applicable to other areas. Relationships are obtained between upper level circulations and smaller scale aerial and time variations of surface weather parameters.

3. The investigation of the requirements for long range research in tropical meteorology. This phase of the research effort consists of a critical review of the provisional long range program published under the previous contract using the assistance of a number of recognized experts in tropical meteorology. As a part of this phase of the research efforts, Research Planning Conferences on Tropical Meteorology were held during May 1962 and May 1963.

ABSTRACT

This report concludes the research activities under Contract DA-36-039 SC 89179 in the field of tropical meteorology. The major contributions have been studies of the upper air flow between 5°S and 40°N in July, of the bi-annual period as reflected in rainfall data, of the atmospheric conditions immediately prior to the formation of hurricanes, and of the accuracy of radiosonde data in the Caribbean.

The first of these investigations is concerned with temperature and pressure height contours evaluated at the 850, 700, 500, 300, and 200 mb levels with descriptions being given of the major circulation patterns and heat sources and sinks. Latitudinal, longitudinal,and height variations of the major features are clearly delineated.

The second study involves the harmonic analysis of rainfall data taken from 19 tropical and many other stations having long term records of observations with emphasis being placed in the existence of the so-called bi-annual period. The major findings were as follows:

1. The length of the periodicity appears to be not substantially different from 27 months.
2. The maximum monthly amount of rainfall which can be ascribed to this periodicity is approximately 2/3% of the annual rainfall regardless of the location of the stations. No effect of latitude, altitude or climate (except on the quantity of precipitation) could be found.
3. The phase angle of the periodicity depends strongly on latitude and longitude with centers of earliest occurrence near and probably southeast of India, over Alaska and over the Eastern Atlantic Ocean from where the waves slowly spread out.
4. Different months seem to respond to the periodicity in approximately the same way.

The third study presents composite upper air charts of 15 cases immediately prior to the time when a tropical revolving storm appeared for the first time in the surface map. It turned out that the formation of a hurricane is preceded by increases of temperature and moisture in the middle troposphere approximately over the place where the hurricane appears in the next surface map. This is obviously due t an organized fairly widespread rising of the air and produced by dynamical convergence in lower layers.

Warming of the middle troposphere means increase of the thermodynamical stability in the lower, and its decrease in the upper troposphere. It appears to be worthwhile to further investigate whether dry ice seeding can break up the warm core into several parts and prevent in such a way the formation of a full-fledged hurricane.

The fourth study deals with the fact that the radiosonde ascents in the Caribbean do not satisfy the requirements of the forecaster nor of the research worker. Discussion of the errors leads to the conclusion that faulty calibrations by the manufacturer and mesoscale weather phenomena produce most of the data discrepancies. A suggestion is made how to gradually improve the measurements with little or no cost.

PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

Publications, Lectures, and Reports

Electrical Engineering Research Laboratory Report No. 7-22, "Summary Proceedings of the Conference on Tropical Meteorology," was completed and distribution made following USAERDL review and approval. Distribution was also made of the subject area, bibliographic index cards on tropical meteorology.

A summary review paper entitled "Conference for the Planning of Research in Tropical Meteorology" has been published in the Bulletin of the American Meteorological Society, Vol. 44, pp. 79-82.

A paper entitled "Rainfall and the Bi-Annual Period" by W. H. Portig was presented at the International Symposium on Stratospheric and Mesospheric Circulation, Berlin, August 1962.*

A paper entitled "Thunderstorm Frequency and Amount of Precipitation in the Tropics, Especially in the African and Indian Monsoon Regions," by W. H. Portig has been submitted and accepted for publication in the Archiv für Meteorologi· Geophysik und Bioklimatologie (Series B).

On March 19-20, 1963, Dr. W. H. Portig visited Stanford Research Institute, Menlo Park, California, where he discussed problems of objective and subjective weather analysis in tropical regions with Mr. Roy Endlich.

Mr. J. R. Gerhardt and Dr. W. H. Portig participated in the Second Conference on Tropical Meteorology, Asbury Park, New Jersey, on May 9-10, 1963.

Dr. Portig took part in the Third Technical Conference on Hurricanes and Tropical Meteorology, June 6-12, 1963 in Mexico City, and presented his paper "Atmospheric Conditions Immediately Prior to the Formation of Tropical Revolving Storms" and showed his short film "Seasonal March of Rainfall and Thunderstorm Belts in Tropical Africa."

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* It will be published in Meteorologische Abhandlungen, issued by the Institut für Meteorologie und Geophysik der Freien Universität Berlin.

I. INTRODUCTION

This is the Final Technical Report to be prepared under Signal Corps Contract No. DA-36-039 SC 89179 and will briefly summarize our research activities since July 31, 1962. Specific sections will include discussions involving the completion of the 1962 Conference report and the subject area bibliography as well as current research investigations on various tropical mesometeorological problems. Four technical reports by the senior author, "Upper Air Flow Between 5°S and 40°N in July," "Rainfall and the Bi-Annual Period," "Atmospheric Conditions Immediately Prior to the Formation of Tropical Revolving Storms," and "On the Accuracy of Radiosonde Data in the Caribbean, and a Suggestion for Improvement," have been added.

Reference should be made to the previous Interim Technical Reports for a description of prior research activities.

II. SUMMARY OF RESEARCH ACTIVITIES

A. The 1962 Conference on Tropical Meteorology

All activities pertinent to this Conference were completed before Fall 1962 with the preparation and distribution of EERL Report No. 7-22, "Summary Proceedings of the Conference on Tropical Meteorology."

B. The Subject Area Bibliography

This phase of our research activities was completed in Summer 1962 with the preparation and distribution of a partially annotated subject area, index card bibliography covering approximately 3200 entries. Although no further active work is contemplated at this time, it is felt that the present effort covers only some 50% of the pertinent references and that plans should be made in the near future to carry the project through to completion. A specific additional bibliography should also be prepared with regard to data availability and sources.

C. Upper Air Flow Between 5°S and 40°N in July

1. Introduction

The author's paper[1] on thunderstorm frequency and rainfall in the tropics, especially in the Indian and African monsoon regions, required the consultation of upper air maps for the month of July. Since it appeared relatively easy to extend the maps around the whole globe, they are presented herewith. Care should be taken not to apply or extrapolate the results presented herein to other parts of the year.

2. Data sources

The main data source was the U.S. Weather Bureau's publication, Monthly Climatic Data of the World. The first radiosonde data appeared in that publication in 1949 and have become substantially more numerous since 1950. All published monthly mean contour heights and temperatures were extracted through 1961 inclusive. In general, the data coverage is not bad north of the equator except over the eastern Pacific Ocean where there are no stations, and over the Atlantic Ocean. In the case of Kindley Field, Bermuda, and Lajes, Azores, where the mean data is available in published form for only one month, it became necessary to compute the average July values from the individual ascents as published in the U.S. Weather Bureau's Daily Northern Hemisphere Data Tabulations. While this computation took as much time as the extracting and averaging of all other 120 stations, the two island stations were considered as being too important to be neglected.

Table 1 shows the number of stations and the years available for the construction of the maps. A total of 122 stations were used in this study.

Table 1

Number of Stations (N) with (Y) Years of Record

Y	1	2	3	4	5	6-8	9-11	12	13
N	10	11	10	12	14	16	14	18	17

In constructing these maps, six other publications were consulted. These were:

(1) Upper Winds Over the World, 1960, by H. Heastie and P. M. Stephenson.[2] These maps were of relatively little value since excessive smoothing has been employed. The 500 mb map for July, e.g., does not

show a single contour over the entire Pacific Ocean between 10°S and 35°N with the exception of a doubtful line near the South American coast. This is in complete contrast to -

(2) Analyses of Monthly Mean Resultant Winds for Standard Pressure Levels Over the Pacific, 1961, by C. T. Wiederanders.[3] While the maps here were constructed solely by using contour heights, Wiederanders used only mean vector winds. It is very encouraging to see that certain particular features of the mean flow over the Central Pacific appear in both independent presentations. In Southeast Asia, the radiosonde material is rather inhomogeneous and this is the only place where the mean winds were consulted for the construction of the contour lines.

(3) The Structure of the General Circulation Over the Asian Continent in Summer, 1957, by Dao Shih-Yen and Chen Lung-Shun.[4] The maps of this work coincide so well with those constructed for this study that only very small changes over China appeared to be appropriate.

(4) Statistical Analysis of Upper Air Temperatures and Winds Over Tropical and Subtropical Africa, 1961, by W. L. Hofmeyr.[5] The work which was consulted after the analyses had been made, led to some minor corrections.

(5) A Persian[6] and a

(6) Siamese[7] publication offered some wind data which - at that latitude - could be utilized to refine the contour lines.

As Table 1 shows, there is a great lack of homogeneity in the periods for which data were available, and the uniformity is further reduced by the use of different radiosonde systems, even at the same station, and by differences in the evaluation methods. In spite of these inconsistencies, however, the map analyses were not too difficult. While this does not mean that the analyses were free from ambiguities and the contour lines in several places could have been drawn in a different fashion, it is felt that many of the details will remain in the way they are presented when better observations are available.

With the exception of Southeast Asia, the presented maps are pure contour maps. That implies that they do not represent the mean flow near the equator. Contour lines have been drawn for spacing of 10 meters for levels through 500 mbs and at 20 meters for the upper two levels. The contour heights and temperatures for the 850, 700, 500, 300 and 200 mb levels are shown in Figs. 1-5. Due to data accuracy limitations, an isotherm spacing of 2.5°C was employed on all maps.

3. Discussion of the maps

a. General

For latitudes of approximately 10° and greater, the contour lines represent the general direction of the flow. When the mean isotherms include an angle with the contours which is substantially different from zero, a permanent heat source or sink exists. No interpretation, however, can be made from the maps as to the nature of such sources, i.e., whether they are based on radiation, subsidence, heating from the ground, or condensation.

b. The 850 mb level

Over East Asia, the Pacific, America, and the Atlantic, the pressure is low over land, and high over water. This simple rule does not hold over Africa although its land mass is larger than any other on the maps. Africa appears to be a passive link between the low pressure steering center of south central Asia, and the Azores HIGH.

The contour lines show a long, flat ridge from Tunisia to the Guinea coast and while one would be tempted to consider it as a result of inaccuracies of the radiosonde data, Fig. 6 shows that this ridge coincides very well with a minimum of rainfall between two well expressed maxima.

As expected, the 850 mb chart shows very strong heat sources over the Arabian Desert, the Sahara, China, Southwestern U. S. A. and Northwestern Mexico. The contour line indicates transport of the heated air in many places and how fast it is consumed. It is very remarkable that, at this low level of the atmosphere, the intertropical belt is much colder (15°C!) than parts of the subtropics, and even colder than the Mediterranean. Assuming that the isotherms over the Indian Ocean are correct, they denote the consumption of heat for evaporation and the release of latent heat over the Indian subcontinent.

c. The 700 mb level

Although only a moderate altitude change is involved, there are significant changes at this level from the 850 mb charts. The subtropical HIGH over the Atlantic now has a counterpart over the Sahara desert and the formerly northerly flow over the Mediterranean Sea has been converted into a predominantly westerly flow of remarkable speed. The meridional ridge over West Africa at the 850 mb level has been replaced by a relatively strong circulation from the east at the 700 mb level. Only rudiments of the potent 850 mb LOW over the Southwestern U. S. A. remain at the 700 mb level. On the other hand, there is little difference between the 850 and 700 mb levels over the Pacific Ocean and over most of the Asian continent.

Temperatures at the 700 mb level still show maxima over the Sahara desert and the dry regions of Southwest Asia. However, the horizontal temperature gradient to the equator has been significantly reduced. This means that the regions which were considered as heat sources for the 850 mb level have much steeper (vertical) temperature lapse rates. If it were not known from common climatological data that these source regions are very dry, the fact could be derived from the lapse rates. The point 27° N latitude, 0° longitude has, for example, at the 850 mb level (1530 meters) a mean July temperature of 30°C. The corresponding figure at 700 mbs (3220 meters) is 15°C, corresponding to a mean lapse rate of 8.9°C/km which would be impossible in a predominantly moist atmosphere.

The reduced temperature contrasts of the 700 mb level also indicate a smaller effectiveness of heat production and consumption. Only over Southeast Asia with a center over Iran does a heat source still exist. Although not documented, but doubtlessly existing, another stronger one will be found over Tibet.

d. The 500 mb level

By comparing the 500 and the 700 mb level, it can be seen that the meridional wind components have been reduced in the region between India and central North Africa. Over New Mexico where a LOW was found at the 850 mb level, a HIGH now exists at the 500 mb level. The most significant change occurs in the central Pacific where immediately north of the Hawaiian Island a well marked trough appears in the 500 mb map in contrast to the large HIGH at the 700 mb level. The Asian continent still appears to be a heat source (with its efficiency undocumented over Tibet) while no such indication can be found for America and Africa.

e. The 300 mb level

At this level the westerly and the easterly jets are well established over Africa and Asia. Contrasting to this increase of the zonal circulation, an enlargement of the meridional circulation can be noted over the central Pacific where the trough between the east and the west Pacific HIGHs has widened considerably and extends to the equator.

The temperature contrasts between Asia and all other regions are considerable. Although the atmosphere over the Sahara desert at the 300 mb level is 60°C colder than at the 850 mb level, it is still warmer than for regions near the equator. It is remarkable that the big trough over the central Pacific is a heat sink where a part of the heat produced over China disappears. Likewise, it is noticeable that the temperature over the Near East is relatively high in spite of the permanent advection of colder air from the west.

f. The 200 mb level

At this level, the trough over the central Pacific finds its counterpart over the western Atlantic. In both cases, a broad meridional strip of low temperatures results. The warmest region at this level is Central Asia, but contour lines and isotherms are more or less parallel so that one cannot speak of a heat source in the sense of heat advection. This heat, however, represents the energy that maintains both the westerly and easterly jets. Again, one finds a temperature decrease towards the equator.

4. Special features

Whereas the previous paragraphs were concerned with conditions at each of several levels, the following text describes the characteristics of certain regions or phenomena through all levels.

a. Easterly winds

Organized easterly or trade winds appear at the 850 mb level over the Pacific, over the Atlantic, and over the Caribbean region. At the 700 mb level, they extend into West Africa where they seemingly are stronger than in the previously listed regions. At the 500 mb level, the easterlies extend to east Africa and become weaker over the non-African regions, especially over the central Pacific while at 300 mbs they form a band from the western Pacific over India and Africa into the Atlantic. At the 200 mb level the easterlies are limited to the hemisphere between approximately 150°E and 30°W and are best developed over India, i.e., where their basis is farthest from the ground.

Although the easterlies of different regions may merge, three groups can be distinguished, i.e., the tradewinds, the African easterlies at elevations exceeding about 700 mbs, and the Indian easterlies which begin at approximately 400 mbs.

b. Westerly winds

When such winds blow near the equator they cannot be detected in contour maps. Westerly winds are found in the lower levels over the Arabian Sea, India, and Indo-China, disappearing with increasing altitude to the extent that only a weak flow over southern India still remains at the 500 mb level.

The mid-latitude westerlies, on the other hand, which can be found at all levels, branch out into lower latitudes. Such is the case at and above the 500 mb level in the central Pacific, and at or above the 200 mb level in the western Atlantic. The two systems of westerlies seem to have no connecting link, and in this respect are in contrast to the three systems of easterlies.

c. Africa at Central India's latitude

The contour lines over India are very different at all levels from the contour lines over Africa at the same latitude, as can be seen in Table 2.

Table 2

Contour Line Patterns at the Same Latitude

	Africa	India
200 and 300 mbs	center of anticyclone	easterly jet
500 and 700 mbs	anticyclone	cyclone
850 mbs	flow from N or E	flow from W

As is well known, the climates of the two regions are correspondingly different.

d. Thermal effects

There are three areas on the maps which have temperature maxima at the 850 mb level, i.e., Arabia, the Sahara, and the area comprising southwestern U.S.A. and the northernmost part of Mexico. Due to its elevation, such a maximum cannot be found for Tibet at the 850 mbs level and is only poorly defined at the 700 mb level. The 300- and 200-mb maps show that the axis that separates the westerly and the easterly flow runs over these four hot spots. It can be assumed that such is also the case over Bolivia in the southern hemisphere.

e. Global averages

At several points in the previous discussions, the temperature differences between the equator and higher northerly latitudes have been mentioned. Fig. 7 shows the mean July conditions for latitudes from 5°S to 40°N averaged over all longitudes.

From the temperature contours it can be seen that at all the standard levels considered in this paper, the latitudes 25-30°N are approximately 4°C warmer than the equator. The very high temperature differences over Africa are compensated by smaller differences elsewhere. It is remarkable that, in spite of local effects, the global average shows almost the same temperature difference at all levels.

From the pressure height contours it can be seen that the higher levels of the troposphere show a distinct high pressure belt at the same latitude where the highest temperatures are found and this high pressure belt gives rise to the well known westerly and easterly jet streams. However, it is remarkable and, to a certain extent, unexpected, that the lower layers do not show such a zone of high pressure. Although every model of the general circulation contains the subtropical HIGH pressure belt from which the tradewinds are derived, global averaging shows that the pressure gradient that produces the tradewinds, is obviously compensated by gradients of the opposite direction. This is particularly the case in the northern Indian Ocean, and Fig. 7 shows that the monsoons during July on the northern hemisphere must not be considered as secondary, local phenomena, but that they are of the same order of magnitude as the tradewinds whose role in the planetary exchange of air is much more recognized.

D. Rainfall and the Bi-Annual Period

1. Introduction

A periodicity of the upper level winds in the tropical zone has recently been discovered.[8, 9] These alternating easterly and westerly winds near the tropopause are especially well illustrated by a figure in an article by Reed. It is evident that a meteorological process will not be confined to just one element. Therefore, it is logical to look for the bi-annual period in other weather elements. In the current study, the rainfall has been chosen. There are many advantages to using rainfall data instead of winds. Some stations have almost a hundred years of rainfall data as compared with very few years of wind measurements. This allows us to check the persistence of the period as well as its real length. In addition, there are also more rainfall measuring stations than wind measuring stations, which permits us to make regional differentiations, although they may be hampered by orographic effects. Furthermore, rainfall, in contrast to wind measurements, are time integrations and are less sensitive to mesoscale modifications as well as errors. And, last but not least, many rainfall data are easily accessible through the World Weather Records.

The study to be discussed here is nothing but a pilot study. It gives a quite encouraging outlook and suggests the need for additional work.

2. Data analyzed

Because of the time necessary to perform an analysis of this type, all of the available data have not been used. A choice was made such that there was a fair coverage around the entire earth and that in some few cases stations were sufficiently close together to permit a mutual check. Table 3 is the list of the stations arranged according to geographical longitude.

Table 3

Stations Used for Rainfall Analysis

Freetown, Sierra Leone	9N	12W
Accra, Ghana	5N	0
Calabar, Nigeria	5N	8E
Entebbe, Uganda	0	32E
Colombo, Ceylon	7N	80E
Trincomalee, Ceylon (east coast)	9N	81E
Djakarta, Indonesia	6S	107E
Amboina, Indonesia	4S	128E
Apia, Samoa	14S	172W
Fanning Island, Central Pacific	4N	159W
Honolulu, Hawaii	21N	158W

Table 3 cont'd.

San Salvador, El Salvador	14N	90W
Colón (Cristobal), C. Z.	9N	79W
Quito, Ecuador	0	78W
Bogotá, Colombia	5N	74W
San Juan, Puerto Rico	18N	66W
Hamilton, Bermuda	32N	65W
Georgetown, Guiana	7N	58W
Recife-Olinda, Brazil	8S	35W

Most of the stations are coastal stations. This is not intentional but results from the fact that the bulk of published tropical climatic stations are along the coasts.

3. Length of period

According to Reed[10] and others, the harmonic analysis was initially based on the assumption of a 26-month period. However, it soon became evident that the period is longer than that and that a 27-month assumption would be better.

The monthly rainfall data of Colón (Cristobal) at the Atlantic side of the Panama Canal Zone were submitted to harmonic analysis with respect to a 26- and to a 27-month period. In order to get safely rid of the annual variation of rainfall, several cycles had to be grouped. For the 26-month period, 13 years = 6 cycles formed one group; for the 27-month period, 18 years = 8 cycles. The phase angles are shown in Fig. 8. Assuming that the result of harmonic analysis is expressed in the form $\sin(t + \theta)$, we know that equality of θ in subsequent intervals means that the chosen period corresponds to the natural period of the variable; an increase of phase angles θ means that the true period is smaller than assumed in the calculation; and irregularity of phase angles signifies that there is no persistent natural period. In our case, the phase angles of the harmonic computed under the assumption of a period of 26 months decrease by 300° from the first to the last interval. One can compute from this a "true" length of period of 27.15 months or approximately 825 days. The calculation under the assumption of a 27-month period does not show a tendency to decrease or to increase. Phase analyses of other stations yielded a somewhat shorter length: Djakarta 26.52 months since 1864, Bermuda 26.74 months since 1866, Entebbe 26.86 months since 1900. The phase analyses show that 27 months seem to be more appropriate than 26.* Therefore, all further calculations have been made under the assumption that the period has a length of 27 months exactly.

* There is strong evidence that there is another period of 26 months length which seems to be independent from that discussed here. Since 26 and 27

One of Schuster's criteria says that for a true period the computed amplitude remains in the same order of magnitude when the number of analyzed data is increased. It states further that, when the amplitude is nothing but a computational result without a physical background, the computed amplitude will decrease proportionally to the root of the number of observations. Table 4 shows the amplitudes of the 27-month rainfall period for Colón, C. Z.

Table 4

Amplitudes of the 27-Month Rainfall Period for Colón, C. Z.

Number of analyzed months	216	432	648
Amplitude of first harmonic	0.875	0.679	0.744 inches
In case of non-reality	0.875	0.619	0.504
		$= \frac{0.875}{\sqrt{2}}$	$= \frac{0.875}{\sqrt{3}}$

It can be seen that the amplitudes do not show the trend typical for non-real periods. In particular, the increase of amplitude when the number of data is raised from 432 to 648 should be noted. This provides a strong argument in favor of considering the 27-month period of rainfall as a physical reality.

4. Analysis of different months

The analyses thus far have not differentiated between different months even though the normal seasonal variation of rainfall is considerable. In order to explore this point, the data of individual months were submitted to harmonic analysis. Some difficulty is encountered because data for a particular month will not be found throughout the entire array of the 27-month period but only at 9 out of 27 places. Further, the computed phase angles have to be reduced to a common time-zero which was chosen to be January 1900 $\pm 9n$, n = integer.

It turned out that monthly data are too much disturbed and irregular to show an appropriate effect. However, three-month overlapping values show it in sufficient clarity. Fig. 9 shows the phase angles of overlapping months for two different intervals for Colón (also called Cristobal), C. Z. The curve for 1918-44 is disturbed by the August value.

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month periodicities are 180° out of phase after approximately 30 years, analysis of longer series precludes the possibility that there is only one period, supposed the phenomena are persistent. A comprehensive bibliography will be published soon by Helmut Landsberg.

The dotted curve simply disregards it. Considering this uncertainty and comparing the curves for both intervals, we conclude that there is no noticeable difference in the response of the particular months to whatever causes the 27-month periodicity.

5. Analysis of nearby different rainfall regimes

The conclusion of the last paragraph does not necessarily hold for all regions. We have available long-term data for two interesting stations separated by a relatively short distance. One of them is Colombo on the southwest side of Ceylon with two well marked rainfall maxima during a year, one in May, the other in October/November. (It may be noted that this very well expressed double maximum of Colombo is generally neglected in the attempts to explain the Indian monsoon circulation.) The other stations of interest is Trincomalee, on the northeast side of Ceylon. The rainfall regime there is very different from Colombo's. True, there is also a maximum of rainfall in May, but Colombo receives 15.5 inches, and Trincomalee only 3.2 and after this maximum Trincomalee has an almost complete drought in June with only 0.8 inches of rain, which is 1/10 of what Colombo receives. In the fall, the rainfall maximum at Trincomalee is 4-6 weeks later than Colombo's. The rainfall variations are presented in Fig. 10.

T e same figure shows the 3-month overlapping phase angles for the stations. One sees that there is a very good coincidence between both stations even through their rainfall regimes are different. If we assume that the small differences between the stations are real, we may interpret them as a lag of 2 months of the 27-month extremes of Colombo in the first rainy season, and a lag of 3 months of Trincomalee in the second. But with regards to the experience obtained with the Panama data, one should be very careful with such conclusions. This is true also for conclusions that try to derive different responses of the seasons to the 27-month period from Fig. 10.

It should be mentioned that the amplitudes of the period are 2% of the monthly rainfall (the range is twice the amplitude) for all months and both stations with the exception of December at both stations and May at Colombo. December is in the transition from the moist to the dry season, and the May rainfall of Colombo is very peaked so that the amplitude of the 27-month period "cannot catch up" with this rapid change.

The conclusion of this section is that apparently the 27-month period disregards differences in nearby rainfall regimes but is superimposed on them as a certain percentage of the falling rain.

6. The 27-month period as a function of geographic longitude

The phase angles of the analyzed stations show a rather clear-cut dependence on the geographic longitude, but there are some few exceptions unexplained so far.

Fig. 11 shows the computed phase angles which refer to January 1900 $\pm 9n$ for 21 stations of the equatorial zone. The tropical data of an earlier paper by Visser[11] have been added. Most of the symbols can be connected tentatively by the curve. Only three of them show more than 90° deviation from the curve. These stations are Fanning Island in the middle of the Pacific Ocean, Entebbe in the middle of the African continent, and Cuiabá in the middle of South America.

Of course, the curve could be drawn in another fashion but also any other curve would have to acknowledge that the phase angles from India as well as from South America descend to the values of the mid-Pacific. That means that the wave is first felt at the limits of the Pacific Ocean and advances towards its center where it arrives approximately a year later (the difference of the straight lines in the diagram corresponds to 27/2 months = 1 year 45 days).

A similar movement of the wave crests towards Africa seems to be indicated, too.

This simple picture is substantially disturbed by the three mentioned exceptions. The data from Fanning Island has several gaps which had to be filled by data later than 1944. This could have produced the bias with Apia and Honolulu.

The African data, however, do not have an obvious deficiency but a marked discrepancy. Things become more complicated there through the fact that Entebbe with its badly matching phase angle has a very high amplitude, 1.01 inches, to be compared with 0.10 at Accra, 0.54 at Calabar, and 0.25 at Zanzibar. Further, Entebbe has a simple 27-month wave, whereas the wave is highly overshadowed by a 27/2 month wave at Accra and Zanzibar.

Table 5 shows the harmonic constituents of the four African stations.

Table 5

Harmonic Constituents of Four African Stations
27-Month Period of Rainfall

	First Harmonic		Second Harmonic		
	A_1	maximum at Jan. 1900 plus	A_2	maximum at Jan. 1900 plus	A_1/A_2
Entebbe	1.01	16 months	0.52	6 and 19 months	1.94
Zanzibar	0.25	6 months	0.43	8 and 22 months	0.58
Accra	0.10	1 month	0.17	11 and 25 months	0.59

Amplitudes A are in inches

One can see that the second harmonic of Entebbe is in phase with the first hamonic of Zanzibar (East coast) and Calabar (Guinea coast). This was the reason that Entebbe's first harmonic phase angle was disregarded in Fig. 11. Nevertheless, it is evident that the conditions in equatorial Africa are too complicated to be clarified with the data used thus far.

7. The 27-month rainfall period as a function of geographic latitude

The data considered thus far have come from stations located between 14° S and 21° N. The question arises as to whether we might find the 27-month period at higher latitudes. The meridional strip along approximately 80° W was chosen to examine this question.

Since the meridian crosses many different climates, a check appeared appropriate whether there is a relationship between the amplitude of the periodicity in question and other parameters. Only one parameter was found on which the amplitude obviously depends and that is the annual rainfall amount. There seems to be a linear relationship of the form amplitude A is equal to 6.4×10^{-3} times the annual rainfall R(A and R in the same unit, of course). The factor was derived by the method of least squares for all American stations used in this part of the study. Fig. 12 shows the data as full dots and the straight line representing the least square interpolation. The original working diagram showed also the names and locations of the stations. Since they appeared to be distributed randomly, they were omitted in this figure. Also the Asian, Pacific, and, with the exception of Fanning Island, all non-African data cluster around the line computed by means of the American data. As a matter of fact, when we compute regression lines for all except the American data, we obtain practically the same value:

$$A = 6.4 \times 10^{-3} R \text{ for American stations}$$

$$A = 6.2 \times 10^{-3} R \text{ for all other stations.}$$

The result is, to a certain extent, nothing but good luck, since even the odd African data are used in the computation. The figure contains the names of some African stations. It is confirmed, as was said earlier in another part of this report, that the interpretation of the 27-month rainfall period poses difficult problems in Africa.

After we have seen that the amplitude of our periodicity follows - with exception of Africa - a simple pattern depending only on the amount of rainfall, and not on geographic location nor climatic or orographic particularities, we can study the phase angle, i. e., the time at which the periodicity has its extremes.

Fig. 13 shows the phase angle as a function of latitude reduced to 80°W by means of the curve of Fig. 11. Except for the stations White River in Canada and Cuiabá in Brazil, there is a rather distinct pattern to be seen. Expressed in words, the interpolating curve means that the maximum (or any other phase) of the 27-month rainfall period occurs first off the U. S. southeast coast; it spreads from there to the north and to the south and arrives eight months later at Hudson Bay and at the equator. Since angles are cyclic, the interpretation of the data is not without ambiguity. The dashed line shows an alternative interpolation between the calculated data. We may also use the solid line in the upper, the broken line in the lower part of the diagram and vice versa. Fig. 13 allows only the conclusion that for the region analyzed, the 27-month period travels from North to South. * For further conclusions, we have to use more data in another arrangement.

8. The 27-month rainfall period over the Atlantic and adjacent continents

Visser[11] tried to arrive at the same conclusions in another way than was done in the previous sections. He stated simply that continental areas have the opposite phase of maritime regions, i. e., one has its maximum of rainfall when the other has its minimum. This answer to our problem is to be abandoned.

The number of stations submitted to harmonic analysis was increased to 61, and Visser's results for 19 stations were added. There

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* The author found 1937-1939 that for forecasting the position and condition of the ITCZ, it was sufficient to know the synoptic situation only on the North Atlantic. This also points to processes traveling southward rather than northward.

are mor data available, but these appeared to be sufficient for a basic solution of our problem.

Fig. 14 shows the phase angles of the 27-month rainfall period in upright numbers as obtained by this author, in italics as obtained by Visser. All angles θ refer to the form $\sin(t+\theta)$ where $t = 0$ corresponds to January 1900. Reductions to a certain location, as has been done in constructing Fig. 13, have not been made. (Therefore, the data do not agree except at 80° W.)

In the continents, the analysis of the phase angles was relatively simple;* on the eastern Atlantic, it is problematic and other solutions can be imagined.

Considering that a decrease of phase angles means an advance of a periodicity, we have to interpret Fig. 14 as follows: The 27-month rainfall period moves into the U. S. from the NW and crosses the continent slowly. Another center of origin is located in the eastern central Atlantic from where the wave spreads slowly towards South and East Africa and to southern South America. The formerly contradictory African data fit well into this scheme, but their number is admittedly too small to consider this result as definitive. The second harmonic which is observed there (Table 5) may be the effect of an overlapping with a wave coming from the Gulf of Bengal (Fig. 11).

No further conclusions should be drawn from Fig. 14, especially because of some obvious discrepancies between this author's and Visser's findings.

The concept of running waves derived from Fig. 14 is in contradiction to the African part of Fig. 11. Considering the sparcity of data over the Indian and Central and Eastern Pacific Ocean, no attempt can be made to remove the discrepancies.

9. Connection of rainfall and stratospheric winds

Figs. 9, 10, 11, and 14 can easily be related to the periodicity of the stratospheric wind. The publications by Angell and Korshover and by Reed et al. show that we have to assume a phase angle of approximately

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* Galveston (World Weather Records) had to be substituted by Houston (Local Climatological Data). As can be seen in the author's Atlas of the Climates of Texas, 1962, Galveston cannot be regarded as a representative for the climate of its hinterland; the considerable climatic differences to nearby Houston are well documented.

0° for the easterlies at the 50 mb level when we continue to count January 1900 +9n as time zero. That means that the tropical easterlies are at their best when we have rainfall maxima along the isophases 0° in Fig. 14; viz., a strip from Manitoba to Oregon, in equatorial South America with exception of its Atlantic region, in former French Equatorial Africa, in parts of South Africa and in extreme South America. The westerlies in the tropical stratosphere coincide with rainfall maxima in NW Canada, in most of Central and Eastern U. S. A., New Mexico, most of the Atlantic Ocean, and a small strip running from the Red Sea over Angola to Central Argentina.

For the Central Pacific, we find from Fig. 11 that the maximum of rainfall corresponds to the maximum of stratospheric easterlies, while it is associated over Ceylon with westerlies.

In due consideration of all the pitfalls which are behind the calculations of this paper, no attempt will be made to explain the statistical relationship between rainfall and wind direction.

10. Results

The examination of rainfall data with respect to a periodicity of approximately the length which has been established for winds in the stratosphere had some results which cannot be considered as facts, but which may serve as bases for working hypotheses. Briefly, they are as follows:

(1) The length of the periodicity is not substantially different from 27 months.

(2) The maximum monthly amount of rainfall which can be ascribed to this periodicity is approximately 2/3% of the annual rainfall regardless of the location of the stations. No effect of latitude, altitude or climate (except the quantity of precipitation) could be found.

(3) The phase angle of the periodicity depends strongly on latitude and longitude with centers of earliest occurrence near and probably southeast of India, over Alaska and over the Eastern Atlantic Ocean from where the waves slowly spread out.

(4) Different months seem to respond to the periodicity in approximately the same way.

The statement on the amplitude of the periodicity implies that the technique cannot be used for long range forecasts.

E. Atmospheric Conditions Immediately Prior to the Formation of Tropical Revolving Storms

1. Introduction

In a 1948 paper presented before the American Meteorological Society, E. Palmén[12] stated that cumulonimbus convection is not sufficient for the production of a hurricane. Instead, he said that the air must be lifted over a relatively wide area.

Workman[13] recently noted the necessity for the storage of energy before a hurricane can form while Kuo[14], Syōno[15], Lilly[16], and other theorists have investigated the thermodynamical stability conditions of the atmosphere prior to the development of a hurricane. They tried to predict from the horizontal and vertical distributions of stability - or better, conditional instability - the consequences, i.e., either the development of cumulus convection or hurricane formation.

Yanai[17] made a very thorough analysis of radiosonde and other data taken during a typhoon which formed in the Pacific Ocean, and Erickson[18] studied the formation of a hurricane near Dakar with results similar to Yanai's.

2. Method

This paper approaches in another way the problem of the formation of a tropical revolving storm. Fifteen Caribbean hurricanes or tropical storms were found with sufficient radiosonde data around the places of their formation as to allow reasonably complete analyses, making use of a rectangular grid 20 deg longitude wide and 10 deg latitude high whose origin is the place where the hurricane formed a short time later. Because of uncertainties in formation time and due to the twelve-hour interval between international observing hours, this "short time" varies between 6 and 18 hours. After transformation of the coordinates, the analyses were averaged.

Previous work has shown that there is not much hope that analyses of surface weather alone will bring much enlightenment. It turned out that four levels have to be analyzed in order to obtain a reasonable estimate where a tropical storm may form within the next 24 hours. These levels are:

(1) 1000 mb as a representative of the flow near the ground

(2) 500 mb as the upper boundary of the lower layer. One could just as well use 600 mb, but 500 mb is a main analysis level at middle latitudes and for practical purposes it is reasonable to use it here as well.

(3) 250 mb as the upper limit of the middle troposphere; one can just as well use 300 mb.

(4) 150 mb as representative of the upper limit of the troposphere. A higher level would occasionally lie above the tropopause and less data would be available.

3. Evaluation

The lefthand side of Fig. 15 shows mean contour lines for the fifteen hurricanes at 6 to 18 hours prior to the time when they appeared in the surface map for the first time.

The 150 mb level shows the expected anticyclone close to the position where a hurricane forms in the near future. The individual maps from which the figure was averaged show considerable differences and the location of the HIGH is statistically not significant.

At the 250 mb level we see a col-like pattern with an anticyclone on either side and one cyclone north, another south of it.

The 500 mb level shows a cyclone near the location where a revolving storm will be found the next day.

The 1000 mb level shows a kind of easterly wave at the southwest of the future hurricane. In this case, the dispersion of the individual cases is much smaller than at the 150 mb level.

Differences of consecutive contour maps are thickness or isothermal maps which are shown in the righthand column of Fig. 15.

The upper troposphere (150/250 mb) shows a tongue of warm air pointing approximately to the location where we noticed the easterly wave in the 1000 mb map.

The 250/500 thickness chart or the mean temperature of the middle troposphere shows a remarkable pattern which is essentially repeated in each of the individual cases: high temperatures with circular isotherms near the place where the revolving storm later forms. That means that the warm core precedes the very strong winds and is not their consequence. This result fits Palmén's prediction and Yanai's and Ericksons's analyses of individual storms.

The thickness chart of the lowest layer shows - somewhat unexpectedly - relatively high temperatures near the easterly wave we observed in the 1000 mb level.

In the 250/500 mb chart, we find as dashed lines the moisture content of the highest level from which we regularly have measurements, i.e., from the 300 mb level. We see that the greatest moisture occurs at almost the same location where we found the highest temperatures of the middle troposphere. Both results together indicate that the air rises ov^r a fairly large area - 4 to 5° lat. in diameter - before a hurricane forms at that very place. This rising is, as predicted by Palmén, not a convective process but must be the consequence of some large scale convergence.

The immediate result of the rising air is a characteristic change of the distribution of thermodynamic stability. While the contour maps do not permit the numerical evaluation of the lapse rate, good estimates of their relative values can be obtained. Thicknesses are equivalent to mean layer temperatures; hence differences of thicknesses correspond to temperature differences. Only with exact assumptions of the vertical temperature distribution can we find the altitude at which the actual temperature equals the mean layer temperature, thus permitting the calculation of a mean lapse rate. One can, however, show that the range in which this altitude can be found is very small in comparison with the variation of the layer temperature differences so that we are allowed to consider areas with larger differences as less stable than areas with small differences.

Fig. 16 shows the differences of the mean temperature of the upper minus the middle, and the middle minus the lower layer of the troposphere. It indicates that the small scale convection of the lower layers is hampered by an increase of stability while the upper troposphere displays a decrease of stability. Cloud analyses* of the same hurricanes indicate maxima of altostratus and multilayered altocumulus near the place of the future hurricane. The reduction of stability of the upper troposphere is suggested by a maximum of cirrocumulus observations in spite of the obstruction to vision by the above mentioned As clouds. The latter form in the lower part of the middle troposphere and indicate its relatively great stability.

4. Twenty-four hours before

The analyses were extended to the time 24 hours prior to the maps shown in Figures 15 and 16, and they were checked by the evaluation of the actually observed winds. The results can briefly be summarized as follows:

(1) The low level inverted trough does not come in from the East, i.e., it is not an easterly wave in the restricted sense of word as used by Dunn and Riehl, and little 24 hour change can be seen in the streamlines of the lowest layer. Numerical analysis of the wind data reveals, however, that

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* See Appendix

several centers of convergence and divergence travel upstream, i.e., mainly towards the East in such a way that in 24 hours a center of divergence is replaced by a center of convergence at the very place where in the next surface map the hurricane is observed.

(2) The convergence at that point can be found up to the 400 mb level above which it fades out without being replaced by significant divergence up to 150 mb.

(3) The greatest changes in the streamline field occur at the 400 mb level (see Fig. 17).

(4) The well pronounced temperature maximum of the 250/500 mb layer (Fig. 15) does not exist 24 hours earlier.

(5) All data, including those of the Appendix, show a remarkable lack of symmetry. If there is any symmetry at all - as many hurricane models postulate - it is brought into the picture with the development of gales.

5. Non-hurricane developments

Yanai did not go so far as to ask whether the marked warming and moistening of one volume in the middle troposphere is sufficient for the development of a hurricane and, if not, what other conditions might be involved.

This question is not easy to answer. In the procedures described in this study, only the relatively small number of cases where hurricanes actually formed were checked out. An adequate answer to this question would require the analysis of all previous weather conditions of all past hurricane seasons at all locations where hurricanes can form. Such an investigation is far beyond the scope of what can be handled in a reasonable time. Nevertheless, some efforts were made to answer the pertinent question, and the answer is, unfortunately, "Yes, weather situations were found that did resemble in the main those represented by Figs. 15 and 16 where there was no subsequent hurricane formation." These are discussed in the following section.

Case 1. 16 August 1959, 0000Z. The maps (not presented here) have similarities with the composite charts in two locations where the first of these was between Jamaica and Panama. At that time and location, isopleth patterns were found which fit well the stability charts of Fig. 16. The surface winds had speeds up to 30 knots from the east in an easterly wavelike pattern. While moisture measurements in the critical stability areas were not available, one could assume a high moisture content of the middle troposphere. However, the flow pattern at the 150 mb level clearly showed a cyclonic center near the location of the significant stability patterns, and this is in contradiction to Fig. 15.

In the second location, over Florida, the moisture of the middle troposphere was remarkably high with 94% relative humidity over Miami and 75% over Tampa, both at the 300 mb level. The lower troposphere displayed a center of high stability right under the very moist mid-troposphere, and the 500/1000 mb thickness chart showed a cold center close to it. A few degrees latitude farther south, a well defined cyclone already existed at the 500 mb level. Nevertheless, as in the previous instance, cycloric flow was occurring at the 150 mb level, and warm air could not be found in the mid-troposphere connected with reduced stability aloft. The 100 mb level had easterly winds over the entire Caribbean region without any curvature.

Case 2. 28 September 1956, 1200Z. Halfway between Puerto Rico and Trinidad all of the characteristics displayed in the composite charts were found with exception of the circulation at the 150 mb level. The 100 mbs level again showed easterly winds over the entire area. Instead of having an anticyclone close to the point of possible hurricane formation, however, the map showed a well developed cyclone north of Puerto Rico. This case deserves special interest since there did exist a LOW from the surface through the 500 mb charts over which a strong warming center with apparently high moisture was located. The surface LOW, which had many of the characteristics of a hurricane the previous day, died out with the approach to the 150 mb cyclone.

Case 3. 14 June 1959, 1200Z. South of Grand Cayman, the situation was similar to that described in Case 2, with bad weather and somewhat less pronounced stability patterns. The 150 and 100 mb levels, however, showed westerlies with a cyclonic curvature.

Case 4. 13 October 1959, 0000Z. All characteristics of Figs. 15 and 16 were displayed just south of Puerto Rico again, however, with the exception of the 150 mb and 100 mb levels which showed cyclonic curvature. One surface wind report showed a speed of 30 knots. The moisture distribution was very interesting. All radiosonde stations of that region, San Juan, St. Maarten, Raizet, Trinidad, and Curaçao, reported relative humidities of 70% and more at the 300 mb level, with the same high values near the ground. At 500 mb, however, the humidity was unmeasurably small at the three northernmost of the mentioned stations, and even Trinidad reported only 39% at this level.

Since the four specific non-hurricane cases all showed cyclonic curvature of the 150 mb flow with a predominant westerly component, it would appear to be eventually necessary to check whether all hurricane cases showed the opposite. In the meantime, it would be instructive to see if the average pattern shown in Fig. 15 is typical for all members of the sample. Unfortunately the composite 150 mb flow does not apply to each of the hurricane situations from which it was extracted. Thus, GRACIE, JUDITH and CARLA 1961 developed close to an anticyclonic center at 150 mb and while the data coverage of DORA is rather poor, northerly anticyclonic flow seems to be indicated at 150 mb and easterly flow at 100 mb. GRETA and HATTIE developed with a circulation having predominant westerly components at 150 and 100 mb, both with anticyclonic curvature. GERDA, on the other hand, occurred where the upper currents were weak and displayed a transition between cyclonic and anticyclonic, while ETHEL and ARLENE were both found under cyclonic westerly flow at 150 mb topped by anticyclonic conditions at 100 mb. CARLA 1956 developed under a strong cyclonic curvature at the 150 mb level and weak, but also cyclonic, flow at 100 mb. The lowest pressure, however, was at the 100 mb level south of the critical location so that the winds, although cyclonic, blew from the east. This is similar to Case 2 when no hurricane was formed, with the difference, however, that the easterlies over CARLA 1956 were parts of a more complex, ill-defined circulation while they formed a broad uniform band in Case 2.

5. Conclusion

What are the consequences of the statistical findings? The results allow us to conclude that hurricanes are the results of large scale meteorological processes which probably can be forecast with one to two days leeway. Even if the occurrence of the convergence and the subsequent rising of a large airmass have not been forecast, a simple analysis of the upper air data allows a half-day forecast of the birth of a tropical cyclone. It should be noted that only a dense aerological network allows such analyses as utilized here while a dense surface network, e.g., of automatic (NOMAD-type) stations, is of little help. It may be possible to induce horizontal temperature gradients in the compact rising moist airmass, through dry ice seeding, thus producing local release of the instability and causing vertical transformations prematurely before nature can organize the energy release in the form of a hurricane.

F. On the Accuracy of Radiosonde Data in the Caribbean, and a Suggestion for Improvement

1. Introduction

Radiosonde data have their deficiencies. This became obvious through the international radiosonde comparison of Payerne, and within the work of this contract, during the Conference on Tropical Meteorology held on May 11-12, 1962 in Asbury Park, New Jersey.

2. Use and limitations of radiosonde data

The accuracy of radiosonde data has primarily two aspects. First, they have to be used for operational briefing and forecasting. Fig. 18 shows a map with "checked data" taken from the Northern Hemisphere Data Tabulations of the U. S. Weather Bureau. Although the data is free of transmission errors, and although the map does not represent a high level, it cannot be reasonably analyzed without the knowledge of the maps of the following days. In other words, the operational value of the data is extremely questionable. And that, as the date shows, during the formation of hurricane CARLA, one of the most vicious storms of recent years!

By making careful comparisons in all three dimensions and in time, the researcher is able to produce from the published observations a map which could be used for operational purposes. Such a reduction, however, takes much time (at least a week) and involves the use of later maps so that a forecaster could not profit from such a procedure. At the same time, the use of the data for its second purpose, research, becomes questionable, too. The researcher has stricter requirements for accuracy than the forecaster, and he cannot deduce from such a reduced map more than his reduction concepts.

As became obvious during the conference in Asbury Park, no substantial progress in tropical meteorology can be made as long as the radiosonde data remains deficient as it is now.

3. Causes of deficiencies

There are two groups of causes that make the radiosonde data deficient: instrumental errors and station density. Taking the second group first, we can safely state that the free atmosphere has mesoscale phenomena just as the layer near the ground has. The station density does not allow an analysis of such phenomena, but we must consider the measured data as representative for the conditions of an area larger than mesoscale. It is strongly hoped that satellite data will help to overcome this problem. The suggestion for improvement of the data which concludes this section includes also the possibility to improve our ability to distinguish between macro and mesoscale effects without increasing the number of observations.

The other group of causes, making radiosonde data questionable, is of a technical nature. One can split it into human evaluation errors, insufficient quality of calibration, deficiency of measurement principle(s), and discrepancy of measurements simultaneously obtained at the ground by conventional instruments and by the radiosonde.

4. Discussion

In the first checking, it can be stated that the errors are not random. More exactly, the deviations of the published data from what can be considered as reasonable, do not cancel out in the course of a month. Fig. 19 shows that contour lines drawn without knowledge of the wind would give a completely wrong picture although each of the plotted contour values is the arithmetic mean of 30 observations. Even at very low altitudes the mean contours make some sense only when the mean winds are considered. The reader may compare in Fig. 20 the data of Jacksonville with those of Tampa, Cape Canaveral, and Miami, all in Florida; or the Lesser Antilles within themselves.

This result makes it improbable that errors committed by the observers are responsible for the deficiency of radiosonde data. As a matter of fact, a series of original recordings were re-evaluated and then compared with the published values. It was found that the observers' evaluations are among the best to be found in meteorology. Researchers and forecasters would be much better off when more observations would reach the very high standard of the radiosonde operators.

There is no reason to believe that the measuring principle accounts for the deviations from what can be considered to be close to the truth. Many of the stations that show occasional or systematic mutual inconsistencies are equipped with the same type of sonde.

Discrepancies between data taken at the ground with conventional instruments and with radiosonde can contribute to more or less essential inconsistencies aloft. The possibility of such discrepancies cannot be ruled out completely. However, correspondence with the U. S. Weather Bureau showed that they are not probable, and that, if they occur, they are not of the order of magnitude as to affect the upper air contour values as much as we feel they are.

The remaining technical reason is the calibration, and there, indeed, we find very strong evidence for inaccuracy. Fig. 21 shows the thickness 250/500 mb as reported by Grand Cayman (78-383) during the period September 1-7, 1961. One sees that the values jump after the 4th, 00Z, by approximately 50 meters (= 2.5°C), a change which is not confirmed by other stations of that region. According to a written communication from the U. S. Weather Bureau (dated September 21, 1962) the records of stations 78-383 show a change of serial number on the day in question, but no change in manufacturer or specifications. This seems to be an important clue. When changes of serial numbers are correlated with changes of instrument performance something on the side of the manufacturer seems to be wrong.

5. Suggestions for improvement

This discussion of radiosonde data shows that two major causes for deficiencies could be isolated: mesoscale effects and calibration or manufacturing faults. In order to have a closer insight into the nature of the errors, the following plan suggests a way of inexpensive inspection.

There can be no doubt that a person should inspect who knows how to analyze and who is well familiar with all technical details related to radiosondes. There may be forecasters who meet these requirements, but a forecaster has difficulties with his scheduled duties just when and because actual data are dubious. Hence, it appears to be more practical that another meteorologist makes the checks. Such men can be found in some radiosonde stations, and it is suggested that the radiosonde personnel of one certain station control from time to time the most recent data by plotting and analyzing maps and vertical cross sections. This should be done on days with apparently simple weather conditions, and the radiosonde ascent of this particular station should be skipped. The checking team should immediately inform stations whose data appear faulty or dubious. Only an immediate action ascertains that the "attacked" station can verify what happened. The change of serial number reported above could have been detected on September 5, 1961 instead of September 21, 1962, and effective measures could have been taken (1) to prevent its repetition, and (2) to correct the data before publication. In other cases, the observers may find that all technical details seem to be in order, but that the clouds show a particular configuration. In such a case one would conclude that mesoscale phenomena made the correct data unrepresentative on a synoptic scale. Such events would probably lead to new insights of the mesoscale structure of the atmosphere, and they would at future occasions lead to "warnings" issued by the observing team together with the coded data.

The checking agency as well as every radiosonde station should be charged with tracking some specific observations in form of time diagrams such as Fig. 21. (Of course, no overlapping is necessary, i.e., a level whose data are diagrammed by stations need not be traced by the central.) The control by presentation as a function of time causes, at least at the observing stations, only seconds daily and gives already valuable hints concerning the quality of the observations. This effect can be enhanced by the coordinating comparison of a central agency which should also collect all reports concerning the experience gathered by the station's personnel with the time diagrams.

6. Conclusion

Meteorology of all latitudes is now advanced to such a degree that it is necessary to measure ageostrophic components. Contour heights and winds must be of such a quality that they can be analyzed independently. Before this can be done with the daily data, it should be possible with averages over certain periods of time. The results will probably introduce a new chapter in the history of meteorology. At least a series of questions still open as yet will be answered.

There is an increasing number of meteorologists who feel that the era of radiosondes is over because it is not possible to separate geostrophic from ageostrophic components. All new devices, however, require the development of new techniques, and it cannot be said in advance if they hold what they promise. The radiosonde principle, too, is good and promising. It is only necessary to check with very little cost the current performance a little more than it is done now. Development of new devices and improvement of old ones must keep pace with the requirements of the daily routine work. Many parts of this contract work show that the possibilities of the radiosonde have not yet been exhausted, and that the continuation of such measurements is justified, if the obvious deficiencies are drastically reduced.

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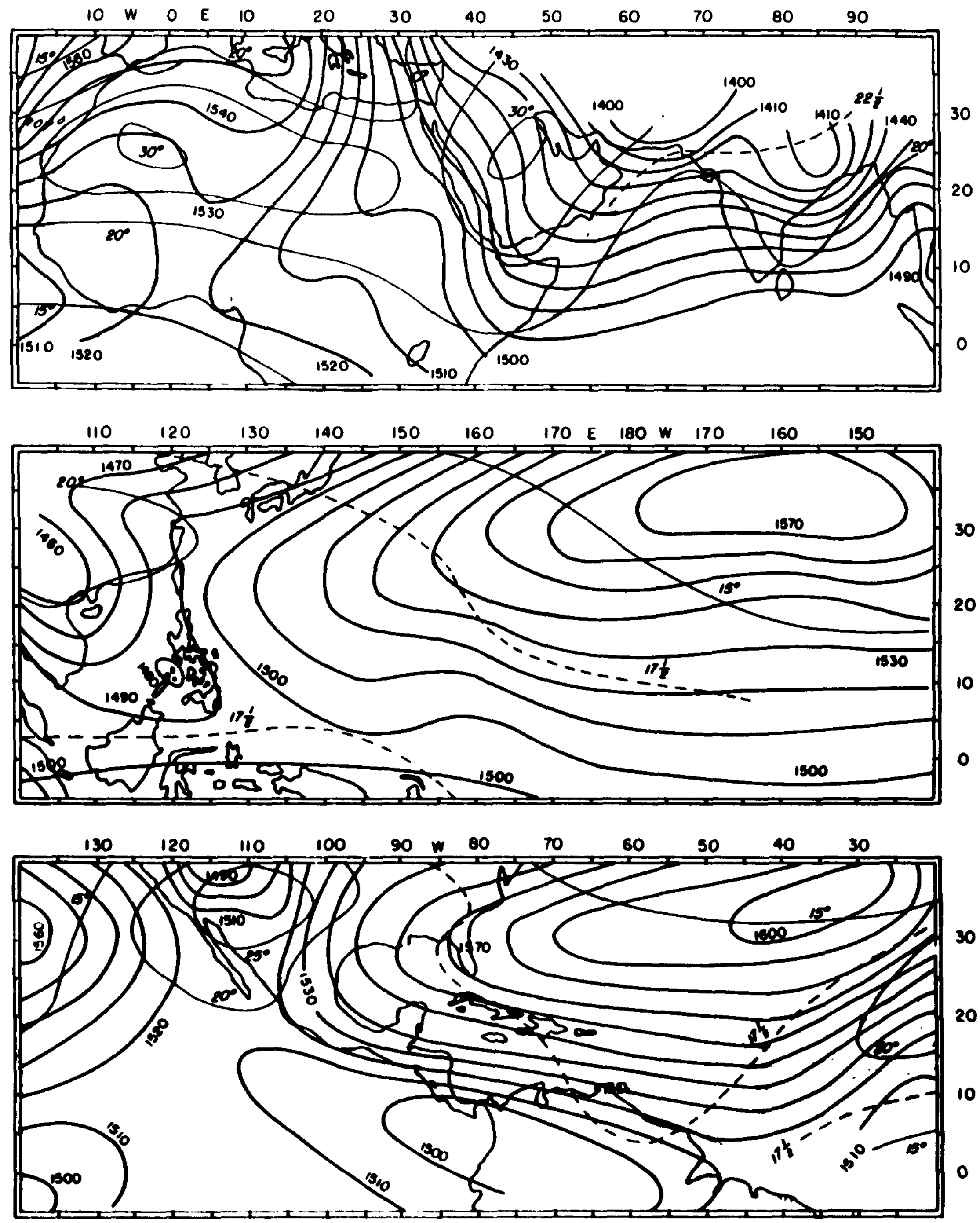
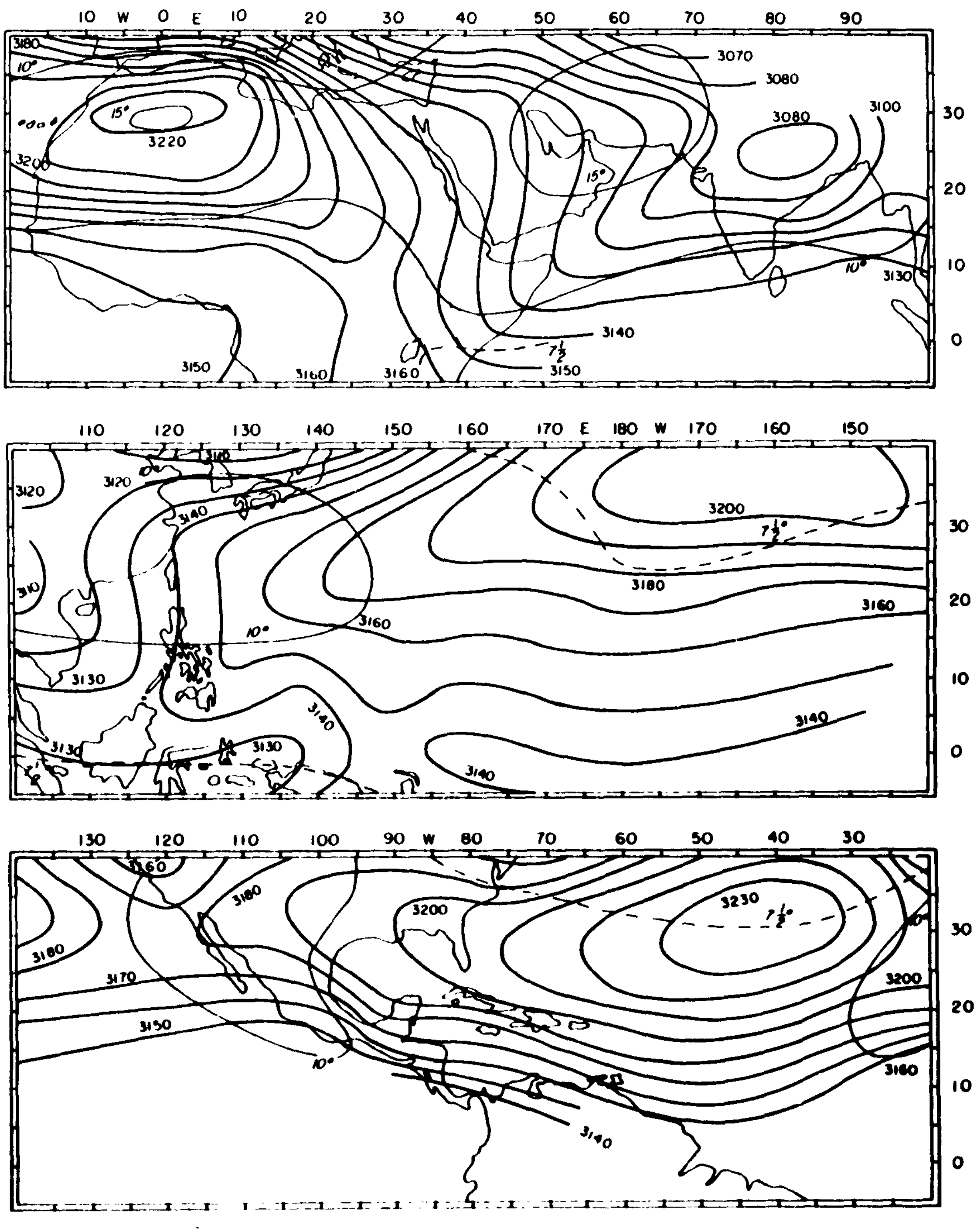


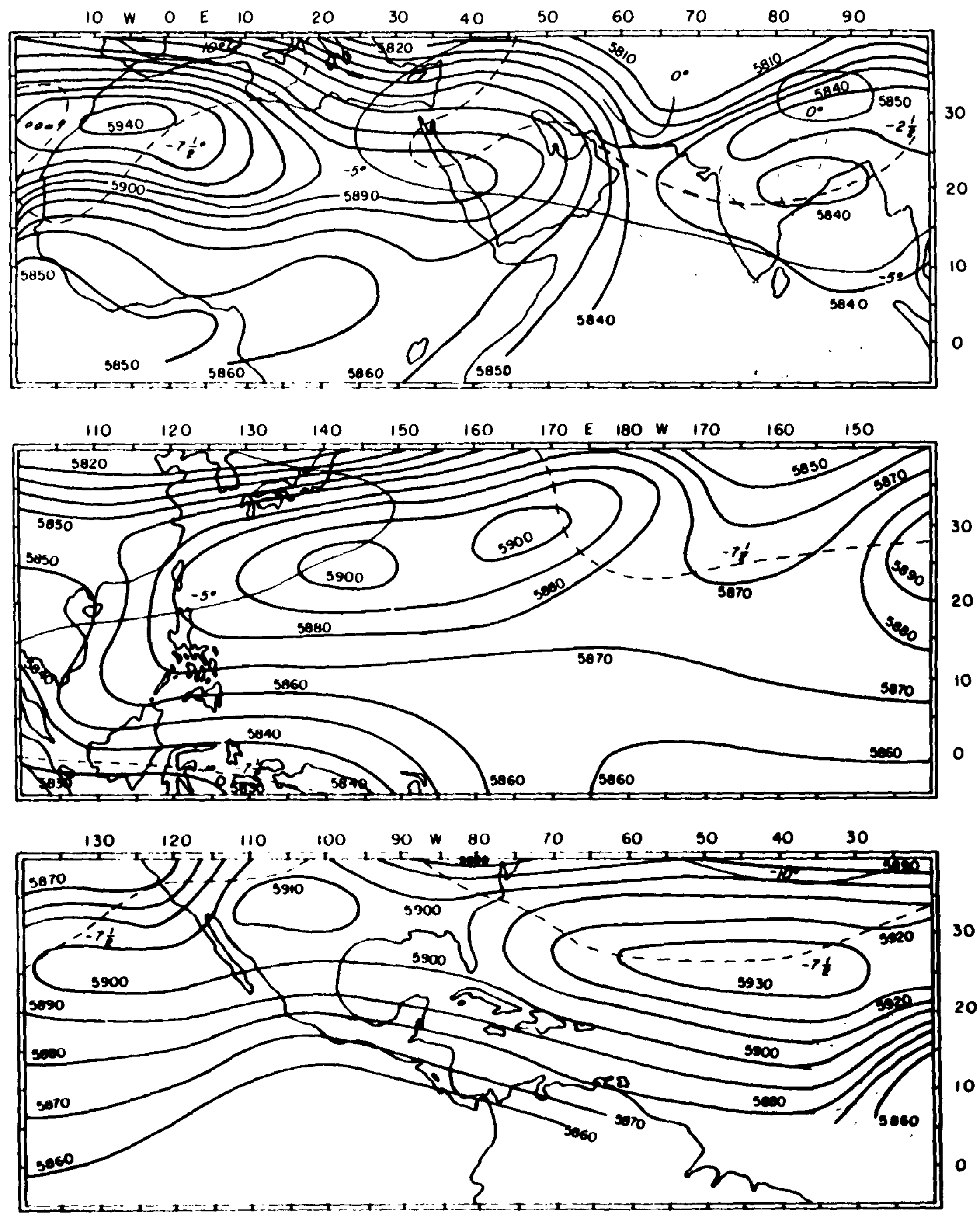
MEAN JULY CONTOUR HEIGHTS
AND TEMPERATURES, 850 mbs

FIG 1



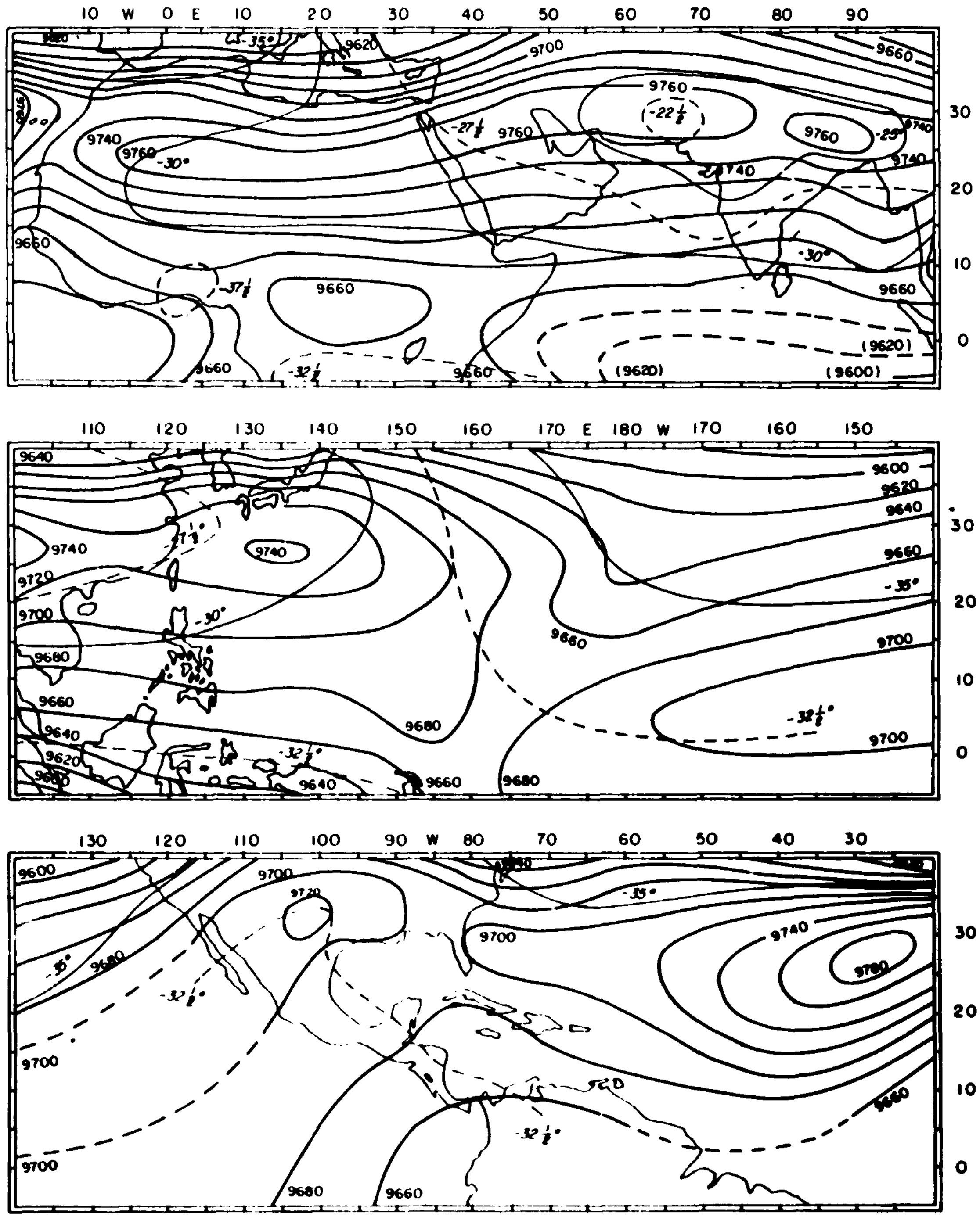
MEAN JULY CONTOUR HEIGHTS
AND TEMPERATURES, 700mbs

FIG 2



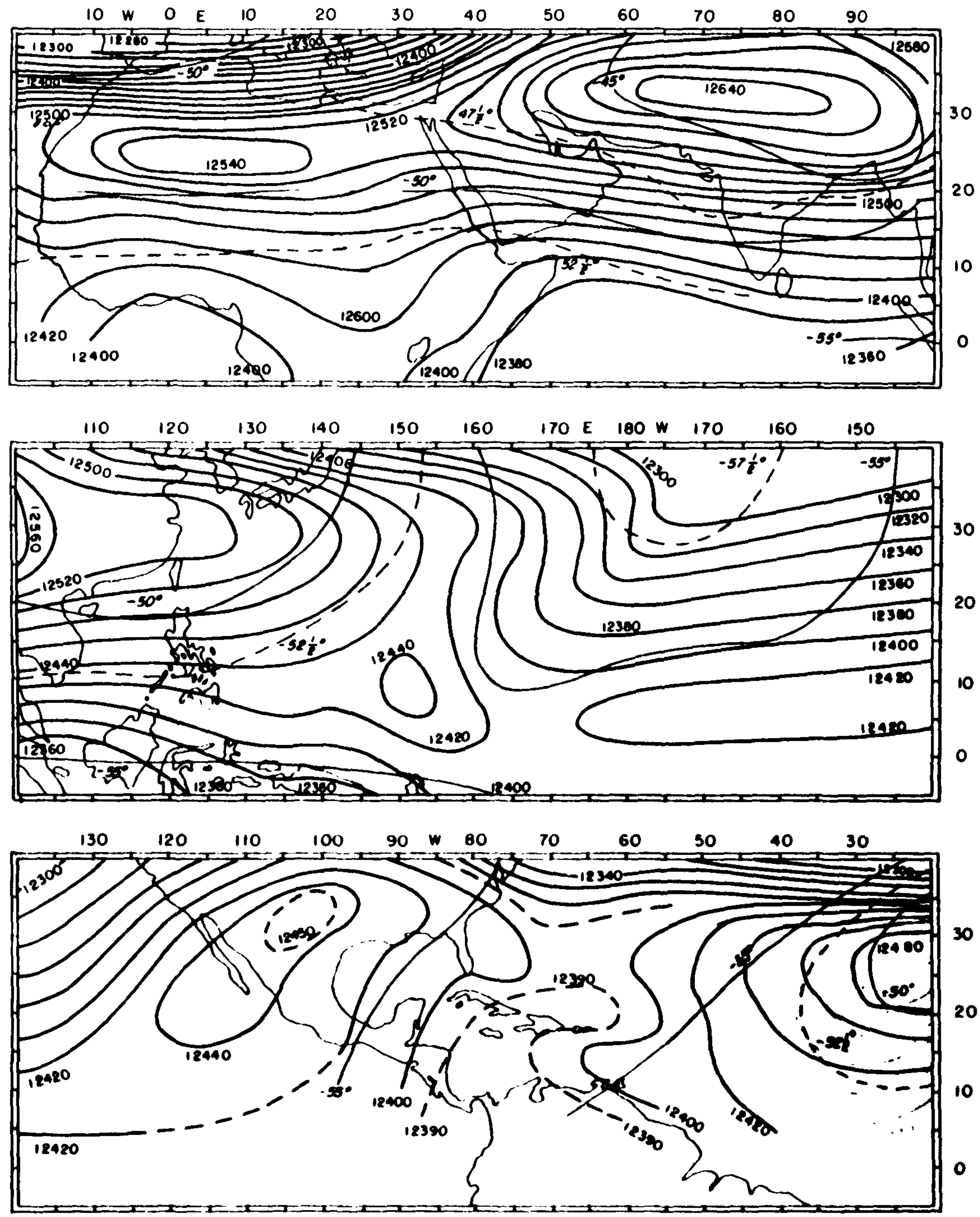
MEAN JULY CONTOUR HEIGHTS
AND TEMPERATURES, 500mbs

FIG 3



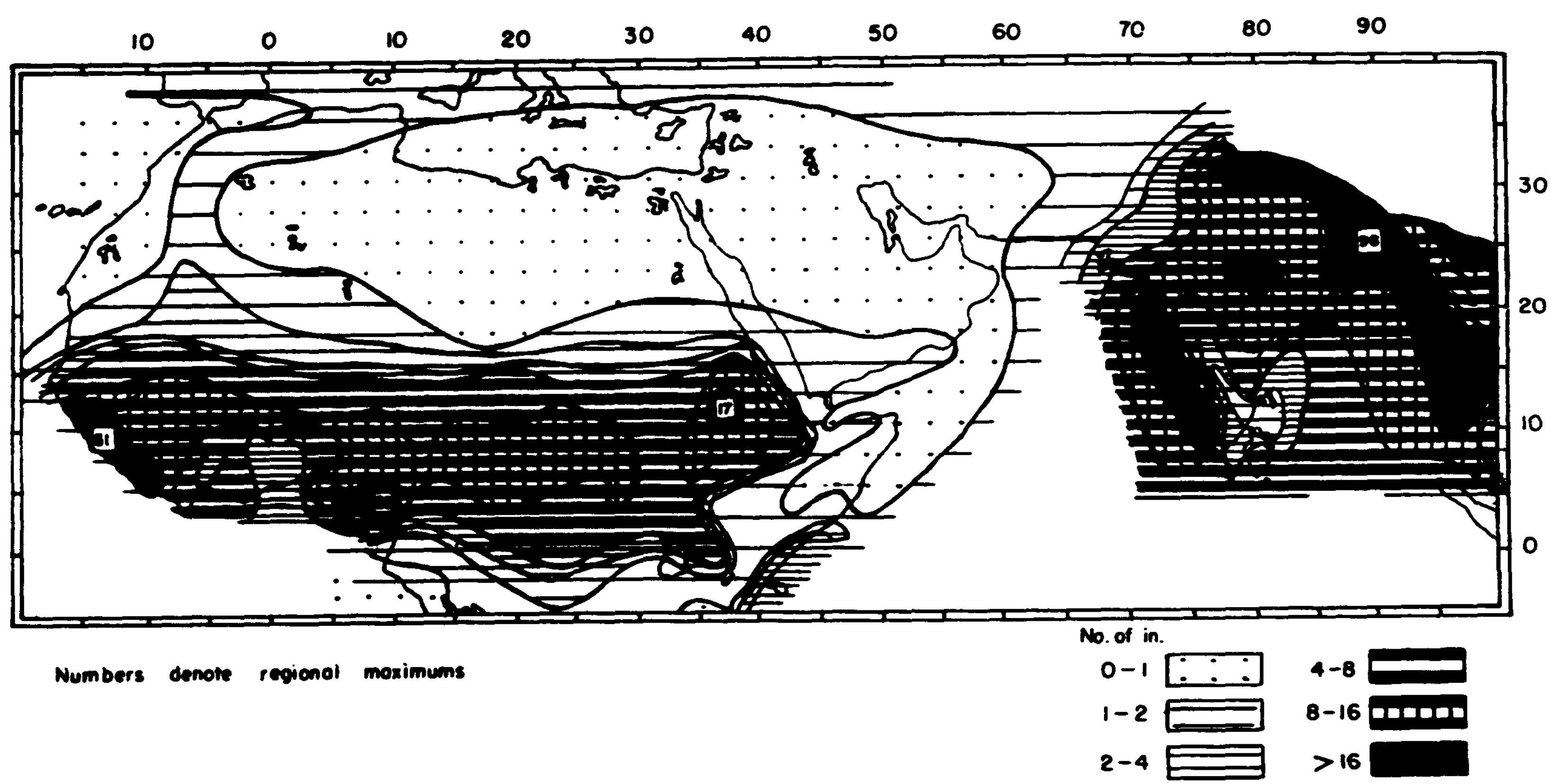
MEAN JULY CONTOUR HEIGHTS
AND TEMPERATURES, 300mbs

FIG 4



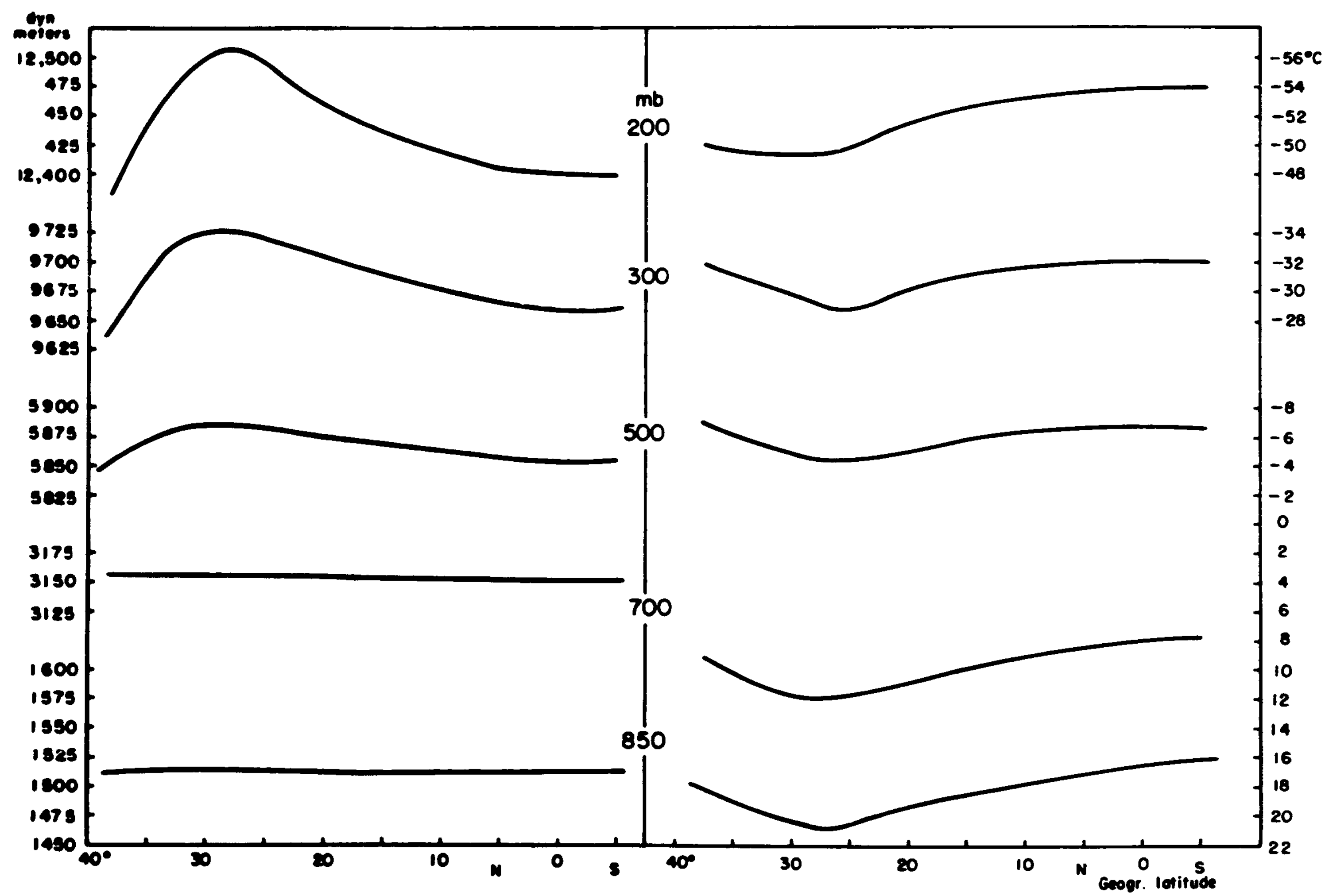
MEAN JULY CONTOUR HEIGHTS
AND TEMPERATURES, 200mbs

FIG 5



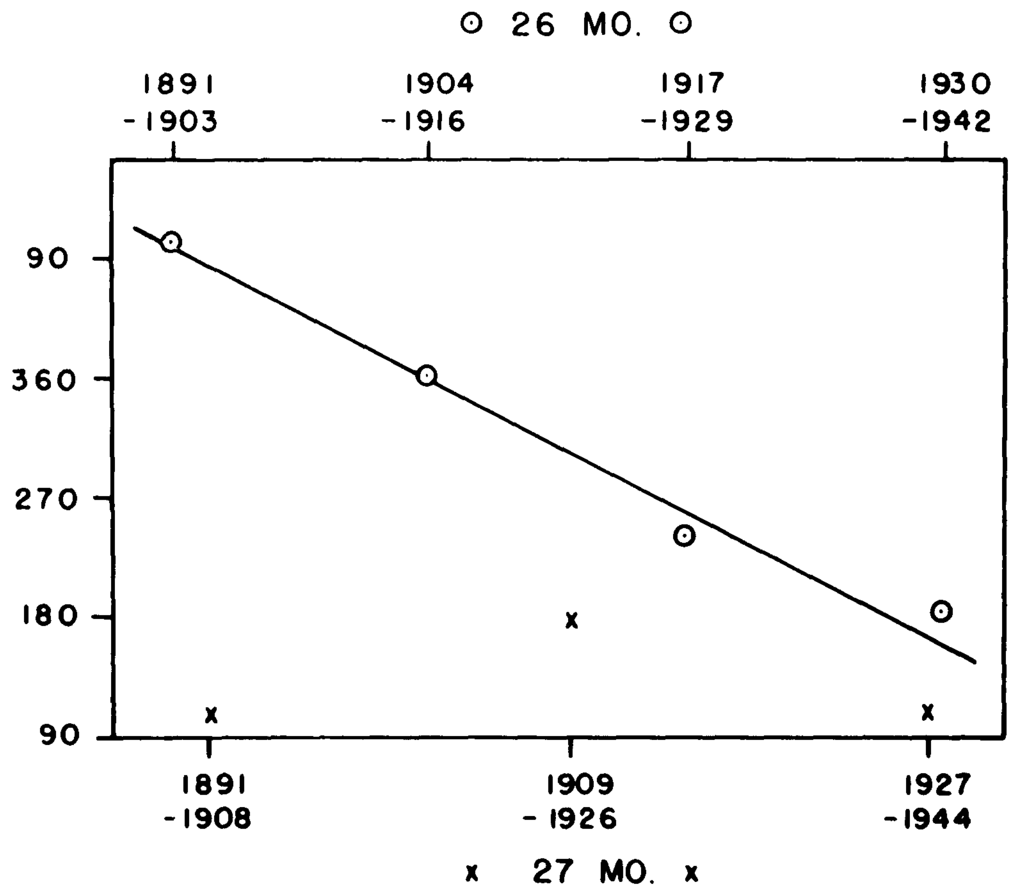
MEAN JULY PRECIPITATION, IN INCHES

FIG. 6.



LATITUDINAL DEPENDENCE OF HEIGHT AND TEMPERATURE OF STANDARD LEVELS IN JULY. AVERAGE OF ALL LONGITUDES

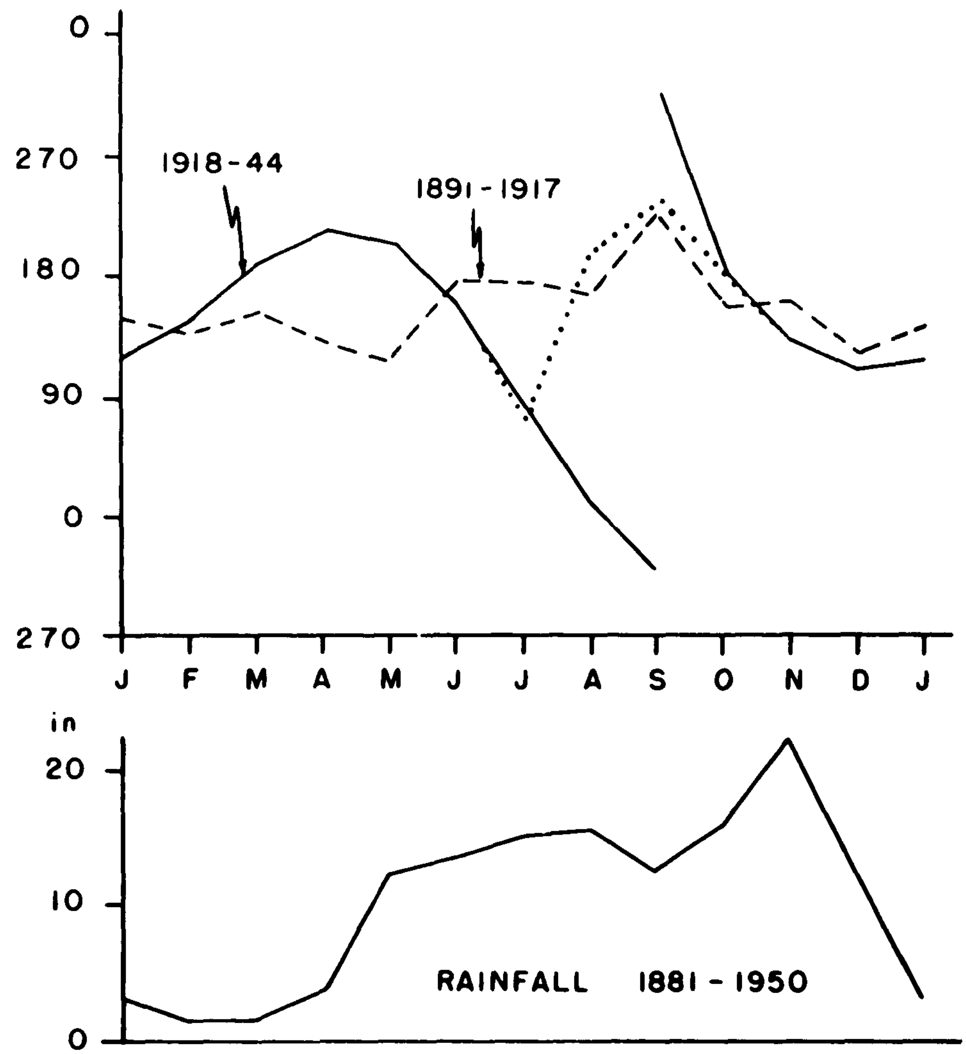
FIG. 7.



COLÓN, C.Z., RAINFALL

PHASE ANGLE OF FIRST HARMONIC

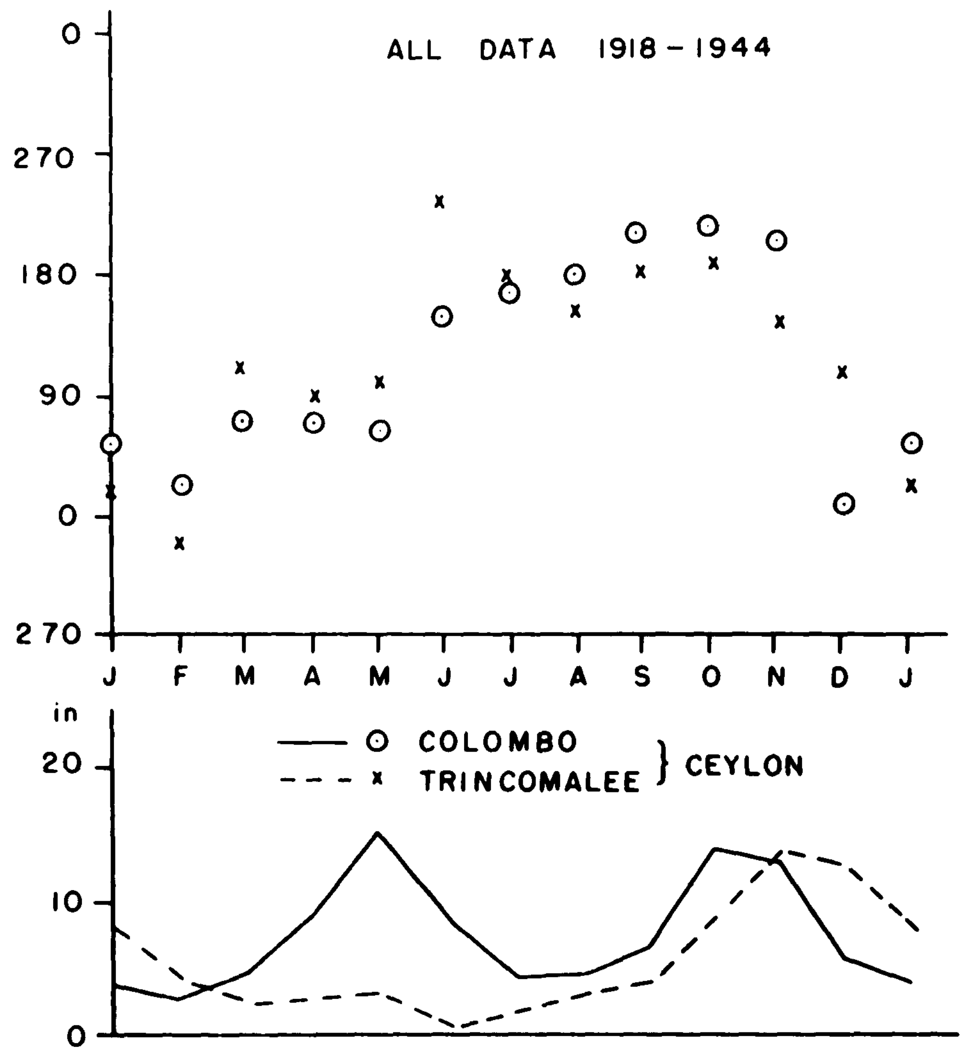
FIG. 8.



ANNUAL VARIATION OF PHASE ANGLE &
MEAN RAINFALL AT COLÓN, C.Z.

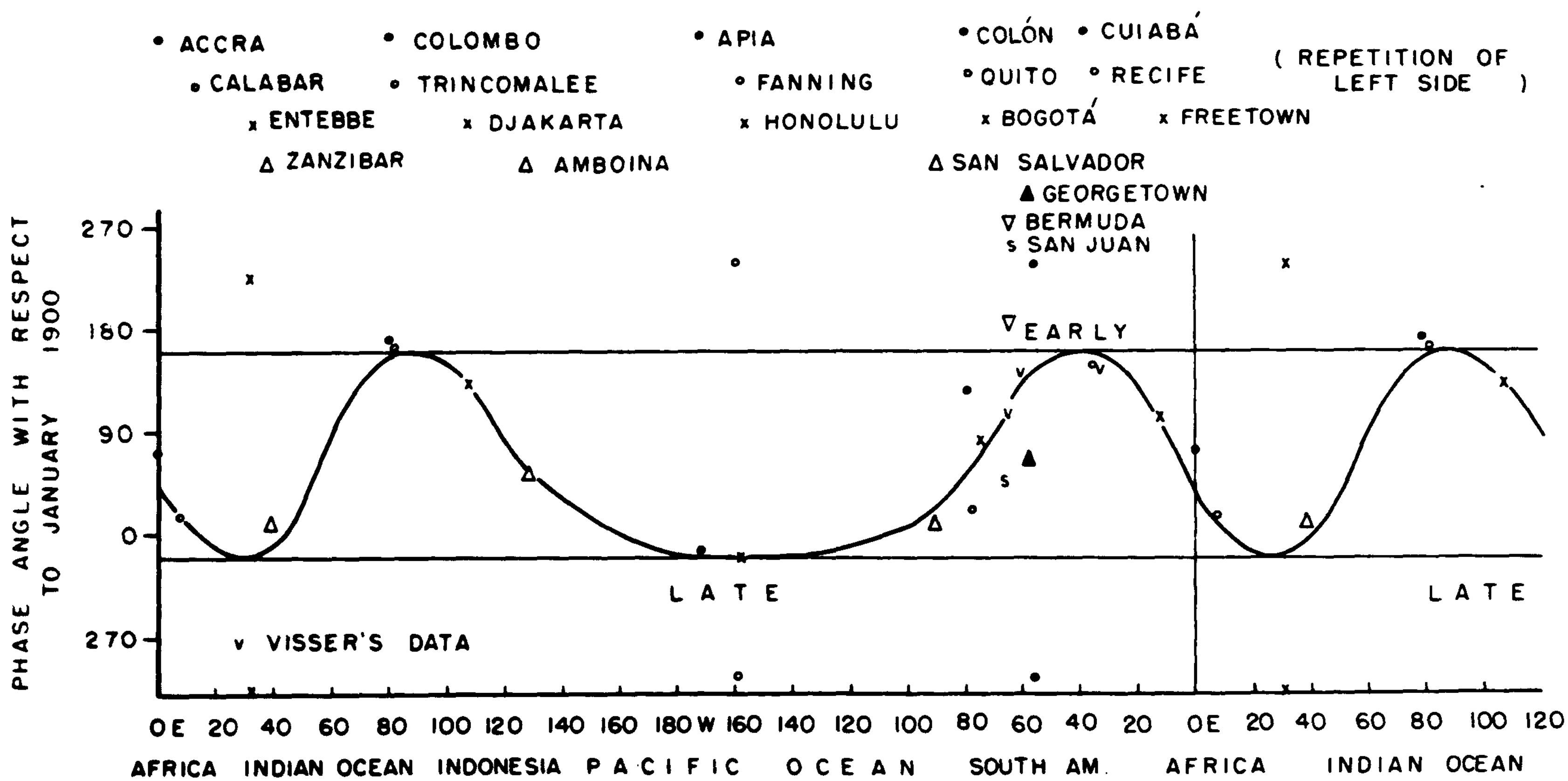
(DOTTED LINE DISREGARDS THE AUGUST VALUE)

FIG. 9.



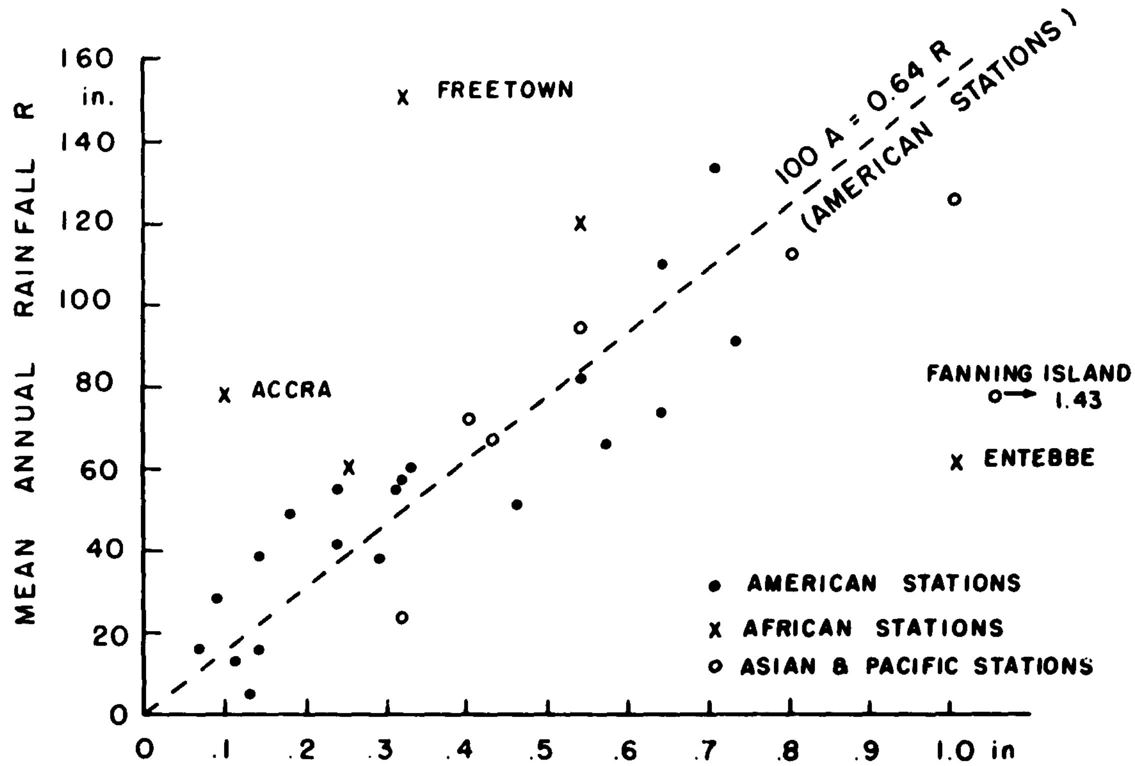
ANNUAL VARIATION OF PHASE ANGLE AND MEAN RAINFALL ON CEYLON

FIG. 10.



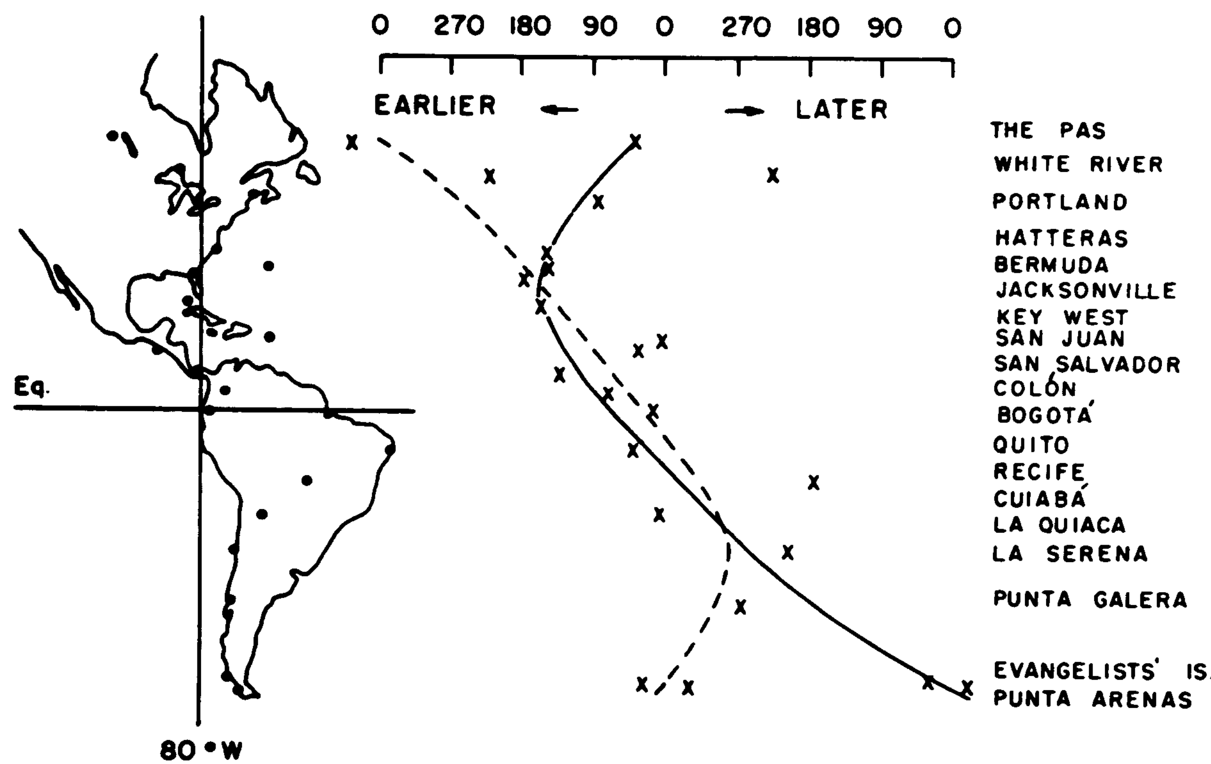
PHASE ANGLE OF 27 MONTH RAINFALL PERIODICITY
AS A FUNCTION OF LONGITUDE IN THE EQUATORIAL BELT

FIG. 11.



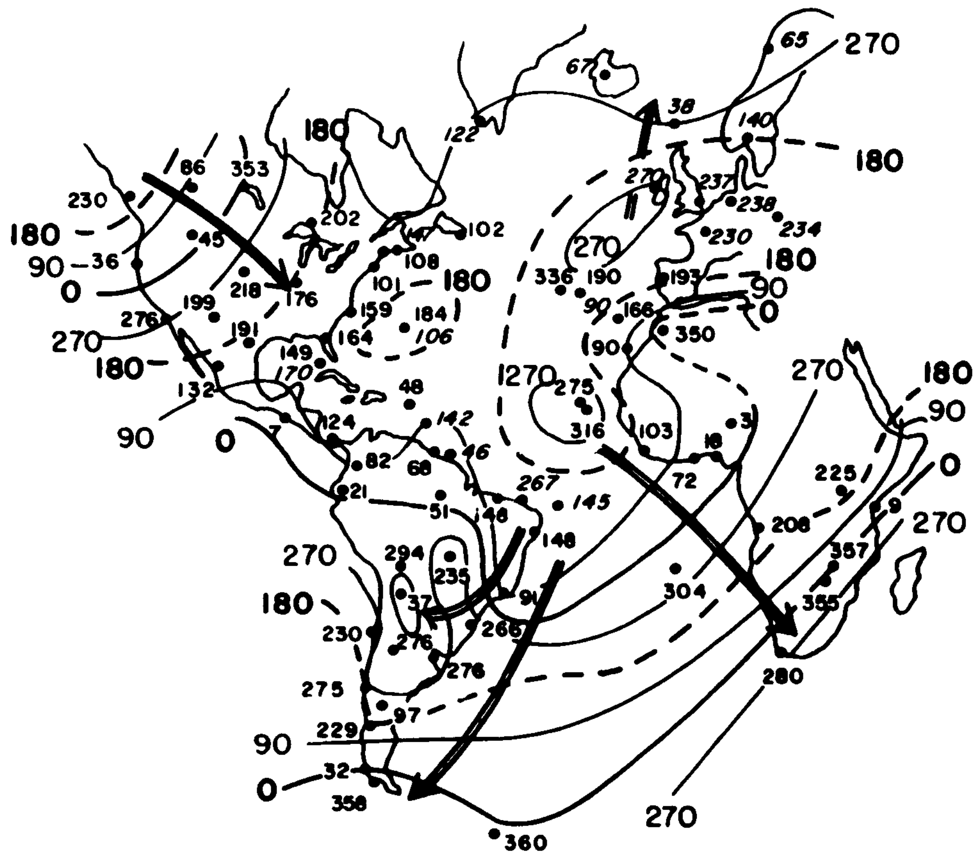
AMPLITUDE A OF 27 MONTH RAINFALL PERIOD

FIG 12.



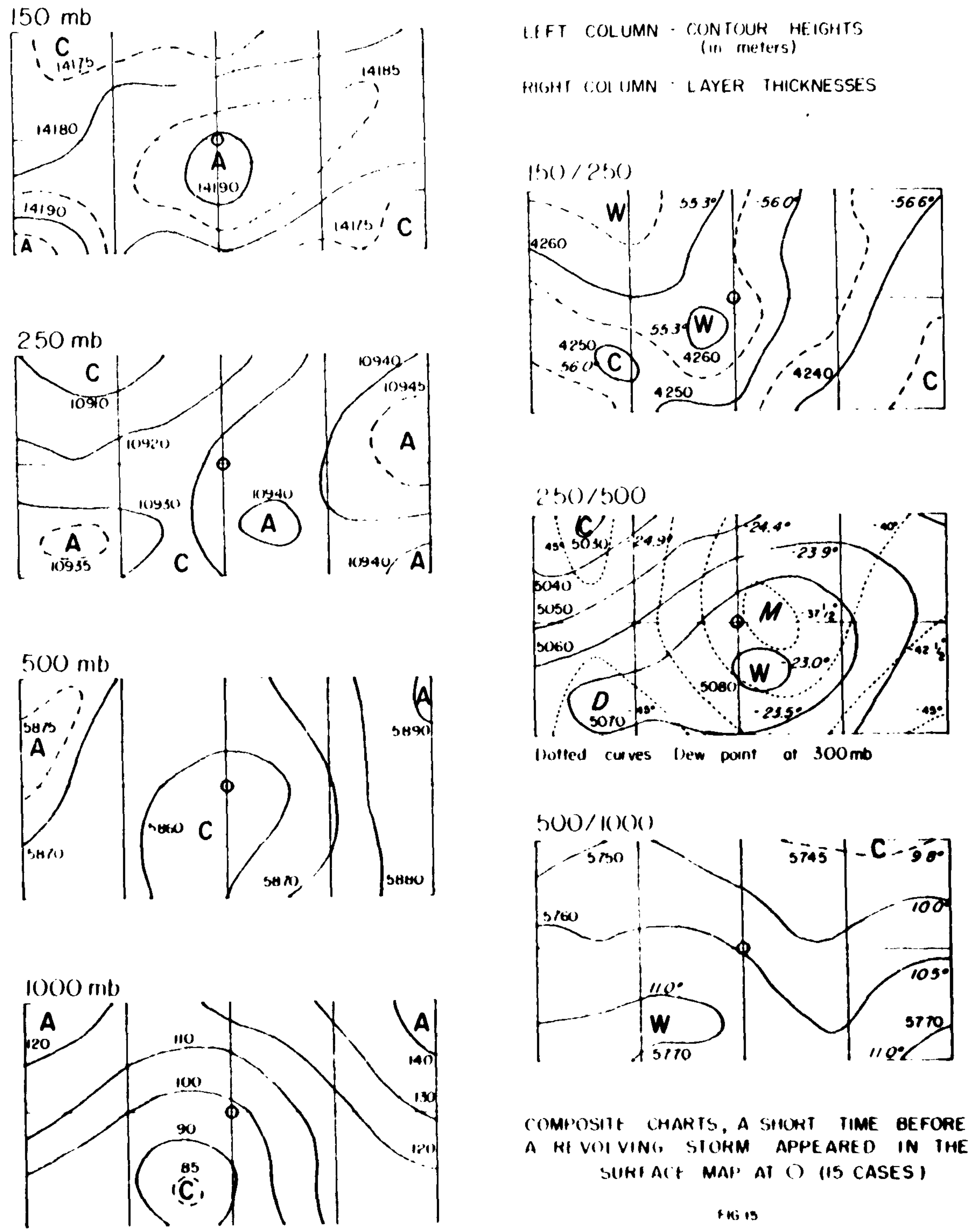
PHASE ANGLE OF 27 MONTH RAINFALL PERIODICITY (REDUCED TO 80° W BY MEANS OF FIG. 11.)

FIG. 13.



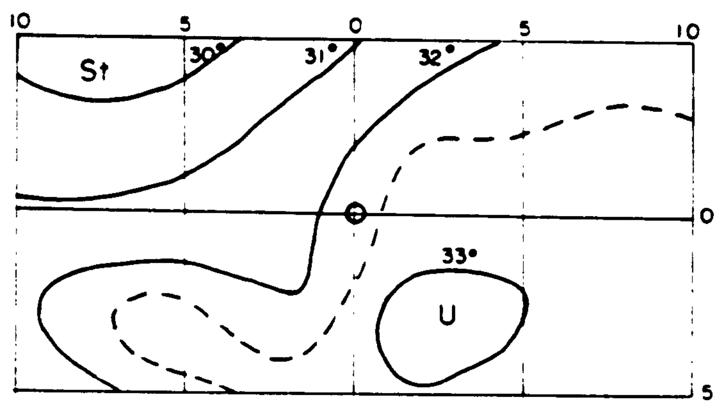
ISOPHASES OF 27 MONTH RAINFALL PERIODICITY. (Visser's data in italics)

FIG. 14.

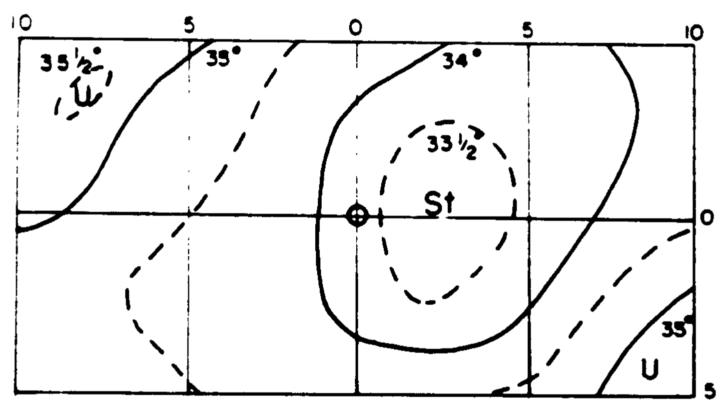


COMPOSITE CHARTS, A SHORT TIME BEFORE A REVOLVING STORM APPEARED IN THE SURFACE MAP AT ○ (15 CASES)

FIG 15

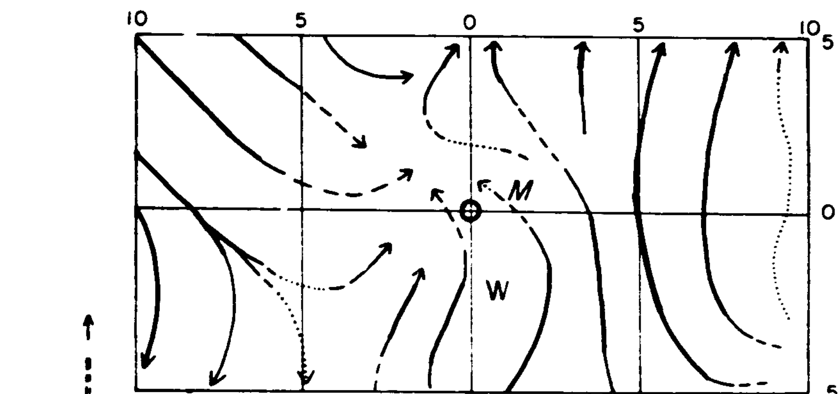


"Stability" OF THE UPPER TROPOSPHERE
(Mean temp 150/250 minus 250/500)

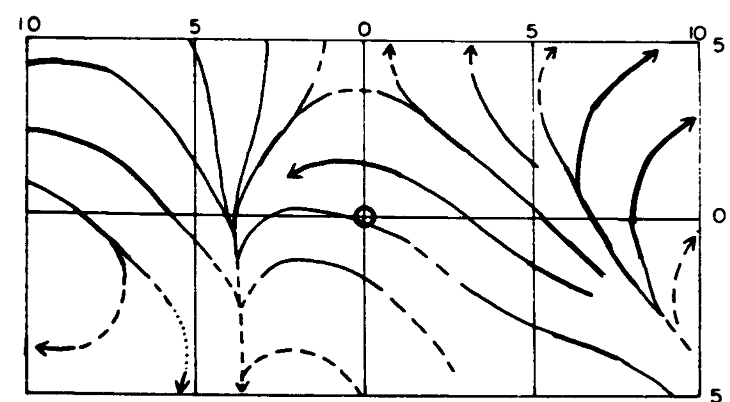


"Stability" OF THE LOWER TROPOSPHERE
(Mean temp. 250/500 minus 500/1000)

FIG. 16.



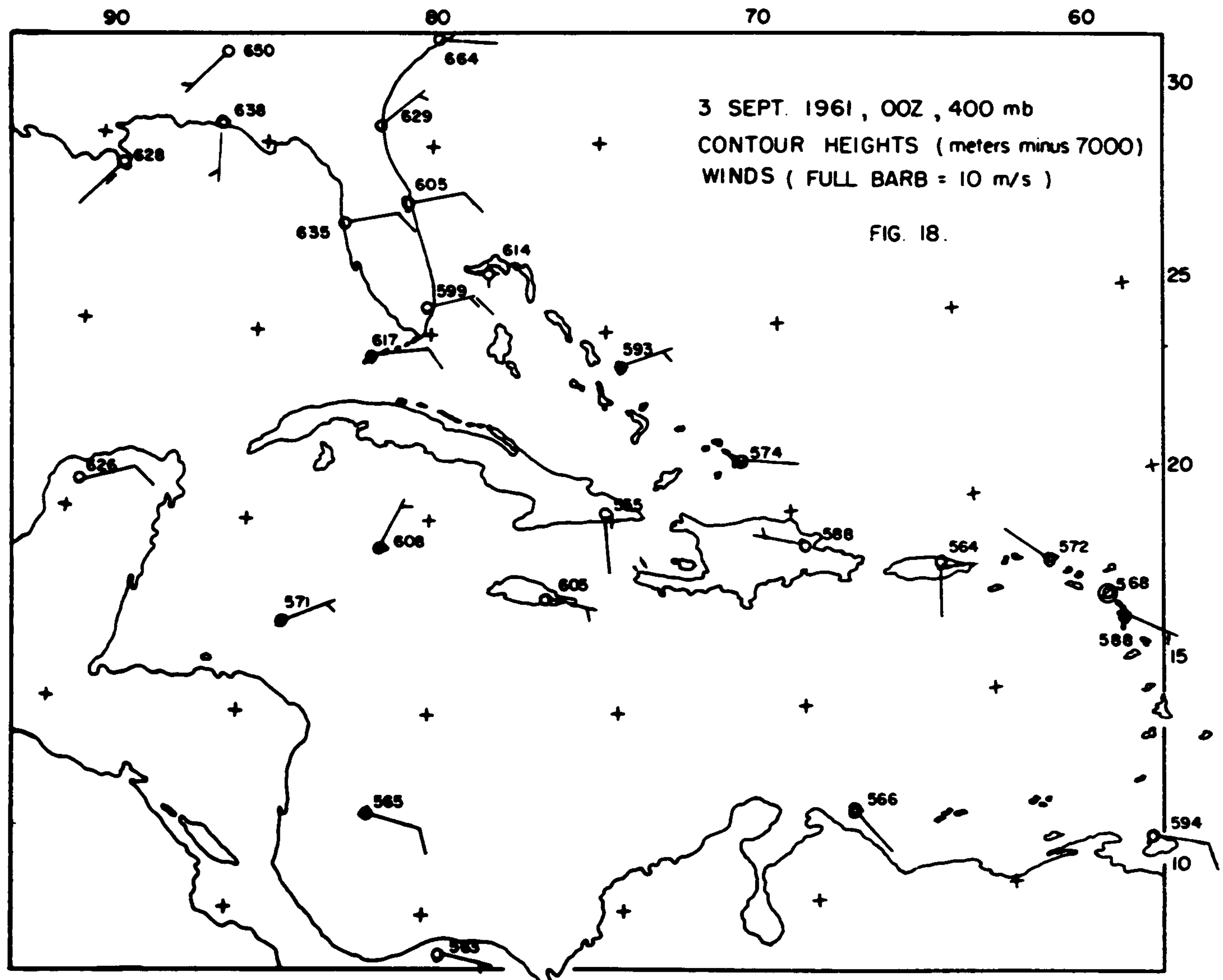
I A short time before a revolving storm appeared in the surface map at O (W, M = Temp and dew point max. of the 250/500 layer)



II. As I, but 24 hrs. earlier (based on the same stations)

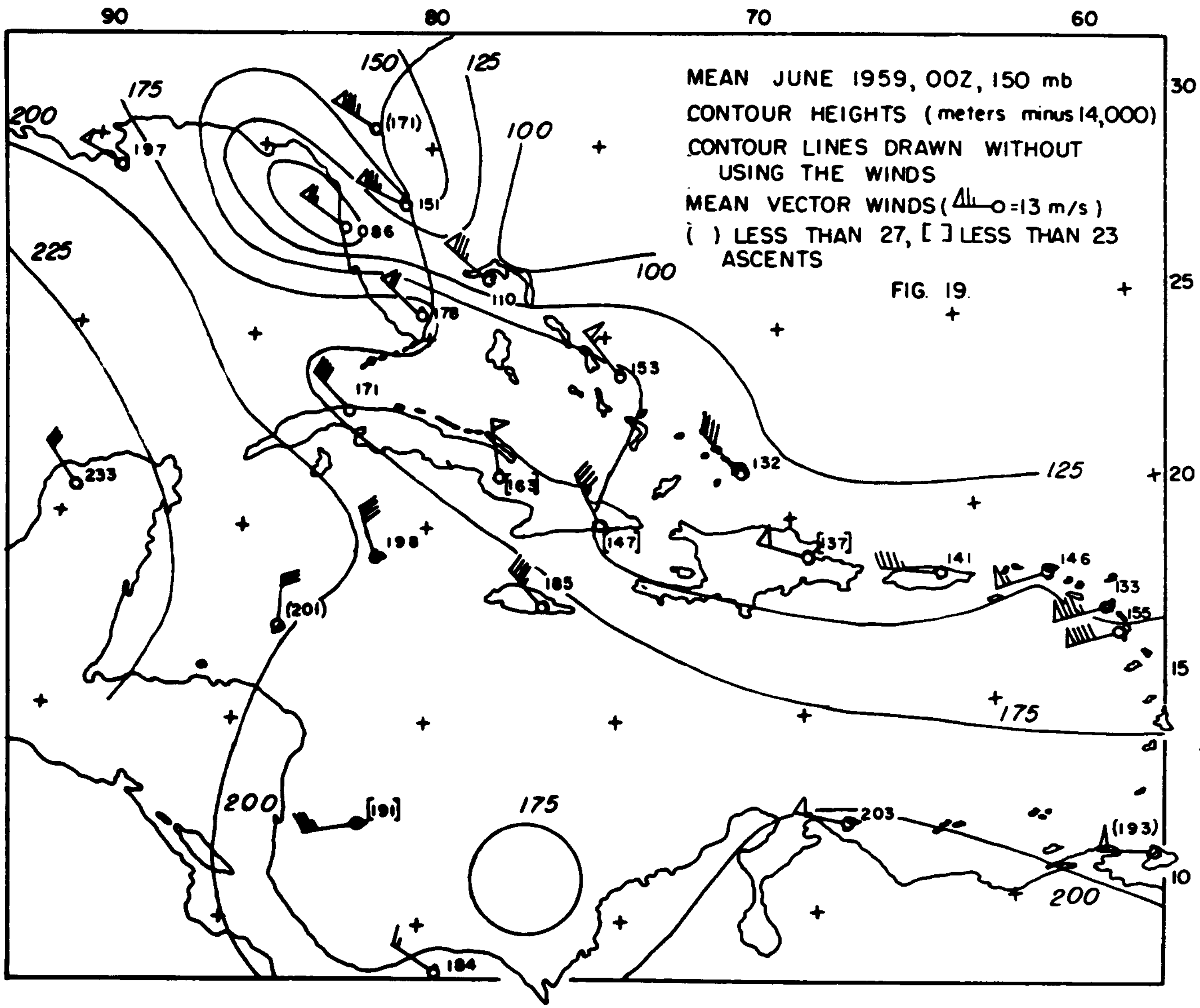
STREAMLINES AT 400 mb
(Derived from 180 wind observations)

FIG. 17.



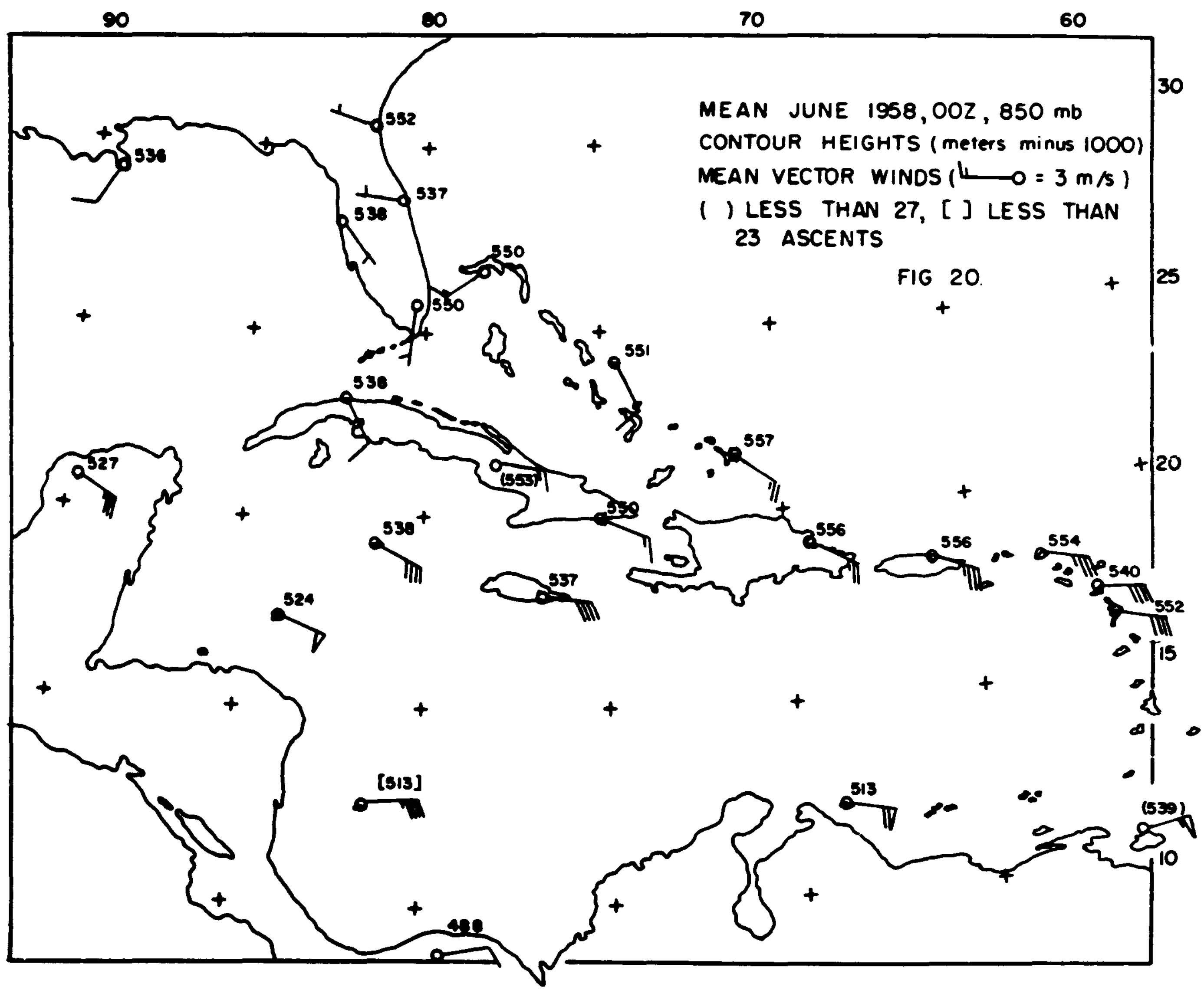
3 SEPT. 1961, 00Z, 400 mb
CONTOUR HEIGHTS (meters minus 7000)
WINDS (FULL BARB = 10 m/s)

FIG. 18.



MEAN JUNE 1959, 00Z, 150 mb
CONTOUR HEIGHTS (meters minus 14,000)
CONTOUR LINES DRAWN WITHOUT USING THE WINDS
MEAN VECTOR WINDS (=13 m/s)
( ) LESS THAN 27, [ ] LESS THAN 23 ASCENTS
90
80
70
60
30
25
20
15
10
100
125
150
175
200
225
197
(171)
151
086
110
178
171
153
132
233
163
147
137
141
146
133
155
198
185
(201)
191
203
(193)
184

FIG. 19.



MEAN JUNE 1958, 00Z, 850 mb
CONTOUR HEIGHTS (meters minus 1000)
MEAN VECTOR WINDS (└——o = 3 m/s)
( ) LESS THAN 27, [ ] LESS THAN 23 ASCENTS
90
80
70
60
30
25
20
15
10
552
536
537
538
550
550
551
538
557
527
(553)
550
556
556
554
540
552
538
537
524
[513]
513
(539)
488

FIG 20.

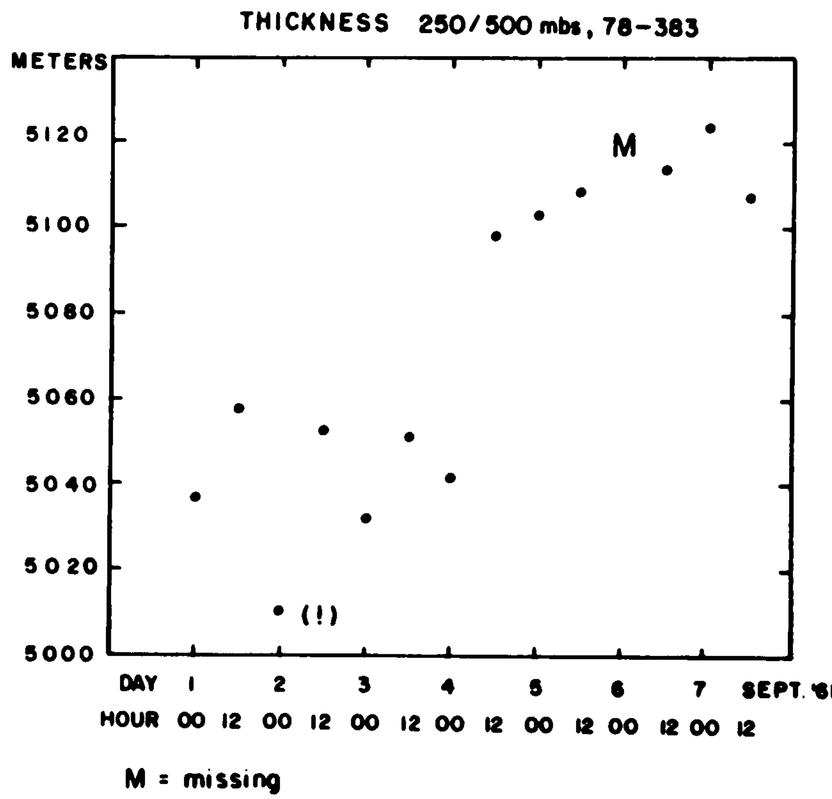

THICKNESS 250/500 mbs, 78-383
METERS
5120
5100
5080
5060
5040
5020
5000
M
(!)
DAY 1 2 3 4 5 6 7 SEPT. '61
HOUR 00 12 00 12 00 12 00 12 00 12 00 12 00 12
M = missing

FIG. 21.

APPENDIX

A. Frequency of cloud types around a forming tropical revolving storm for overlapping 5 x 5° fields in per cent of the available observations.

The square in the middle refers to the field which extends 2.5° in either direction from the location where a revolving storm formed 6-24 hrs. later.

◯ absolute maximum of the map
◡ secondary maximum
number of observations in parenthesis

Total Observations
(15 cases)

	10°		5°		0°		5°		10°
5°	57	69	74	76	63	57	59	53	53
	57	63	72	69	60	59	55	49	50
0°	56	52	57	63	66	60	54	54	50
	52	49	51	55	62	61	54	52	43
5°	38	42	51	59	66	67	57	51	41

Synoptic Code

1 (94)

7	9	14	13	13	14	14	17	13
16	11	6	6	12	8	9	14	6
21	13	7	5	3	3	9	9	4
17	16	10	9	10	10	13	10	7
13	12	10	12	12	12	14	14	15

(36)

2	3	8	9	8	7	3	6	6
4	3	6	7	7	7	4	4	4
5	8	5	3	5	7	4	6	4
4	6	4	2	5	5	4	6	2
0	2	2	0	2	3	5	6	2

(109)

16	16	20	24	14	12	12	6	9
18	16	15	19	10	10	13	14	12
14	17	14	11	9	7	7	13	16
13	18	16	9	10	11	9	6	5
5	10	12	15	15	15	12	10	12

2 (212)

21	19	22	32	29	26	32	30	34
16	17	29	36	30	29	35	24	34
16	17	28	27	20	22	28	28	36
17	16	24	22	11	15	28	35	33
13	14	22	24	12	16	33	35	37

(62)

9	6	4	4	6	7	3	4	4
5	10	10	7	7	10	7	2	0
4	10	12	8	14	20	17	9	4
8	8	6	4	13	15	11	8	7
11	5	6	7	8	7	7	4	2

(59)

9	13	11	12	13	9	8	8	9
5	11	10	10	12	7	4	4	6
2	4	7	5	3	7	7	4	2
6	2	4	4	2	5	9	6	0
11	7	10	10	2	1	7	10	5

3 (85)

19	15	14	9	6	4	5	6	4
16	14	15	15	12	8	5	6	4
11	10	14	19	17	13	7	6	4
12	16	12	9	13	16	11	4	5
11	21	12	3	10	10	9	6	5

(79)

16	10	9	8	6	11	10	17	19
18	11	8	7	7	8	7	12	10
13	13	9	3	3	10	11	7	8
12	16	12	4	3	10	17	12	7
11	12	10	3	3	4	9	8	7

(64)

11	12	11	8	11	14	8	6	9
11	10	6	9	10	7	4	6	12
9	10	7	14	11	3	4	6	6
6	8	12	18	6	3	6	4	5
5	5	6	7	3	4	5	4	5

4 (28)

0	3	4	8	8	0	0	2	4
0	2	4	6	3	3	4	2	4
0	0	2	2	2	7	6	2	2
0	2	2	2	3	3	6	8	7
0	2	4	5	5	3	9	10	5

(52)

2	1	3	7	8	4	3	4	4
5	3	4	12	8	7	9	2	4
7	6	5	8	3	10	13	2	2
6	4	8	11	6	8	9	4	2
5	7	8	8	8	10	14	10	10

(15)

0	1	3	3	2	0	0	0	2
0	3	4	3	2	0	4	4	2
2	4	2	2	2	0	4	6	4
4	2	0	2	2	0	0	2	5
3	0	0	0	0	0	2	4	5

Synoptic Code

5 (53)

21	9	3	4	6	7	5	2	4
14	8	3	3	2	5	9	4	0
9	4	4	2	2	5	7	4	2
10	4	2	0	5	7	4	4	5
5	5	6	8	12	7	4	6	5

(30)

2	3	4	3	3	9	12	8	4
4	2	0	1	3	7	11	10	4
4	2	0	2	2	2	7	7	2
2	0	0	0	0	2	6	6	2
3	0	2	3	2	4	4	6	5

(49)

7	7	5	9	16	9	2	4	2
7	8	6	4	5	2	0	0	0
4	6	5	3	3	2	4	6	2
6	8	6	2	0	0	6	8	5
13	14	10	5	3	4	7	6	7

6 (21)

7	3	1	3	2	2	3	2	2
4	0	1	3	2	2	2	0	0
0	2	4	3	2	0	2	4	4
2	4	4	4	3	2	2	4	5
8	7	0	2	5	3	0	0	0

(70)

5	7	8	13	17	18	12	4	2
9	5	7	10	12	8	9	6	8
11	8	9	11	8	5	9	11	14
4	4	4	11	10	8	7	8	9
5	2	6	7	6	6	5	4	5

(65)

7	3	3	7	8	4	3	8	8
4	3	7	9	3	3	5	10	8
9	6	14	11	0	3	6	7	12
13	4	10	9	5	7	7	10	14
18	14	10	10	12	9	9	8	10

7 (60)

4	1	4	5	6	7	7	13	8
2	0	1	3	12	12	5	8	6
5	4	5	8	24	23	9	13	10
8	6	6	7	16	15	7	12	9
11	7	4	2	5	7	4	0	0

(96)

18	19	8	7	11	11	14	17	9
11	16	8	7	12	14	13	8	6
11	12	12	13	15	13	7	7	12
14	10	12	9	13	13	7	6	14
11	5	10	14	14	12	5	8	15

(29)

2	3	3	0	2	5	7	8	4
2	2	1	1	3	5	5	4	2
2	4	2	2	3	5	6	4	2
12	10	2	2	3	3	6	6	2
16	10	0	2	3	1	2	4	5

8 (103)

5	7	7	8	13	23	17	11	15
7	11	17	15	12	17	20	22	22
9	13	14	14	11	8	15	15	16
10	10	2	13	19	15	13	12	19
11	7	6	17	18	13	12	14	17

(23)

4	3	3	3	5	4	3	2	4
7	2	1	1	3	2	2	4	2
9	0	0	0	0	0	2	4	2
6	4	4	0	0	0	4	4	0
0	5	4	0	0	0	4	4	2

(31)

5	3	4	1	0	2	3	2	0
2	0	0	1	3	3	4	2	6
5	2	0	3	5	3	4	6	14
6	4	0	4	3	7	7	6	12
5	2	0	2	2	4	5	4	5

9 (88)

7	12	3	4	8	11	8	6	8
11	13	7	10	15	8	4	14	18
9	12	11	17	15	7	7	17	14
12	10	18	20	13	8	7	8	5
13	12	18	15	15	16	7	6	10

(24)

0	0	3	7	5	2	3	4	2
0	2	6	9	7	3	2	2	2
5	8	4	8	9	3	0	2	2
8	8	2	4	3	3	2	2	2
3	2	2	2	0	1	2	2	2

(17)

0	1	1	0	0	2	7	8	2
2	0	1	3	5	7	7	6	2
[illegible]	0	2	3	5	5	2	4	4
0	0	0	2	3	2	0	2	2
0	0	0	3	5	1	0	0	0

0 0 (94)

9	22	24	16	11	5	7	11	9
14	24	18	7	3	5	4	2	6
18	25	14	3	5	12	7	2	8
13	16	22	11	3	10	9	6	7
16	10	18	10	5	10	9	4	7

0 (318)

32	45	50	41	30	21	25	32	41
30	46	47	35	27	17	18	37	54
32	37	40	35	24	15	20	33	42
37	41	47	47	32	26	30	42	46
45	50	45	54	50	45	44	43	49

0 (272)

23	28	36	32	30	30	32	43	43
28	35	43	35	28	22	24	31	28
34	35	33	32	23	17	26	24	18
23	31	39	38	34	25	28	35	33
18	26	41	39	38	38	40	39	46

X X (6)

0	0	0	0	0	2	2	0	0
2	0	0	0	0	2	4	2	0
2	0	0	2	2	0	2	2	0
0	0	0	4	3	0	0	0	0
0	2	2	2	2	0	0	0	0

X (56)

12	3	0	1	2	9	10	4	6
9	2	3	4	10	17	18	12	6
5	4	4	10	18	15	9	11	8
8	4	2	9	15	10	4	4	7
8	10	6	2	9	9	2	0	0

X (138)

25	12	3	7	16	25	17	9	11
21	11	8	9	20	34	31	18	12
18	13	16	16	38	41	31	22	20
12	12	12	13	32	38	22	17	19
5	12	12	7	18	21	11	6	2

B. Frequency of (groups of) selected cloud types around a forming tropical revolving storm for overlapping 5 x 5° fields in per cent of all cloud observations of the same altitude layer, i.e. the reference level excludes C = 0 and C = X.
Grouping has been done only for correlation of frequency distributions, not for meteorological reasoning.

+ (good weather)

8	15	3	25	23	15	15	21	19
19	17	12	12	16	13	14	17	11
27	18	10	7	4	11	16	12	7
20	22	15	13	14	15	20	18	15
16	16	17	19	18	17	25	26	21

+ (showers)

29	35	37	47	46	54	53	47	54
27	38	56	53	43	49	59	49	60
31	41	49	43	38	34	47	44	56
31	32	32	40	33	33	45	49	55
28	24	34	46	35	33	50	54	58

+ ... + (bad weather)

33	35	34	22	23	22	22	28	21
33	36	29	29	40	31	16	30	30
31	33	35	47	54	49	26	36	30
36	39	45	43	45	44	29	26	20
41	46	41	23	32	38	21	13	16

(Notice: Compare the "bad weather" statistics with the tabulations of $C_L = 3$, $C_L = 7$, $C_L = 9$, and - above all - $C_L = 0$, table A).

+ (non-convectional)

31	15	5	8	9	9	9	4	6
21	10	5	6	3	7	12	4	0
11	8	8	5	3	6	10	8	7
13	10	7	4	9	9	6	8	10
16	14	7	12	18	12	4	7	5

+ +

12	19	38	49	43	37	29	21	18
20	18	36	42	38	28	23	24	35
32	35	31	40	37	21	18	33	40
25	30	19	38	33	26	19	29	30
17	18	20	19	18	23	23	23	19

+

47	47	24	18	25	25	26	32	25
26	48	36	23	28	36	31	20	15
21	32	44	37	50	48	34	30	32
34	30	35	29	48	44	28	25	45
44	23	32	46	54	42	23	23	33

+ + M

37	31	32	22	20	14	40	41	50
46	27	19	16	21	26	31	52	40
37	24	16	9	8	17	29	33	24
31	33	31	8	6	18	39	39	20
28	41	32	15	11	13	29	35	29

3	3	5	11	11	5	5	6	7
9	6	8	19	13	10	14	4	10
10	9	9	14	5	14	18	3	4
9	7	15	25	12	13	14	7	5
11	18	16	19	18	23	26	19	19

+

52	46	61	50	39	47	40	24	42
57	48	42	46	37	38	36	40	57
42	50	32	40	54	30	26	34	35
29	46	56	52	48	39	30	20	19
14	23	38	41	41	46	36	28	32

+

31	34	27	33	44	31	20	24	25
25	36	31	24	31	19	8	8	10
10	18	19	12	17	25	26	17	26
18	18	20	11	5	13	30	28	9
31	35	42	28	10	14	28	32	23

+

14	10	11	2	2	13	20	20	8
7	3	3	5	12	19	20	12	13
26	14	22	23	12	20	22	17	26
26	25	4	11	19	26	26	2[illegible]	29
28	19	0	6	10	14	1[illegible]	16	18

+

3	7	9	15	16	6	7	16	21
7	12	22	19	9	8	20	28	17
19	18	24	20	4	10	22	24	26
26	11	20	22	19	17	15	24	38
28	23	21	19	28	21	21	24	27

0	2	2	0	0	3	13	16	4
4	0	3	5	9	15	16	12	3
3	0	3	5	12	15	4	7	6
0	0	0	4	9	4	0	4	5
0	0	0	6	10	0	0	0	0

C. Frequency of certain weather types in per cent of all available observations.

(1) Thunderstorms, ww = 13, 17, 29, 88-99, W = 9
(2) Heavy rain, ww = 62-65, and 81
(3) Clear sky, $C_L = C_M = C_H = 0$

Thunderstorm (Ꞧ)

2	1	0	0	2	2	0	0	2
9	6	3	1	3	3	0	0	2
11	12	9	8	5	3	4	2	0
6	8	8	9	5	7	11	4	2
8	10	6	5	5	7	11	6	5

Heavy rain ($\overset{\bullet}{\nabla}$)

2	1	0	0	0	4	5	6	6
0	2	3	1	2	5	5	8	6
0	4	5	5	9	12	7	7	6
0	2	2	4	8	10	6	4	5
0	2	2	0	0	1	2	0	0

Clear sky

0	3	4	1	2	2	0	0	0
2	8	7	1	0	0	2	2	2
4	8	7	2	2	2	2	2	2
2	4	8	4	2	2	2	2	0
3	2	4	2	2	4	5	2	0

Correlation coefficients between percentage frequencies given in B and C.

r (Ꞧ, ɕ) = 0.46
r (Ꞧ, ῷ) = −0.48
r ($\overset{\bullet}{\nabla}$, ɕ) = −0.22
r ($\overset{\bullet}{\nabla}$, ῷ) = 0.50

r (Ꞧ, $\overset{\bullet}{\nabla}$) = − 0.19

r (ɕ, ῷ) = − 0.18

r(Ꞧ minus $\overset{\bullet}{\nabla}$, ɕ minus ῷ) = +0.71

(45 pairs each)

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