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The Meteorology of Central Africa - and Appendixes I - II

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A comprehensive survey of the meteorology of Central Africa is given. Studies were made of the general circulation in the lower troposphere, the air mass properties, the intertropical front, haze, dust and sandstorms, Harmattan haze, rainfall in the Sudan, and of dynamic climatology. Five basic principles of tropical meteorology were found. The diurnal insolation process is so powerful that other effects are masked. Flow is extremely nongradient both in direction and velocity. The convective circulations occurring in the tropics are superimposed on systematic eddies of varying degrees of magnitude. Inter-hemispheric exchange of mass and momentum determines the character of the intertropical front and controls its fluctuations. In the winter season the westerlies of middle latitudes frequently invade the continent of Africa, and polar-front activity sometimes extends almost to the equator.

* Middle East Areas), Tripoli

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THE METEOROLOGY OF CENTRAL AFRICA

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WASHINGTON, D.C.

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Report of Research

Weather Research Center

19th Weather Region

THE METEOROLOGY OF CENTRAL AFRICA

by

Major Samuel B. Solot

Director of Research

(with author's revisions, Nov. 1945)

Accra, Gold Coast, British West Africa

November, 1943.

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FORWORD

This work is the first attempt at a comprehensive survey of a hitherto neglected part of the world. Because of wartime necessity we could not wait another year to accumulate a more extensive body of data, and consequently the work is incomplete. Most of the detailed analysis concerns The Anglo-Egyptian Sudan, whose weather, though least significant aeronautically, is meteorologically most difficult to explain. Wherever possible the reasoning was extended to include other regions as well. The last chapter attempts to broaden the range of the study by classification of the region into five homogeneous weather zones and by brief discussion of the problems of each zone; we have called this "Dynamic Climatology", because it is an interpretation of climatological data in terms of the circulation.

An effort has been made to keep the text descriptive and uninterrupted by discussions of techniques unless they contribute materially to the comprehension. Such matters have been relegated to the appendices.

The results of this study may be generalized into five fundamental principles of tropical meteorology:

1. The diurnal insolation process is so powerful that other effects are masked. It is therefore necessary to remove diurnal variations in order to analyze important changes.

2. Flow is extremely non-gradient both in direction and vel-

ocity. Indeed, it may be stated that the assumption of gradient motion is least applicable in low latitudes, and, since the isobars often do not reflect the real flow, refined methods of wind analysis are necessary.

3. The usual description of the tropics as a region of chaotic convective circulations is correct as far as it goes but is incomplete and therefore misleading. The convective circulations are superimposed on systematic eddies of varying degrees of magnitude. The largest scale eddies constitute the prevailing normal circulation which is here called the "stationary" type of circulation. Periodically there occur widespread disturbances of the stationary circulation. These are not always well marked in the isobaric patterns, but their existence is evidenced by changes in the winds aloft.

4. Interhemispheric exchange of mass and momentum is not merely an academic problem, but a very real and important phenomenon; it determines the character of the intertropical front and controls its fluctuations.

5. In the winter season the westerlies of middle latitudes frequently invade the continent of Africa, and "polar" front activity sometimes extends almost to the equator.

Although no information is available which proves positively that the air called "Indian Ocean air" in this paper actually originates in the Indian Ocean, the probabilities are in favor of this hypothesis. Hence, for lack of a better name, the title "Indian Ocean air" is used throughout.

This work was begun in November 1942 when Major Solot was assigned to the Sudan Meteorological Service at Khartoum. It progressed slowly until the 19th Weather Region Weather Research Center was established at Wadi Seidna, Anglo-Egyptian Sudan in May 1943. In September 1943 the research center was moved to Accra, B.W.A., where the final draft of this paper was completed. The scientific staff of the research center has varied from time to time, but the bulk of the work was performed by the following technically trained weather officers:

Major Samuel B. Solot, Director of Research.

1st Lt. Justus Chancellor, III, Research Associate.

1st Lt. Guy L. Fairbanks, Jr., Research Associate.

The forecasting staff of the Wadi Seidna base weather office deserve credit for their advice and criticism. The enlisted personnel of the research staff worked hard and faithfully at routine tasks under trying circumstances. S/Sgt. W. H. Morse is especially commended for high quality of performance of work not ordinarily entrusted to men of his grade. The staff of the Royal Air Force, under the senior meteorological officer, S/Ldr. R. M. Hay, and the Sudan Meteorological Service under the direction of Mr. W. Ireland are thanked for their whole-hearted cooperation. Acknowledgement is made to Mr. E. O. Norris, assistant government meteorologist, for the consistent courtesy and patience with which he acceded to our requests. F/Lt. Archbold, Royal Air Force, assisted

in the early stages of the work, and El Fandi Effendi, the noted Egyptian meteorologist, was helpful with suggestions and criticisms. Finally the entire project was made possible only through the foresight and good will of Col. R. F. Fulton, Regional Control Officer, 19th Weather Region.

ADDENDA

During the full year which has elapsed since the completion of this work a great amount of additional data, together with a significant increase in forecasting experience, have resulted in a more detailed understanding of the weather problems of Central Africa. In addition, there has been an exchange of ideas with students of other tropical regions, as well as the submission of this paper to rather extensive professional criticism. These factors have tended to confirm the basic ideas expressed in this report. However, it was found desirable to include certain modifications in the form of addenda.

1. Red Sea Trough (Par. 3). The concept of the Red Sea trough as an inactive dynamic front is valid in the tropics. However, it has recently been discovered that its northern extension in the vicinity of the Sinai Peninsula often becomes an active discontinuity between the warm and relatively moist air to the east and the cold, continental air to the west. Here the front would, of course, slope upward to the west. Activity along this front produces rain, moderate to severe thunderstorms, and turbulence in the winter season.

2. Source of Harmattan (Par. 5 and Chapter V). Throughout the discussion of harmattan haze it is stressed that the source of cold air is the Russian, or Asiatic, air mass, and this is proved to be true in the example cited. Further experience, however, has shown that while this source of cold air produces

the most widespread form of harmattan haze, there is another type which is associated with the prevalence of this phenomenon in Nigeria and West Africa. This arises from an intensification and southeastward extension of the Azores High*. Both the dynamic and thermodynamic discussion are still applicable to this case as well. Of the two types of harmattan haze the latter is the more common form, although its effect is localized in the western part of Central Africa.

3. Mediterranean Low (Par. 5). Recent investigations have shown that the Mediterranean Low is rarely generated as an open wave cyclone**. However, insofar as this affects the weather of Central Africa, it merely emphasizes still further the importance of the surge of cold air from the north.

4. Break in Intertropical Front (Par. 9). "The complete break in the intertropical front along the Red Sea Coast" is a statement which evidently requires clarification in view of questions which have been put to the author. The discontinuity certainly exists aloft, but because of the rugged topography it is sometimes very difficult to locate on the surface. In such cases some analysts omit this portion of the front from the sea level charts.

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* A Study of Harmattan Haze at Maiduguri, Nigeria, by Capt. Thomas P. Condron, Research Section, 19th Weather Region, Report No. 4, January 1944.

** Forecasting Manual - Tripoli to Karachi - Part I - October, November, December; Research Section, 19th Weather Region, October 1944.

5. Easterly Wave (Par. 11, 71, 85). In the discussion of the circulation during the rainy season it is shown that there are two cells, an anticyclonic cell east of El Fasher, and a cyclonic cell west of El Geneina. It is explained in great detail that rainfall in the Sudan is produced by a distortion of the circulation from anticyclonic to cyclonic. On the other hand, it is pointed out that general rainfall (or "line squalls") in the western portion of Central Africa is produced merely by an intensification of the already existing cyclonic circulation. The description is in terms of isentropic flow and is deduced from the observed thermodynamic properties of the various interacting air masses. It is apparent, however, that the cyclonic cells (or "moist tongues") are identical with easterly waves, as described by Riehle and other meteorologists of the Institute of Tropical Meteorology. Thus the theory of rainfall in Central Africa may be restated as follows: whereas in the western portion of Central Africa an easterly wave is produced by an intensification of the existing circulation, in the eastern part of Central Africa it requires a large scale disturbance of the normal circulation to produce an easterly wave.

6. Harmattan Haze Front (Par. 32 c and 55). The harmattan haze front, which is a discontinuity between the cold dry haze air to the north and the relatively warmer maritime air to the south, has been found to be so persistent during the dry season in West Africa, especially in Nigeria, that it may be regarded as practically a quasi-stationary front.

7. Local Blowing Sand (Par. 40). The problem of local blowing sand is indeed very complex. At Aden, alone, four different types of sandstorms were discovered. Many factors, such as soil condition, insolation, humidity, and previous rainfall seem to affect the critical velocity. It is better, therefore, to think in terms of a critical range of velocities than a single critical velocity. This problem is being intensively studied at present.

8. Haboob (Par. 42). "As precipitation falls from the cloud base it evaporates and cools the air underneath to its wet bulb temperature". It has been pointed out by Lt. Col. B. Holzman that this is a controversial point, and not a necessary condition to the theory of the haboob.

January 1945

CHAPTER I

GENERAL CIRCULATION IN THE LOWER TROPOSPHERE

1. Rainfall regime may be used as a logical basis for seasonal classification of the annual weather cycle in Central Africa. In addition to the Dry and Rainy Seasons it is possible to identify two intermediate periods which may be designated as the Season of Approaching Rains and the Season of Retreating Rains. The exact periods and durations of these vary with each locality, but, in general, this classification agrees well with the seasonal trend of the general circulation. For the Sudan in particular the seasons are as follows: Dry Season, November through April; Season of Approaching Rains, May and June; Rainy Season, July and August; and Season of Retreating Rains, September and October.

2. DRY SEASON. The Dry Season circulation is dominated by two large-scale anticyclones (Fig.1); both of these, the Sahara and Arabian highs, are integral parts of the general hemispheric circulation. The Sahara high is an extension of the Azores anticyclone and is therefore dynamic in character. Hence the anticyclonic circulation extends to high levels and, as a result of large-scale subsidence, the air is dynamically heated and dessicated. Thus the Sahara high is the ultimate cause of the hot, dry desert climate. The Arabian dynamic high has a similar structure and produces the same effects over Arabia.

3. The two anticyclonic circulations converge toward each other to form a well marked trough~~, well marked by a sharp trough line or stationary front~~. Although, because of insufficient data, the exact extent ~~nature~~ of these systems ~~discontinuity~~ is not fully understood, it seems probable that ~~of the two circulations the western one extends to higher levels and hence the frontal surface~~ the trough slopes upward to the east. ~~However,~~ Since the thermodynamic differences between the ~~two~~ air masses from both cells are very slight, mixing will readily take place and the front is inactive. (any front existing there would be inactive in the lower latitudes.) It is an accidental fact that this front lies along the Red Sea coast and that the topography adjacent to the coast is high and rugged. It sometimes happens that the eastern current has had a long trajectory over the northwestern Indian Ocean, thus producing a moisture discontinuity in the surface layer. The moist air moving upslope will at times produce orographic rain or fog in the Red Sea Hills. This must not be confused with ~~the~~ a true dynamic front. ~~It is important to remember that the trough is an induced circulation and that its~~ The position of the trough is of great significance as a guide to the relative extension of the two anticyclones.

4. A low pressure area, characterized by extreme horizontal convergence and intense convective activity, is centered at 10 degrees north latitude. Because the low is thermal, its position and intensity vary diurnally. ~~and~~ The flow is extremely non-gradient in character. Although the instantaneous flow patterns may at times indicate strong flow in

some particular direction, the diurnal wind variation tends to produce motion in the form of eddies.

5. Later in the Dry Season wave cyclones tend to develop in the Mediterranean Sea, move eastward and occlude very rapidly. This region is a potent zone of ~~wave~~ cyclogenesis, ~~because of the proximity of the warm moist Mediterranean air to the cold dry continental air.~~ When the outbreak of the Asiatic air mass is of sufficient intensity a strong cold front develops which sweeps across Africa. This constitutes a "disturbed" type of Dry Season weather and will be further discussed in Chapter V.

6. The mean January flow chart (Fig.2) agrees well with the typical surface chart (Fig.1). The Sahara and Arabian highs as well as the trough line between them are clearly marked. There is also a very definite cyclonic circulation in the Mediterranean region. The flow patterns indicate intense horizontal convergence in the vicinity of the thermal low. The shallowness of the low ~~and the non-gradient character of the winds are~~ is evidenced by the fact that in a ten thousand-foot layer the circulation is actually anticyclonic in spite of the existence of a low pressure center at sea level. It is important to note that the air mass sources are the same on both sides of the low and that therefore no front exists here. ~~This again bears out the conclusion that the low is purely thermal.~~ One can also infer from this chart that there is a net transfer of ~~momentum~~ air from the northern to

the southern hemisphere during this season.

7. <u>SEASON OF APPROACHING RAINS</u>. During the Season of Approaching Rains the Sahara high, still a prominent feature of the circulation, has shifted northward, the axis now being oriented from northwest to southeast (Fig. 3). The Arabian surface high, however, becomes transformed into a shallow thermal low, so that southern Arabia now comes under the influence of the Indian Monsoon system. It can be seen that this low is already well developed by the middle of the season, as represented by Fig. 3.

8. Cyclonic activity in the Mediterranean Sea during this Season, although of lesser intensity, is still characteristic. The cold continental air mass to the north has retreated considerably but is still potent. Undoubtedly the most important change in the circulation pattern is the advent of the intertropical front. This is clearly shown in Fig. 4 where it appears as an abrupt wind discontinuity between two distinctly different air masses in contrast to the air mass homogeneity in January. The exact nature of this front will be discussed in Chapter III. However, at this point it may be mentioned that it slopes upward towards the south. Associated with the intertropical front there is a stationary cyclonic system which is centered in the Sudan. The trough slopes southward with the front and, immediately above the surface position of the low center, there is an anticyclonic circulation aloft. As the season progresses,

the front, together with its cyclonic system, is gradually displaced northward but not without marked ~~periodic~~ fluctuations, which are sometimes accompanied by minor precipitation and blowing sand. This is the season of maximum temperature in the Central Sudan and marks the first appearance of convective clouds, dust devils and other instability phenomena. The air, however, is still quite dry and thus cumulus cloud bases are observed on the average at 12,000 feet. The strong insolation in this region undoubtedly intensifies the Sudan low.

9. Fig. 4 is representative of conditions during mid-April, ~~before the Season of Approaching Rains.~~ The Arabian high is still present, as is also the trough between the two anticyclones. As was previously explained, there is no great thermodynamic difference between the two air masses on either side of the trough, and the front represents a sharp convergence of two opposing circulations. As the Arabian cyclone develops, the air masses no longer oppose each other but tend to converge in parallel streams, and the sharp front is replaced by a broad mixing zone. This is represented in Fig. 3 by the weak trough north of the center of the Sudan low. During this season the Sudan is a region of conflict between three air masses: the warm dry air to the northwest, the warm and somewhat less dry air to the northeast, and the cold moist air to the south. The configuration of the isobars is important in determining the source region of the air to the north

of the intertropical front. Fig 3 is typical of the Arabian regime, but if the Mediterranean cyclonic system is displaced toward the northeast the Sahara air behind it spreads southward and eastward and finally becomes dominant. Toward the end of this season when the cyclonic activity ceases, the Arabian air is permanently displaced eastward. Thus it may be seen that the Mediterranean wave cyclones, by their effect on the position and orientation of the Sahara high, are the principal control of the flow patterns. Moreover this relationship is fundamentally significant, because at this season the fluctuations of the intertropical front are controlled by the flow of air from the Sahara high.

10. The daily fluctuations in air masses are brought out by Fig. 5. In comparing the surface thermodynamic properties produced by the various trajectories, it may be seen that the temperature differences are minor but that the moisture differences are quite large. There is a range of 5°F. in morning temperatures, and 9°F. in maximum temperatures, compared with 31°F. in dew point temperatures. It is, in fact, a general rule that during the warmer part of the year the maximum temperature does not depend so much on the source region or trajectory as on the amount of insolation.

11. RAINY SEASON. During this season the Mediterranean cyclonic activity is negligible; thus, as shown by a typical synoptic chart (Fig. 6), the Sahara high has shifted eastward with a north-south orientation. Arabian air no longer flows

over Central Africa and only two air masses meet along the intertropical front. The Arabian low now extends to greater heights and is also more intense. (Fig. 7) The intertropical front has advanced to 20 degrees north latitude and swings northward into the Sudan low. The topography of the Red Sea Hills and of the more rugged Abyssinian Mountains is the ultimate cause of this distortion and is likewise responsible for the complete break in the front which occurs along the Red Sea Coast. ~~An important change in the circulation pattern is the establishment of three cold high pressure cells just north of the equator. The central cell is a plateau high and deserves close scrutiny because its circulation is most important in the production of rainfall. Since the flow chart (Fig. 7) represents the mean circulation in a ten thousand-foot layer, the shallow configurations on the surface synoptic chart (Fig. 6) are not well marked.~~ It is important to note two diverging streams from the south: (Fig. 7) a counterclockwise ~~cyclonic~~ flow to the west and an clockwise ~~anticyclonic~~ flow to the east. These have a significant effect on the rainfall regimes, as will be shown later. (Chapter VI) In contrast to the January flow chart, this chart indicates a transfer of air ~~momentum~~ from the southern to the northern hemisphere.

12. <u>SEASON OF RETREATING RAINS</u>. The sample synoptic chart (Fig. 8) represents conditions at the very end of this season, and is, therefore, not completely typical. The dynamic trough is already well marked, and the Arabian high is be-

ginning to develop. The Sahara high again has an east-west orientation as it does during the Dry Season. The intertropical front, already showing signs of disintegration, has retreated southward. Mediterranean cyclones are again becoming active.

13. The flow chart for October (Fig. 9) shows that there is now a conflict between two air masses in the Northern Sudan. During this season trajectories from Arabia are predominant, although the Arabian high is not yet fully established as a separate cell. It is interesting to note the flow over Arabia where the transition from cyclonic to anticyclonic circulation is just taking place.

14. SUMMARY. The Sahara high is present throughout the year, its position and axis undergoing a cyclic change. From a southerly position with an east-west axis in the dry season it rotates anticyclonically to a northerly position with a north-south axis during the Rainy Season. It then reverses its rotation back to the Dry Season position. It seems definitely established that there is a relationship between the position of this cell and the cyclonic activity in the Mediterranean region. The intertropical front fluctuates north and south in conjunction with the latitudinal displacement of the Sahara high and in the Dry Season it disappears from the northern hemisphere. Over Arabia there is a complete reversal from a ~~dynamic~~ high pressure cell in the Dry Season to a deep surface cyclone in the Rainy Season. Thus the system of winds over

Southern Arabia is part of the Indian monsoon. The interaction of the Sahara and Arabian high pressure cells induces a trough of low pressure which lies roughly parallel to the Red Sea. ~~In the Dry Season there is a thermal low just north of the equator which is replaced by two cold highs in the Rainy Season.~~ Normally there is only one air mass, the Saharan, over North Central Africa in the Dry Season. In the Rainy Season, however, there are two moist currents from the south, the Atlantic and the Indian Ocean, and the dry Sahara current from the north. During the transitional periods the Arabian air is present as well.

CHAPTER II

AIR MASS PROPERTIES

15. ANNUAL VARIATION IN SOURCE REGION. The only available data for this study were the upper air soundings taken at Khartoum. While this would seem to impose severe restrictions on the generality of the conclusions, it is possible, by utilizing the concepts discussed in the last chapter, to extend the area for which the findings are valid. For this purpose a chart (Fig. 10) was prepared which traces the mean path of a ten thousand-foot layer back from Khartoum in the general direction of the ~~to the~~ source regions. This computation is permissible in most months because the wind shear with height is sufficiently small.

16. As was previously pointed out, the Dry Season is characterized by anticyclonic flow from the Sahara. The chart shows that, beginning with November, the source regions shift rapidly to this high pressure cell and that the trajectories assume an extreme anticyclonic curvature. The large shift from March to April reflects the rotation of the axis of the high, and the displacement northward in June and July is also apparent. Another significant fact is the beginning of cyclonic curvature of the trajectories as they approach Khartoum; this is first apparent in May and persists through October. The July trajectory is not entirely representative, because the shear between the lower southerly winds and the stronger northerly winds aloft is not reflected in the mean flow of the 10,000-foot layer. The intertropical front, by

August, is well north of Khartoum, and the trajectory of the entire layer is from the south. The May and June trajectories fail to indicate the occasional flow from the south but they are valid as a mean picture. The September trajectory is not completely representative since the great conflict between the three air masses is smoothed out in the mean. It does, however, show the transition from the southerly to Arabian flow. The October trajectory shows conclusively that the air flows from the Arabian anticyclone. This accounts for the secondary maximum temperature which occurs in early October, two months behind the second annual occurrence of vertical sun.

17. Great distances between consecutive monthly source regions may be interpreted as representing transitional periods. Good examples of this are the distances between the source regions of August and October, October and December, March and May, and May and August. ~~Another important fact is that there are no trajectories from the Atlantic Ocean. A similar chart for Maidiguri would show a stream of air from the Atlantic Ocean in July and August.~~

18. MEAN SEASONAL SOUNDINGS. Because of faulty observational technique the Khartoum wet-bulb curves have a tendency toward excessive values in the upper levels °C. ~~between the levels of zero wet-bulb and zero dry bulb temperatures.~~ This is especially the case in soundings taken in dry air. ~~This error is gradually adjusted as the ascent reaches 20,000 feet. Moreover, the magnitude of the error is a direct function of the wet bulb-temperature difference near the freezing point.~~ This error

~~probably arises from the lack of opportunity for the moisture in the wet bulb to freeze. By taking into account the wet bulb lapse rates and the fact that the readings well above the freezing isotherm were more nearly correct, it is possible to construct true wet bulb curves.~~ Mean monthly and season pseudo-adiabatic charts and Rossby diagrams were then constructed of which the seasonal charts were selected for display and discussion. (Figs. 11 to 18).

19. Among other peculiarities the intertropical front is lacking in a normal frontal inversion for reasons which will be discussed in the next chapter (Par. 33). It has already been shown that this front is characterized by an abrupt wind shear. In the Rainy Season the shift in wind has a mean height of approximately 8,000 feet above Khartoum. Correspondingly, at this level there appears a slight decrease in temperature lapse rate (Fig. 15); on the Rossby diagram (Fig. 16) there is a ~~decided~~ discontinuity in convective stability from an ~~extremely~~ unstable air mass below to a slightly stable air mass above 8,000 feet. The sounding ~~thus~~ represents a moist maritime current overrun by Sahara air.

20. If it is assumed that the Dry Season sounding (Fig. 12) is representative of Sahara air, it is possible to compare the thermodynamic properties of this air mass in both seasons. Since the air mass is extremely dry, condensation processes may be neglected, and the conservative properties which are

the coordinates of the Rossby diagram will not be affected by vertical motion. It follows, therefore, that the surface properties of the Dry Season may be directly compared with those of the base of the Sahara air mass which has been lifted to 8,000 feet in the rainy season. ~~In the same way this comparison may be extended aloft level for level.~~

21. In the Dry Season the value of specific humidity ~~decreases from~~ 7.5 gm/kg. at the surface ~~to 3.1 at 12,000 feet~~, and in the Rainy Season ~~from~~ 7.8 at 8,000 feet. ~~to 3.4 at 20,000 feet.~~ Thus ~~it may be concluded that~~ the two soundings have similar ~~are identical with respect to~~ moisture properties at the base of the Saharan air. ~~The~~ Comparing the layer from surface to 1200 feet in the dry season with the layer ~~ing the same 12,000-foot height interval, it is found that~~ from 8000 to 2000 feet in the Rainy Season, it is found that the partial potential temperatures of the Rainy Season sounding exceed those of the Dry Season by 8.5° C at the base and 13.5° C. at the top. Thus ~~presumably~~ the Sahara air is considerably warmer at all levels in the Rainy Season. It has been mentioned in the last chapter that during the Dry Season there are invasions of cold air from the continents of Europe and Asia. These are frequent enough to affect the average temperature. For example, the average surface partial potential temperature in January 1943, a month in which there were many cold outbreaks, was 301.0° A. compared with 308.0° A. in February 1942, a normal month. Thus at least part of the seasonal difference in potential temperature is accounted for by the fact that the Dry Season sounding is not representative of a pure Sahara air mass. ~~It can be concluded that the air~~

~~mass properties of Sahara air are very nearly constant through-out the year except for an annual variation in heat.~~

22. In the transitional seasons the data in the lower layers represent a mean of several different air masses, but aloft there is only the Sahara air mass. A reasonable mean height of the intertropical front for the season of approaching rains, which is supported by the wind data, is 4000 feet above the surface. ~~It is to be expected that under these conditions the frontal discontinuity should be less distinct. A careful study of the data does show the discontinuity to exist at 4,000 feet in the Season of Approaching Rains~~ (Fig. 14). Assuming that the base of the Sahara air has been lifted from 4,000 feet in the Season of Approaching Rains to 8,000 feet in the Rainy Season, then the May-June dry and wet bulb temperatures at 4,000 feet, cooled adiabatically and pseudo-adiabatically, respectively, to 8,000 feet, should agree with the 8,000-foot July- August values. Performing this operation results in a dry bulb temperature of 12° C. and a wet bulb temperature of 7° C. as compared with Rainy Season values of 12° C. and 8° C., respectively. Furthermore, the partial potential temperature and specific humidity values at the 4,000-foot level are 314.5° A. and 7.7 gm/kg., which agree well with the Rainy Season values at 8,000 feet. ~~These results show that during the Season of Approaching Rains Sahara air exists above 4,000 feet.~~

23. The sounding for the Season of Retreating Rains (Figs. 17 & 18) is less satisfactory, because there is a wide divergence between September and October air masses as shown by the following table:

H (ft.)	q (gm/kg.)		RH (%)		θ_d (°A)	
	Sept.	Oct.	Sept.	Oct.	Sept.	Oct.
Sfc.	13.7	9.0	25	37	312.0	311.0
4,000	9.3	8.5	42	42	313.5	311.5
8,000	7.0	4.7	52	39	316.5	314.0
12,000	5.3	3.8	67	51	318.5	317.5

The conditions in the lower layers in September are transitional between the moist unstable air in August and the Arabian air in October. The October sounding represents a predominantly Arabian air mass to 8,000 feet with Sahara air overrunning aloft.

24. REPRESENTATIVE AIR MASS PROPERTIES. ~~By taking the foregoing discussion into account~~ It is ~~then~~ now possible using the available observations to construct typical Rossby curves for five different air masses from the surface to 12,000 feet as they would appear at Khartoum: winter Sahara, summer Sahara, modified Indian Ocean, Arabian, and modified polar continental air (Fig. 19).

25. As previously stated, Sahara air is a dry stable air mass subjected to large scale subsidence, and its moisture characteristics remain constant throughout the year. It contains more heat in summer and hence the partial potential temperature is 11° C. higher than in winter. Both soundings show slight convective instability in the lower layers as a result of turbulence and convection produced by intense heating; this effect is more pronounced in summer, as shown by the mois-

ture distribution. Relative humidities are extremely low, and the amount of lift required to saturate the air mass varies from 260 mb. in winter to 320 mb. in summer.

26. The curve labeled NP_c (modified polar continental) is derived from a study of several cold outbreaks. While it may seem strange to find polar air at such low latitudes, this sounding unquestionably represents air of polar origin, as evidenced both by the absolute values of the thermodynamic properties and by the shape of the characteristic curve. The lowest 2,000 feet, characterized by constant equivalent potential temperature, indicates a convective layer which varies diurnally from a surface inversion in the early morning to an adiabatic lapse rate in the afternoon. Above this there is a normal subsidence inversion from 2,000 to 4,000 feet with a sharp increase in potential temperature and a corresponding decrease in moisture. Aloft there is an extremely stable layer of cold air which ~~in which the moisture gradually increases with elevation. This type of curve~~ is definitely characteristic of real polar air. The great temperature difference between this air and the Sahara air mass is notable and, as will be shown later (Chap. V), the polar air underruns Sahara air as a cold front.

27. The Indian Ocean air is a typical example of a warm, moist and unstable maritime air mass. It is colder only than summer Saharan air. Its normal state over Khartoum is such that the surface layers require considerable lifting in order to produce condensation. This

air mass is both conditionally and convectively unstable.
Whereas the conditional instability is realized daily by parcel convection produced by intense insolation, the mass lifting required to re convective instability is normally prevented by the prevailing dynamic conditions (Par. 35).

28. Of considerable interest is the orographic effect shown in the Arabian air mass sounding, ~~the most striking feature of which is the abnormal difference in the length of the curves in the first 8,000 feet.~~ It is probable that in its original state the lowest 8000 feet ~~this layer~~ was represented by a straight line with the 4,000-foot point more or less equidistant from both ends. From the flow and trajectory charts (Figs. 9 & 10) it is evident that the path of the air is not directly from the east over the high mountain ranges but from the northeast over the foothills. The turbulent flow over the Red Sea Hills produces a net transport of moisture upward and heat downward, resulting in a thoroughly mixed layer near the ground and a corresponding stratification aloft. This process is reflected on the Rossby diagram by ~~an extreme~~ a shift of the 4,000-foot point to the right and by the constant equivalent potential temperature in the lowest layer. On account of the low relative humidities, averaging 35% in the first 8,000 feet, and the lift imparted by the Red Sea Hills, whose average height does not exceed 3,000 feet, do not produce an overturning of the air mass sufficient for cumulus formation. ~~, and since the condensation level is above 12,000 feet,~~ Therefore the total amount of moisture

remains practically unchanged. ~~Although the moisture content of this air mass is low, its slope on the Rossby diagram or, in other words, its convective instability, resembles that of modified maritime air. However, in October the Arabian high is not yet fully developed. It is probable that as the season progresses the air mass becomes more stable and assumes a more characteristic continental curve although it remains colder snd more moist than the Sahara air.~~

29. The representative values of temperature and dew point are the surface values that exist after the early morning stable layer has been removed by insolation, and thus they lie between the daily minima and maxima. For purposes of comparison a table of representative temperatures and dew points was prepared as follows:

REPRESENTATIVE AIR MASS VALUES.

	Temp. (F.)	Dew Point Temp. (F.)
Modified Polar Continental	54	30
Sahara (Winter)	89	48
Sahara (Summer)	101	48
Modified Indian Ocean	87	72
Arabian (October)	92	55

Khartoum experiences a vertical sun twice a year, on May 4 and again on August 10. Although the highest temperatures of the year occur normally in May in close accord with the march of the sun, the secondary maximum temperature does not occur until

October, and hence lags approximately two months behind the second annual occurrence of vertical sun. The reason for this lag is apparent from an inspection of the above table. The occurrence of first vertical sun coincides with the prevalence of the Sahara (summer) air mass, which has the highest representative temperature. Hence the occurrence of the primary maximum temperature. During August, however, at the time of the second vertical sun, the dominant air mass is modified Indian Ocean air which, although previously described as warm, is relatively colder than even the Sahara (winter) air mass. Thus the secondary maximum is delayed until the advent of Arabian air in October which has the second highest representative temperature.

CHAPTER III

THE INTERTROPICAL FRONT

30. Theoretically the intertropical front is considered to be the boundary between the northeast and southeast trades of the northern and southern hemispheres, respectively. It has already been pointed out (Para. 6 & 11) that there is a large scale interhemispheric transfer of ~~momentum~~ air over the African continent, southward in the winter and northward in the summer. Thus the boundary between the flow from each hemisphere does not remain stationary at the equator but fluctuates seasonally, lagging behind the march of the vertical sun (Fig. 20). At the longitude of Khartoum this lag was found to be approximately 40 days.

31. It has also been shown that the front disappears from the northern hemisphere in November and reappears in April. The flow charts for April, July, and October (Figs. 4, 7, & 9) show the front as a definite discontinuity between two distinct air masses, one maritime and the other continental; in January, however, in the region of the central low pressure belt (Fig. 2) there is a convergence between two streams that have the same continental origin. The intertropical front, therefore, is not associated with this low. Furthermore, the October position of the intertropical front on the flow chart (Fig. 9) is close to 5 degrees north latitude, and if in January the front were

placed through the line of convergence in the belt of low pressure (Fig. 2), its fluctuation would be in an opposite direction to that of the sun, a motion completely irreconcilable with that during the remainder of the year.

32. In West Africa there are three conditions which may at times be confused with the intertropical front:

A. Throughout the year, especially in the daylight hours, the land is warmer than the sea which gives rise to a perennial sea breeze which extends some distance inland and has the appearance of a cold front with the same direction of slope as the intertropical front (Par. 83). Conclusive evidence that this phenomenon is distinct from the intertropical front may be found in the upper air observations of west coast stations. For example a typical September sounding at Accra shows a southwest wind near the ground shifting to northeast at 4,000 feet, shifting to south at 8,000 feet and then to northeast above 10,000 feet. Considering the fact that the front at the ground is in the vicinity of Dakar, it is obvious that the first wind shift is in no way connected with the intertropical front. Thus it may be concluded that the lower wind shift is the "seabreeze front" and that the upper wind shift is the true intertropical front.

B. In the winter months there is a return circulation from the Sahara high along the west coast which may acquire enough moisture in its lower layers to produce rain (Par. 84). This is, however, a ~~slightly~~ modified continental air mass and is

far different from the maritime air mass of the Rainy Season.
C. The harmattan haze cold front tends to remain stationary for some length of time in West Africa, and is characterized by a marked thermodynamic discontinuity with warm moist air to the south and west, and cold dry air to the north and east. This front, however, slopes in a direction opposite to that of the intertropical front (Par. 55).

33. Over the continent of Africa the intertropical front bounds the Sahara air to the north and the maritime air to the south; the latter flows in two streams: from the Atlantic Ocean in the west and from the Indian Ocean in the east. From the discussion in Chapter II it is known that the northern continental current is warmer than the southerly maritime air. Since the slope of the front is determined partially at least, by the difference in density between the two air masses, it may ~~readily~~ be seen that the front must slope upward to the south. This presents the anomalous situation of warm dry air ascending over cold moist air. The implications of the above statement are profound, and therein lies the key to Central African meteorology. Considering the thermodynamic characteristics of Sahara air, it is apparent that frontal precipitation produced by ascent of this air is ~~impossible~~ unlikely. This air is so dry indeed that it is axiomatic in forecasting to presume that no precipitation will occur at a given station if the front is south of it. Thus the cloud base is usually in the lower maritime air and the rainfall convective in char-

¶ 34.

acter. In its trajectory northward the maritime air is constantly undergoing convection, condensation, and precipitation. These processes tend to decrease the lapse rate so that it is always approaching the pseudo-adiabatic. The northern current, however, undergoes intense insolation and dry adiabatic convection so that its lapse rate tends to be steeper than the pseudo-adiabatic. Thus, although the northern current is potentially warmer, the process described above prevents the development of a frontal inversion, but the frontal surface is characterized by a slight decrease in lapse rate (Par. 19). Furthermore, since there is a moisture decrease instead of increase, the characteristic appearance of the frontal inversion on the Rossby diagram is also lacking. Hence, since there is no abrupt discontinuity either in moisture or in temperature, mixing between the two air masses takes place readily under the influence of intense insolation. As the cumulus development increases during the afternoon, the cloud structure penetrates through the front and becomes dessicated. This daily phenomenon has been verified by observation. The effect of the front, then, is to prevent the building up of cumulonimbus, and thus it actually inhibits the occurrence of precipitation. Only in those regions far enough removed from the front to possess sufficiently deep layers of moist unstable air, can cumulonimbus clouds become fully developed. Thus there exists a line approximately 200 miles south of the front which marks the northern limit of precipitation.

35. Another peculiarity of the front is the extreme convergence at the frontal surface. Whereas an ordinary front usually has some component of the wind parallel on both sides, the winds in this front blow practically head on. ~~this front has practically a 180 degree shift of wind.~~ Not only is there a transfer of heat and moisture between the two air masses, but there is also transfer of momentum. This accounts for the diurnal fluctuations of the ~~This accounts for the diurnal fluctuations of the~~ intertropical front (Par. 61.)

~~35. Proximity of the intertropical front prevents not only local convective activity but also large scale storms which are associated with ascent over isentropic surfaces. Since, in general, the isentropic surfaces in the moist unstable air will parallel the slope of the front, it can easily be seen that there will be a general down slope motion along the isentropic surfaces. Thus it may be said that the normal flow patterns in the vicinity of the intertropical front prevent the occurrence of precipitation. A large disturbance in the normal flow is required to produce rain in the Sudan. (Chap. VI).~~

36. Although the intertropical front inhibits precipitation over the land mass of Africa, this is not true over the oceans, where maritime currents converge on both sides of the front and a more normal type of discontinuity results.

CHAPTER IV

HAZE, DUST, AND SANDSTORMS

37. Vast regions of the African continent are covered with loose sandy soil which, during all seasons of the year, may be carried aloft. Turbulent flow with resultant vertical currents over these regions is an agency for the transport of sand and dust. These phenomena vary in size from a single dust devil a few feet in diameter to a well developed harmattan haze storm which may blanket an area the size of the United States. The amount of sand carried aloft depends also on the looseness with which the sand is packed, and this varies with the region and the season. The southern Sudan is an example of seasonal variation, being a source of loose sandy soil in the Dry Season, but having enough vegetation in the Rainy Season to hinder rising sand. The average size of the particles suspended in the atmosphere is an inverse function of the length of their trajectories, since, according to Stokes' Law, the largest sand particles will descend to earth in a few hours whereas the fine dust remains for days.

38. In ascending order of magnitude, haze, dust, and sandstorms may be classified as follows:

1. Dust Devils.
2. Local Rising Sand.
3. Haboob.
4. Rainy Season Cold Front Type Sandstorm.

5. Harmattan Haze (Dry Season Cold Front Type).

Of these, all but the dust devil present more or less serious hazards to aircraft operation, both by reducing visibility and by impeding engine efficiency.

39. DUST DEVILS. A dust devil is a small vortex from ten to fifty feet in diameter which rotates rapidly, either cyclonically or anticyclonically. As it rises, the dust devil is caught in the circulation aloft and hence forms an arc bending in the direction of the wind shear. This phenomenon is caused by intense local heating in dry air which produces super-adiabatic lapse rates and strong convective currents. Dust devils are most frequently observed to the north of the intertropical front during the Seasons of Approaching and Retreating Rains on cloudless days when there is a maximum of insolation. It is not uncommon to see three or four forming simultaneously. While they serve as an interesting visual demonstration of the convective process they are otherwise inconsequential.

40. LOCAL RISING SAND. Each locality has a critical surface wind velocity which, if exceeded, will result in rising sand. The critical velocity in the vicinity of Khartoum is approximately 25 miles per hour; at Aden, 18 miles per hour; and is at present 10 miles per hour in portions of the Libyan Desert as a result of modern mechanized warfare. Wind direction is also of some importance. The extreme localization of this phenomenon is illustrated by the fact that

any southwest wind exceeding 18 miles per hour will cbse the Sheikh Othman airport near Aden, while two other fields in the vicinity will remain open under these conditions. Successful forecasting of local rising sand requires thc.ough knowledge of local conditions and of diurnal wind variation. ~~Since the diurnal wind variation in these regions is a function of insolation (Par. 61),~~ It is necessary to employ both temperature and wind soundings in developing an empirical technique for forecasting critical wind directions and velocities.

41. HABOOB. "Haboob" is an Arabic word sometimes loosely applied to any severe sandstorm, but its present meaning is confined to a unique type of storm. A fully developed haboob is an ~~unusual~~ extraordinary sight. It is invariably observed underneath a cumulonimbus cloud, from which there are usually virga trailing. The leading edge resembles a solid wall of thick dust and has the appearance of a typical cold front with a characteristic bulging nose. (Fig. [illegible]). Toward the rear it becomes diffuse and appears to be an ordinary blowing sand storm. Perhaps its most interesting feature is the visual evidence of the cold front consisting of a churning, tumbling motion as it advances. It varies in color from black to greyish red or yellow depending on its source region and trajectory. Its passage is marked by a sharp drop in temperature and a wind shift. In spite of all precautions, every-

thing indoors becomes coated with a layer of fine dust, and a very disagreeable choking sensation is experienced while one of these storms is in progress. As many as three haboobs have been simultaneously observed at Wadi Seidna (20 miles north of Khartoum.). The usual duration of an haboob is approximately thirty minutes, while severe ones have been known to last for several hours. It is sometimes accompanied by thunder, but if the thunderstorm is violent enough, rain will fall dampening the ground, removing the dust source, washing the particles from the air, and thus terminating the haboob.

42. In its early stages of development the haboob is no different from a common air mass thunderstorm, except that blowing sand is carried aloft by turbulent winds within the convective cell. As precipitation falls from the cloud base it evaporates and cools the air underneath ~~to its wet bulb temperature~~ (Fig. 22). A discontinuity is quickly developed between this air and the air ahead of the cloud, and as precipitation continues to fall the discontinuity builds down to the ground, establishing a vigorous pseudo-cold front. According to J. Bjerknes, the momentum of the descending air may be assumed to equal that of the ascending air. In this case the descending current becomes concentrated along the leading edge of the system, and its relatively small cross-sectional area ~~mass~~ is compensated for by strong wind velocities. This leads to a transfer of momentum downward, and since the upper layers of the system penetrate the northeasterly current above the in-

tertropical front, the winds near the ground back from southwest to east, thereby causing the storm to move in a cyclonic path. Thus haboobs which are observed east of south pass over the station from an easterly direction.

43. Two examples of haboobs are presented here (Figs. 23 & 24). In the first case, that of July 7, 1943, although some light rain fell to the ground, the air was not completely saturated, and a true dry haboob resulted. The temperature decreased from 102° F. to 78° F in a few minutes, (Fig. 25) the wind shifting from southwest 18 mph to south-southeast 34 mph. Had the air become completely saturated, its lapse rate would have become pseudo-adiabatic and at the ground the temperature would have reached 72° F. On July 22, 1943, the entire layer became completely saturated, and the haboob was transformed into a thunderstorm with moderate rain. In this case the cooling was complete to 73° F. It will be noted that the general visibility did not decrease below 2½ miles, another indication that the haboob had ceased to exist. The difference between these two cases illustrates the delicate balance which must be maintained in order for the haboob to develop and persist. On the one hand there must be sufficient instability and moisture to insure the growth of the cumulonimbus cloud, while on the other hand the upper limit of moisture is fixed by the requirement that all the precipitation should be evaporated in the lower layers. The greater the amount of moisture evaporated, the greater will be the

temperature contrast at the pseudo-front, and therefore the more violent the storm. But once the limit of saturation is reached, the dust storm, which is the distinguishing feature of the haboob, quickly disappears. From a theoretical and statistical study of precipitable water from the surface to 12,000 feet (Par. 75) the limiting values for the possible occurrence of an haboob were found to be 1.26 and 1.57 in.. On July 7, 1.36 in. was computed and on July 22, 1.58 in., a value just above the upper limit.

44. The thermodynamic conditions outlined above fix the height of the intertropical front, since obviously if the front is too high there will be too much moisture and if too low, not enough moisture. Although insufficient data were available to determine definitely the required levels, the height of 8,000 feet is tentatively suggested as an optimum value. Thus the northern limit of haboob activity cannot be farther north than latitude 20 degrees. The desert sand required further limits the area of possible occurrence both longitudinally and to the south. Thus it may be stated that haboobs may occur only in sandy areas of the Northern Sudan.

45. <u>RAINY SEASON COLD FRONT TYPE SANDSTORM</u>. That the intertropical front is normally in a stable position bending sharply to the northeast in the Sudan has been previously shown, as has also the fact that the distortion is caused by the topography to the southeast (Par. 11). It is also known

that the wind shift at the front is very abrupt, and thus the balance is maintained by two strong opposing currents. Besides the normal seasonal and diurnal fluctuations there also occur decided deviations from the mean normal frontal position (Fig. 20). These can be explained by changes in the control cells: the Sahara anticyclone, dominating the northerly flow, and the Abyssinian plateau high, which in turn controls the southerly flow. Thus, for example, when the northerly current is relatively stronger the front will have a tendency to be south of its normal position, and so long as the strong northerly flow persists, the frontal slope will remain in balance at a high angle of inclination. But, should the relative northerly flow weaken at any time, the frontal slope will at once be out of balance, and the intertropical front will begin to surge northward as an active cold front. The thermal effect of the abnormal southerly position of the intertropical front is to bring warm air closer to the cold source, which remains stationary on account of the topography, and this in turn intensifies the cold front action. Convergence of the southwest winds against the mountain barrier increases their cyclonic vorticity, ~~which deepens the~~ At the same time the Sudan low deepens and ~~thereby~~ increases the pressure gradient. The increased wind velocities plus the turbulent cold front action finally result in a general sandstorm.

46. The synoptic chart for July 5, 1943 (Fig. 26) is an example of a fully developed sandstorm of this type. In

contrast with the normal chart (Fig. 6), the pressure difference between centers of high and low is 10 mb. instead of 6 mb. The closed circulation around the Sudan low is much greater in extent and the separation from the Arabian cyclonic system more complete. At this stage the front is already far north of its normal position.* It will be noted that there is a distinct gap between the front and the sandstorm. ~~In the region of the strongest surface winds,~~ To the west of the mountains the surface winds are strongest. Therefore the blowing sand becomes thickest, insolation becomes greatly retarded, and the temperature discontinuity develops into a pseudo-cold front. Meanwhile the intertropical front advances rapidly with the circulation aloft. During the afternoon, especially, the pseudo-front becomes most intense, and the violence of the sandstorm is increased.

47 A comparison of the July 3-5, 1943 soundings (Fig. 27) further illustrates the development of these sandstorms. On July 3 the entire sounding represents a homogeneous Sahara air mass, and the front is far south of its normal position. Between 1000 GMT of the 3rd and 4th the front has passed Khartoum and is indicated on the sounding of the 4th by an isothermal layer from 3,000 to 5,000 feet. Although the

* The normal position of the intertropical front should be south of Kareima, station 166. In this respect Fig. 6 is an unfortunate choice as a typical synoptic chart.

lapse rate in the cold air is quite unstable because of turbulence, the usual insolation is not achieved, and thus the temperature contrast between the two air masses results in an abnormal stability of the surface of discontinuity. At 0125 GMT on July 5 the pseudo-cold front and sandstorm have reached Khartoum, and the decided decrease of temperature is indicated on the sounding for that day, the frontal surface now appearing between 5,000 and 7,000 feet. For forecasting purposes the rapid northward advance of the cold front plus the appearance of an extremely stable frontal discontinuity are the forerunners of this type of sandstorm.

48. It was concluded in Chapter III that large-scale precipitation in the Sudan could not occur without a general disturbance of the normal flow patterns. The processes involved in the development of this type of sandstorm lead to just such a disturbed state of the atmosphere. It has been found that general rains invariably follow within 24 to 48 hours. This process will be further amplified in Chapter VI (Par. 69).

CHAPTER V

HARMATTAN HAZE

49. Periodically in the Dry Season the Asiatic high becomes so intense that cold air from the northeast invades the African continent, underrunning Sahara air to the south and quickly developing a vigorous cold front. Three large-scale effects operate in such a manner that great quantities of sand are carried aloft within the polar air mass: scooping action of the downslope currents at the cold front, strong turbulent flow behind the front, and instability caused by heating from below, since this is definitely a "K" air mass in the Bergeron classification. As the quantity of sand in the atmosphere behind the front increases, insolation is retarded, the temperature contrast becomes even greater, and the cold front becomes progressively more active. The coarser sand particles soon fall to earth, leaving a layer of dense haze concentrated aloft. Subsidence inversions develop within the air mass, and these are greatly intensified by reduced insolation and radiation from the top of the haze at the base of the inversions. Thus the haze becomes stratified in several layers, and turbulent mixing is prevented. Even though the suspended particles tend to settle, the condition will persist until insolation finally destroys the inversions. In this respect harmattan haze is similar to high inversion fog, and temperature soundings may be used in the same way

to forecast its termination.

50. The Khartoum soundings for February 22-24, 1943 (Fig. 28) illustrate the thermodynamics of harmattan haze. The curve of the 22nd is typical of warm, dry Sahara air. After the frontal passage about 1900 GMT on the 22nd, the sounding for the 23rd shows the new air mass at the surface with a temperature decrease of 7.5° C. It will be noted that there is an unstable layer in the first 3,000 feet, then an extremely stable layer to 7,000 feet, above which the sounding merges with that of the previous day. Two haze layers are shown, the lower one of which has the poorer visibility. On the next day the air has cooled uniformly in the lower layers by 4° C., the height of the front has risen 1,000 feet, and the stable layer has been divided into two subsidence inversions with a haze top at the base of each. The base of the first inversion has lowered from 3,000 to 2,000 feet. After the 24th the air begins to warm slowly, although the inversions and the haze remain for several more days. Thus the sounding of the 24th represents the maximum effect of cooling. An important consideration here is the lag of temperature reaction to the frontal passage. In contrast to the wind, which increases and shifts abruptly, the temperature decreases gradually and regularly.

51. The widespread nature of harmattan haze is well illustrated by the series of synoptic charts (Fig. 29 to 33). The chart for the 21st (Fig. 29) is typical of the station-

ary Dry Season pattern with the exception of the vigorous wave cyclone developing in the Mediterranean Sea, and an occluding system farther to the east. By the next day, however, the cold air to the north has pushed rapidly southward, almost completely displacing the Sahara dynamic high. The wave cyclone has deepened and moved eastward, and the pressure gradient behind the system ~~is increasing~~. The Red Sea trough, though still present, is extremely weak. The area of harmattan haze is beginning to develop and spread behind the cold front.

52. On the 23rd (Fig. 31) the cyclonic wave, still with an open warm sector, has split into two centers. Pressure gradients and wind velocities north of the front have further increased, the high pressure center having intensified from 1020 mb. to 1032 mb. in two days. The cyclonic sweep of cold air has imparted an eastward surge to the northern portion of the front, and a new surge southward is developing which will appear on subsequent maps. The Red Sea trough and the Sahara dynamic high have disappeared, and the Arabian high has been displaced and weakened.

53. Fig. 32 shows farther eastward movement of the wave cyclone, which has become extremely deep and has started to occlude. The continental high is now splitting, with waves on the front developing to the south. There is still slight evidence of the Arabian high, and the harmattan haze

area has maintained its vastness.

54. By the 25th (Fig. 33) the cyclone has moved out of the area of observation and is probably filling. The split in the high pressure is now complete with a separate center to the east which is becoming dynamic in character and will later form the new Arabian high as part of the normal circulation. A tongue of the western high is also in the process of separation and movement into the position of the Sahara high, while the Red Sea trough is beginning to reappear. This chart represents the initial stage of the return from the disturbed to the stationary type of circulation.

55. It will be noted that the harmattan haze is more persistent in the west, where the front has become stationary. As the front reaches its equilibrium position to the south, several factors create a situation favorable for its maintenance. Since it is now close to the ocean, the southwest flow becomes maritime in character, and thus a great contrast in moisture as well as temperature develops. The warm moist air condenses as it ascends the frontal slope, and frontal clouds further retard insolation in the polar air, so that the discontinuity is intensified, and the front remains indefinitely. This process occurs most fequently in northern and central Nigeria where polar air first encounters fresh maritime air, and therefore harmattan haze is most persistent in this region.

56. The above series shows that it is possible for polar

air to advance to within 5 degrees of the equator. In contrast to conditions in the western hemisphere, where it would be necessary to overcome vigorous opposition from a large mass of tropical maritime air, there is no such opposing force in this case. Once the polar air pushes its way past the Mediterranean, it is free to progress until its power is spent. The rapidity with which the front advances is explained by the fact that both air masses, on either side of the front, have northerly velocity components. To conclude, it may be stated that in this type of storm the westerlies of the middle latitudes invade the tropics and completely alter the normal circulation.

CHAPTER VI

RAINFALL IN THE SUDAN

57. The conclusion has been reached (Par. 33) that rainfall in Central Africa is non-frontal in character. Experience in other regions of the world proves that, besides orographic precipitation and local air mass thunderstorms, there is a third type of non-frontal rainfall which, indeed, is the cause of many floods. This may be described as widespread mass lifting of moist and convectively unstable tropical maritime air from which, as condensation is reached, an enormous quantity of convective energy is released. Its general character and its systematic motion distinguish this type from the purely local convective storm. Henceforth the former will be referred to as a "general storm" and the latter as a "local storm". The solution of two important problems was undertaken: to discover first whether all tropical rainfall is local and sporadic or whether there are also evidences of general storms, and, second, to explain the dynamic and thermodynamic conditions which produce rainfall in these regions. For these purposes all available data for the 1942 Rainy Season in the Anglo-Egyptian Sudan were intensively analyzed.

58. RAINFALL PATTERNS. A complete set of daily isohyetal charts for July and August 1942 was compiled, and these showed that in several cases storms could be traced systema-

tically. However, the analysis was quite difficult on account of the sparsity of rainfall stations and the differences in intensity in the various sections. In order to overcome these disadvantages, the Sudan was divided into te. equal areas within each of which the rainfall characteristics were approximately homogeneous. The average daily rainfall within each region was computed by the Thiessen method, and these in turn converted into percentages of the seasonal total for each region. Values thus obtained were plotted at the geometrical centers of the regions. Smooth curves were then drawn to represent isopleths of regional rainfall percentage. In this way the accidental nature of point rainfall measurements was partially overcome by considering only the average rainfall over a sizeable area. By the reduction of the results to a percentage basis they were made comparable with each other.

59. Careful examination of these charts revealed a number of recurring patterns and general cyclonic motion of the storm centers. The remarkable day to day similarity between the two series of Fig. 34 illustrates the typically recurrent patterns. They leave no doubt as to their general nature both because of their extensiveness and their systematic motions. In fact it was found that nearly all of the more intense rain occurring in the Khartoum area was associated with general storms.

60. <u>DYNAMICS OF RAINFALL</u>. From the rainfall data of sta-

tions in the vicinity of Khartoum a classification was made which included 8 days of heavy rain, 20 of light rain, and 32 with no rain. In order to discover the flow of air existing under various conditions, the upper winds for 13 stations were also classified as above and averaged. Fig. 35 shows the results of this work for the Khartoum data and reveals several important points: the striking diurnal variation of the winds in the air mass above the front, effective even during heavy rain periods; the diurnal variation in the height of the intertropical front from 5,000 feet at 0400 local time to 7,000 feet at 1800; and finally the contrast between the normal veering of the wind with height and the pronounced backing during rain periods. In connection with the last principle the dominance of the east wind, especially before and after heavy rains, is highly significant. Other investigators have also noted the backing of the wind during rainstorms in this region, but by means of a more detailed study of this phenomenon we have found that this is a necessary but insufficient condition for the occurrence of rain.

61. The significance of the above facts could not be fully appreciated from the study at a single station so that a set of flow charts for an area centered at Khartoum was constructed (Fig. 36), using the data from all of the stations. Fig. 37, showing the normal flow, is the first of these. Again there is the diurnal fluctuation of the wind and the frontal position. At 0400 the front is southernmost

and the slope greatest, the Khartoum winds being strong north and north-northeast at 12,000 feet. Thus the air north of the front is most active in the early morning. By 1000 the 12,000-foot Khartoum winds shift to the northeast, but the slope of the front remains steep. As convective activity reaches its maximum, the upper air loses momentum at the expense of the lower, so that its winds shift to easterly, and the frontal slope becomes unstable and pushes northward. This is best seen on the 4,000-foot 1800 chart. A contributing factor to the northward surge of the intertropical front is the temperature contrast produced at this time by the increased cloudiness in the moist air south of the front. As this process continues the front becomes shallower. The front reaches its most northerly position shortly after sunset, by which time, both convection and insolation having disappeared, the upper winds shift back to north, the frontal slope becomes unbalanced, and the front retreats southward again, finally attaining its 0400 position.

62. An interesting feature of the normal circulation is the anticyclonic cell existing at 12,000 feet above the Sudan low, the frontal trough sloping with the front. The fact that the Khartoum winds in May are northerly near the surface and southwest aloft has puzzled synoptic meteorologists, but can now be explained. Since in May the entire system is displaced southward so that the anticyclone is directly above Khartoum, the southwest winds aloft are part of this upper

circulation.

63. In order to bring out the greatest contrast, the corresponding flow for days with heavy rain was then computed (Fig. 38). In this case the first set of charts represents conditions prevailing several hours before the rain, and the second set during and shortly after the rain. Comparing the normal charts with those for heavy rain, many distortions are apparent and these are greatest in the lower layers. The 4,000-foot level shows that the intertropical front is north of its normal position both before and after the rain. Extreme convergence at 8,000 feet before the rain is also well marked. The 12,000-foot level appears quite normal except that conditions both before and after the rain resemble the 0400 normal flow. Undoubtedly the most interesting feature is the cyclonic vortex appearing at 4,000 feet during and after the heavy rain. This shows how the east winds of Fig. 35 are related to the general flow.

64. Since the diurnal wind variation continues even in the midst of a large disturbance, it is important to remove this effect in order to understand the pure effect of the storm. In Fig. 39, the normal flow has been subtracted from the storm flow, and the results represent the deviation from the normal in heavy rain periods. Extreme convergence of the two air masses is definitely indicated by the deviations before the rain begins. Thus the greatly increased southerly flow in the moist air at 4,000 feet is simultan-

eous with the corresponding increased northerly flow at 12,000 feet, and the convergence of the two streams at Khartoum is clearly evident at 8,000 feet. Both the 4,000 and 8,000-foot deviations, after the rain begins, show a strong backing tendency and an increase in cyclonic vorticity. It will also be noted that the center of convergence has been lifted to 12,000 feet.

65. Since the flow charts indicate that the winds undergo convergence and cyclonic vorticity during heavy rain, the values for a combination of convergence and vorticity were computed and plotted on another set of charts (Fig. 40). Here the numerical values are proportional to the sum of the inflow and rotational velocities. Convergence and cyclonic vorticity exist at all levels in the vicinity of Khartoum and are strongest at 12,000 feet both before and after the rain.

66. As a quantitative index of the relationship between the opposing flow on either side of the front, the southwest component of the wind at 4,000 feet was subtracted from the southwest component at 12,000 feet. By adopting the convention of southwest as positive and northeast as negative, the frontal shear will have a negative value. On the shear chart (Fig. 41) the zero line approximates the position of the front at 8,000 feet. It will be seen that there is a decided increase in negative shear before heavy rain, but that after heavy rain the deviation is reversed, reflecting the strong east wind at 4,000 feet.

67. As was already shown (Par. 60), one of the most striking features of the rain process is the extreme easterly deviation of the wind. To amplify this analysis, the daily deviations from the normal of the mean west component of the wind in the layer from the surface to 4,000 feet was computed and plotted, and isopleths of wind deviation were drawn. (Fig. 42). In these charts the numerical values are proportional to velocity, and a negative quantity represents an easterly deviation from normal. The centers of negative deviation show a systematic trajectory and, during rain periods, are always to the east of the positive centers. This indicates a greater than normal horizontal convergence. Furthermore, there is a remarkable resemblance between these charts and the rainfall patterns for the same period (Fig. 34). Whenever the frontal shear is low, or in other words, when the winds aloft are west-northwest or northwest instead of northeast, rainfall does not occur, and the centers of positive west wind deviation are east of the centers of negative deviation. This represents an abnormal horizontal divergence.

68. The following conditions, then, may be enumerated as associated with the rain process:

1. The intertropical front at the surface is north of its normal position and aloft it is farther south than normal.

2. The shallow slope of the front is maintained by an increased southerly flow of moist air near the

ground and a correspondingly strong northerly flow aloft, the two currents converging at about 8,000 feet.

3. Increased horizontal convergence and cyclonic vorticity occur at all levels.

4. The winds back with elevation, and there is a decided easterly shift at 4,000 feet.

69. It has already been shown (Par. 45-47) that the intertropical front may become an active cold front which will push its way north of its normal position under conditions of extreme convergence and active cyclogenesis. The extreme horizontal convergence of the southwest flow against the mountain barrier to the east causes vertical stretching. According to the theorem of vorticity, vertical stretching is in part compensated for by the increased latitude of the northward moving current, but so enormous is the effect that a considerable increase in cyclonic vorticity also takes place. Thus the processes which produce the cold front from the south and its accompanying sandstorm, in their later stages of development, fulfill all the conditions necessary for heavy rain. Every observed occurrence of this type of sandstorm was followed within 48 hours by general rain. However, there is another way in which general rain may develop. If the intertropical front is already north of its normal position, then the southerly flow is relatively strong.

If the northerly flow should suddenly veer to the northeast and increase in intensity aloft, the resulting convergence at intermediate levels would create an increase in cyclonic vorticity and rain would follow. The effectiveness of this process depends on the magnitude of the convergence and the rapidity with which it takes place. It sometimes happens that the winds aloft at Khartoum, instead of being northeast, are west-northwest or northwest, in which case the frontal shear has a small negative value or may even be positive. Thus a subnormal frontal convergence exists, and rain is not likely to occur. Two extreme examples of this type of flow were found, on July 19 and August 2, 1942, when no rain fell anywhere in the Sudan east of El Geneina.

70. ISENTROPIC FLOW. General as well as local rainfall is largely affected by convective processes and is therefore most intense in the late afternoon and early evening. During such times the flow in the lower layers, where the moisture is concentrated, is non-isentropic. Thus the isentropic surfaces are destroyed during the daytime and re-established at night. This process exists also in the United States during the summer but is greatly exaggerated here because of the influence of the intertropical front. Nevertheless, careful study of the circulation indicates that, just as in the United States, in this region also general rains are associated with isentropic upslope motion.

71. By fitting together the dynamic and thermodynamic

principles hitherto discussed, the current wind observations over a considerable area, and the Khartoum soundings, isentropic charts were constructed for July 13 and July 26, 1942 (Figs. 43 & 44). Such a task would ordinarily be too difficult to attempt, but in this case the number of possible solutions is severely limited by the imposed restrictions. These charts are schematic inasmuch as the numerical values indicated may differ considerably from the true values, but the patterns themselves are believed to be logical and correct. The schematic chart for July 13 (Fig. 43) represents the normal isentropic flow in the Rainy Season. The cold dome in the southeast is associated with the plateau high and the warm valley with the intertropical front. The moist tongue in the south originates at the Indian Ocean, the flow being generally anticyclonic and upslope in the southern Sudan. As it approaches the front, however, the flow is deflected into a cyclonic cell. In this particular case the cyclonic cell is somewhat west of its normal position, since the front is too far south in the vicinity of El Fasher. The anomalous relationship between the pressure and condensation patterns is most pronounced in the eastern dry cell, where dry air from the Arabian cyclonic circulation is flowing upslope. The dome of dry air in the northwest is the Sahara air which moves generally downslope. Originating as an anticyclonic current, it becomes part of the cyclonic cell near the front. The most important factor in the rainfall regime is the anticyclonic shape of the southeastern cold dome, which tends to produce downslope motion in the northern Sudan. Here again is evidence of the all important fact that, whereas in the southern Sudan the normal circulation enhances the opportunity for precipitation, the opposite is true father north. In other words, a disturbed state of atmospheric flow is essential for general rainfall to occur in the north. With further reduction of frontal shear, as on July 19 (Par. 69), the dome of cold air becomes more anticyclonic and the downslope motion more pronounced.

72. In contrast to the above, the schematic chart for July 26 (Fig. 44) shows the distortion of the normal patterns which takes place during periods of heavy general rain. The cold dome is situated farther north and is decidedly cyclonic in shape so that the southwest flow is predominantly upslope. The condensation area has the same shape as the cold dome and advances in a cyclonic path. It may be here pointed out that the Sudan rainfall regime extends as far west as El Fasher and does not usually include El Geneina (Par. 86). Another important fact to be noted is the greater wind velocity throughout the area in comparison with the normal chart.

73. <u>THERMODYNAMICS OF RAINFALL.</u> The modified Indian Ocean air mass is extremely conservative in its thermodynamic properties, and the modifications which take place during its movement northward are gradual. Thus the amount of moisture in the air above Khartoum is a function of the height

of the front and the strength of the southerly flow, both of which are automatically determined by the dynamic conditions previously discussed. When there exists a dynamic state necessary to produce rain, by the same token there also exists a deep layer of moist unstable air.

74. Using the same classification as before, three mean soundings for no rain, light rain, and heavy rain were constructed (Figs. 45, 46, & 47). The results show a systematic intensification from no rain to heavy rain of all of the thermodynamic criteria for convective activity. The positive areas and the quantities of precipitable water increase, while the negative areas and the critical levels decrease. It is interesting to note, however, that the curve which represents the temperature of the rising parcel remains constant. Since this curve is determined by the maximum temperature and the average moisture in the unsaturated layer, it is evident that both the maximum temperature and the average wet bulb potential temperature in the unsaturated layer do not change. (The latter property henceforth will be called the limiting pseudo-adiabat.) When the individual daily soundings were examined, it was found that this limiting wet bulb potential temperature is practically invariant.

75. In the theory of effective precipitable water, developed by the Hydrometeorological Section of the United States Weather Bureau, a model convective cell has three layers of equal height: the layer of net inflow, the layer

of maximum lift, and the layer of net outflow. The effective precipitable water is the amount available for precipitation and is computed as the difference in precipitable water between the inflow and the outflow layers. Under conditions of saturation, precipitable water is measured along the limiting pseudo-adiabat by integrating the specific humidities with respect to pressure. The vertical dimensions of the system are assumed to be a direct function of the limiting pseudo-adiabat, since convective energy depends on the amount of latent heat. In this case, the limiting pseudo-adiabat is fixed (wet bulb potential temperature 24°C.), and consequently the effective precipitable water for saturation is constant. The value of the former is 1.96 in. in 12,000 feet and of the latter 1.40 in. When the air mass is unsaturated, however, the effective precipitable water is reduced, since less moisture is flowing into the convective cell, while at the same time, the outflow layer being saturated, there is the same amount of outflow. Furthermore, part of the precipitation must be evaporated into the unsaturated air below. Thus the effective precipitable water is reduced by twice the difference between the precipitable water in a saturated inflow layer, and the actual amount of precipitable water in the inflow layer. In this case, then, the limiting amount of precipitable water in 12,000 feet is 1.26 in. In other words, if the first 12,000 feet contains less than 1.26 in., all the precipitation will evaporate before reaching the ground.

76. The amounts of precipitable water in the first 12,000 feet were computed for each day, and a frequency study of this data was performed. Since it was previously found (Par. 69) an air mass with high moisture content could exist without producing rain if the winds aloft veered to west-northwest or northwest, ten such cases were not included in this study. Fig. 48 shows the results that were obtained. There were only two cases of rain with less than 1.57 in. of precipitable water; in one of these the wet bulb curve was questionable, and in the other the precipitable water was 1.54 in. Three cases of no rain occurred with precipitable water of 1.60 in. or higher and none with more than 1.64 in. Since the critical conditions for the continuance of an haboob are determined by evaporation into the lower layers, the values of precipitable water for the two haboobs previously discussed (Par. 43) are shown on this chart. The lower limit of 1.26 in. and the upper limit of 1.57 in. seem reasonable. The validity of the curve of Fig. 48 is enhanced by the agreement between the two theoretical limits and the observed values. Because of inaccuracies in the method of observation, no further refinements were considered adviseable.

77. In conclusion, it is again emphasized that most of the thermodynamic properties of the air mass are nearly invariant and that the variant properties bear an automatic relationship to the dynamic conditions.

CHAPTER VII

DYNAMIC CLIMATOLOGY

78. The climates of Central Africa, like the climates of all great land masses, are controlled primarily by four factors: the annual march of the sun, the general tropospheric circulation, the relationship between land and sea masses, and topography. The latter two produce local circulations of various degrees of magnitude. The interaction of two opposing large-scale flows, from the north and from the south, produces the intertropical front, which, unlike normal fronts, inhibits rather than enhances the occurrence of precipitation over the African continent. On the basis of the above discussion it is possible to explain the generalized annual isohyetal pattern (Fig. 49). It will be seen that the isohyets tend to parallel the position of the intertropical front. The rainfall decreases northward from maxima at the source region along the coast to minima along the position of the front, with an orographic maximum on the Abyssinian plateau.

79. The air transport route from Dakar to Karachi, India may be divided into five climatic zones: the maritime, Dakar to Lagos (1744 miles); the transitional, Lagos to El Geneina (1475 miles); the Sudan zone, El Geneina to Kassala (952 miles); the orographic zone, Kassala to the Red Sea (235 miles); and the southern Arabian zone, from the Red Sea

to Karachi (2117 miles).

80. South of the intertropical front in the Rainy Season, two large streams of cold maritime air underrun the Sahara air mass: the Indian Ocean anticyclonic current to the east, and the cyclonic Atlantic current to the west. These converge in the region of El Geneina. (Fig. 7). The eastern flow has already been fully discussed. The western current continues to flow cyclonically, reaching the coast at Accra as a northeast wind. The normal isentropic flow being in this case cyclonic and, from Maiduguri southwestward, also upslope, is favorable to the occurrence of precipitation, in contrast to the Indian Ocean current. The shallow thermal high extending off the south coast of western Central Africa does not influence the flow patterns to the same degree as its eastern counterpart, the plateau high. Since there is no mountain barrier, the anticyclonic circulation does not normally extend above 4,000 feet, nor more than 100 miles inland.

81. Along the west coast the rainfall maximum occurs in August when the intertropical front is farthest north and the tropical maritime current is deepest. Just as in the Sudan, precipitation is greatest when the front is just far enough north to produce both a deep maritime current and frontal convergence aloft. Between Accra and Lagos, on the other hand, there are two maxima, in June and October, with a lull in August. The primary maximum in June occurs when

the intertropical front is advancing northward and is sufficiently far to the north to produce maximum convergence aloft, and the secondary maximum in October occurs under similar conditions with the retreat of the front.

82. Precipitation in the maritime zone is of two kinds, local and general. The local rains are heaviest in French Guinea, Sierra Leone, and Liberia, where well over one hundred inches falls during a year. At Monrovia, Liberia, precipitation is recorded, on the average, 25 days a month from June through October, and rain falls every month out of the year. The local nature of the rainfall in this zone is also seen by the fact that at Accra the annual precipitation is only 27 inches, whereas, because of the additional lift, it is probably three times as great in the hills a few miles inland.

83. Along the entire west coast there exists a perennial sea breeze which produces a shear aloft that is sometimes confused with the intertropical front (Par. 32). At Accra, for example, low cumulus develop in the early afternoon, drift inland under the influence of the southwest sea breeze, build up into cumulonimbus, and flow back at night in the northeast circulation above 4,000 feet. Thus most of the local precipitation at Accra is nocturnal. Unlike the frontal shear, the air above the sea breeze is also maritime, and therefore does not dessicate the convective clouds. General rainfall in this region is associated with the cyclonic cell

aloft and can readily be traced from Maiduguri westward. These are the so-called "line squalls" and are simply areas of horizontal convergence similar to those in the Sudan, although not requiring as great a disturbance of the normal flow. Since the isentropic flow in September at Maiduguri is slightly downslope, an increase in horizontal convergence and cyclonic vorticity is necessary to generate a storm of this character. Thus the normal southwest wind at 6,000 to 8,000 feet backs to south with the approach of a general storm. The essential feature of these storms is that they are not frontal and therefore not "line squalls", but rather that they are associated with isentropic flow within a homogeneous air mass.

84. The prevailing air mass in this region is maritime only during the rainy half of the year. During the remainder of the year the Sahara anticyclone definitely predominates. As previously stated, the sea breeze forms a shallow cold front along the coast. An exception to the general continental flow in the Dry Season occurs when the harmattan front appears, and a strong maritime current develops (Par. 55.). Along the west coast, moreover, the return flow of the continental anticyclone becomes modified as it moves over the ocean, and this accounts for the rainfall throughout the year.

85. In general the maritime zone is a region of low ceilings and fog, especially in the Rainy Season. There us-

ually exists an area of broken clouds adjacent to the shore, and in bad weather pilots fly low along the coast line, coming in under the overcast.

86. Inland from the coast in the transition zone there is a progressive decrease in low stratus, fog, and poor visibilities. The maximum precipitation occurs in August when there is enough moisture to produce almost daily local rains. As the moisture decreases inland, so does the average height of the thunderstorms increase, until it is possible to fly underneath all but the most severe ones. The lightning in the large majority of these storms is of the cloud-to-cloud-type; this fact is generally true throughout Central Africa. The general storms in the Maiduguri region have already been discussed. The rainfall at El Geneina is in a special class by itself. The general cyclonic disturbance in the eastern current (Chap. VI), although it extends to El Fasher, 194 miles to the east, rarely reaches El Geneina. On the other hand the general storms associated with the western cyclonic current do not usually occur so far to the east. However, El Geneina is in a region of normal convergence between the anticyclone to the east and the cyclone to the west. Also, there is a small range of mountains with peaks extending over 10,000 feet between El Geneina and El Fasher (Fig. 50), a natural birthplace of thunderstorm activity, which develops and moves westward.

87. Since the Sudan climate needs no further discussion,

the next region to be considered is the mountain climate from Kassala to the Red Sea. The nature of this climate can best be understood by an examination of the cross-section (Fig. 50). From an average height of about 7,000 feet the topography drops to sea level in approximately 50 miles. These are not isolated peaks but present a real barrier. It can be seen that the weather in this region is extremely local, and conditions of wind, temperature and humidity must be studied in great detail in order to forecast successfully. The orographic effect is also well marked on the isohyetal chart (Fig. 49). Almost daily rains occur in July and August, and the Rainy Season endures from May to October. Early morning stratus throughout the year is also an important forecasting problem. The influence of the mountain barrier has the interesting effect at Massaua, on the Red Sea coast, of entirely reversing the Rainy Season to the winter months. This is, of course, caused by the upslope winds from the Arabian high.

88. Along the southern Arabian coast the monsoons control the climate, although, lacking the high mountains of India, they cause little rain. Salalah, from May to October during the southerly regime, has considerable drizzle, fog, and low visibility. Karachi, India records only 7 inches of rainfall per year.

89. As an index of rainfall regime, the cumulative

daily maximum rainfall percentages for the greatest two month period were plotted against the number of days (Fig. 51). Thus an arid station will have a very steep curve, and a wet station a flatter curve. The wet regime at Roberts Field, Liberia, is outstanding. The transitional character of the regimes at Maiduguri and El Geneina are well marked. Also the difference between El Geneina and El Fasher, only 194 miles apart, is in sharp contrast to the almost complete identity between Khartoum and El Fasher, over 500 miles from each other. This shows clearly that El Fasher rainfall is part of the eastern circulation, to the exclusion of El Geneina. The latitudinal progression of the rainfall regime in the Sudan is well brought out by comparison of the Wau, Khartoum, and Kareima curves. And finally, the individuality of the Gura curve shows the special orographic effect by its extreme steepness in the beginning and its abnormal flattening at the end. This reflects both the intense character of the precipitation and its regular recurrence.

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APPENDIX I

SUGGESTIONS ON MAP ANALYSIS

The surface synoptic weather chart in the tropics is not always the same kind of forecasting tool that it is in temperate latitudes. For the most part, the systems are stationary, and, of course, the very basis of synoptic forecasting involves the concept of motion or change. The above does not imply that the systems are dead. They frequently exhibit apparent shifts in position and orientation. If real, these are important and must therefore be carefully analyzed. Furthermore, as has been previously shown, the weather periodically changes from a stationary to a disturbed type. During such periods the synoptic weather chart is of prime importance as a forecasting tool. The usual abruptness of the transition demands alertness on the part of the forecaster.

The essential function of the surface synoptic chart in this region is to serve as an ideal model of the gradient flow patterns. Used in this way, it helps transform in the forecaster's mind a jumble of disconnected and confusing facts into an organized and logical whole. Combined with the winds aloft, it is a substitute for an isentropic or fixed level upper air chart. It is an excellent practice, by the way, to plot the winds for at least two upper levels on the surface chart. It is important to remember, however, that the synoptic chart represents the gradient, but that the real flow deviates considerably from this. Thus the streamlines will have a tendency to intersect the isobars at a sharp angle.

In order to utilize the synoptic chart in the manner outlined, every effort should be put forth to receive an extensive network of reports. Although practical forecasting can be carried out with a limited set of data, real understanding of the atmospheric processes in this region is impossible under these conditions. The accumulation of extensive data will result in an inevitable delay in the final completion of the chart. However, it is possible to use the chart for forecasting even before it is completed, provided the continuity is good. It is important constantly to go back and correct the analysis as more data becomes available. In extremely hot climates it will be difficult to erase lines, so that it is better to delay completion of the chart until all the data has been plotted.

Since, at best, the station density is quite low, each report must be weighed carefully in drawing isobars. If isobars are drawn mechanically for each pressure value, a meaningless set of lines results. While, on the other hand, if too many values are ignored in order to fit a preconceived analysis, a rigidity of pattern results, which will tend to conceal many significant details. Barometry standards are not high in Central Africa. Most observations are taken by semi-trained native personnel, so that the percentage of personal error is greater than in the United States. Furthermore, many elevated stations have not been accurately surveyed, so that reduction to sea level is another source of error. Also, for any considerable area, there is an unavoidable absence of simultaneity. Thus, on the whole, the analyst has more freedom of interpretation in isobaric analysis. However, if a number of reports seem consistent with each other, it is not safe to deviate too far from them. Wind directions and velocities are important criteria in shaping isobars. The exceptions are coastal breezes, if light, and orographic winds.

In frontal analysis, historical continuity of pattern and wind discontinuities are by far the most important considerations. In tracing winter cold fronts from the north, the shift in wind direction may not be very great, but there will be considerable discontinuity in velocity. The 0600 GMT chart, for example, might show a station south of the front to have a normal surface wind of northeast, force 2, and behind the front the wind would be north-northwest, force 4 or 5. Moisture content reacts much more slowly to a frontal passage and is therefore of lesser importance as a frontal criterion. In considering moisture discontinuities, caution should be exercised in determining whether the moisture values are representative or whether they occur only in the surface layer. It should be remembered that in Central Africa, especially in the Dry Season, large natural surface moisture gradients exist because of variation in vegetation and relative position with respect to large bodies of water. Temperature discontinuities alone should never be used to determine frontal position. It has already been pointed out that temperatures are largely a function of cloud cover, and also that the diurnal cycle masks other effects. Even in the case of the most vigorous cold fronts, the temperature drop may lag by as much as 12 to 18 hours. This is stressed because experience has shown that the most common errors in analysis in these regions can be traced to overemphasis of surface temperature discontinuities.

In general, the analysis should be simple. Complex double front structures should be studiously avoided. It is well to remember that this is a region thermodynamically unfavorable to the development of fronts and that they exist at all only by virtue of large scale discontinuities in the general circulation. It may be important for forecasting purposes to outline ~~certain moving~~ boundaries or zones. These might be areas of thunderstorm activity, or moist surface air. This is perfectly legitimate provided such markings are differentiated from fronts. Such zones do show systematic motion, as has been shown in Chapter VI, but they are not fronts, and should therefore not be confused with fronts.

APPENDIX II

TECHNIQUES EMPLOYED IN THE STUDY

This appendix is an attempt at clarification of the less obvious methods of analysis and presentation of data which were used in this study.

THE WIND COMPONENT DIAGRAM OR UV CHART. The construction of the UV chart, or wind component diagram, is the preliminary step in the process of detailed circulation analysis employed in the present study. If the UV chart is improperly constructed or carelessly analyzed, the construction of further, derived charts is completely pointless. The computation of the values to be entered on the chart is, of course, completely mechanical. A logical analysis of the chart, however, requires that the analyst have a complete knowledge of the general circulation and the possible deviations therefrom in the area under consideration. The UV chart may be constructed either for a level or for a layer, the essential technique involved being the same in either case.

Given a wind of velocity v and direction angle α, the two components of the wind, U (west-east) and V (south-north), are expressed as follows:

$$U = v \cos \alpha \qquad ; \qquad V = v \sin \alpha$$

Thus, a positive value of U results when $180^\circ < \alpha < 360^\circ$, and a negative value when $0^\circ < \alpha < 180^\circ$. Similarly, V is positive when

$90^\circ < \alpha < 270^\circ$ and negative when $270^\circ < \alpha \leq 360^\circ$ and when $0^\circ \leq \alpha < 90^\circ$. In cases where the units of v, as taken from the observed data, are different from those of U and V, as desired in the analysis, a conversion factor must be employed. The entire computation may be greatly facilitated by the construction of a table by means of which the observed data in their original units are converted directly into values of U and V in the desired units.

When the values of U and V have been computed for the level desired or averaged by approximate integration for the layer desired, they are entered on the surface map, and isopleths of U and V are drawn by the analyst. A comprehensive discussion of the technique of analysis of the UV diagram is unnecessary here, it being merely necessary to point out that the analyst must exercise the same care that he would use, for instance, in isobaric or isallobaric analysis of the surface synoptic chart.

Once the analysis is complete, grid points over the entire area are selected, their selection depending upon the degree of refinement justified by the data. To facilitate further computations, the grid points should be at the corners of square areas of equal size. In an area near the equator, such as the one in the present study, the grid points may be chosen at the intersection of equally spaced lines of latitude and longitude without significant error, since a degree of longitude near the equator represents very nearly the same distance as a degree of latitude. Once the grid points have been selected, values of U and V at each grid point are determined from the analysis by interpolation and are entered directly on the chart.

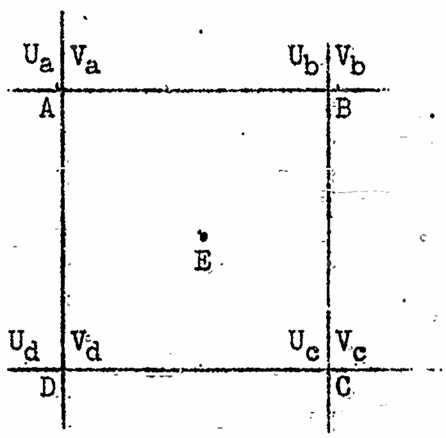
THE FLOW CHART. The flow chart is derived immediately from the analyzed UV chart. Using the values of U and V previously found by interpolation, the wind direction and velocity for each grid point are found by entering the values of U and V in a table which, except for the absence of a units factor, is exactly the inverse of the table originally used to determine U and V. The subsequent procedure is at the discretion of the analyst and depends mainly upon the degree of refinement desired. The simplest procedure is merely to compute the wind travel during a period of, say, 6 hours by multiplying the wind velocity in miles per hour by 6 and plotting the resulting distance as a vector emanating from the grid point; this was the method employed in the construction of Figs. 37 & 38. The wind travel vector pattern can be smoothed out and made more representative of actual wind travel by using a second approximation. This process was employed in the construction of Figs. 2, 4, 7, & 9, in which each arrow represents 24-hour wind travel and is the second approximation to a secant to the true streamline of the air proceeding from the position of the grid point.

THE MONTHLY MEAN FIVE-DAY TRAJECTORY CHART. Fig. 10, the chart of monthly mean five-day trajectories ending in Khartoum, was constructed from the monthly mean UV charts representing the mean wind for a layer from the surface to 10,000 feet above mean sea level. The trajectories are actually portions of mean monthly streamlines passing through Khartoum. Over a period of a month, however, mean trajectories and mean streamlines should be practically identical, especially in the area under consideration. The trajectories were constructed by the usual method of successive approximation except that the UV chart, instead of the surface map or ordinary upper-wind chart, was used to determine the wind direction and velocity at each point encountered.

<u>THE DIVERGENCE CHART</u>. This chart is a graphical representation of horizontal divergence. The basic equation is:

$$\text{div} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$

Thus, in an area where this quantity is positive, there is a net outflow and hence a net subsidence of air, and, in an area where this quantity is negative, there is a net inflow and hence a net ascendance of air. The computation of this quantity is accomplished as follows:



The figure represents a portion of the UV chart grid formed by the intersection of equally spaced latitude and longitude lines. Values of U and V are shown plotted at the four grid points, A, B, C, D. As previously pointed out, the figure ABCD is very nearly a square in the latitudes under consideration. If the length of the side of the square is denoted by L

$$\frac{\Delta U}{\Delta x} \text{ (along line AB)} = \frac{U_b - U_a}{L};$$

$$\frac{\Delta U}{\Delta x} \text{ (along line DC)} = \frac{U_c - U_d}{L};$$

$$\frac{\Delta V}{\Delta y} \text{ (along line DA)} = \frac{V_a - V_d}{L};$$

$$\frac{\Delta V}{\Delta y} \text{ (along line CB)} = \frac{V_b - V_c}{L};$$

At point E, the center of the square,

$$\frac{\Delta U}{\Delta x} = \frac{1}{2}\left[\frac{U_b - U_a}{L} + \frac{U_c - U_d}{L}\right] \text{ (approximately);}$$

$$\text{and } \frac{\Delta V}{\Delta y} = \frac{1}{2}\left[\frac{V_a - V_d}{L} + \frac{V_b - V_c}{L}\right] \text{ (approximately);}$$

$$\text{and } \operatorname{div} = \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = \frac{\Delta U}{\Delta x} + \frac{\Delta V}{\Delta y} \text{ (approximately)}$$

$$= \frac{1}{2L}\left[U_b - U_a + U_c - U_d + V_a - V_d + V_b - V_c\right]$$

Since, however, the numerical magnitude of divergence is of no practical interest except in the relative sense, the factor $\frac{1}{2L}$ may be omitted. The mechanical process of computation is as follows: $U_b - U_a$, $V_b - V_c$, $U_c - U_d$, and $V_a - V_d$ are computed and plotted on a worksheet on which the grid-point network has been reproduced on a smaller scale. These quantities are then added algebraically, giving the quantity 2L x div, which is then plotted at point E on the divergence chart. Lines of equal divergence are then drawn for convenient intervals by the analyst.

THE VORTICITY CHART. The vorticity chart is constructed in a manner similar to that employed in the construction of the divergence chart. The fundamental equation is:

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

This quantity is positive in the case of cyclonic vorticity and negative in the case of anticyclonic vorticity. Referring to the figure included in the discussion of the divergence chart, we have:

$$\zeta = \frac{1}{2L}\left[V_b - V_a + V_c - V_a + U_d - U_a + U_c + U_b\right]$$

The quantities $V_b - V_a$, $V_c - V_a$, $U_d - U_a$, $U_c - U_b$ are computed and plotted on the separate work-sheet as in the construction of the divergence chart. These values are then added algebraically to give the quantity $2L\zeta$, which is plotted at point E on the vorticity chart. Lines of equal vorticity are then drawn by the analyst for convenient intervals.

THE CONVERGENCE PLUS VORTICITY CHART. This chart is constructed from corresponding divergence and vorticity charts by adding, for each grid point, the negative value of divergence, i. e., convergence, to the positive value of vorticity, i. e., cyclonic vorticity. Fig. 40 is an example of this type of chart. No examples of charts of divergence or vorticity alone are included in this study.

THERMODYNAMIC ANALYSIS ---RAINY SEASON CHARTS. Two methods of analysis of the rainy season pseudo-adiabatic charts were employed in this study. In the first method, the convective condensation level is assumed to be the intersection of the average q line for the first 1,000 feet above the surface with the environment curve. The average q is computed from the surface and 1,000-foot values, giving double weight to the surface value. Negative and positive areas and critical temperature are determined in the usual manner. The analysis arrived at by the second method gives the actual thermodynamic structure of the upper air at the time of maximum convection as inferred from the sounding and from the recorded maximum temperature. The recorded maximum temperature is plotted on the pseudo-adiabatic chart at the surface level, and a dry adiabat is drawn upward from this point through the environment curve. The adiabatic layer thus determined is assumed to be thoroughly mixed and to have a uniform specific humidity throughout. Thus, the convective condensation level is the intersection of the average q line for the mixed layer thus found with the environment curve or the maximum temperature dry adiabat, whichever it intersects first. Positive and negative areas are put in in the usual manner.

The superiority of the second method as a technique of analysis is graphically illustrated by fig. 53, which shows daily values of the surface dew point temperature at the time of the maximum temperature compared to values corresponding to the average q values found by the two methods. The use of the first method results in a consistently large overstatement of the moisture content in the lower layers and hence, in practically every case, an overstatement of the in -

tensity of convective activity.

The days of the 1942 Rainy Season were classified by amount of rainfall into three groups: no rain, light rain, and heavy rain according to recorded 24-hour rainfall at Khartoum, Wadi Seidna, and Shendi, the three closest rainfall stations to the point where the airplane observations were made. A day's rainfall was classified under heavy rain if, during the 24 hours from 1000 GMT on that day to 1000 GMT on the following day, at least a trace fell at each of the stations and at least 25 mm. fell at one or more of the stations. The remaining rain days, that is, the days on which at least a trace fell at one or more of the stations, were classified under light rain. All the other days in the season were, of course, grouped under no rain. Only heavy rain and no rain days are compared in this study. Average pseudo-adiabatic charts and Rossby diagrams were prepared for the two classifications.

A daily calculation of the amount of precipitable water in the first 12,000 feet above the surface was also made for the days of the Rainy Season. The formula used was:

$$W_p = K \int_0^h q \, dp$$

where W_p is the amount of precipitable water in inches in the layer from the surface to height h, q is the specific humidity in grams per kilogram at pressure p millibars, and K is a units factor.

RAINFALL ANALYSIS---RAINFALL PATTERNS. Rainfall pattern charts, as illustrated by Figs. 34A & 34B, were constructed from rainfall data supplied by the Sudan Government Meteorological Service. The data available consisted of 24-hour rainfall totals for each day of the year 1942 for each of the 30 rainfall stations in the Anglo-Egyptian Sudan. Due to the inequitable distribution of the stations over the area (Fig. 52; W = upper wind station, R = rainfall station.), it was necessary to utilize a modified Thiessen network in order to arrive at a smooth picture of the actual pattern.

The first step in the analysis was the division of the Sudan into ten regions of equal area; this division was carried out in such a manner as to preserve the greatest possible degree of homogeneity of rainfall within each region. That is, the regions were not chosen arbitrarily but were selected only after due consideration of the effect of topography on rainfall, the latitudinal variation of rainfall intensity, and the distribution of rainfall with respect to the intertropical front.

Next a modification of the Thiessen network method was used to determine the weight to be given each station within or immediately adjacent to any particular region in determining the average rainfall for the region. An example of the Thiessen network is shown in Fig. 54. The average rainfall for the area ABCD is to be determined approximately on the basis of the rainfall data furnished by stations E, F, G, and H. The sphere of influence of any particular station,

i. e., the area of which the station may be assumed to be representative, is determined as being that area in which every point is closer to the station under consideration than to any other station in or adjacent to the region. According to a common theorem of geometry, the perpendicular bisector of a line joining two points is everywhere equidistant from the two points. Hence the boundary lines of the area represented by any station are the perpendicular bisectors of the lines joining the station to surrounding stations. Thus, in Fig. 54, the connecting lines, EF, FG, GH, HE, HF, and EG, were drawn, and their respective perpendicular bisectors, E'F', F''G'', G' H', H''E'', H'''F''', and E'''G''', were constructed. The portions of region ABCD represented by stations E, F, G, and H are then, respectively, areas AE'IE'', E'BJI, BCG'J, and DE''IJG'. (It will be noted that line EG and it's perpendicular bisector E'''G''' are superfluous.) The magnitudes of the four areas may be determined by any convenient method, (In this study the entire map of the Sudan was reproduced on finely squared plotting paper, and the areas were determined by counting squares.) but they are, in any event, finally expressed as percentages of the total area ABCD. The average rainfall for the region is then computed as the sum of the products of the individual station rainfall observations and their respective weight percentages.

Due to the large latitudinal variation in the intensity of rainfall in the Sudan, the individual daily rainfall amounts for each of the ten regions were expressed as percentages of Rainy Season (July and August) total for the region instead of as actual amounts. Finally, isopleths of percentage were drawn for each day of the Rainy Season, and Figs. 34A & 34B were chosen for presentation as typical series.

RAINFALL ANALYSIS--RANKED RAINFALL PERCENTAGES. Fig. 51 was prepared to demonstrate differences in rainfall regime between various stations in Central Africa. It was prepared from 24-hour daily rainfall amounts observed at each of the stations during the Rainy Season. The first step in the method consisted in ranking the daily rains at each station in descending order of magnitude. Next, cumulative totals, starting with the largest 24-hour rainfall amount as the first total, were prepared, and corresponding cumulative percentages of the grand total were computed. The results were plotted on rectangular coordinate paper, the coordinates being ranked against cumulative percentages.

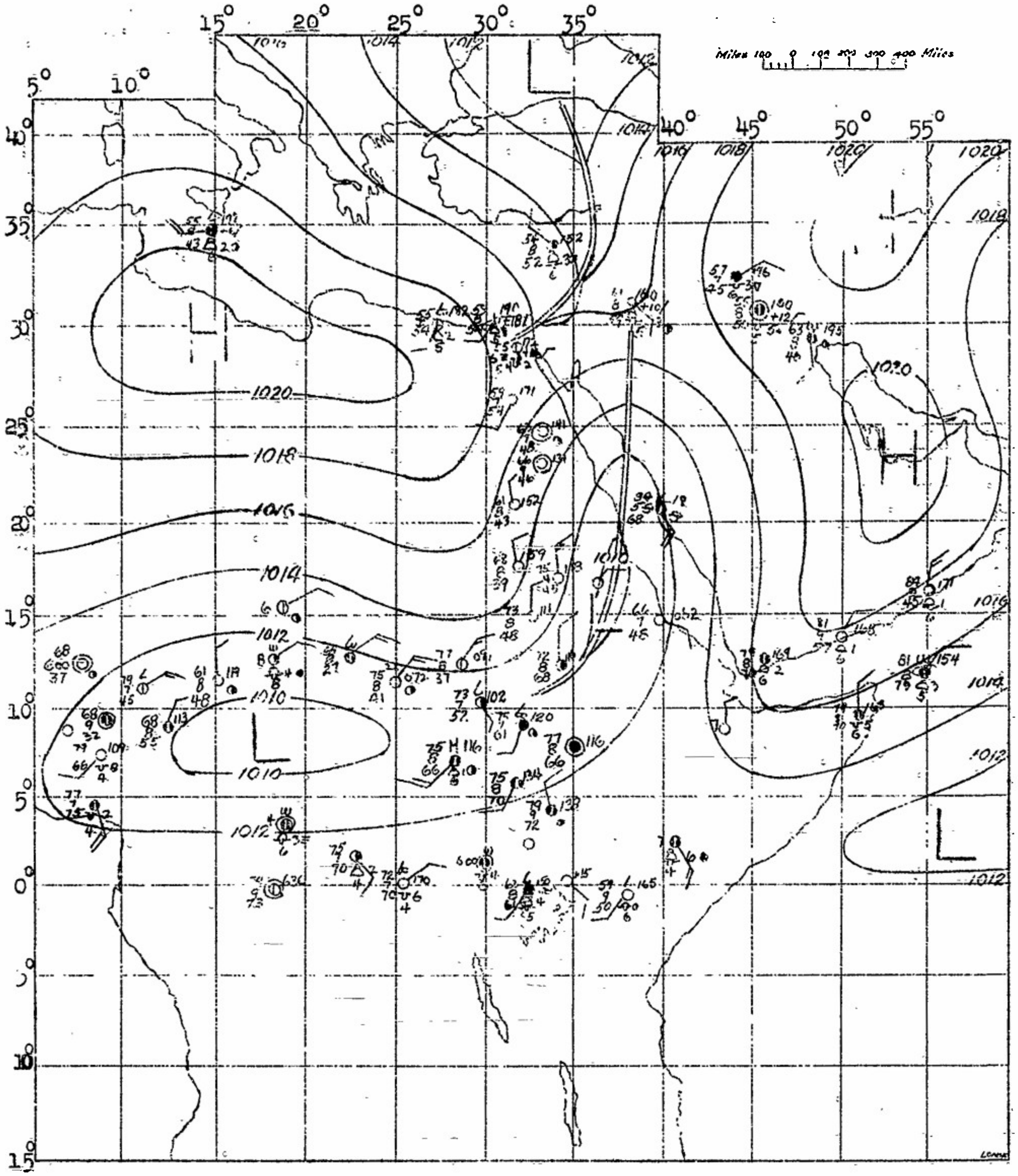


Figure 1 - Typical Chart, Dry Season (0600 December 4, 1942)

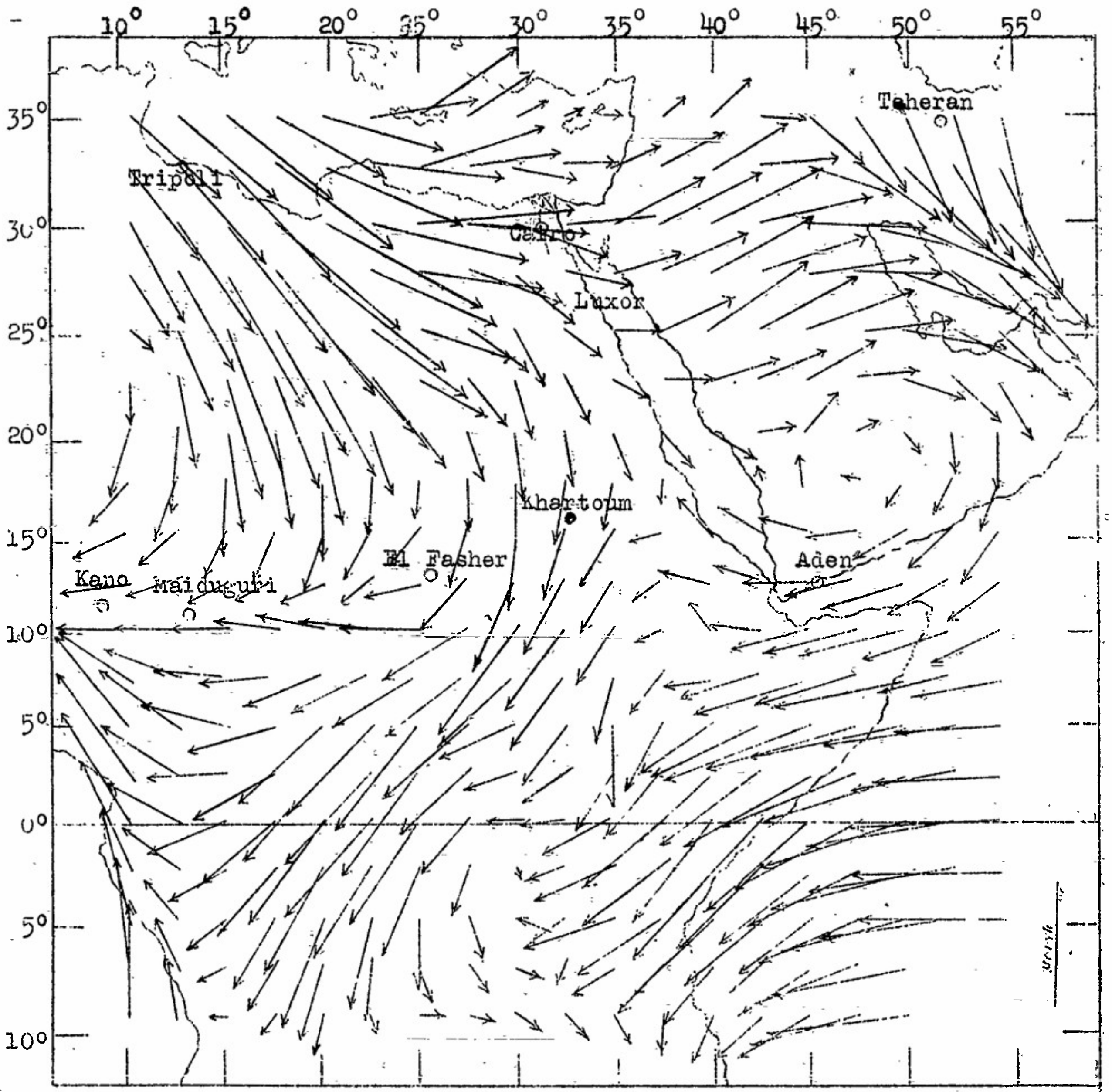


Figure 2 - One Day Trajectories
Layer :- Surface to 10,000 Feet
January

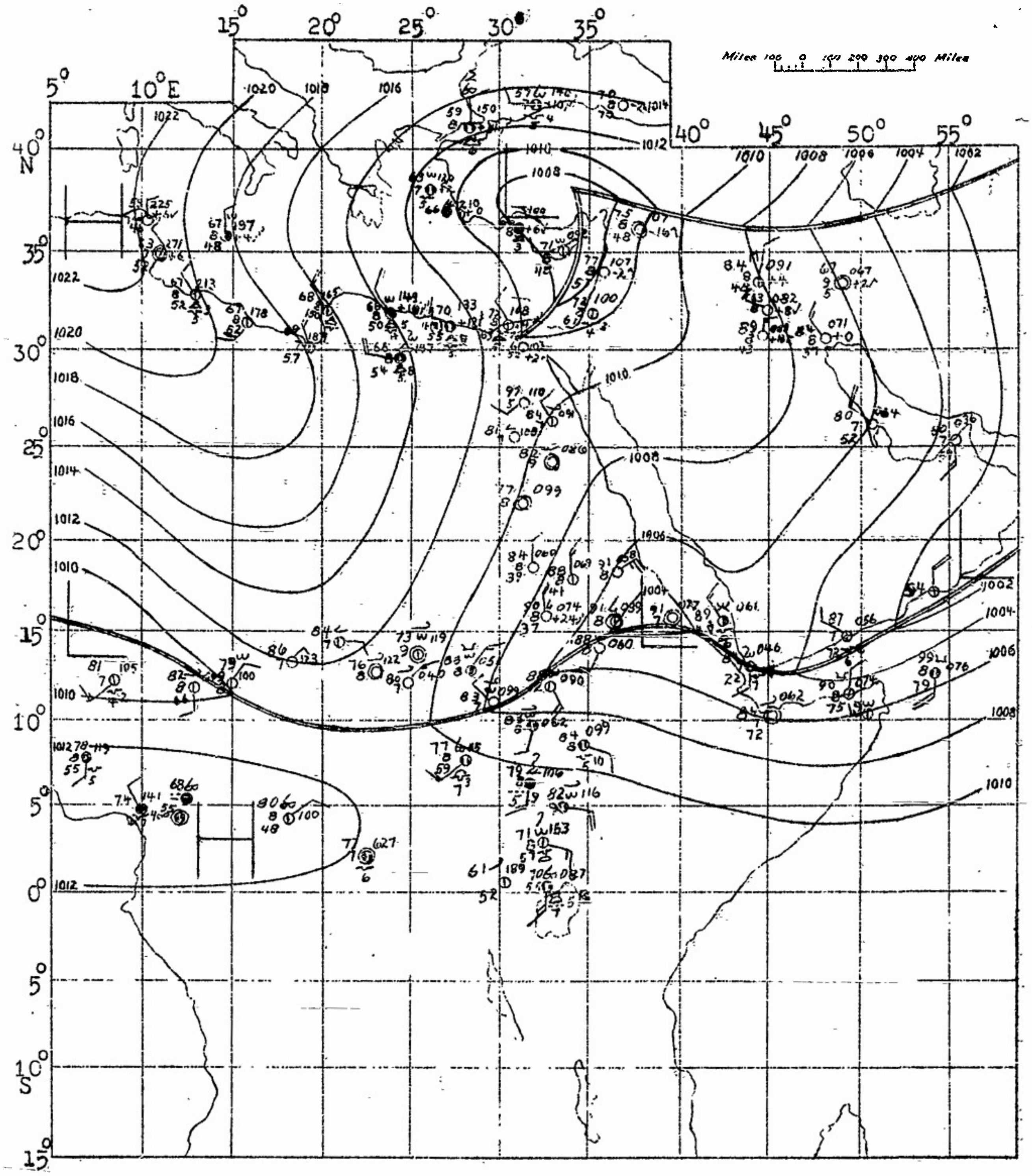


Figure 3 - Typical Chart, Season of Approaching Rains
(0600 May 28, 1943)

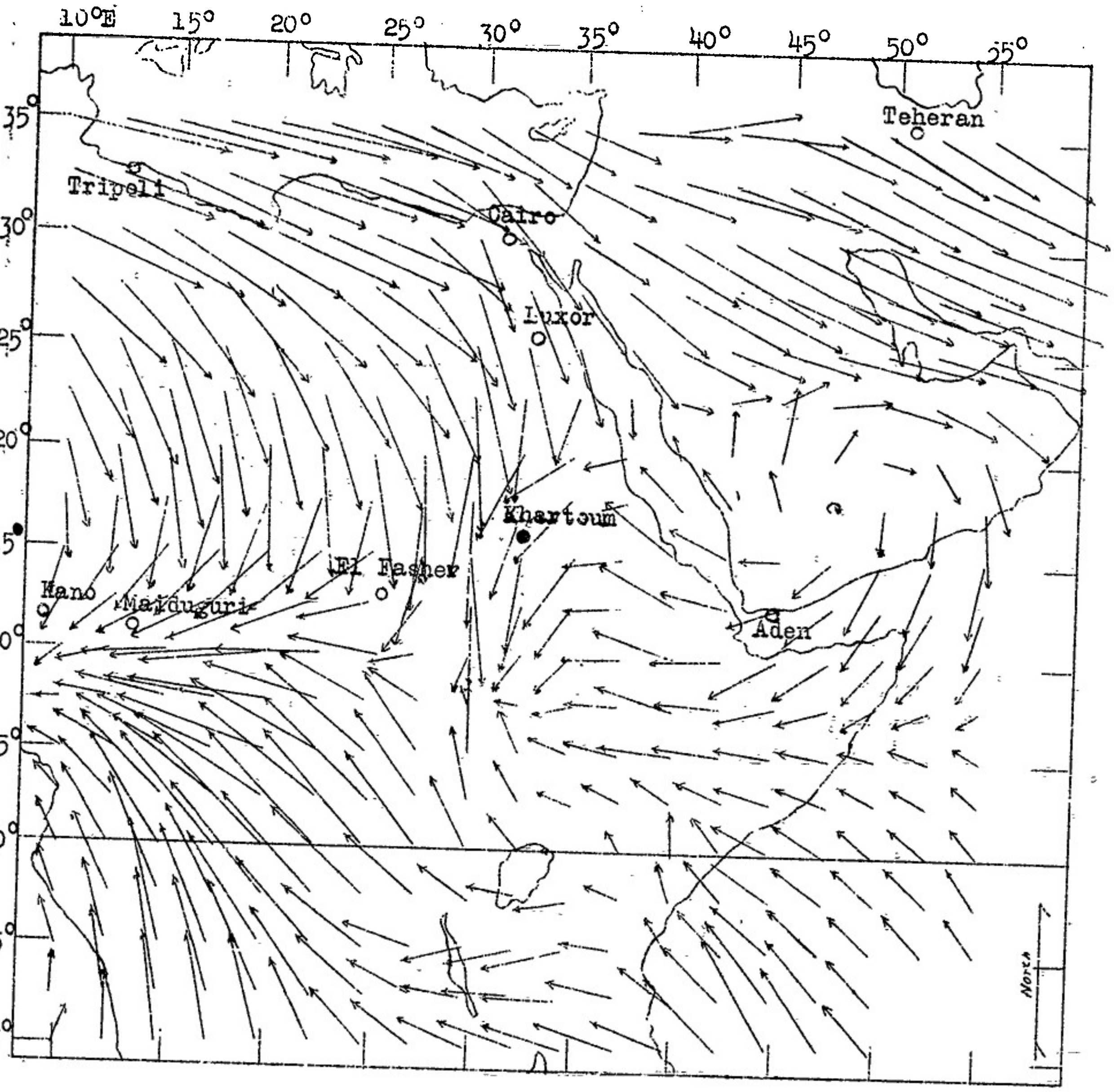
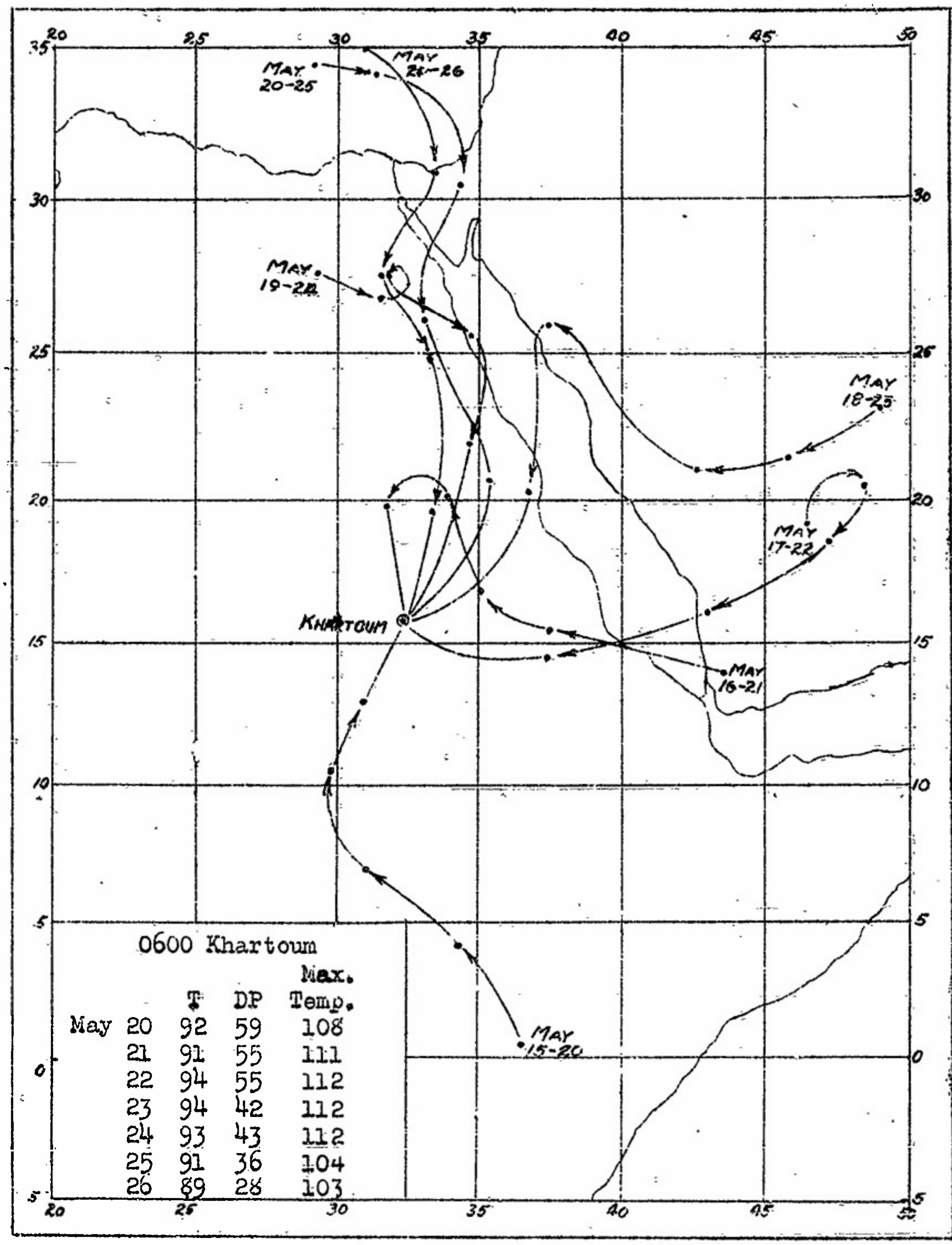


Figure 4 – One Day Trajectories
Layer :– Surface to 10,000 Feet
April



0600 Khartoum

		T	DP	Max. Temp.
May	20	92	59	108
	21	91	55	111
	22	94	55	112
	23	94	42	112
	24	93	43	112
	25	91	36	104
	26	89	28	103

Figure 5 - Five Day Trajectories in the Lower Troposphere
May 1943

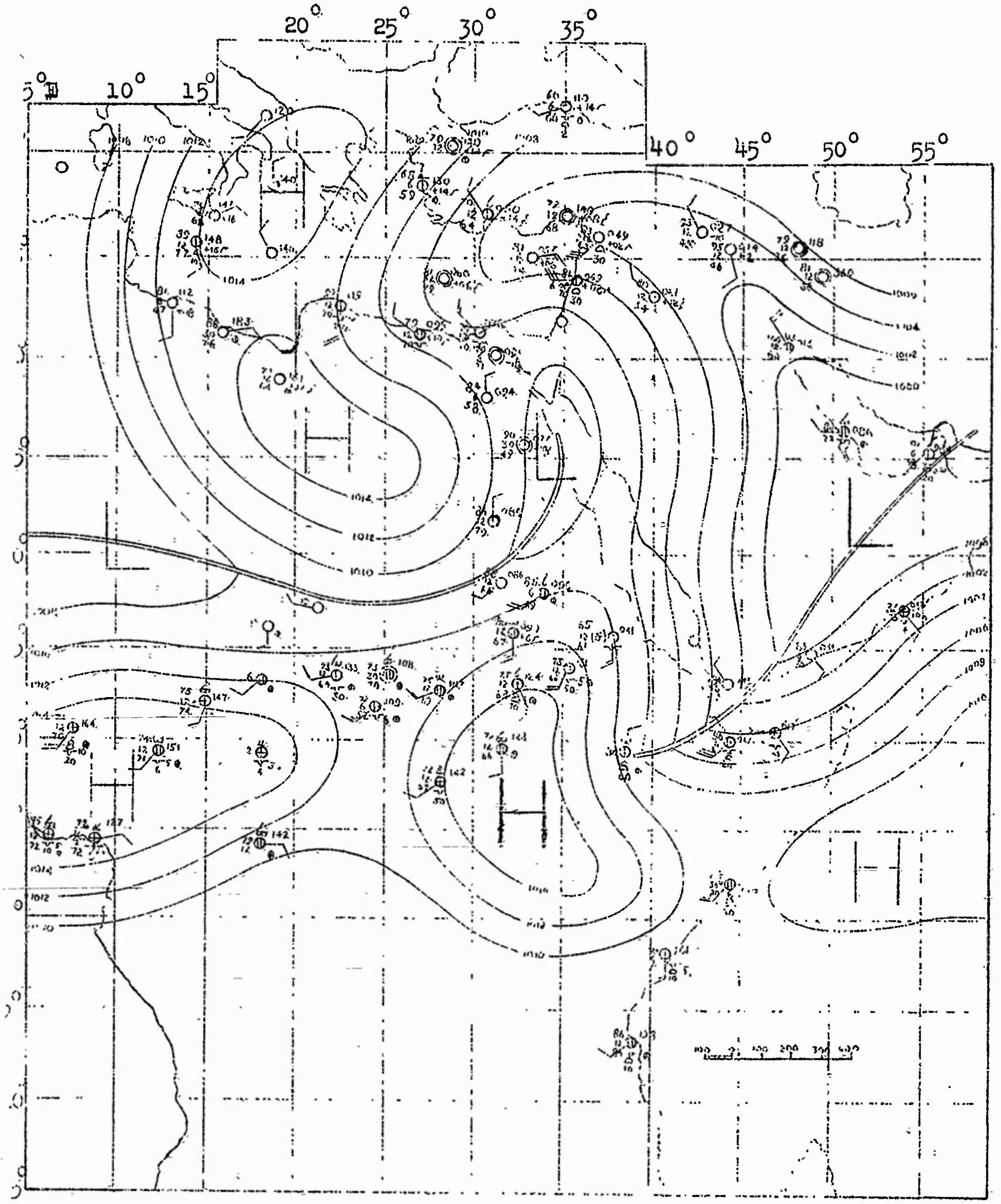


Figure 6 - Typical Chart, Rainy Season
0600 GMT Monday July 26, 1943

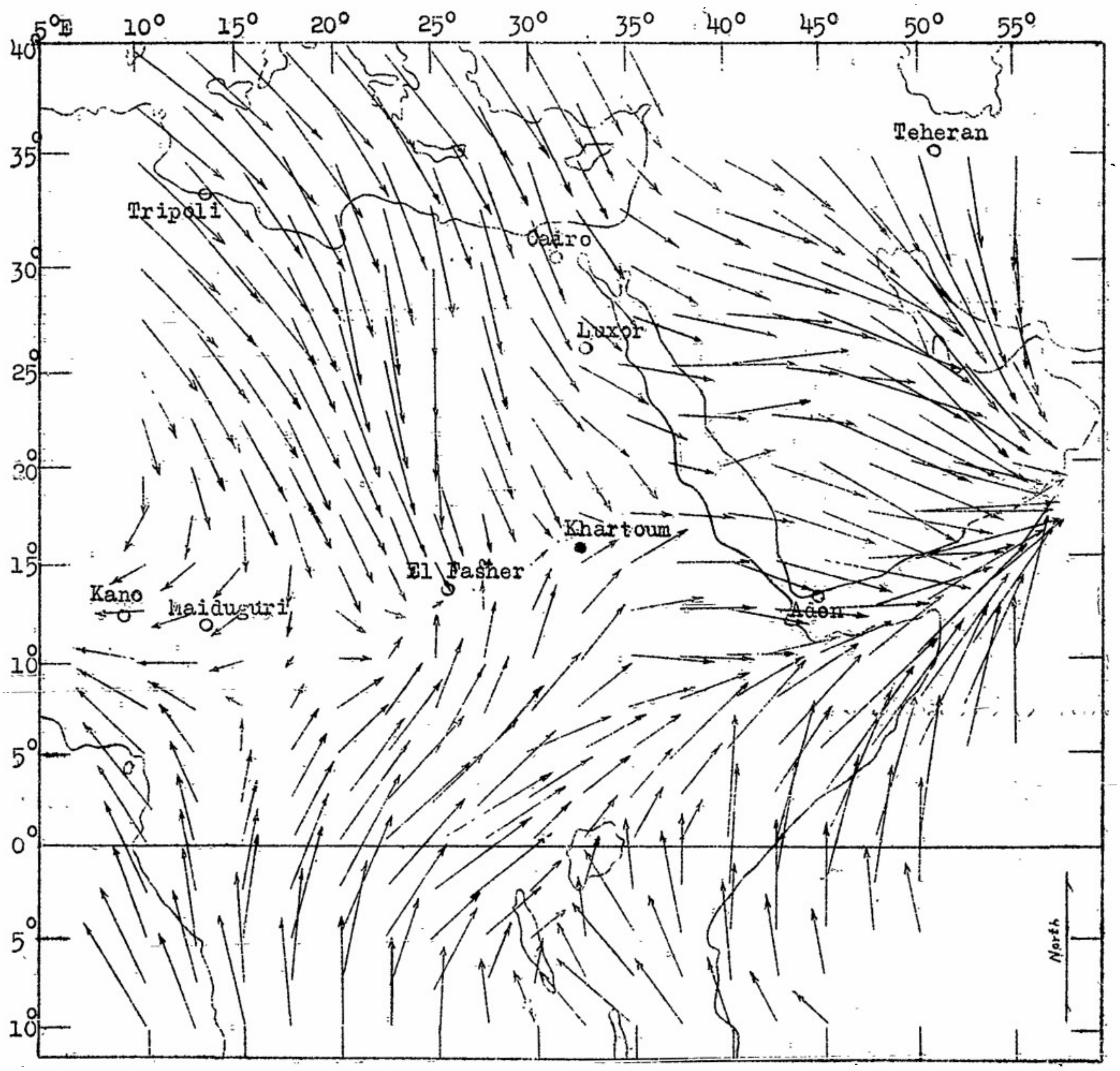


Figure 7 – One Day Trajectories
Layer :– Surface to 10,000 Feet
July

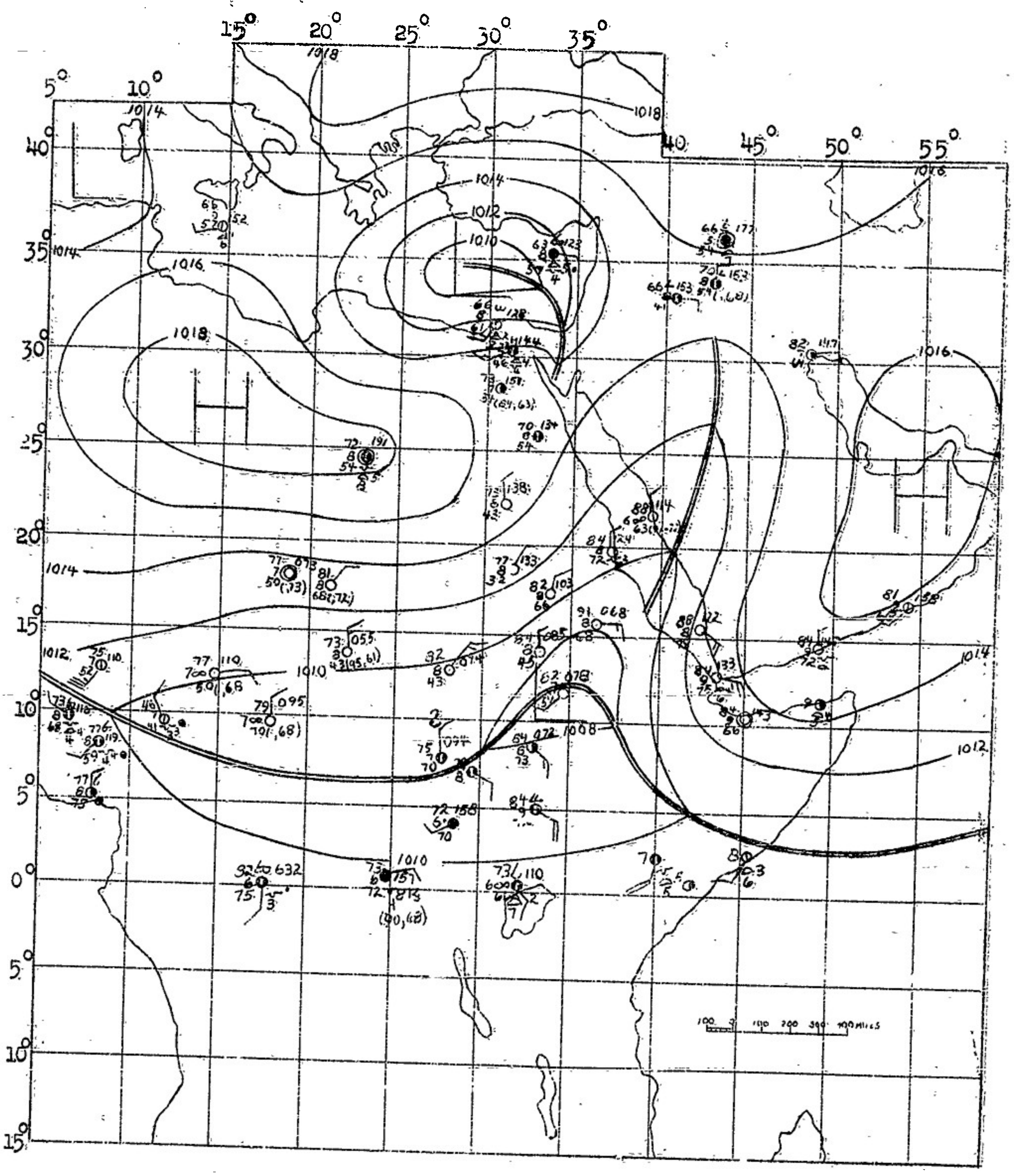


Figure 8 – Typical Chart, Season of Retreating Rains
(0600 October 25, 1942)

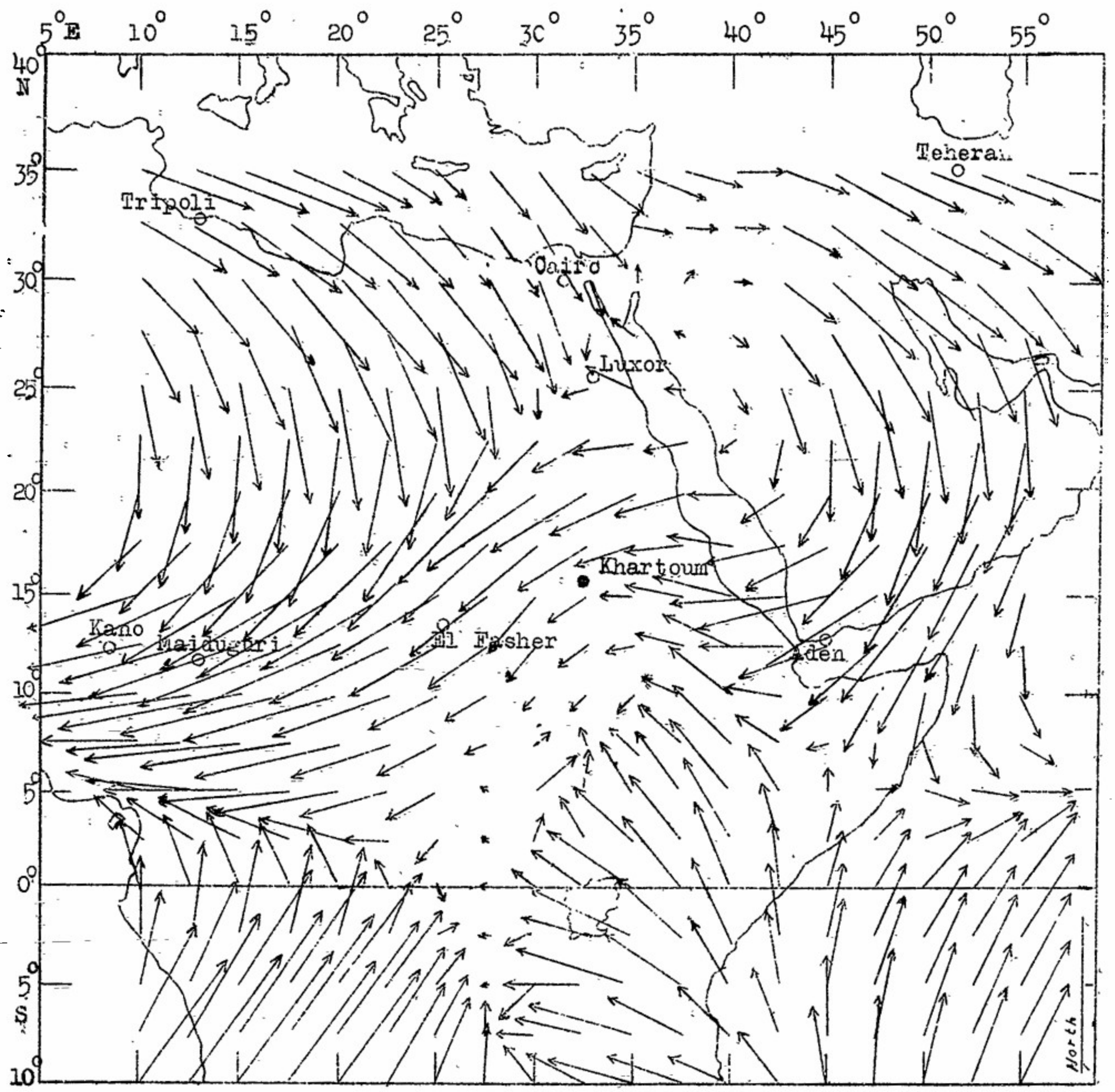


Figure 9 - One Day Trajectories
Layer:- Surface to 10,000 Feet
October

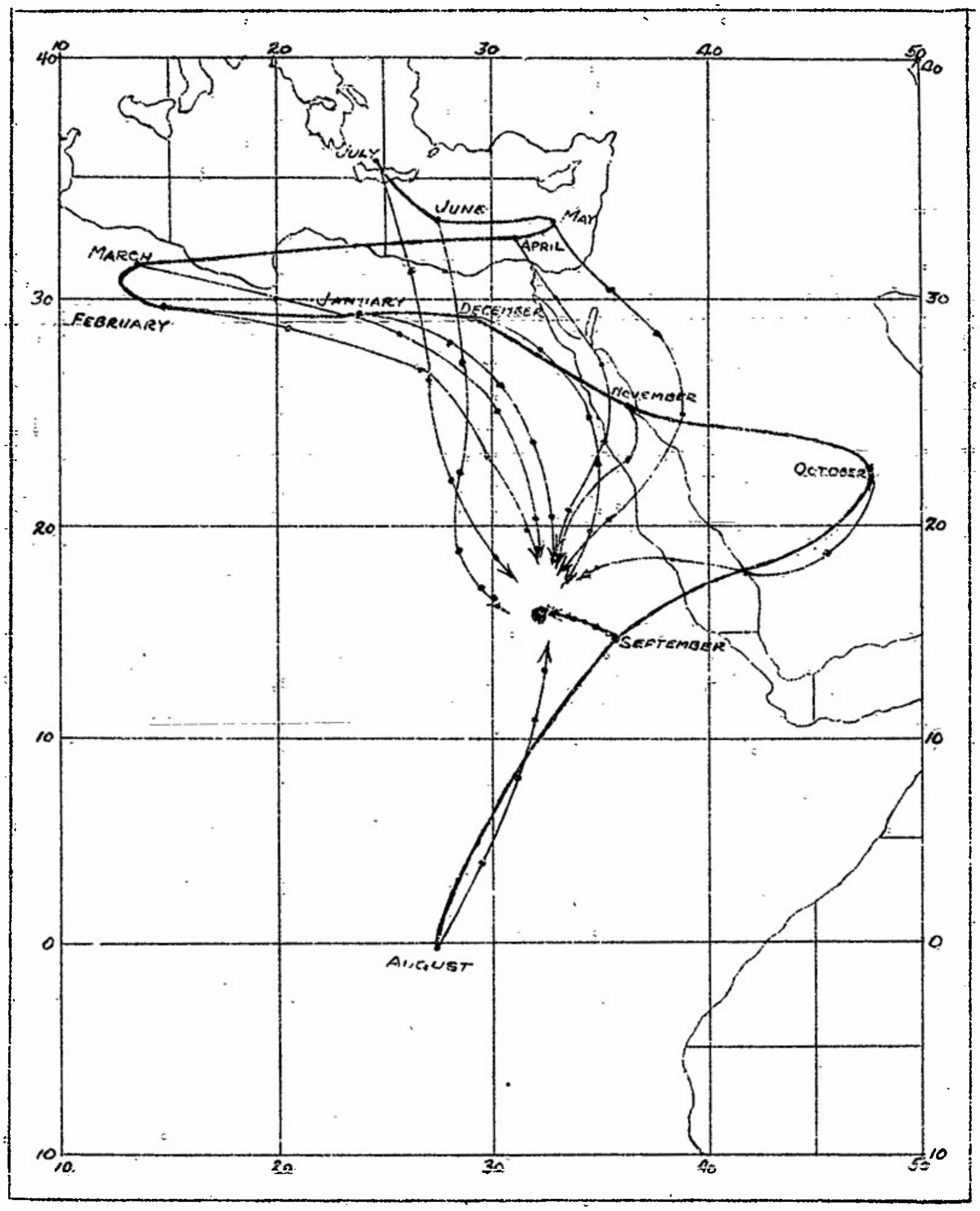
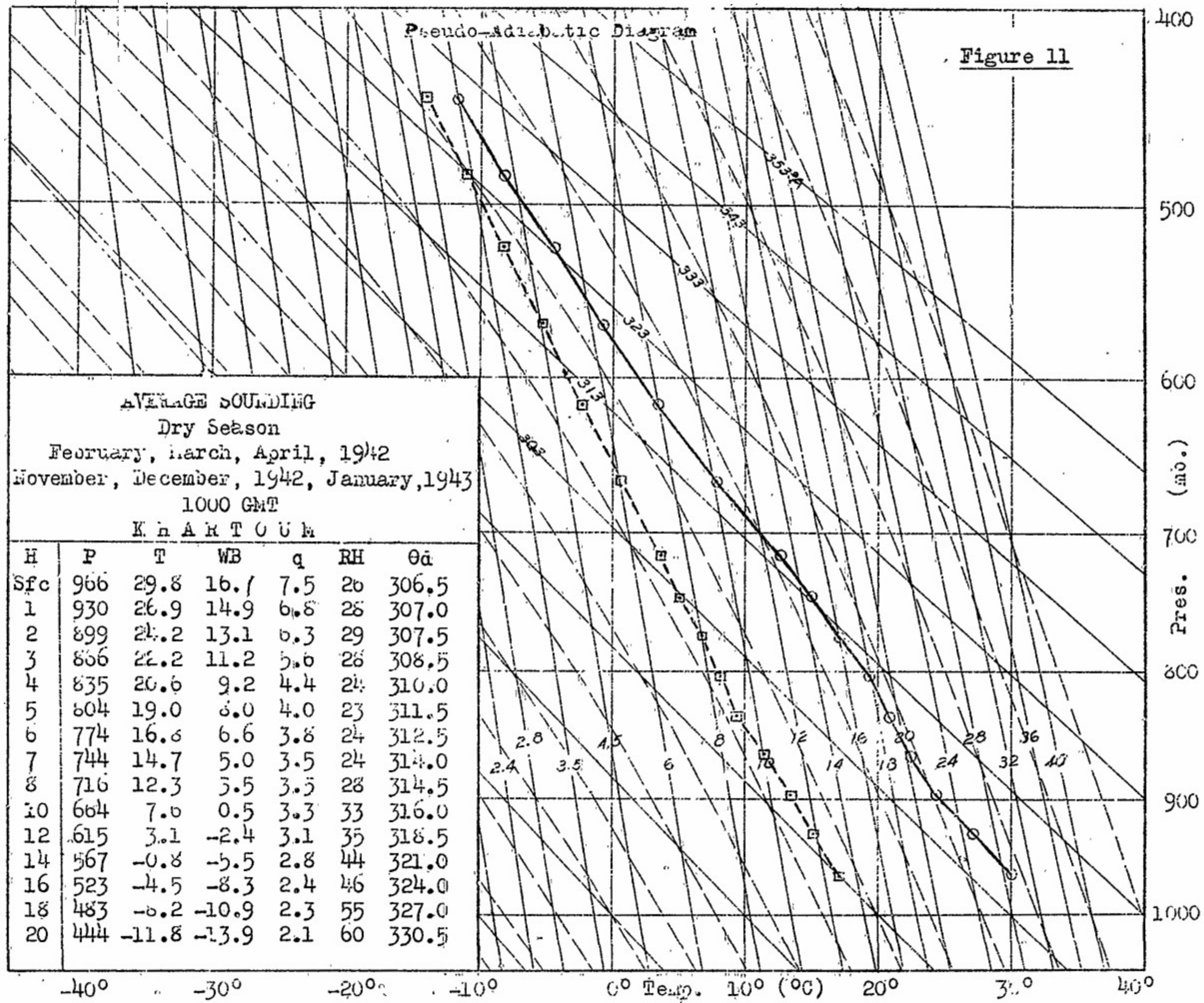


Figure 10 - Monthly Mean Five Day Trajectories
Terminating at Khartoum

Figure 11

Pseudo-Adiabatic Diagram



AVERAGE SOUNDING
Dry Season
February, March, April, 1942
November, December, 1942, January, 1943
1000 GMT
KHARTOUM

H	P	T	WB	q	RH	θd
Sfc	966	29.8	16.7	7.5	26	306.5
1	930	26.9	14.9	6.8	28	307.0
2	899	24.2	13.1	6.3	29	307.5
3	866	22.2	11.2	5.6	28	308.5
4	835	20.6	9.2	4.4	24	310.0
5	804	19.0	8.0	4.0	23	311.5
6	774	16.8	6.6	3.8	24	312.5
7	744	14.7	5.0	3.5	24	314.0
8	716	12.3	3.5	3.5	28	314.5
10	664	7.6	0.5	3.3	33	316.0
12	615	3.1	-2.4	3.1	35	318.5
14	567	-0.8	-5.5	2.8	44	321.0
16	523	-4.5	-8.3	2.4	46	324.0
18	483	-8.2	-10.9	2.3	55	327.0
20	444	-11.8	-13.9	2.1	60	330.5

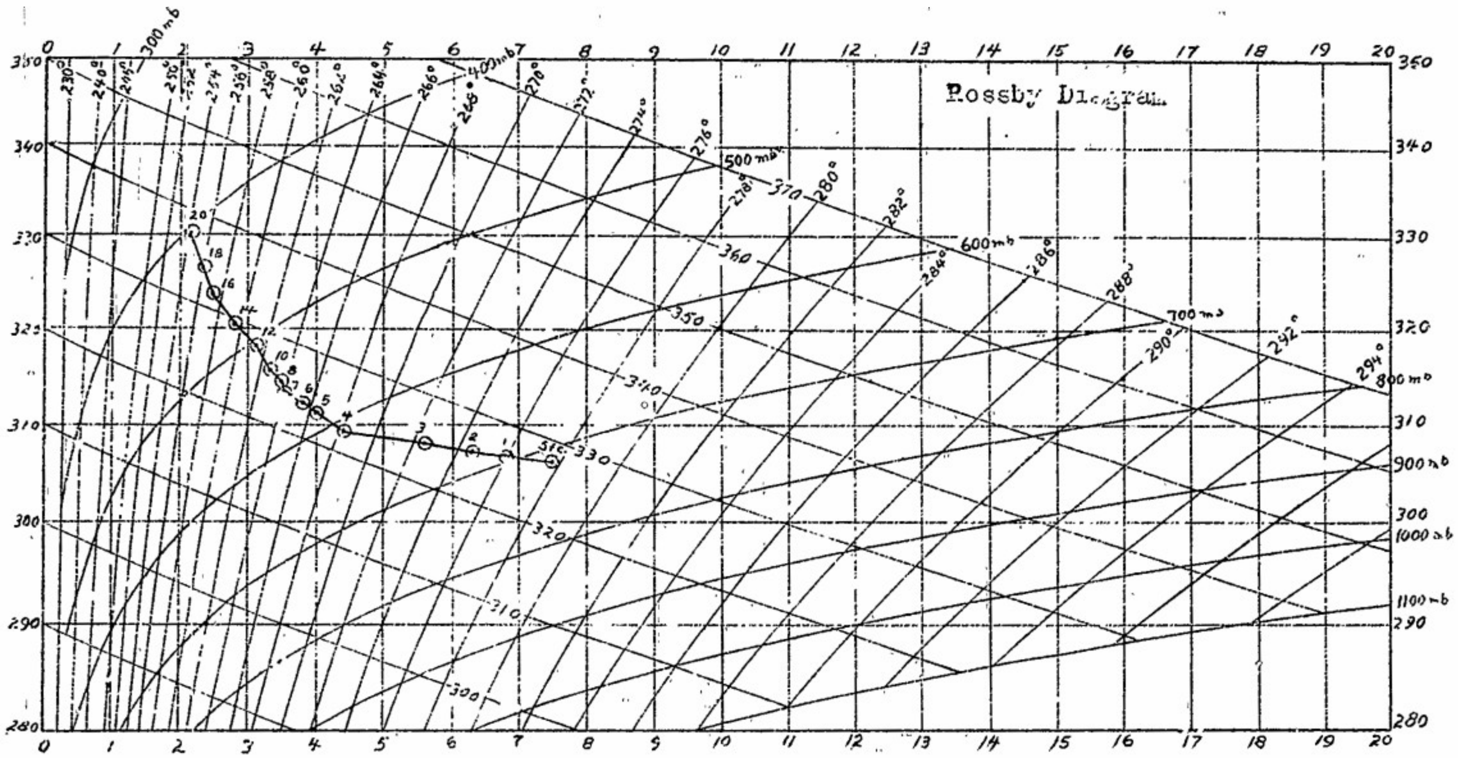
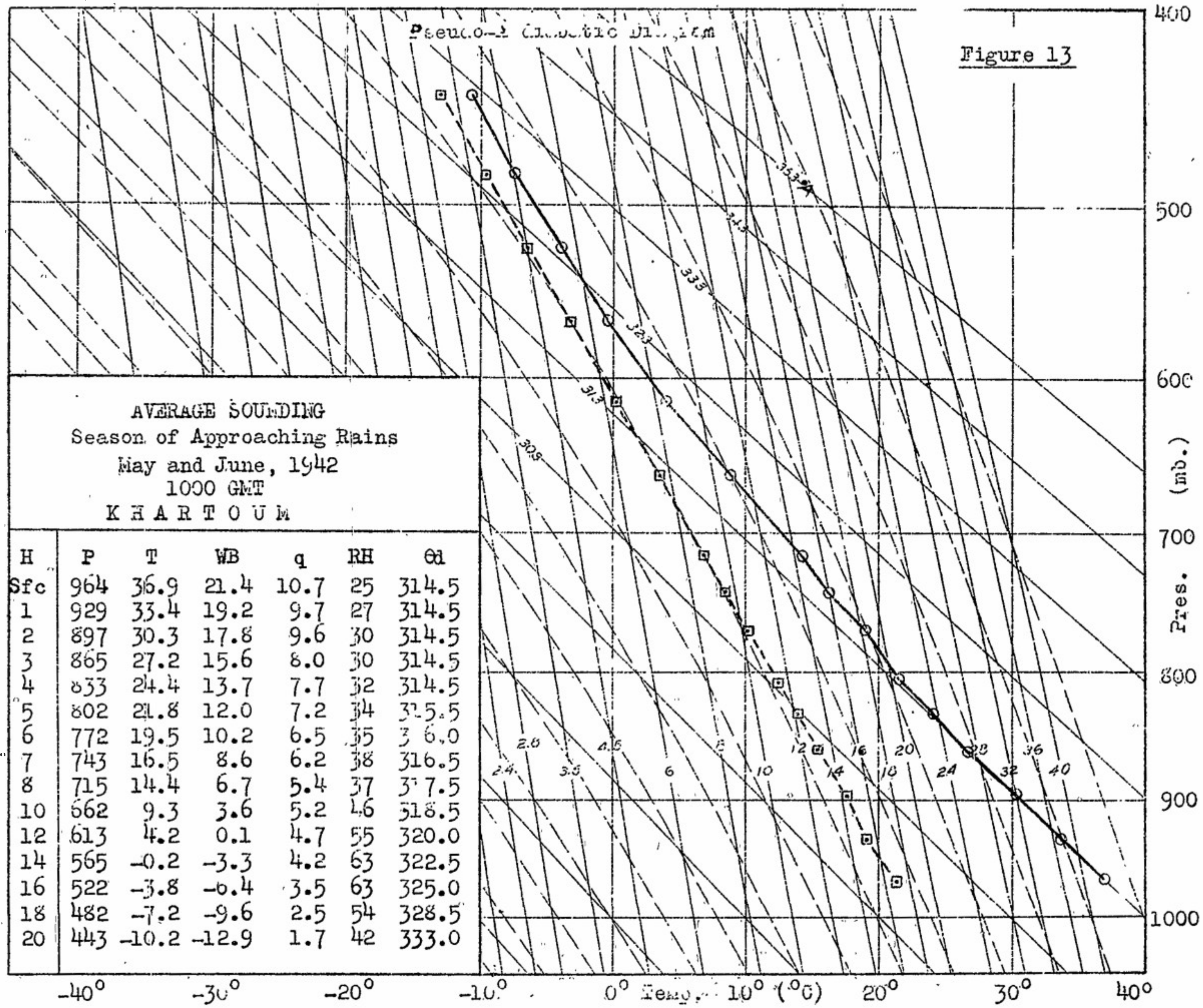


Figure 12 - Average Sounding
Dry Season
February, March, April, November, December, 1942
January, 1943
1000 GMT
K H A R T O U M

Figure 13



AVERAGE SOUNDING
Season of Approaching Rains
May and June, 1942
1000 GMT
K H A R T O U M

H	P	T	WB	q	RH	θd
Sfc	964	36.9	21.4	10.7	25	314.5
1	929	33.4	19.2	9.7	27	314.5
2	897	30.3	17.8	9.6	30	314.5
3	865	27.2	15.6	8.0	30	314.5
4	833	24.4	13.7	7.7	32	314.5
5	802	21.8	12.0	7.2	34	315.5
6	772	19.5	10.2	6.5	35	316.0
7	743	16.5	8.6	6.2	38	316.5
8	715	14.4	6.7	5.4	37	317.5
10	662	9.3	3.6	5.2	46	318.5
12	613	4.2	0.1	4.7	55	320.0
14	565	-0.2	-3.3	4.2	63	322.5
16	522	-3.8	-6.4	3.5	63	325.0
18	482	-7.2	-9.6	2.5	54	328.5
20	443	-10.2	-12.9	1.7	42	333.0

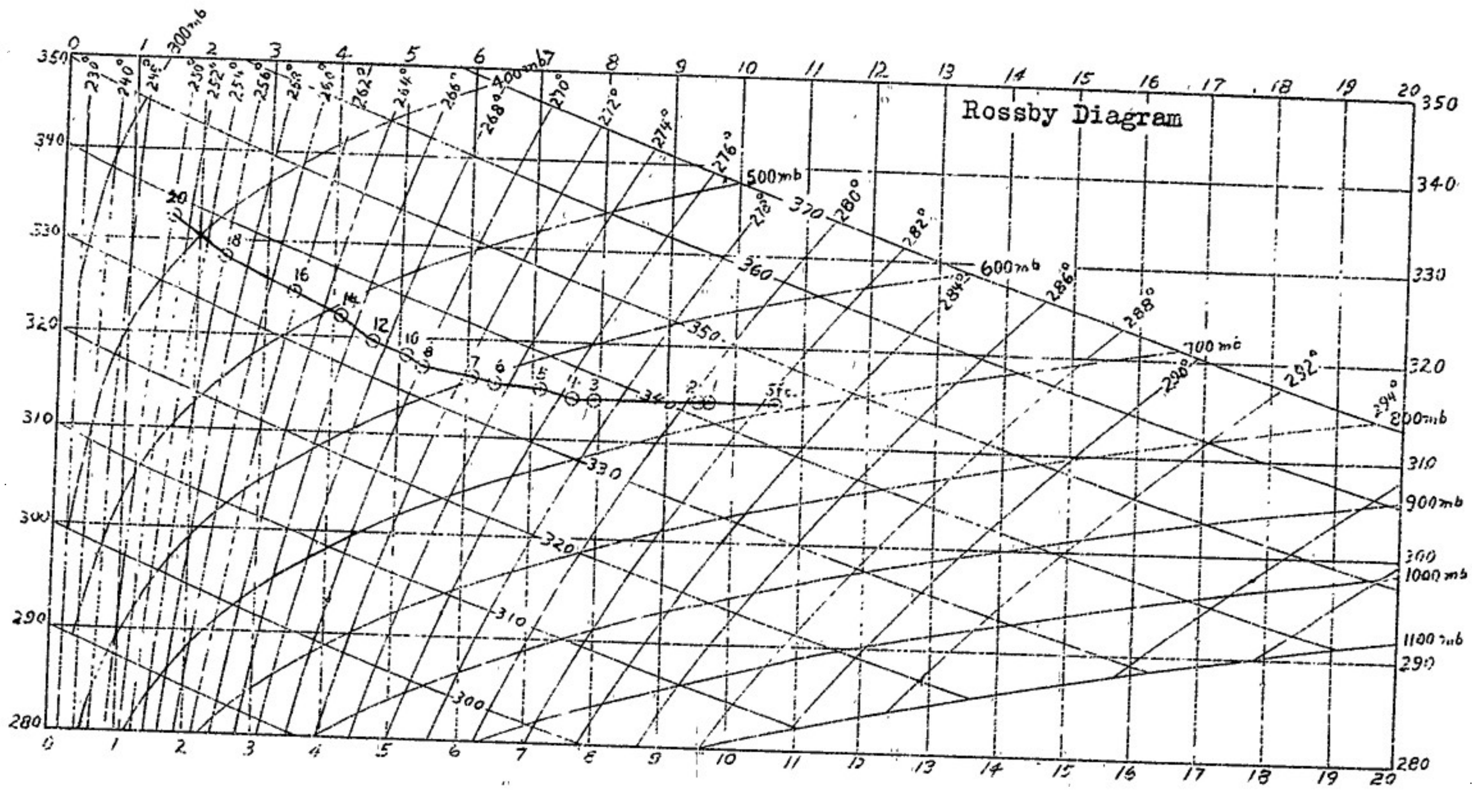
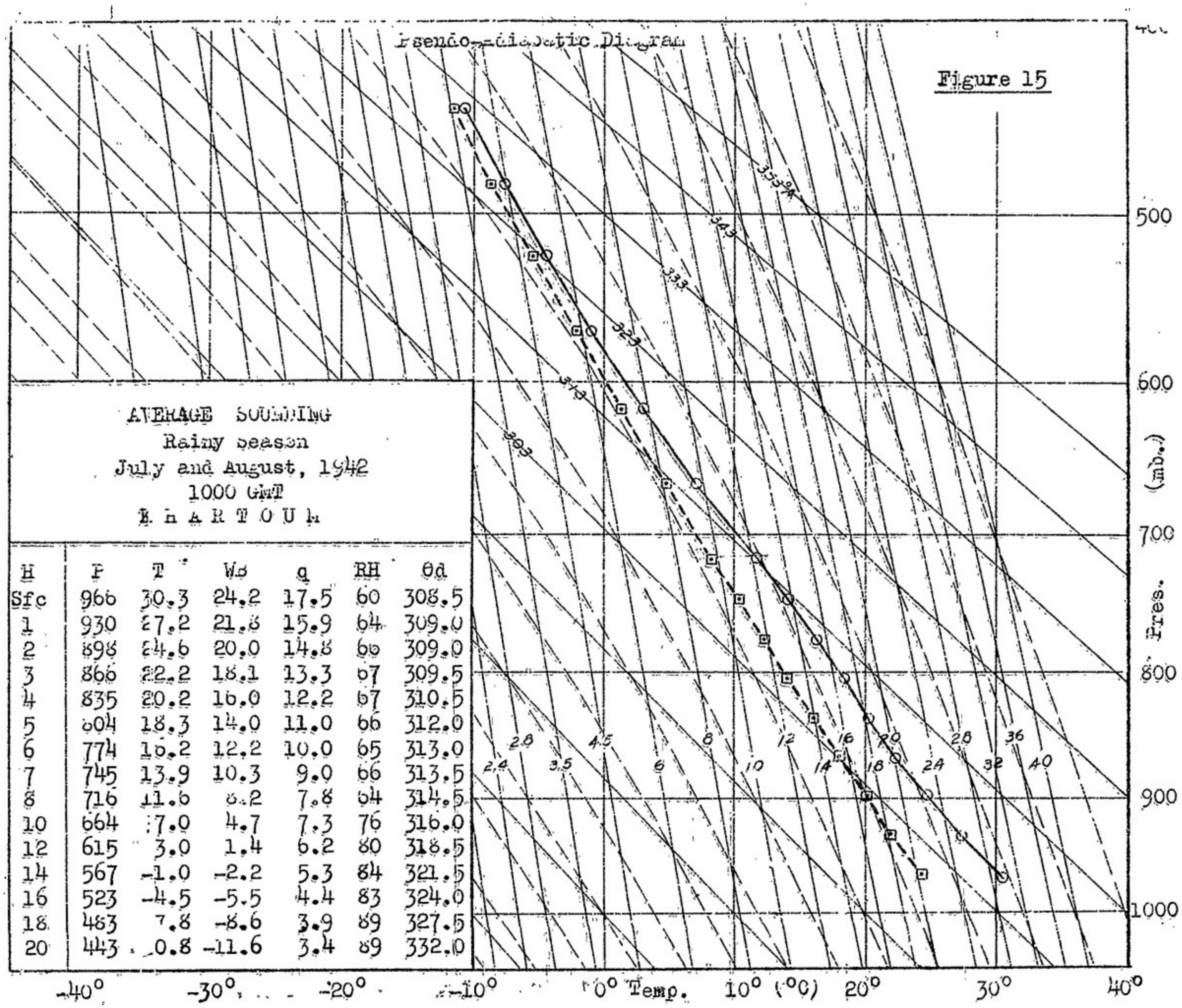


Figure 14 - Average Sounding
Season of Approaching Rains
May and June, 1942
1000 GMT
K H A R T O U M



H	P	T	Ws	q	RH	θd
Sfc	966	30.3	24.2	17.5	60	308.5
1	930	27.2	21.8	15.9	64	309.0
2	898	24.6	20.0	14.8	66	309.0
3	866	22.2	18.1	13.3	67	309.5
4	835	20.2	16.0	12.2	67	310.5
5	804	18.3	14.0	11.0	66	312.0
6	774	16.2	12.2	10.0	65	313.0
7	745	13.9	10.3	9.0	66	313.5
8	716	11.6	8.2	7.8	64	314.5
10	664	7.0	4.7	7.3	76	316.0
12	615	3.0	1.4	6.2	80	318.5
14	567	-1.0	-2.2	5.3	84	321.5
16	523	-4.5	-5.5	4.4	83	324.0
18	483	7.8	-8.6	3.9	89	327.5
20	443	0.8	-11.6	3.4	89	332.0

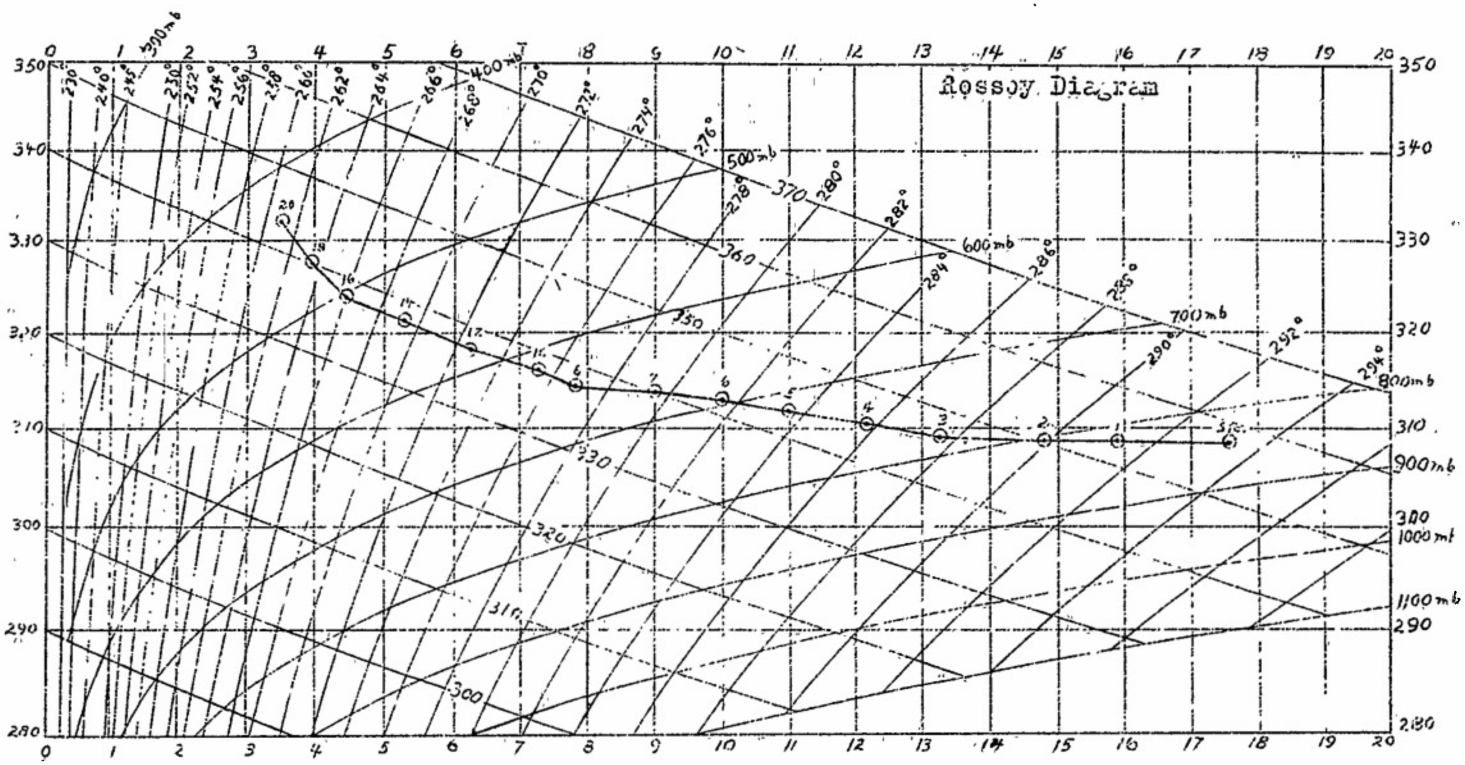
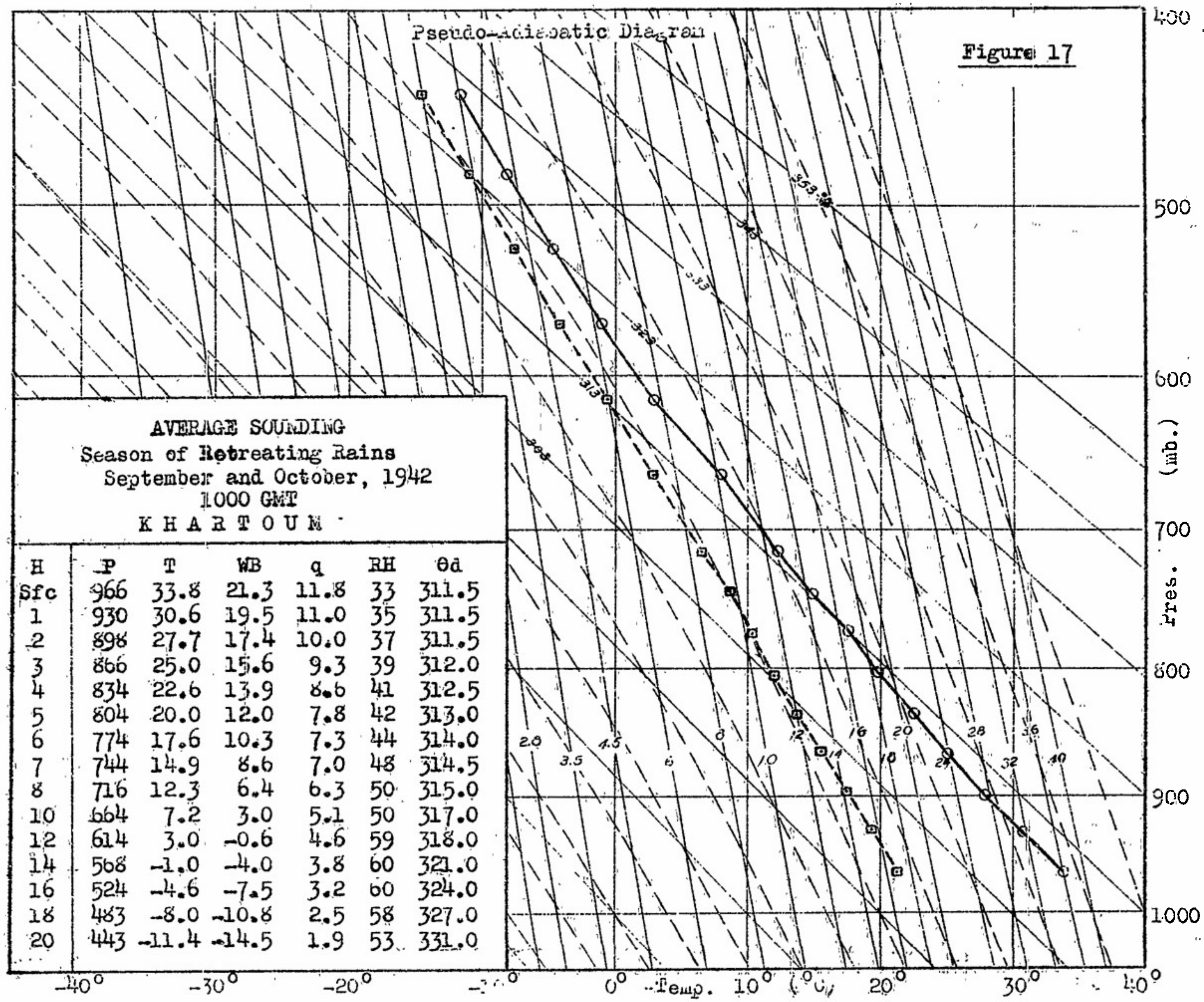


Figure 16 - Average Sounding, Rainy Season
July, August, 1942
Khartoum 1000 GMT

Figure 17



AVERAGE SOUNDING
Season of Retreating Rains
September and October, 1942
1000 GMT
K H A R T O U M

H	P	T	WB	q	RH	θd
Sfc	966	33.8	21.3	11.8	33	311.5
1	930	30.6	19.5	11.0	35	311.5
2	898	27.7	17.4	10.0	37	311.5
3	866	25.0	15.6	9.3	39	312.0
4	834	22.6	13.9	8.6	41	312.5
5	804	20.0	12.0	7.8	42	313.0
6	774	17.6	10.3	7.3	44	314.0
7	744	14.9	8.6	7.0	48	314.5
8	716	12.3	6.4	6.3	50	315.0
10	664	7.2	3.0	5.1	50	317.0
12	614	3.0	-0.6	4.6	59	318.0
14	568	-1.0	-4.0	3.8	60	321.0
16	524	-4.6	-7.5	3.2	60	324.0
18	483	-8.0	-10.8	2.5	58	327.0
20	443	-11.4	-14.5	1.9	53	331.0

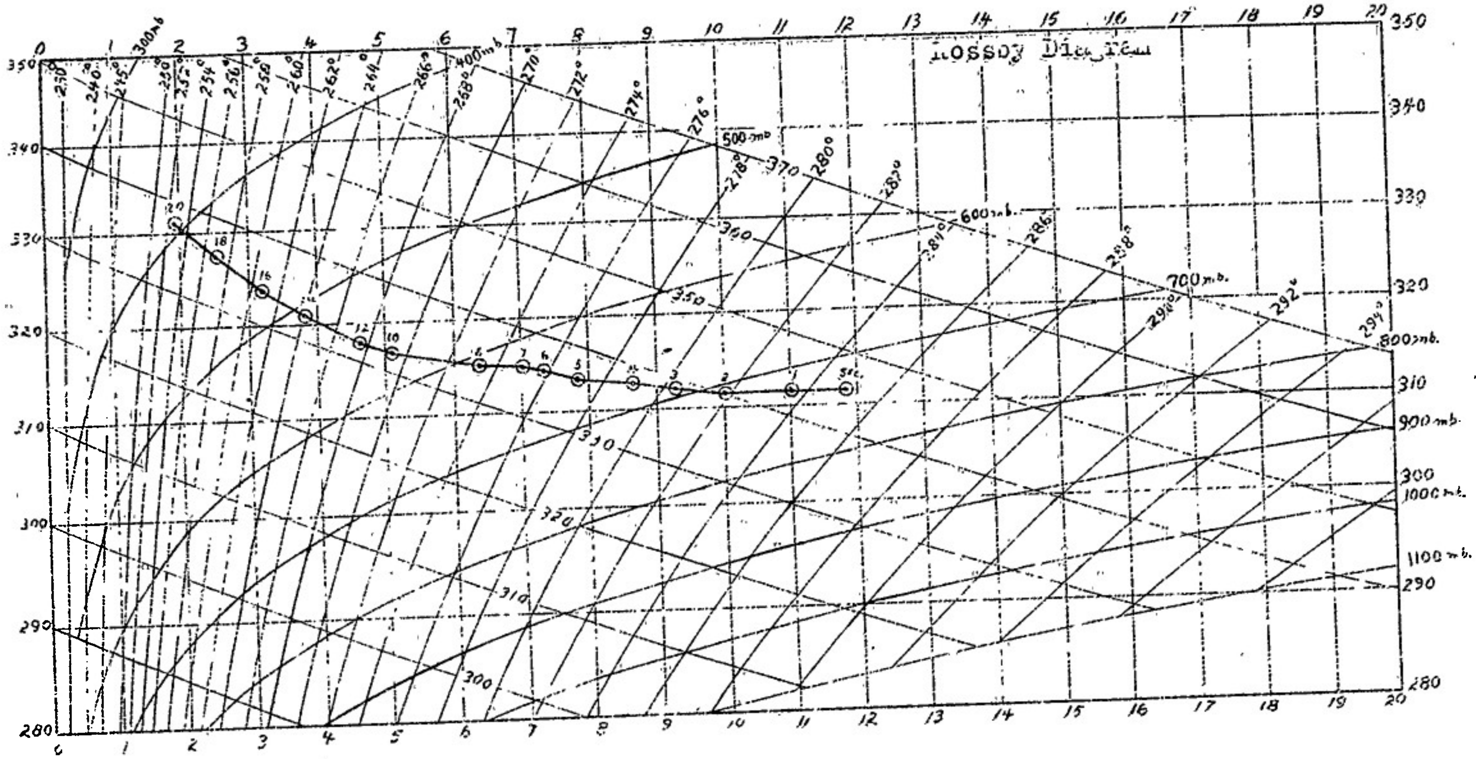


Figure 18 – Average Sounding, Season of Retreating Rains
September, October, 1942
Khartoum 1000 GMT

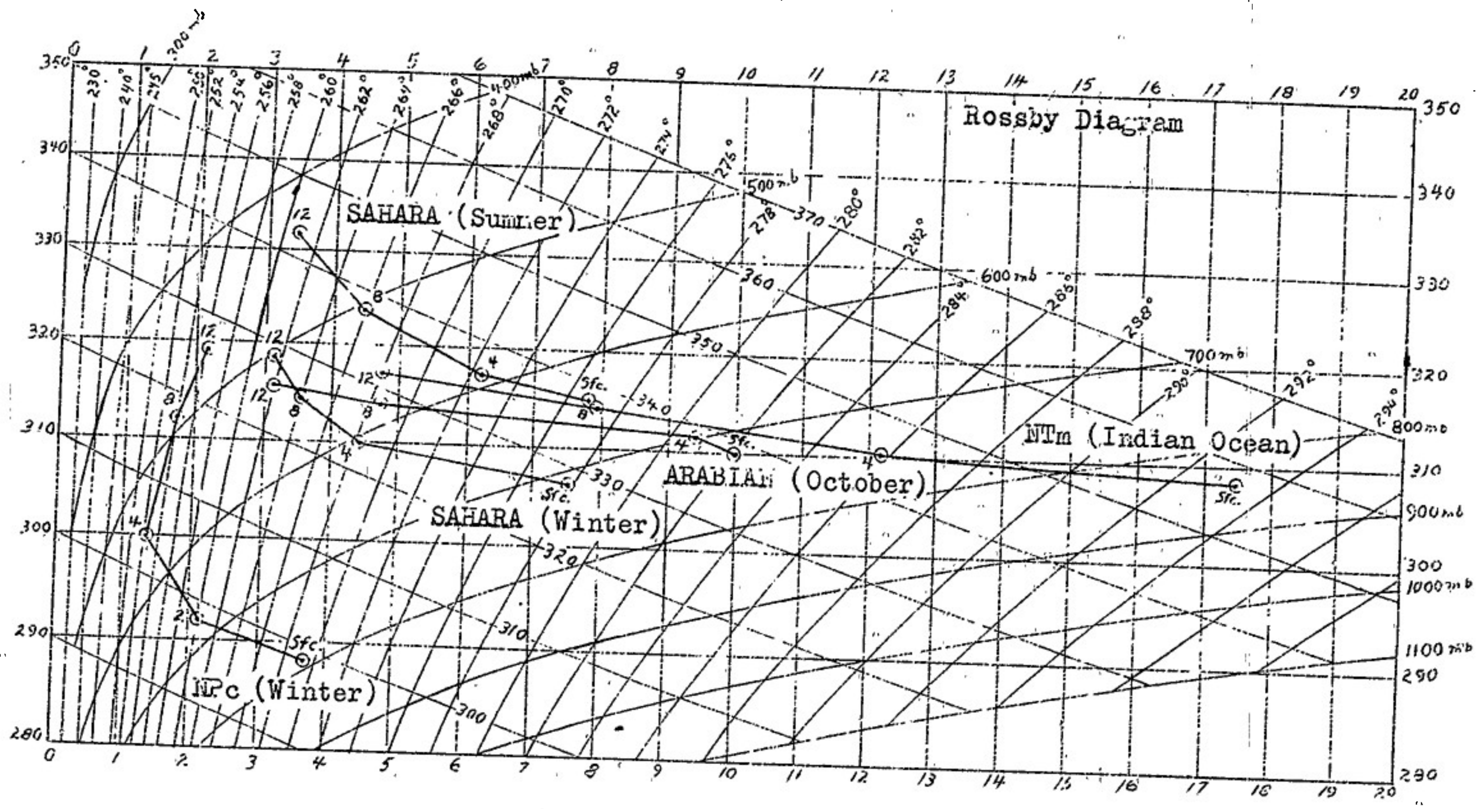


Figure 19 - Representative Air Mass Properties

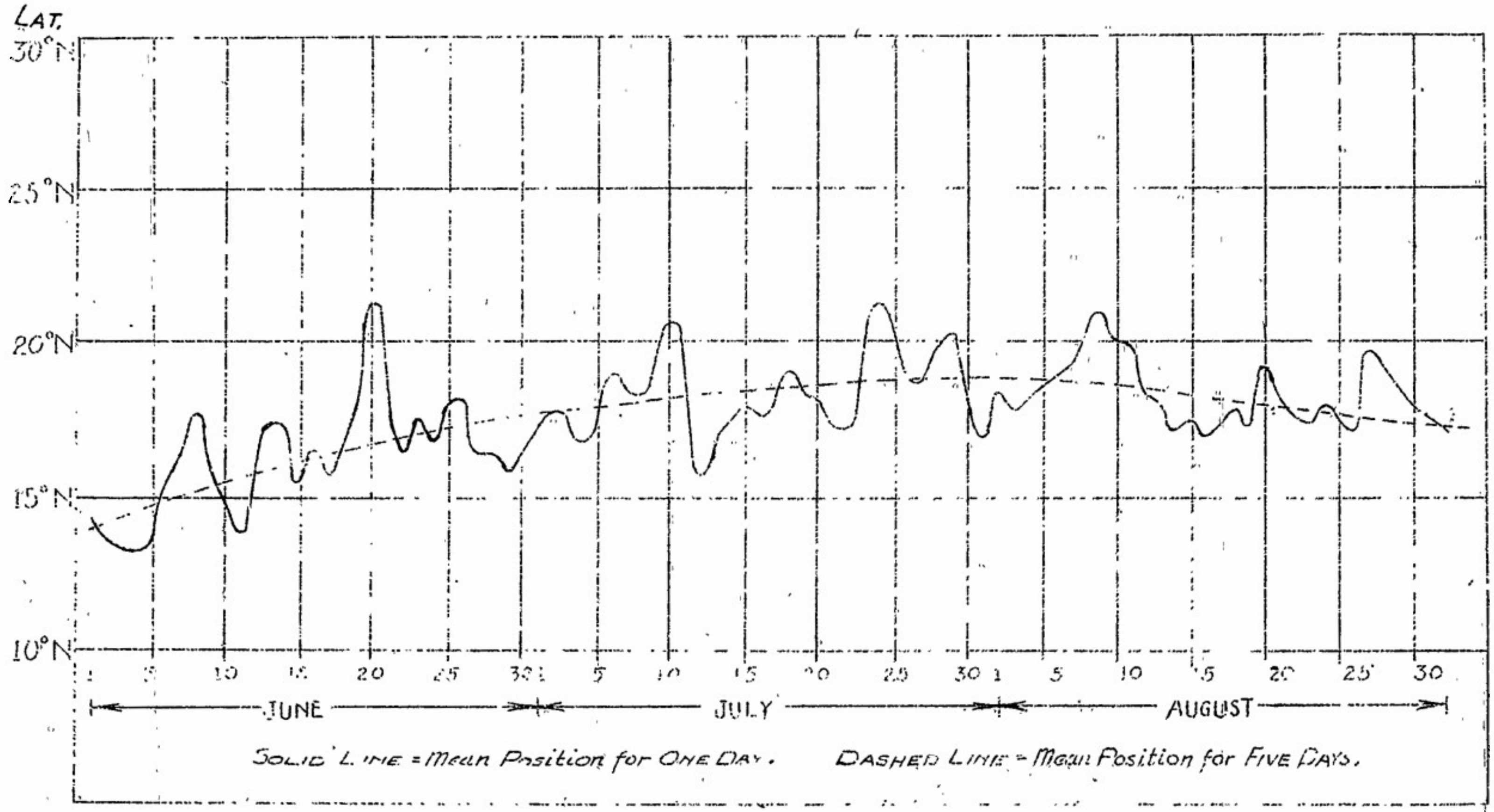


Figure 20 - Surface Position of Intertropical Front at Longitude 32°E.

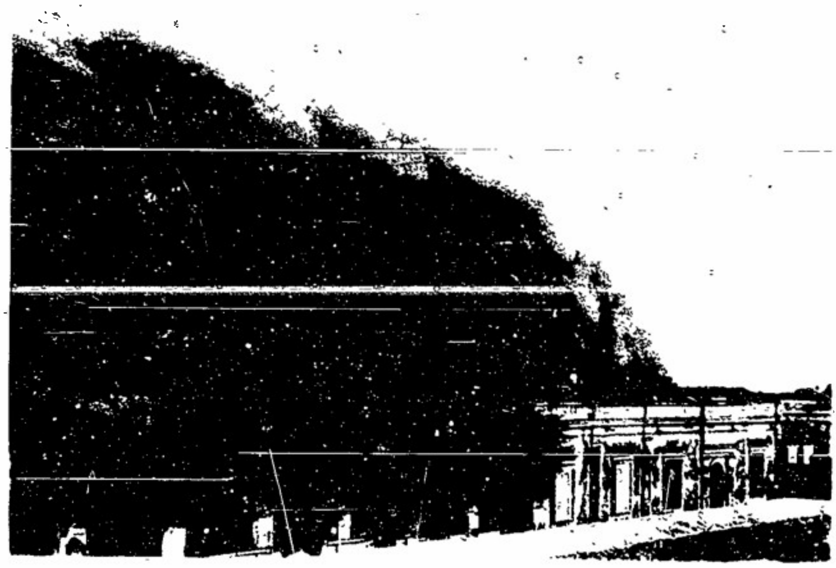


Figure 21

Photograph of Haboob

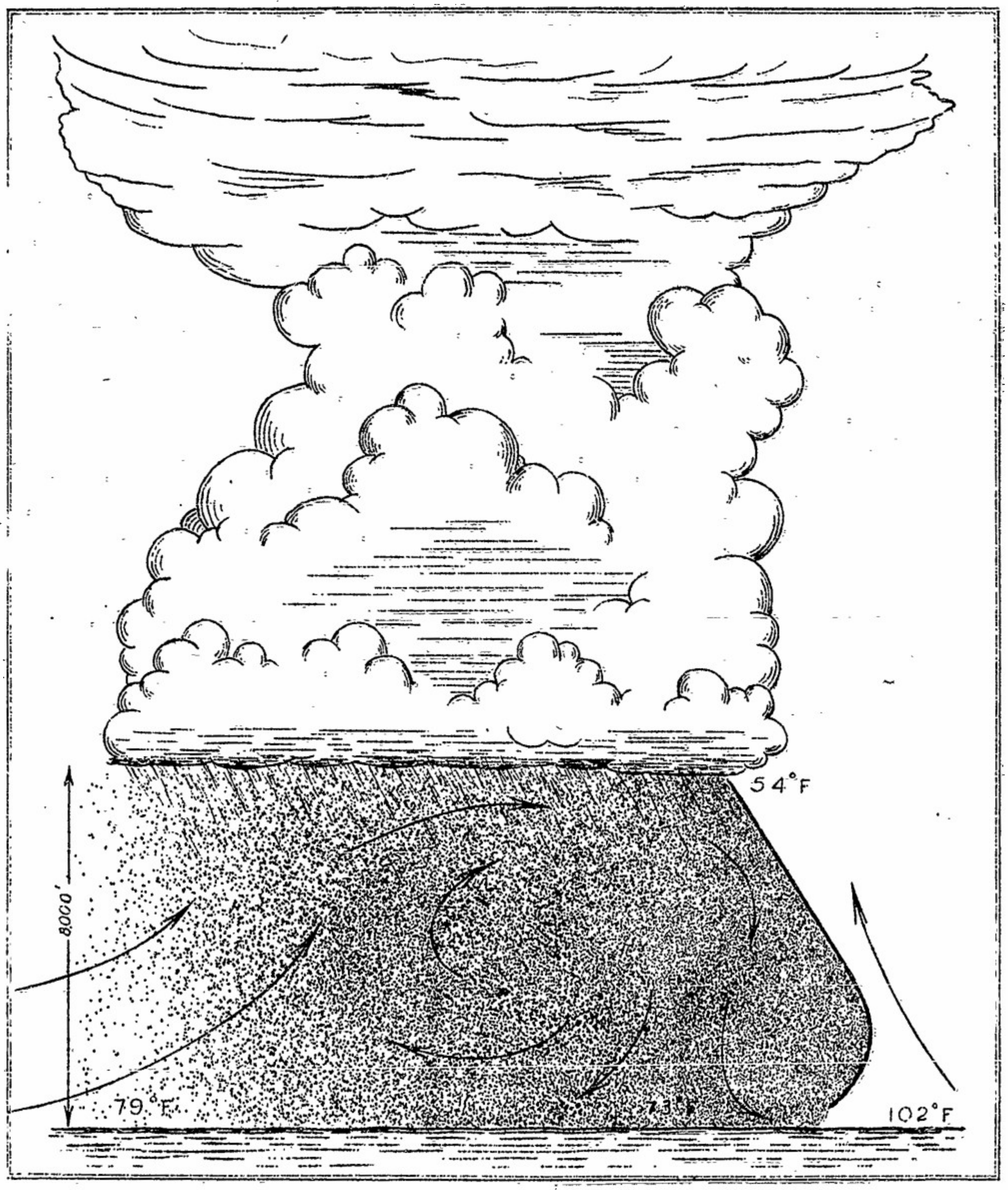
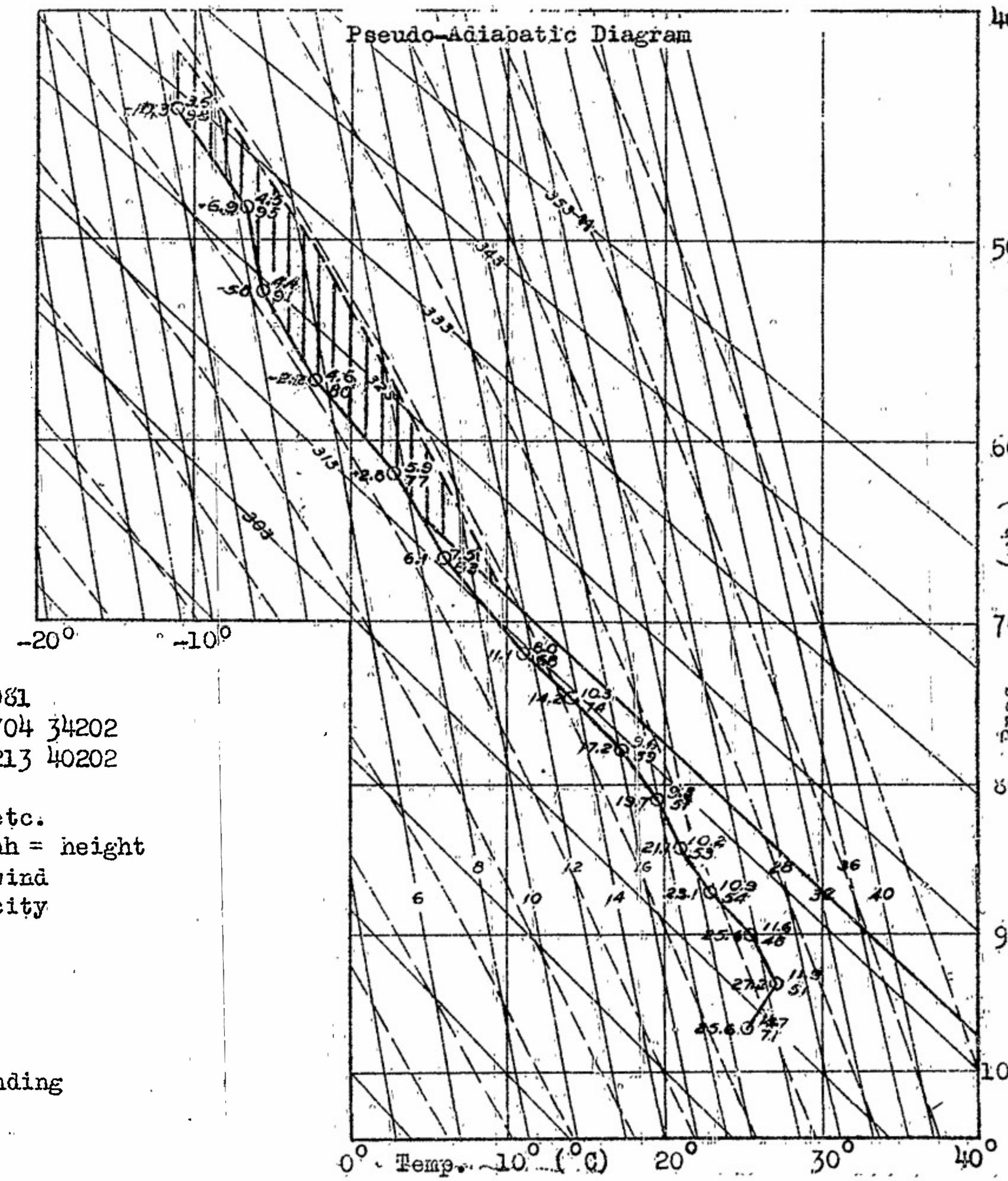


Figure 22 - Haboob model

GMT				
0000	⦶/		85/61	SSW11
0600	D/		90/63	SSW11
1100	D/90⦶		102/59	SW13
1330	80⦶	T	104/57	W 2 Dst. Stn. to E of Stn.
1400	80⦶	R-	102/56	SW18
1405	80⦶	2BN-	78/57	SSE34+
1408	80⦶	1/2BN	78/57	SSE34 +
1425	70⦶	5R-BN-	79/59	SE26+
1500	⦶/70⦶	6R-	84/61	SSW18
1800	-⦶/		88/62	NW 6
2100	⊕/	3BN-	85/64	SE31+
2115	⊕/	5R-	85/64	SSE28
2300	⊕/	6H	79/69	SSW14



20301 06225 10205 15195 20172 25141 30081
20304 06226 10228 15216 20205 25142 30704 34202
20311 06246 10246 15232 20232 25234 30213 40202

(Upper Wind Report Code = IIITT hhDDV etc.
III = Station Number, TT = time GMT, hh = height above m.s.l. in hectometers, DDx10 = wind direction in degrees, Vx3 = wind velocity in miles per hour.)

Figure 23 – Haboob Sounding
0400 July 7, 1943
K H A R T O U M

GMT						
0000		Φ/		84/68	C	
0100		Φ/		81/71	C	
0200		Φ/		83/73	S 6	
0300		Φ/50Φ		83/70	S 2	
0400		Φ/50Φ		82/69	SSW12	
0500		-Φ/50Φ		85/68	SSW14	
0600		-Φ/		87/69	S13	
0700	E180	-Φ/		91/65	SSW21	
0800	E180	-Φ/		93/66	SSW19	
0900		-Φ/		96/66	WSW19	
1000		-Φ/60Φ		97/64	WSW16	
1100		-Φ/60Φ		99/62	SSW10	
1200		-Φ/75Φ		99/64	SW17	
1300		-Φ/70Φ		100/64	SW15	
1400		-Φ/60Φ		102/63	SW 5	R to NW
1500		Φ/60Φ		100/60	SW14	Snd.Stms,RW-NW,Ltng NW
1512	E60	Φ/Φ	T	100/60	SW14	RW-NW, Snd.Stm.-S
1523	E60	Φ/Φ	2 1/2TBN-	100/60	N32+	Vis. 1mi.-S
1530	E60	⊕/Φ	6TR-BN-	100/60	N28+	Vis. 1mi.-S
1547	E55	⊕/Φ	6TR	73/72	E16	Vis. 2mi.-S
1600	E55	⊕/Φ	6TR-	73/72	E16	Vis. 4mi.-S
1642	E55	⊕/Φ	6TR-	73/72	SSW16	Vis. 4mi.-S
1700	E60	⊕/Φ	TR-	73/72	SSW16	
1800	E50	⊕/Φ	TR-	77/73	S12	
1842	E50	⊕/Φ	R-	77/73	S12	LTNG ALL QDNTS
1845	E50	⊕/○		77/73	S12	RW to S LTNG-S
1900	E140	⊕/50Φ		78/72	SSW14	RW to S LTNG-S
2000	E140	⊕/60Φ		79/70	SW10	LTNG-SW
2100	E140	Φ/70Φ		78/72	C	LTNG-SW
2200	E70	⊕/Φ		76/68	NNE14	
2300	E70	⊕/○	7R-	74/69	W14	

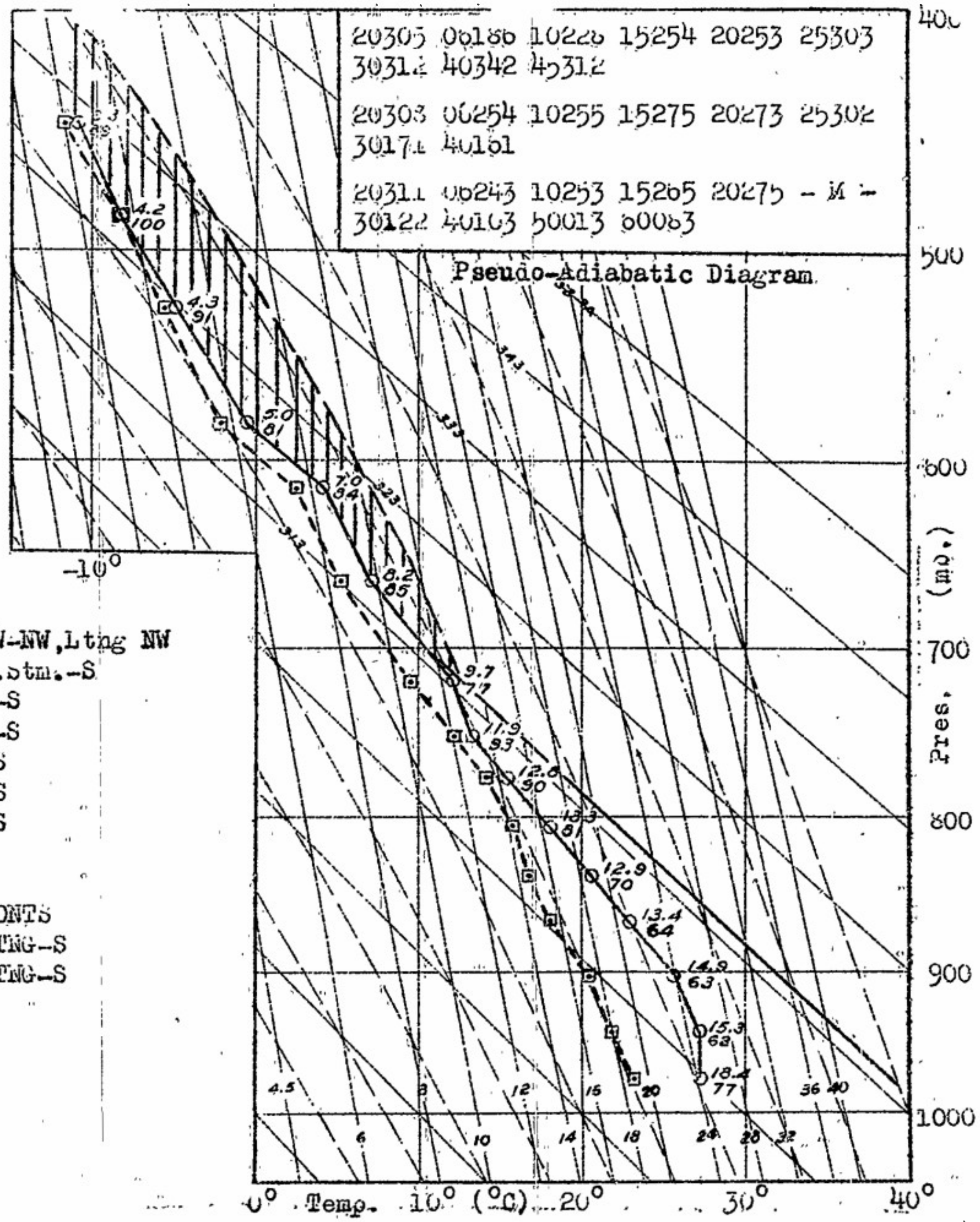


Figure 24 – Haboob Sounding
0400 July 22, 1943
K H A R T O U M

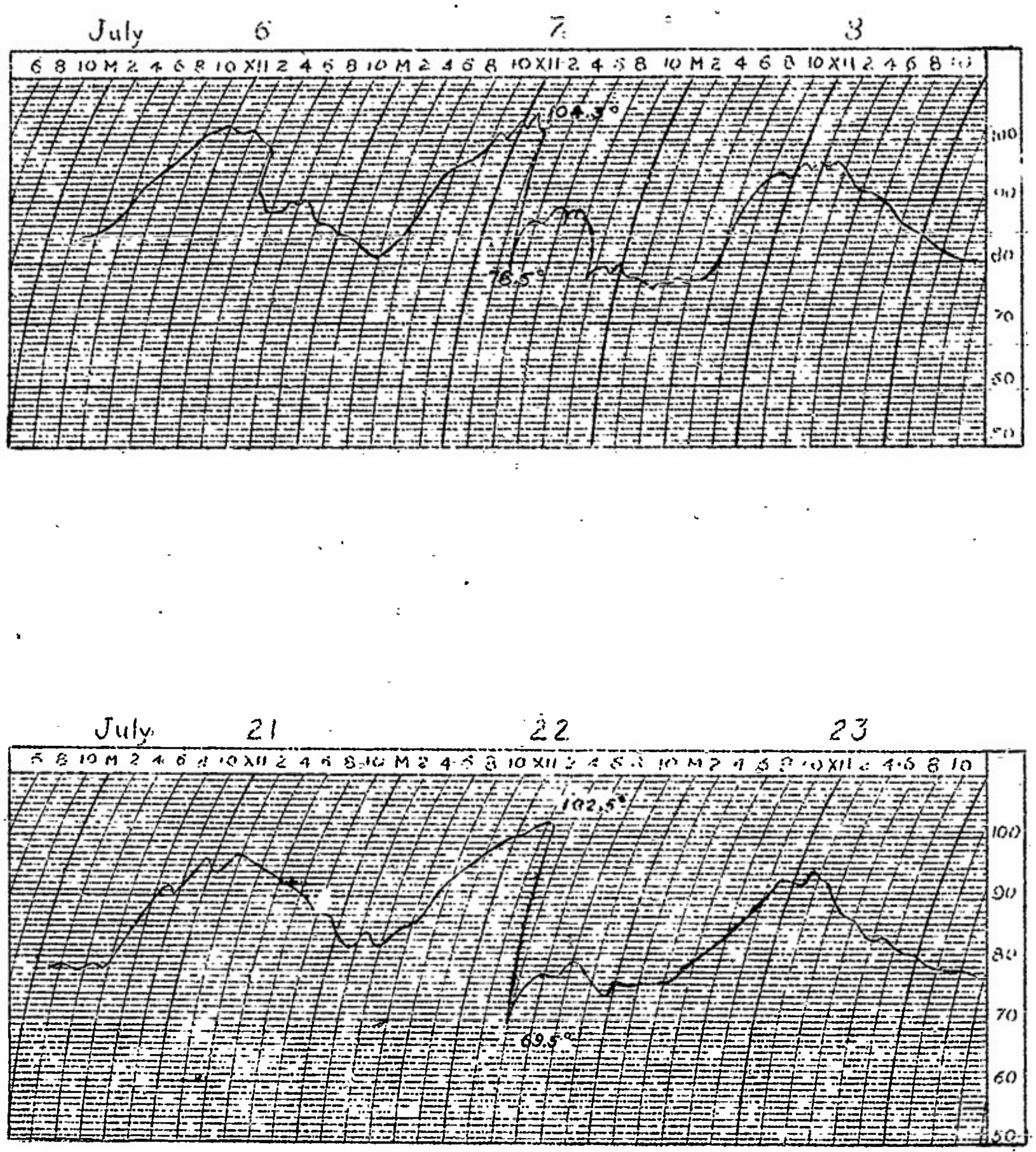


Figure 25 — Haboob Thermograph Traces.

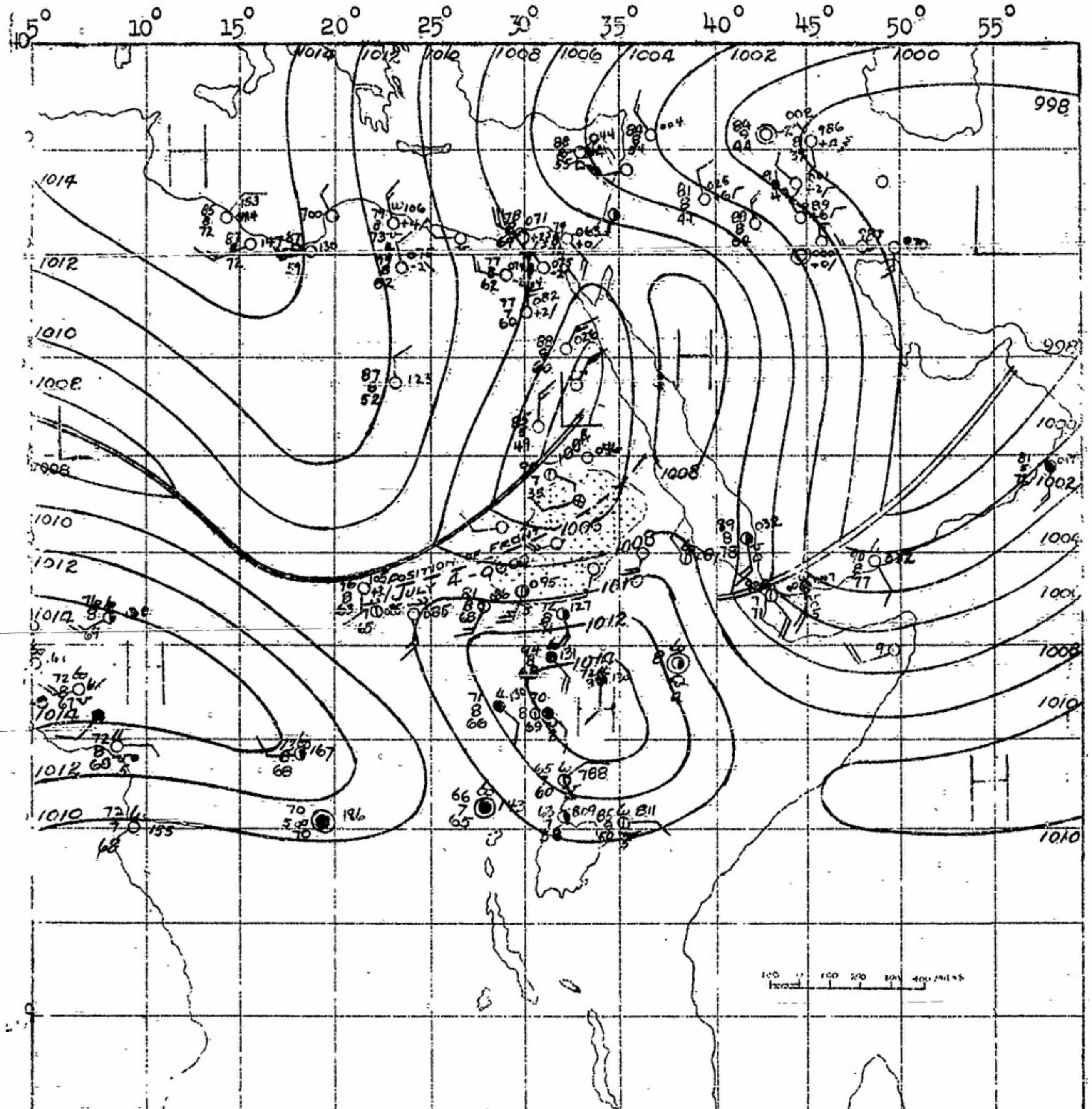


Figure 26 - Typical Chart, Sandstorm (0600, July 5, 1943).

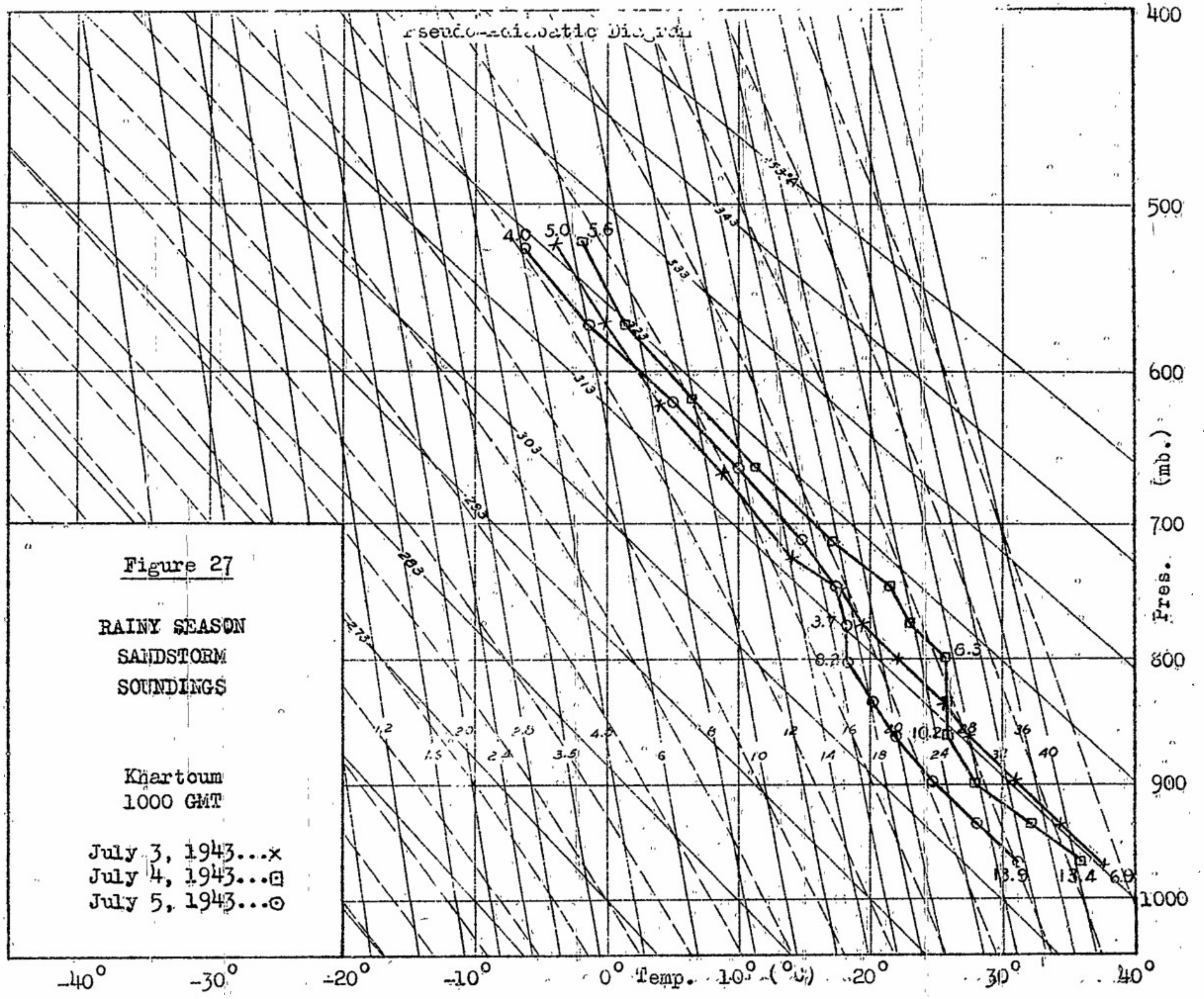


Figure 27

RAINY SEASON
SANDSTORM
SOUNDINGS

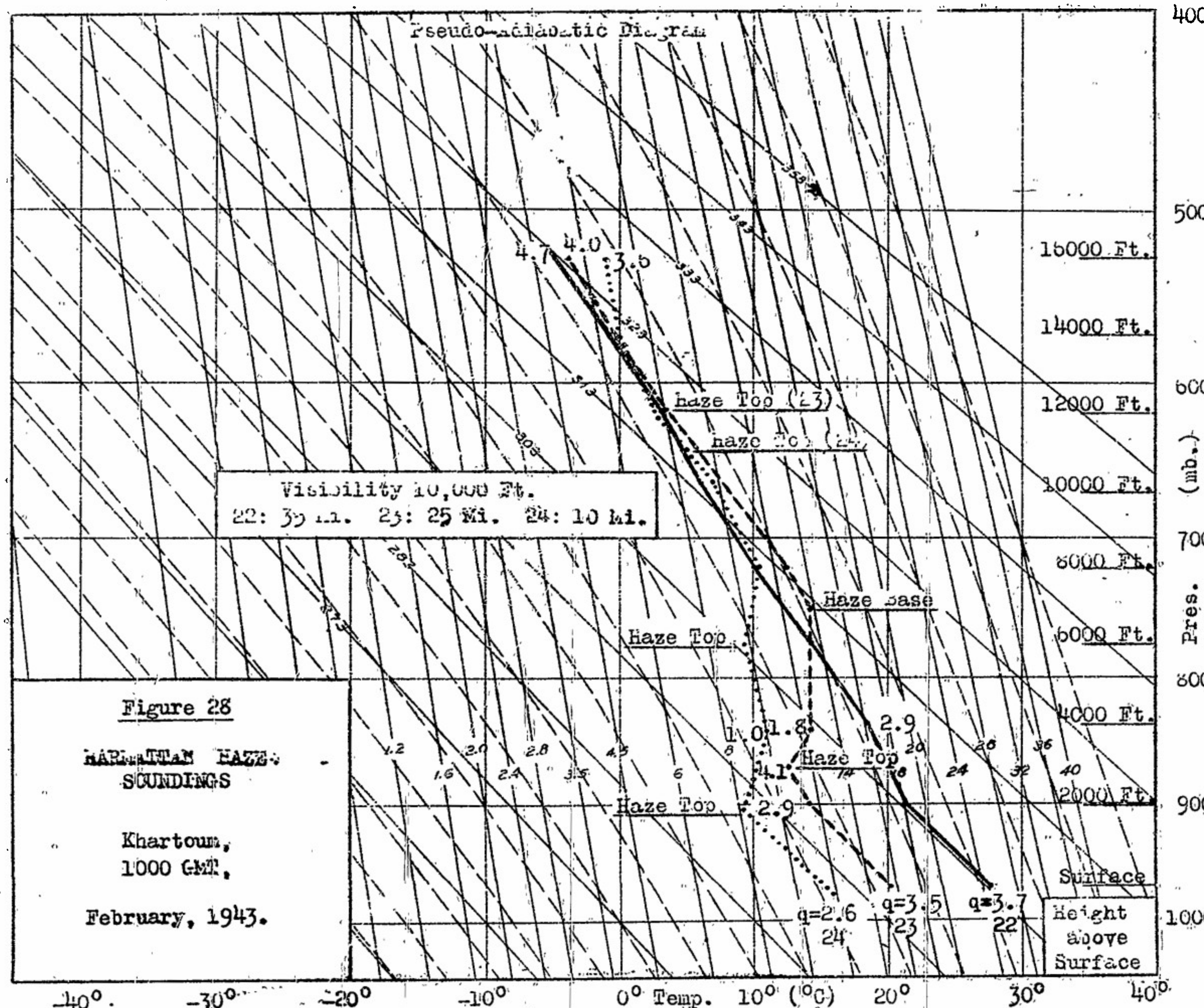


Figure 28

HARMATTAN HAZE SOUNDINGS

Khartoum, 1000 GMT,

February, 1943.

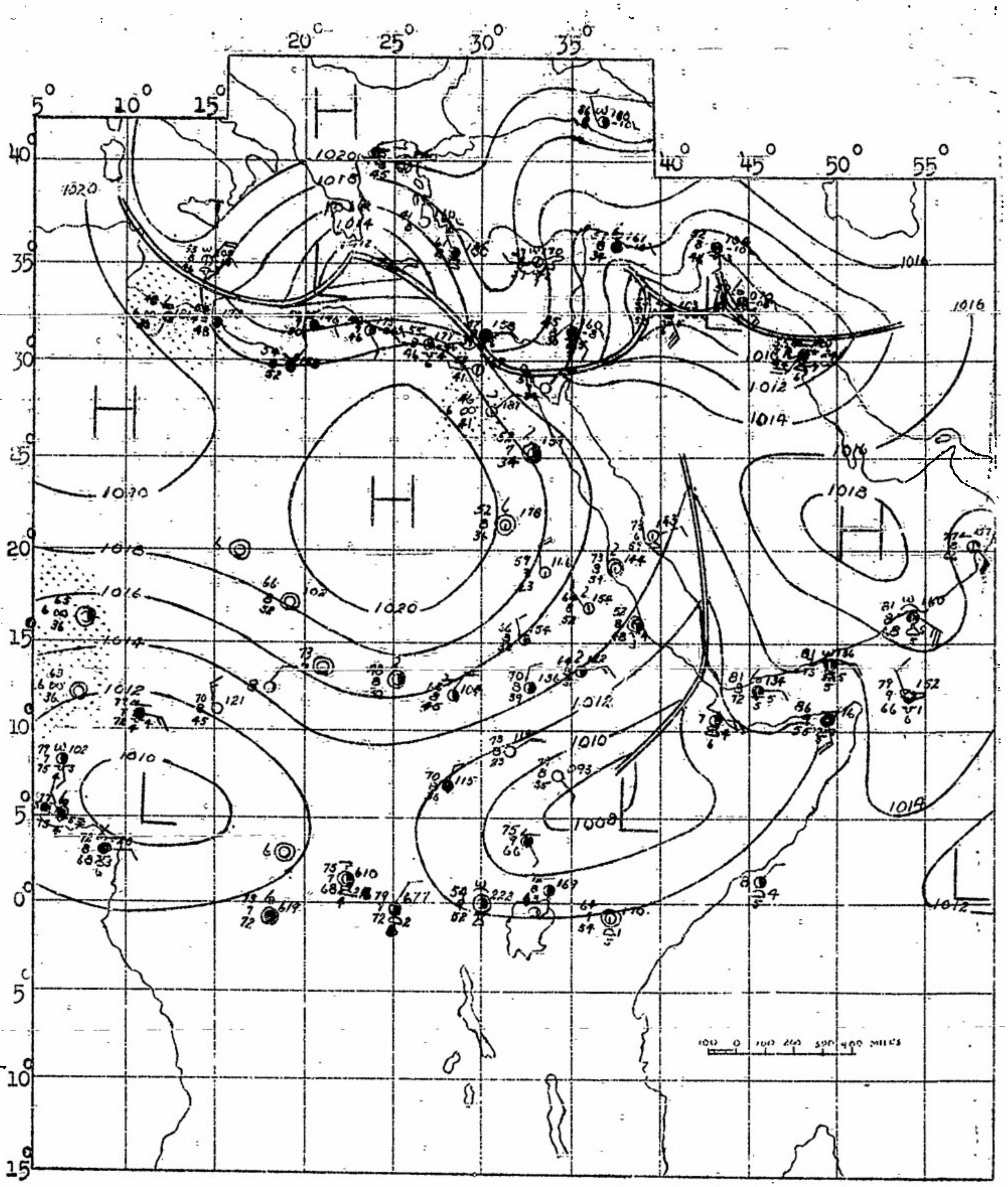


Figure 29 - Harmattan Haze (0600, Sunday, 21 February, 1943).

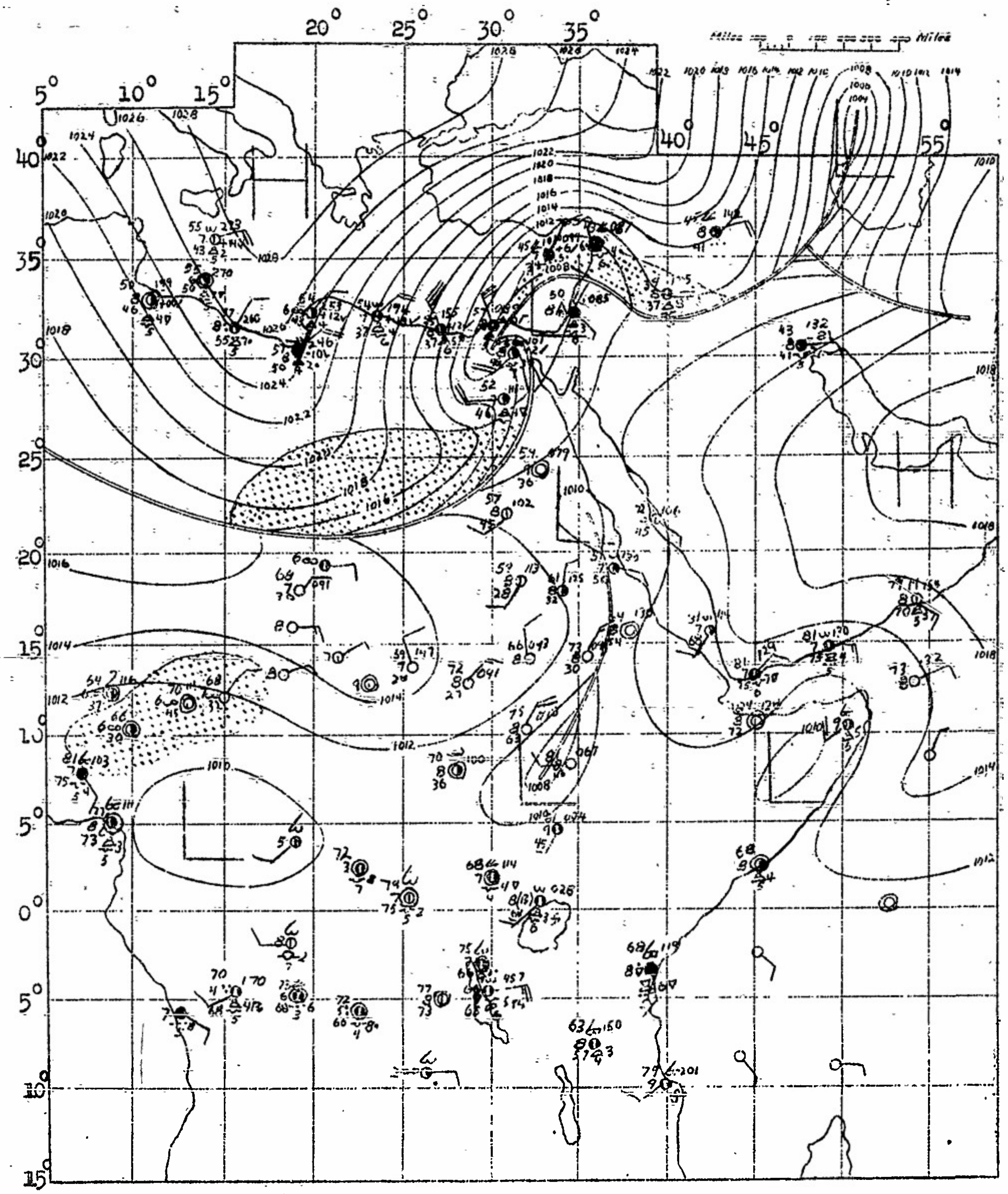


Figure 30 - Harmattan Haze (0600, Monday, 22 February, 1943).

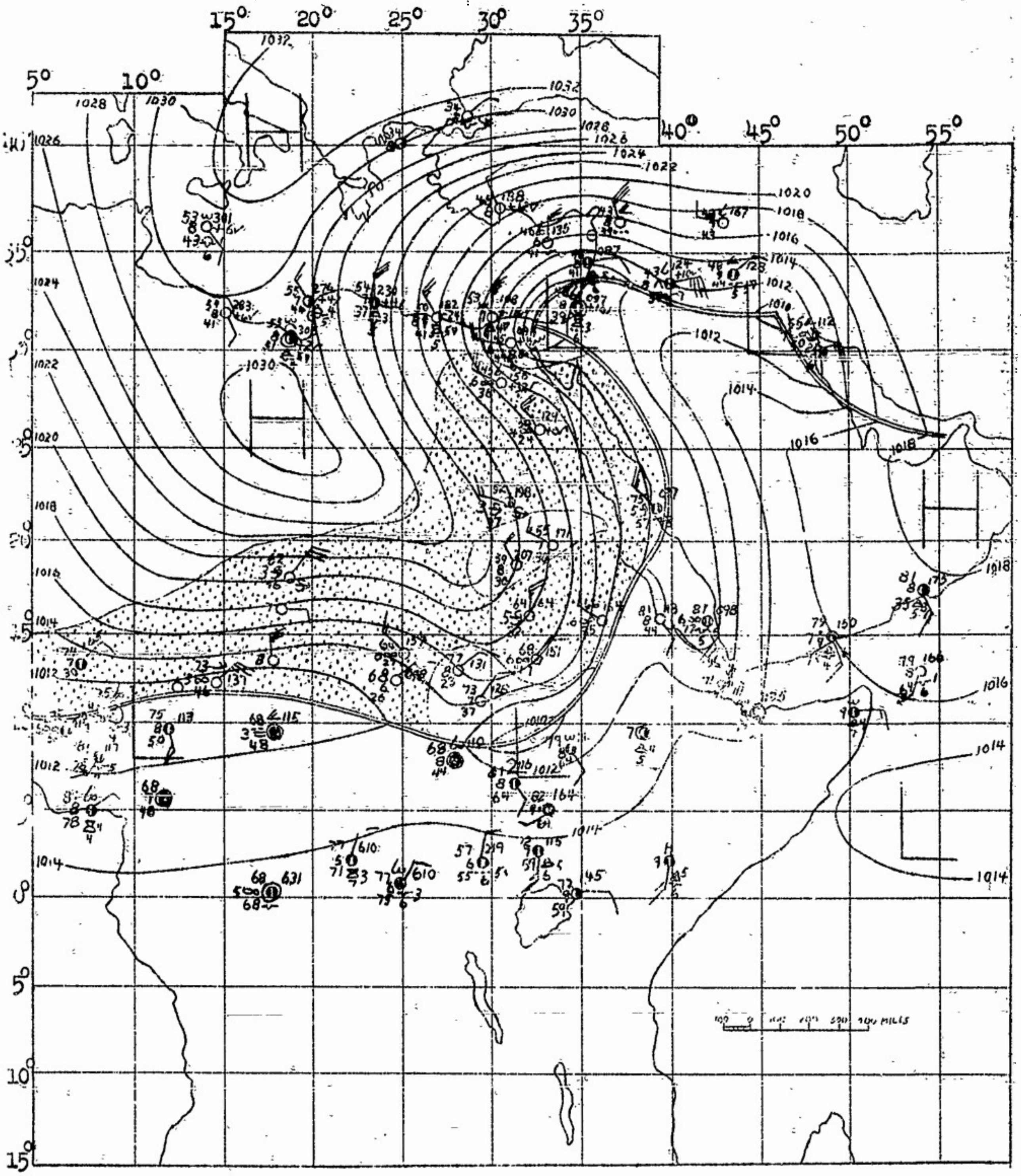


Figure 31. - Harmattan Haze (0600, Tuesday, 23 February, 1943).

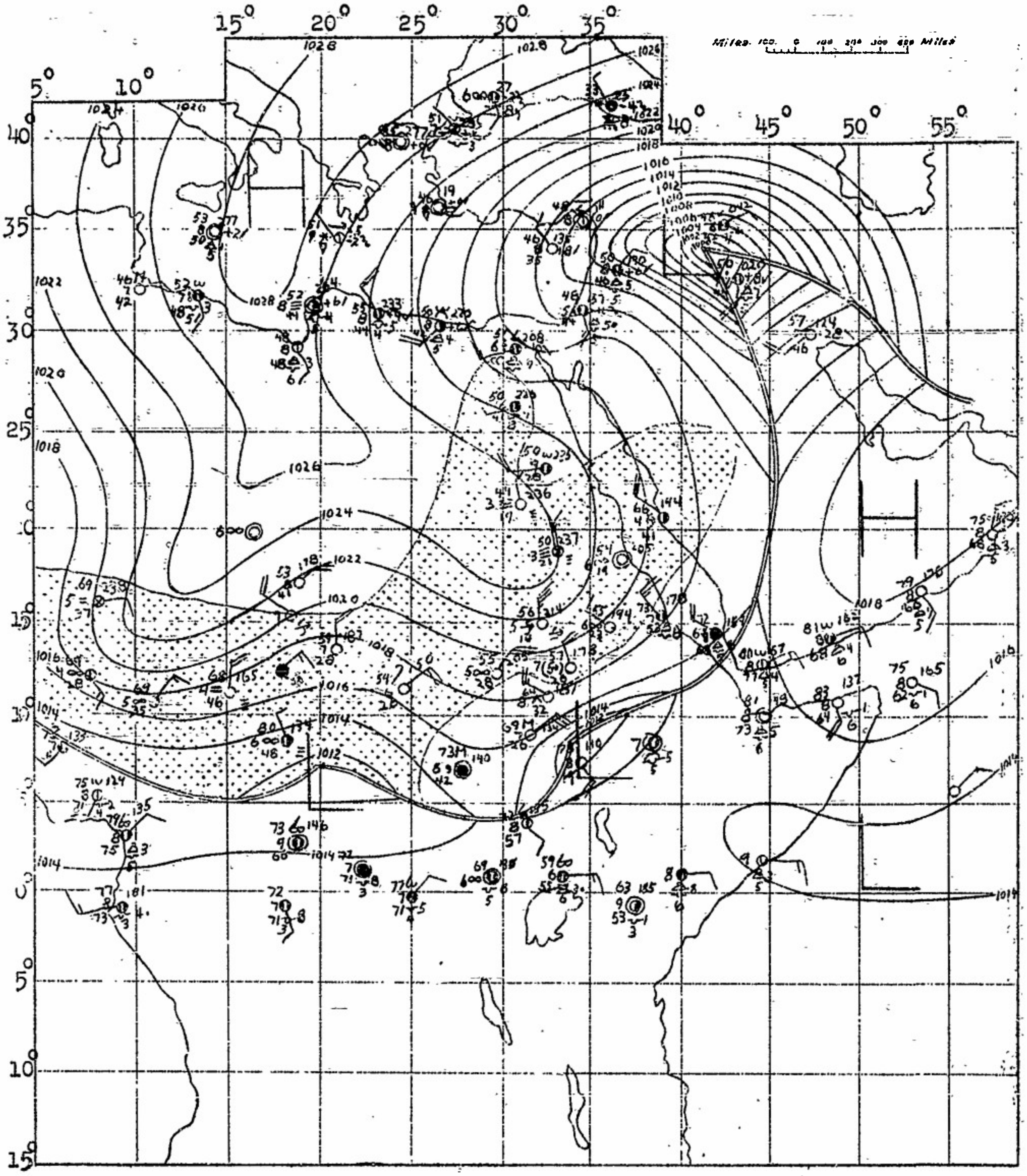


Figure 32 - Harmattan Haze (0600 Wednesday, 24 February, 1943).

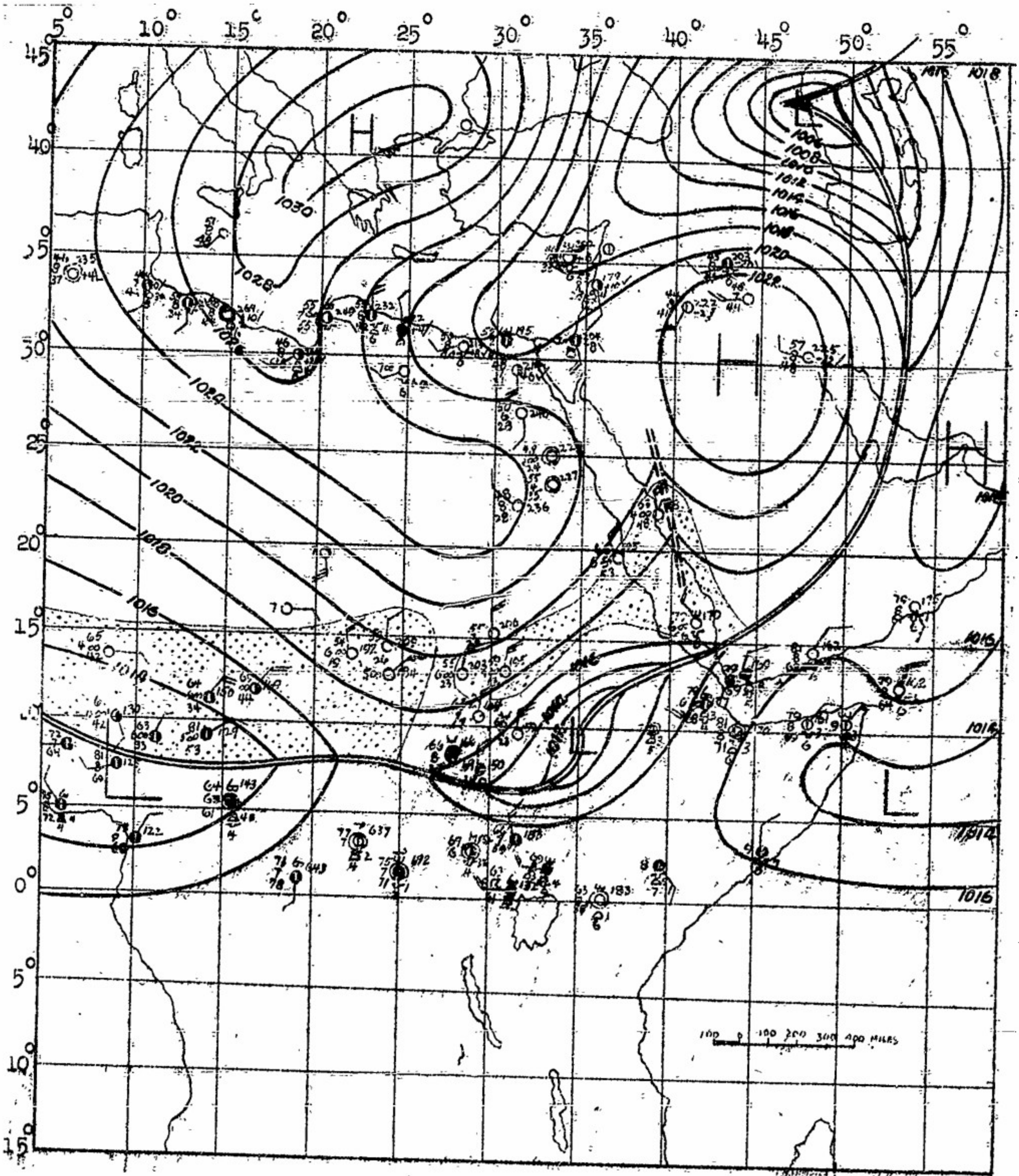


Figure 33 - Harmattan Haze (0600, Thursday, 25 February, 1943.)

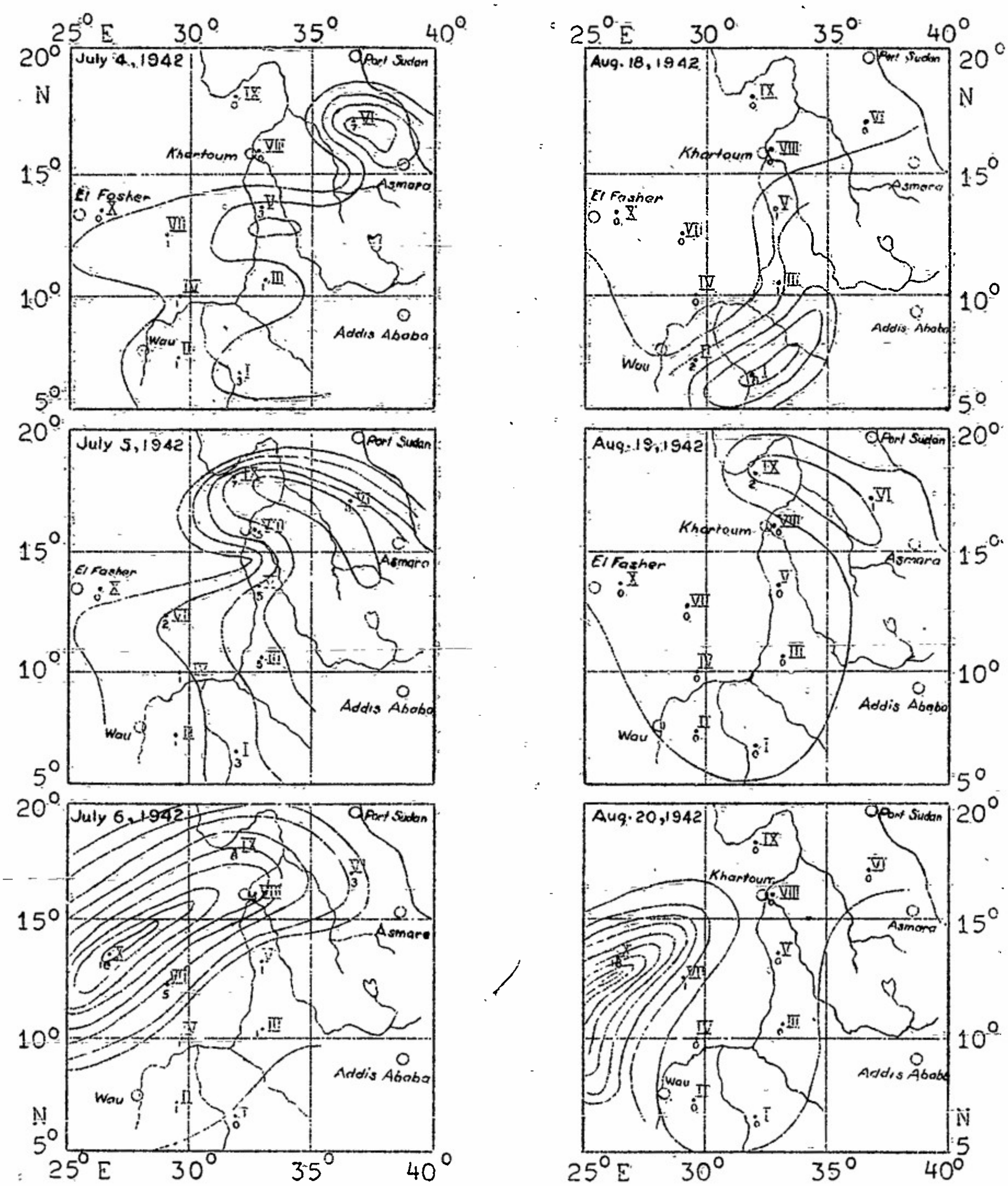


Figure 34A - Rainfall Patterns - Isopleths of Seasonal Percentage.

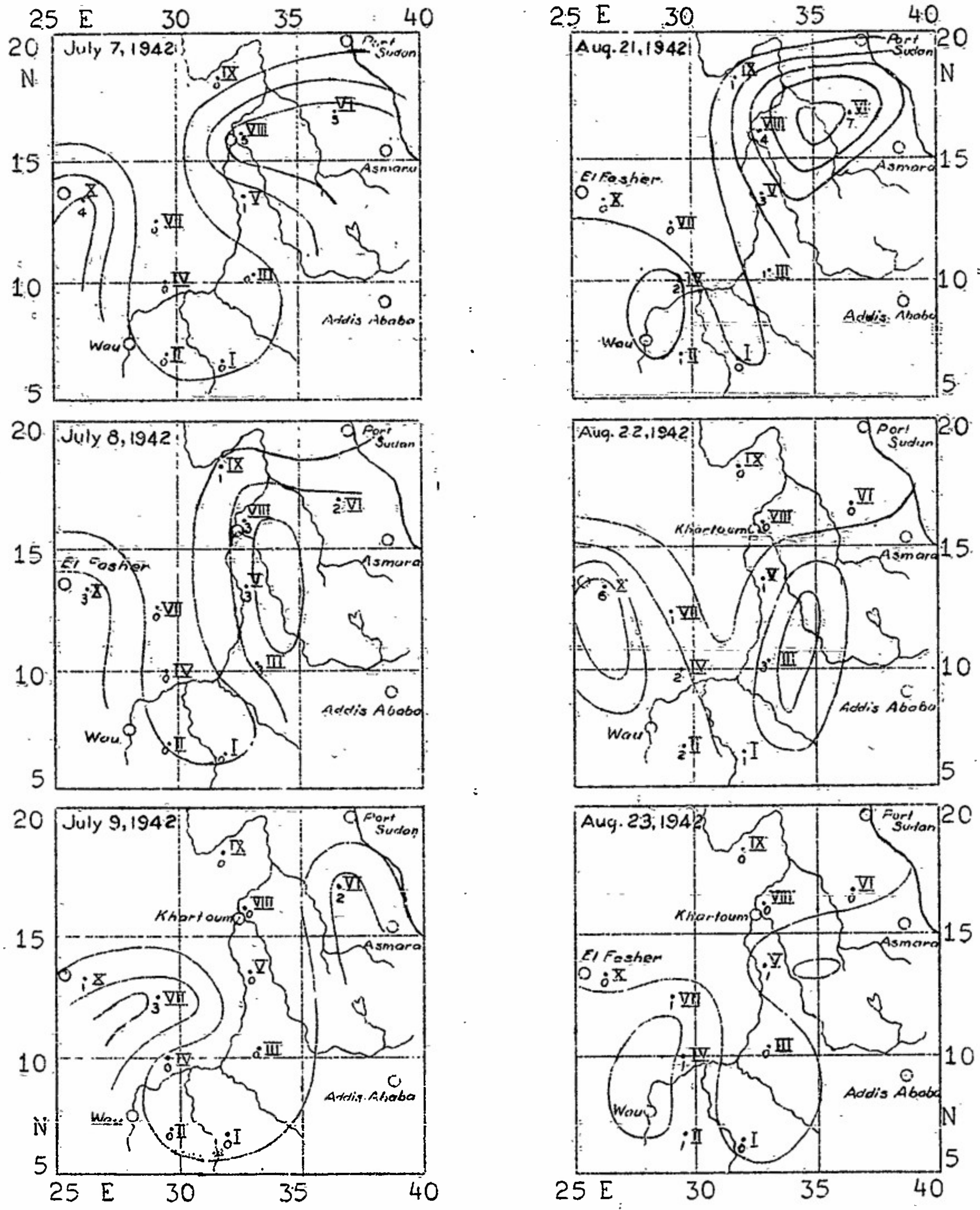


Figure 34B - Rainfall Patterns - Isopleths of Seasonal Percentage.

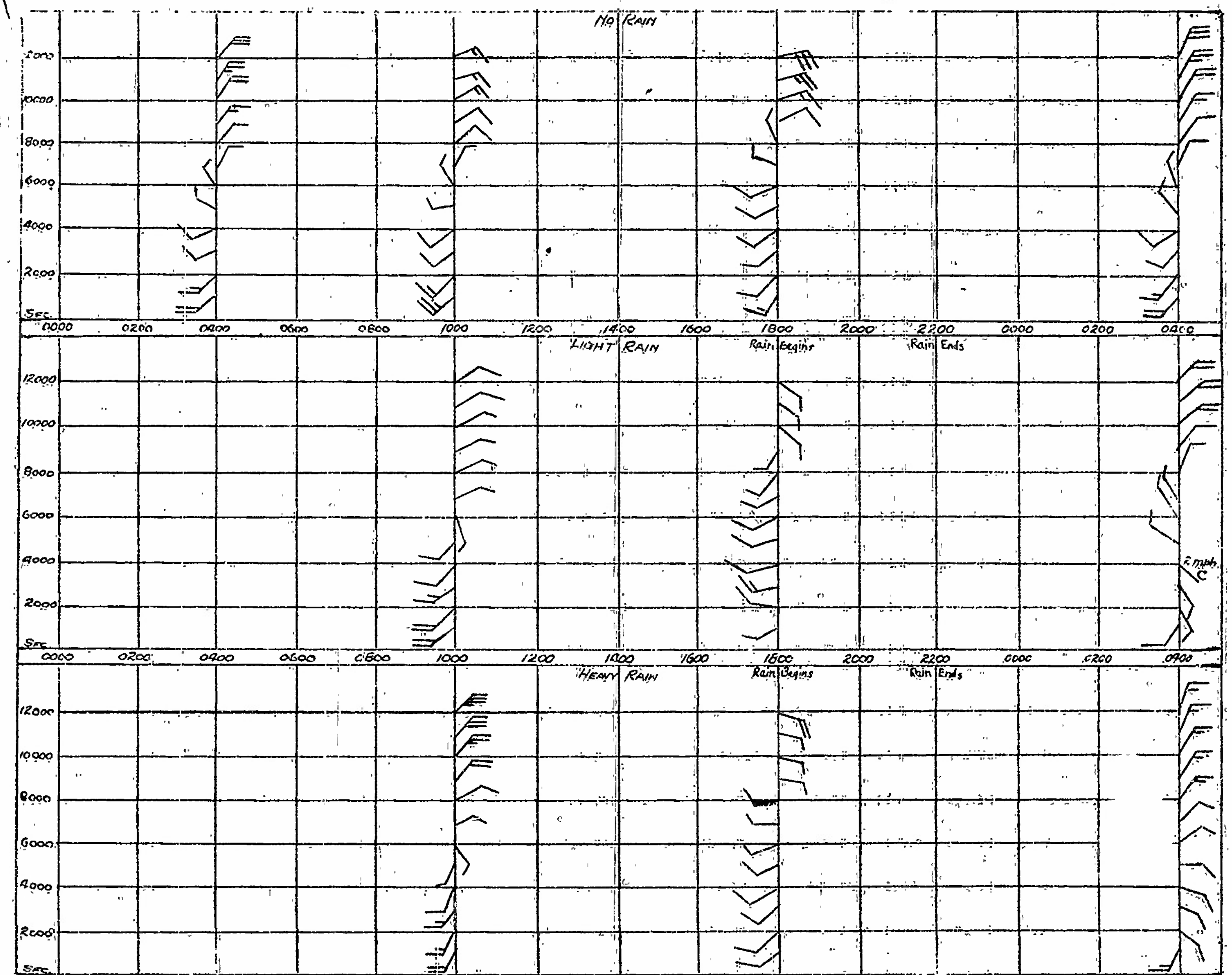


Figure 35 - Khartoum Winds Aloft - July and August, 1942 (full barb = 10 mph)

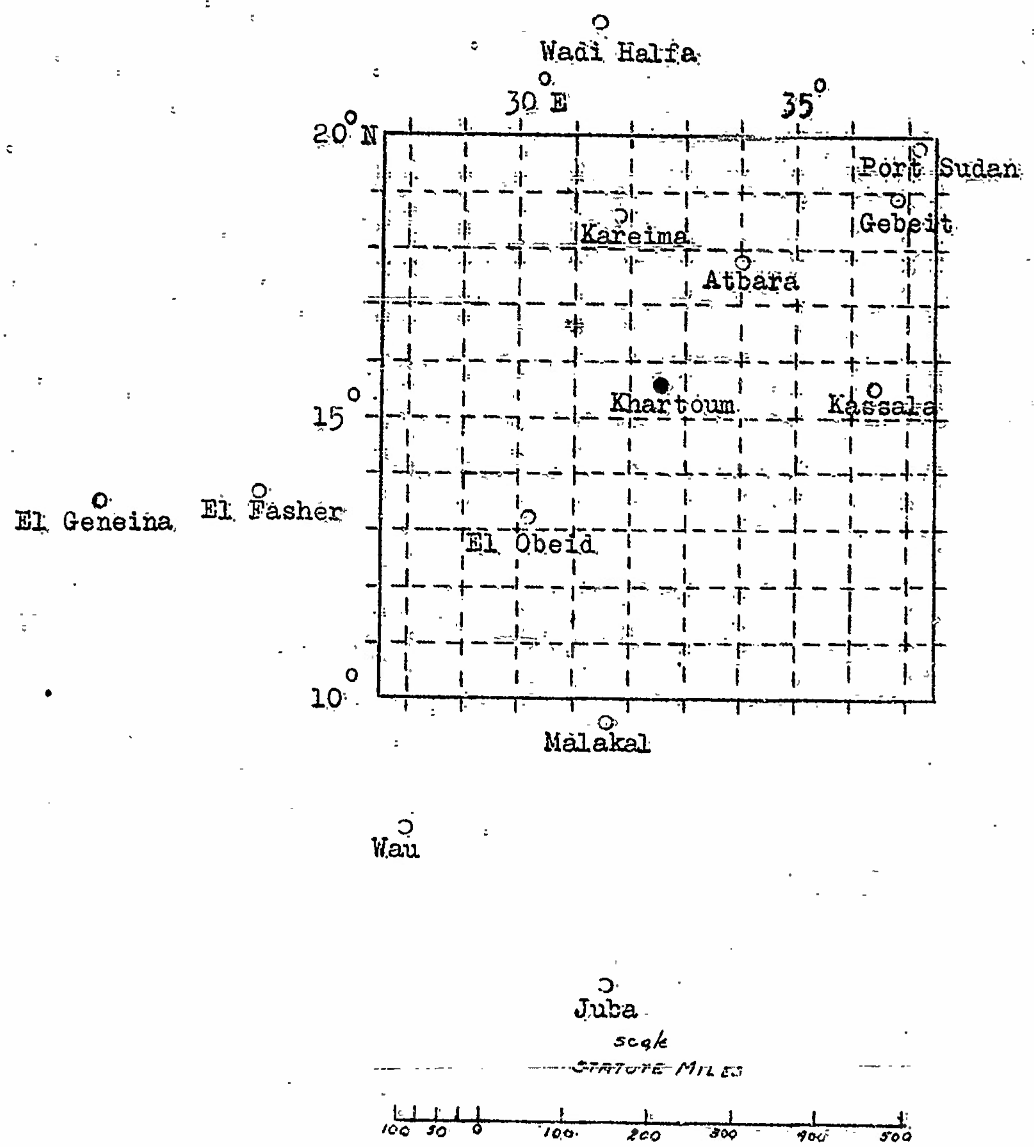


Figure 36 - Index Chart

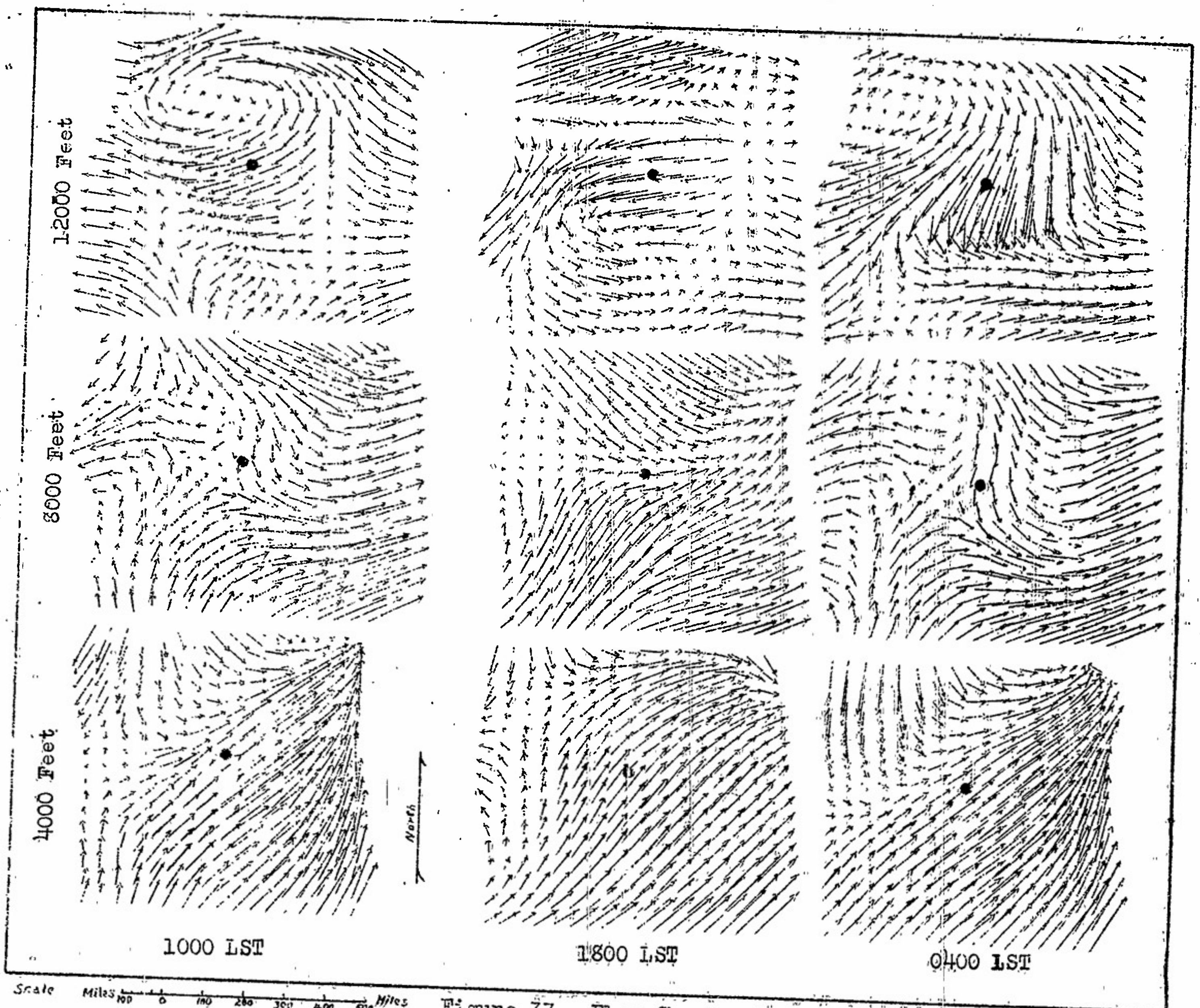


Figure 37 - Flow Charts, Normal ● (Khartoum)

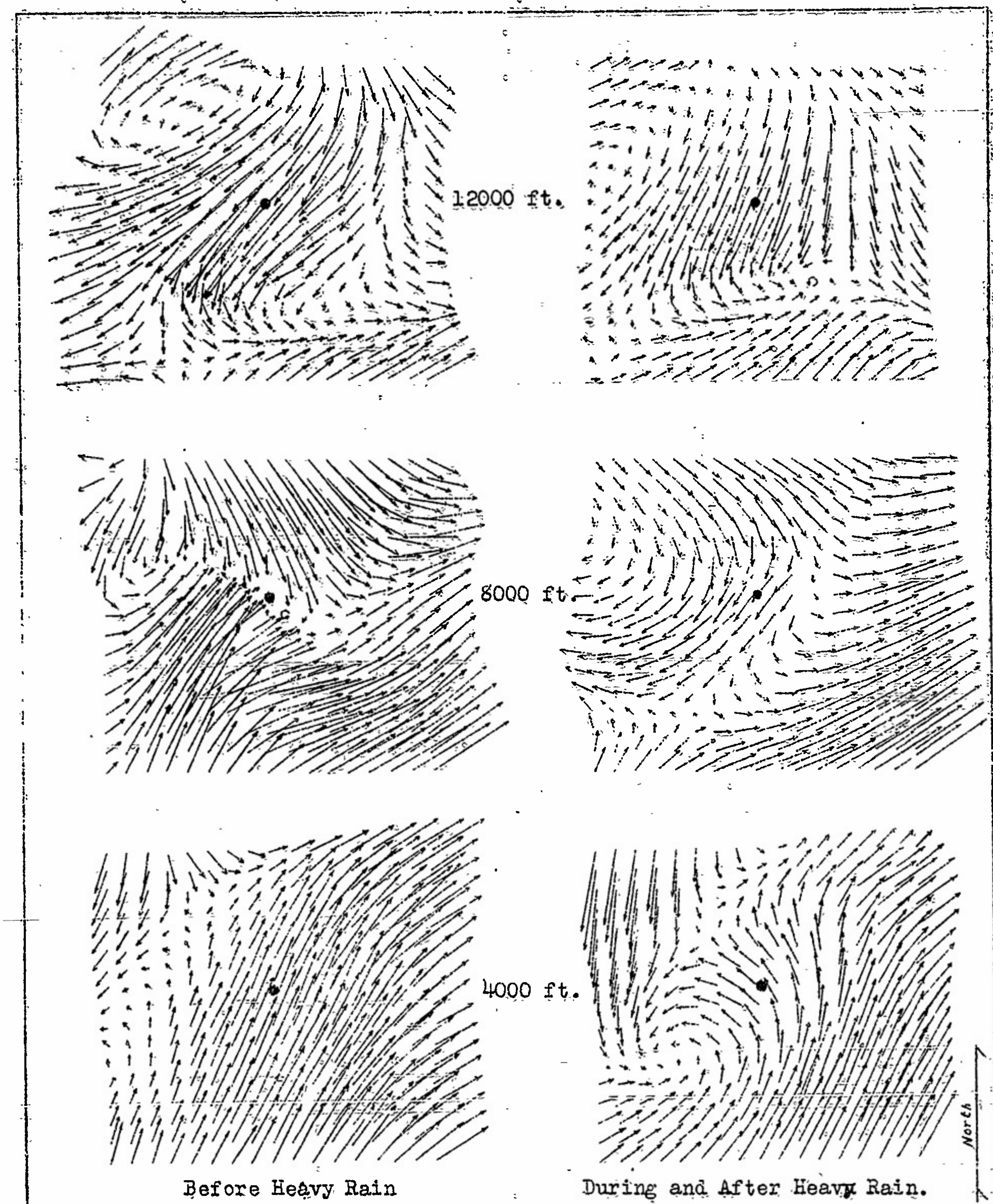


Figure 38 - Flow Charts - Heavy Rain.
● (Khartoum)

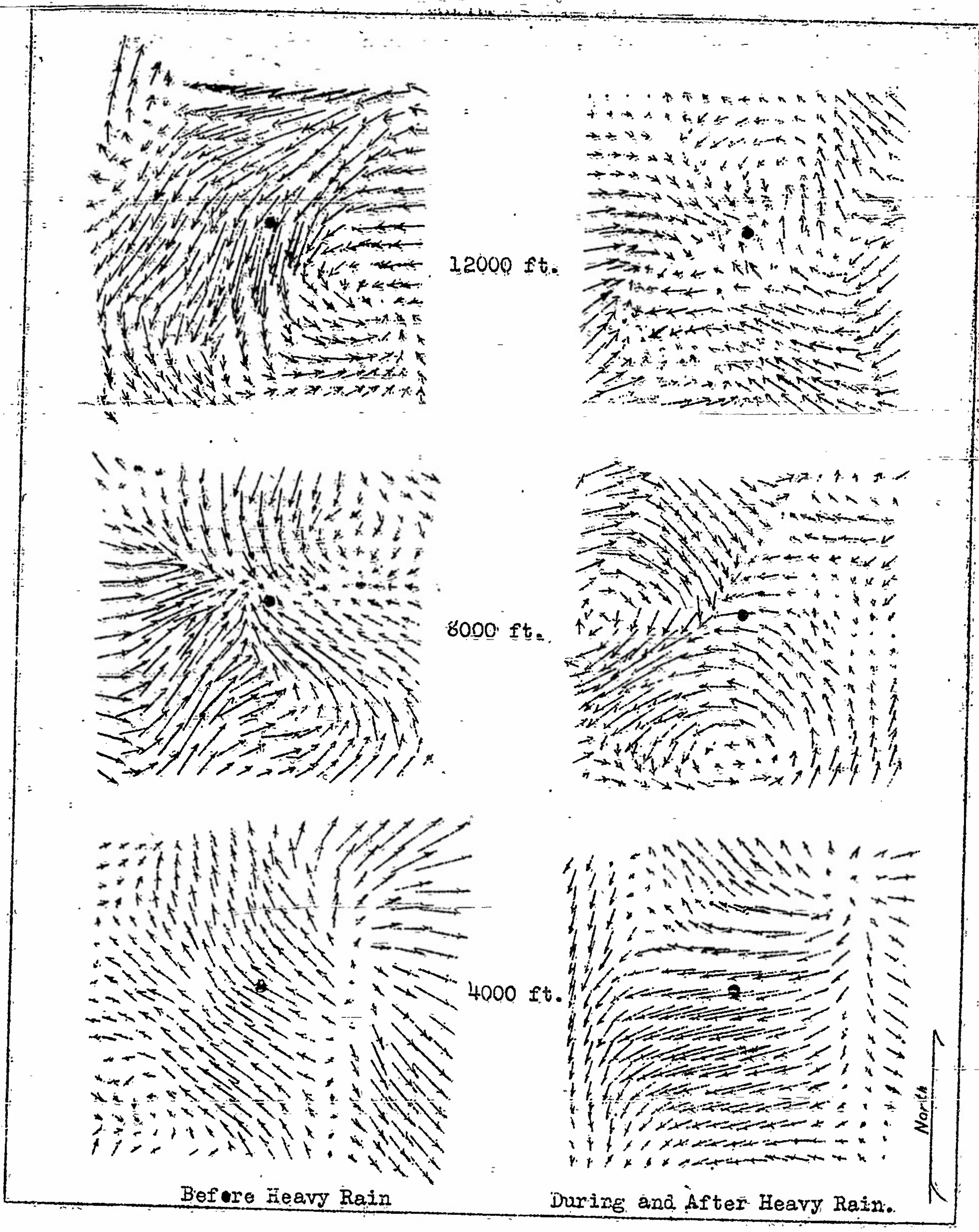


Figure 39 – Deviation of Heavy Rain from Normal – Flow Charts.
● (Khartoum)

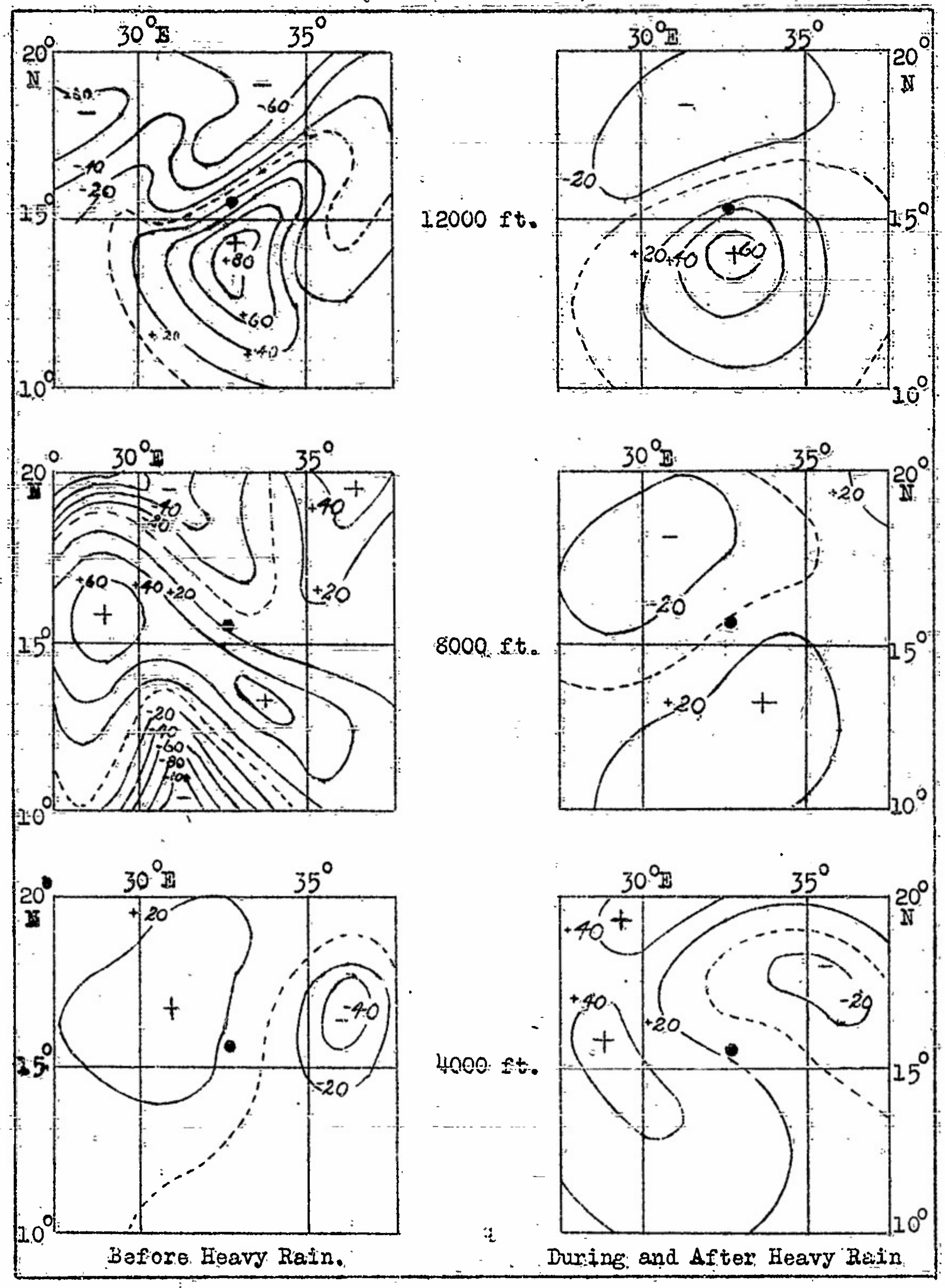


Figure 40 - Convergence + Vorticity Heavy Rain

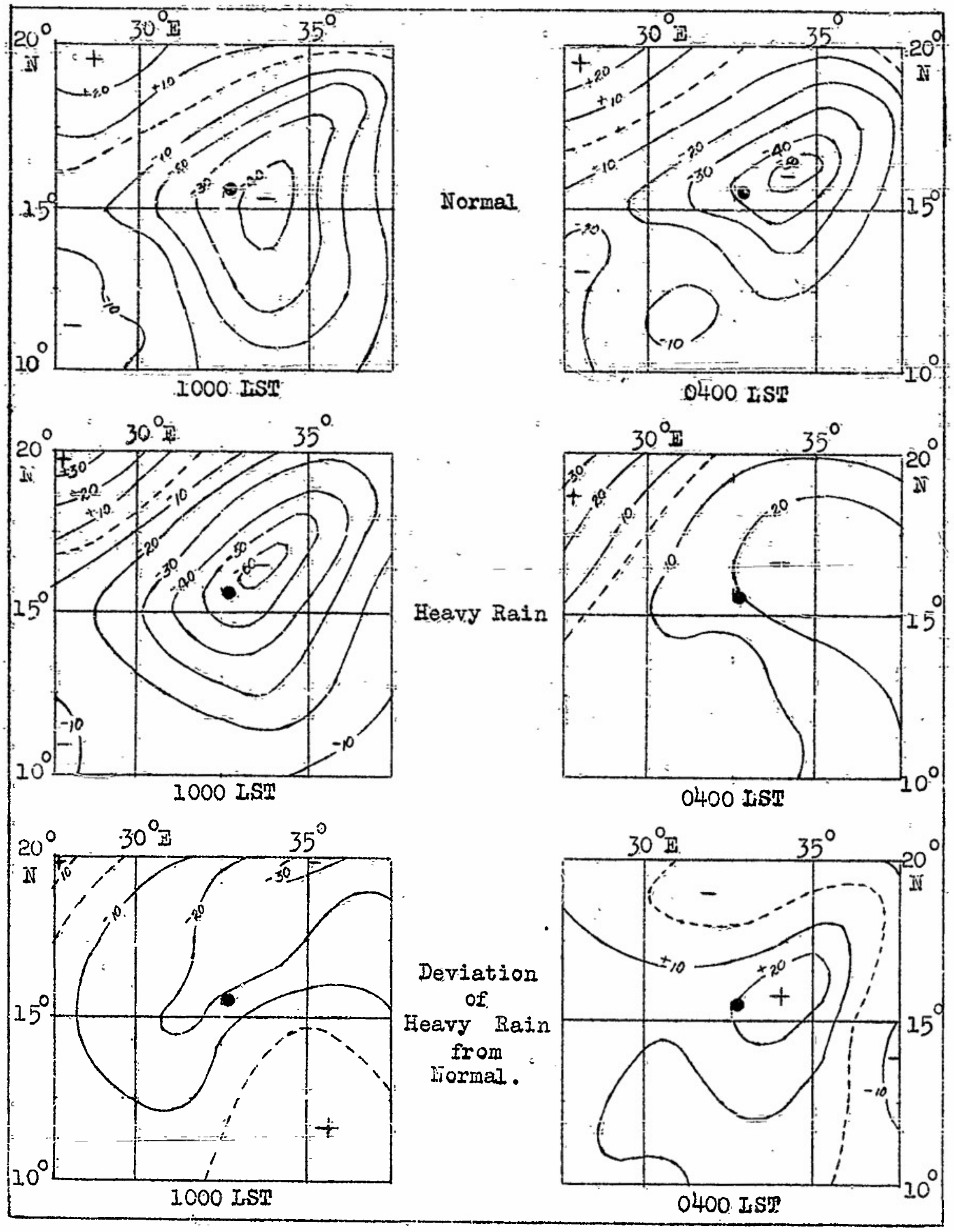


Figure 41 – Wind Shear.
($SW_{12000} - SW_{4000}$)

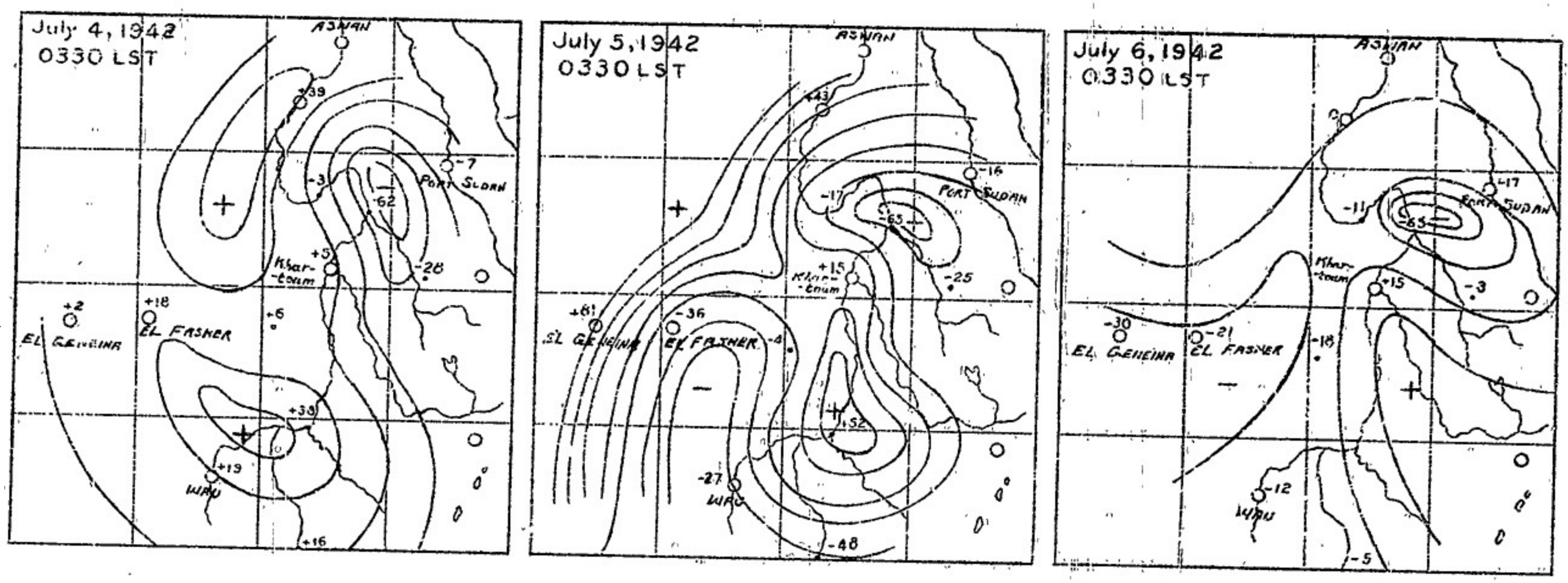


Figure 42 - West Wind Deviation From Normal

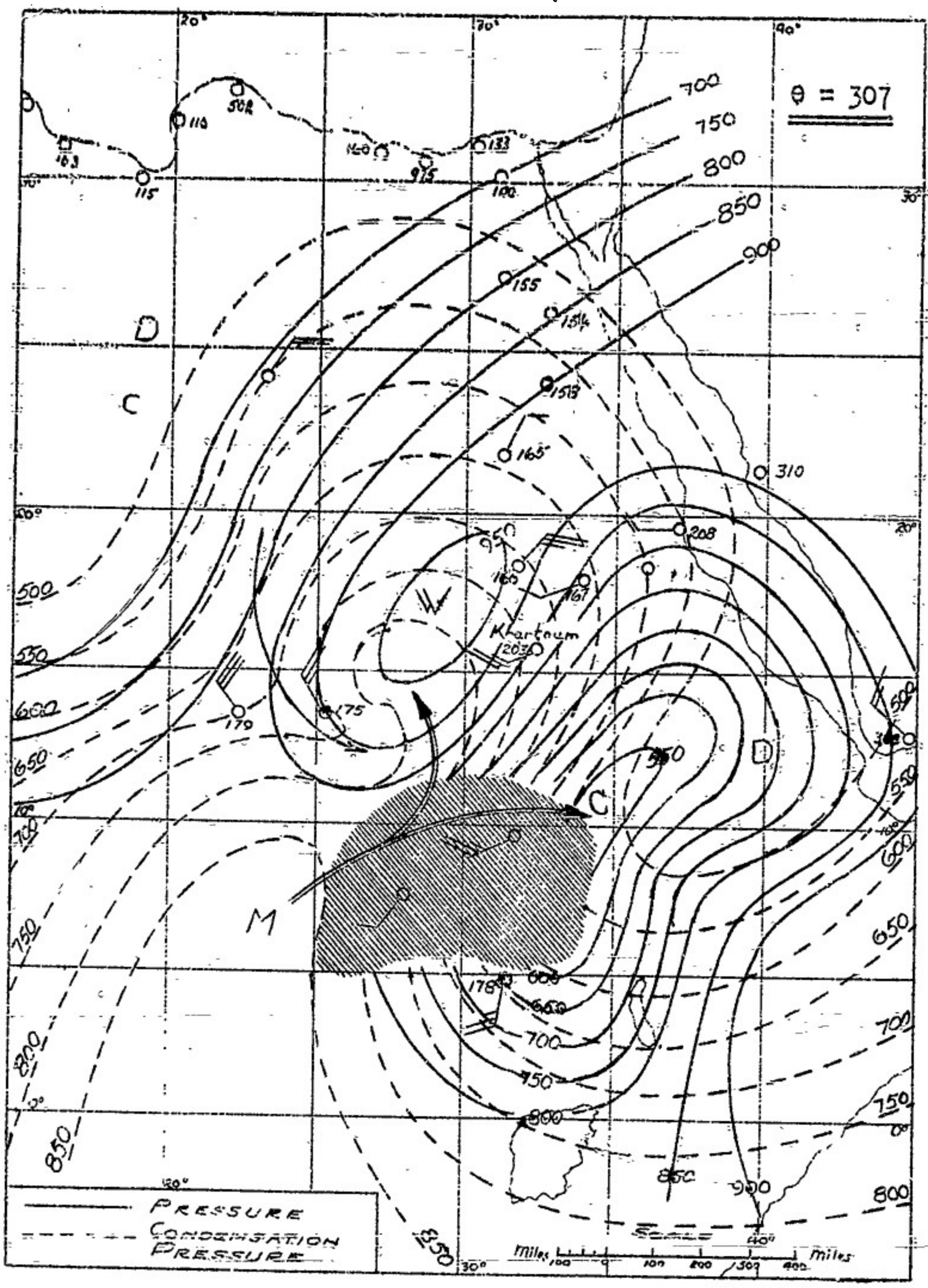


Figure 43 - Schematic Isentropic Chart

0600 GMT
13 July, 1942

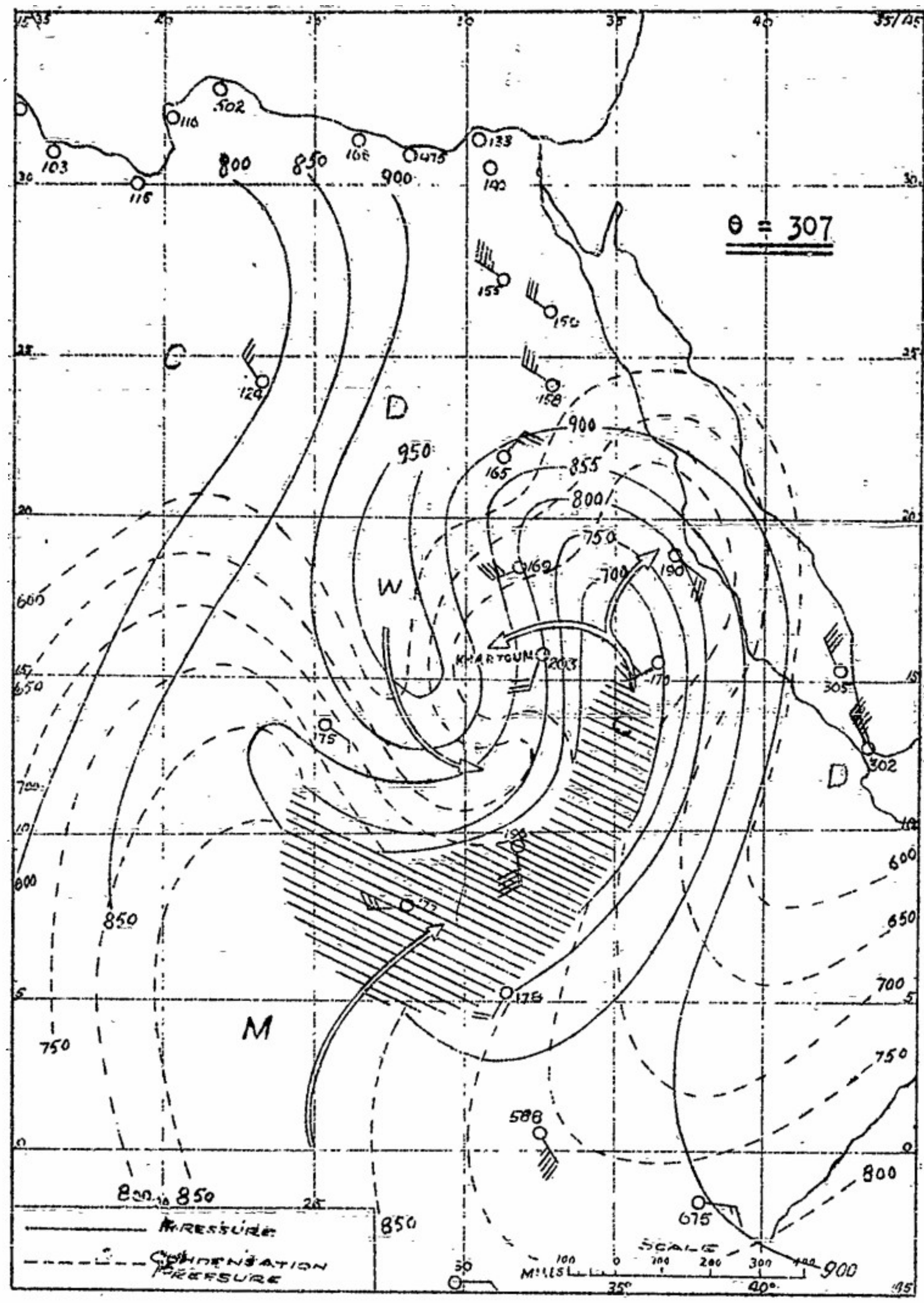
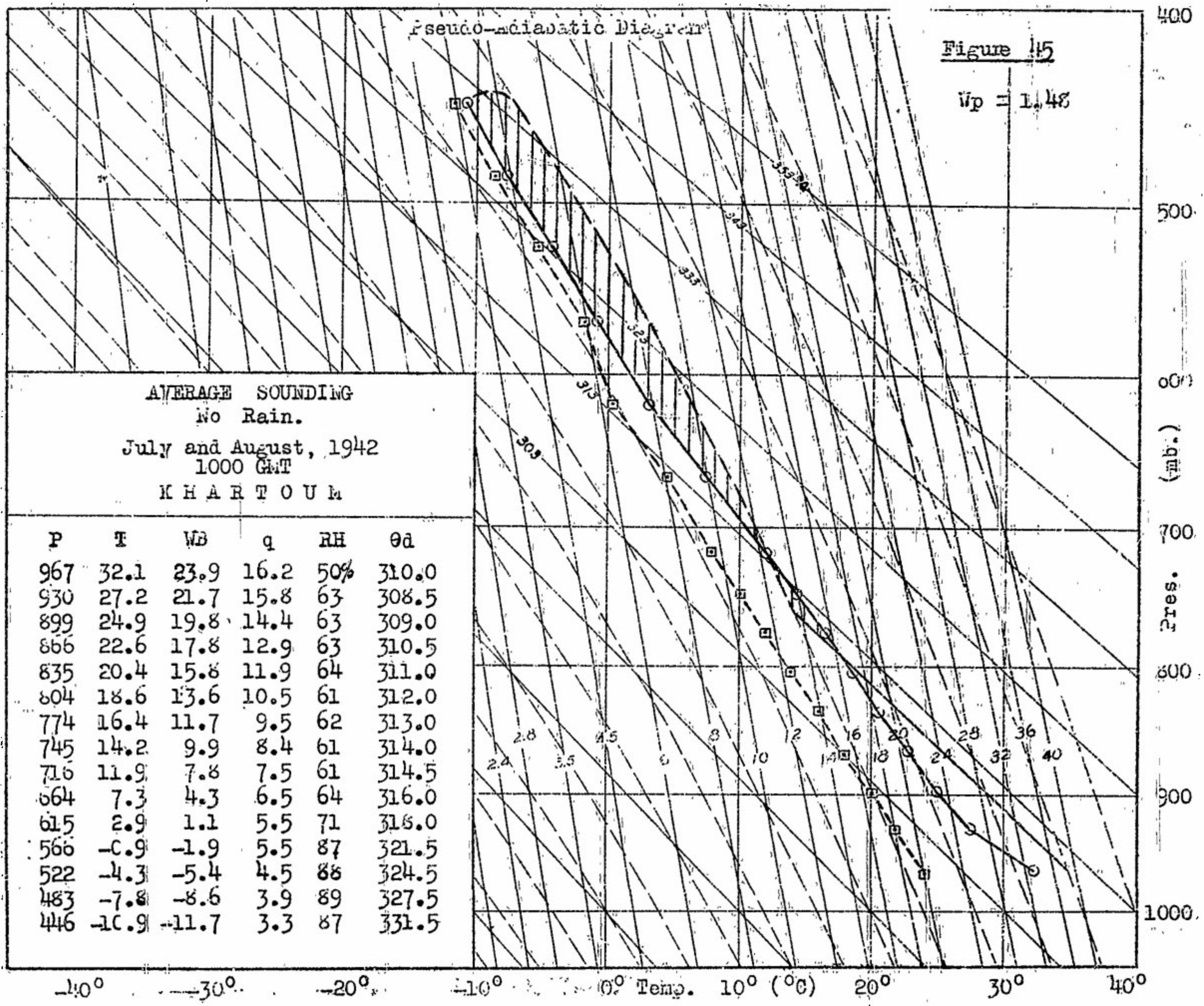


Figure 44 - Schematic Isentropic Chart

0600 GMT
26 July, 1942

Figure 15

Wp = 1.48



AVERAGE SOUNDING
No Rain.

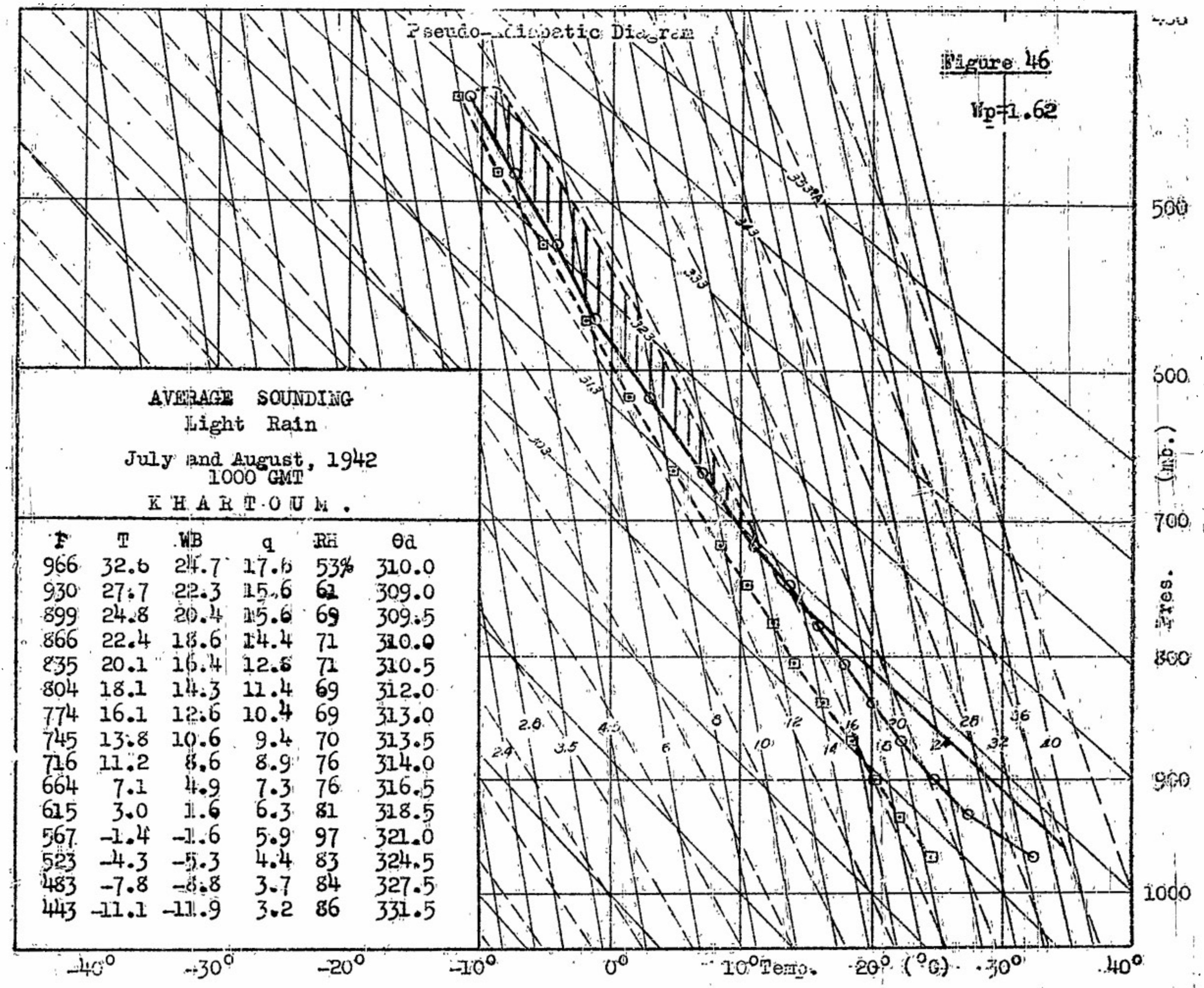
July and August, 1942
1000 GMT

K H A R T O U M

P	T	WB	q	RH	θd
967	32.1	23.9	16.2	50%	310.0
930	27.2	21.7	15.8	63	308.5
899	24.9	19.8	14.4	63	309.0
866	22.6	17.8	12.9	63	310.5
835	20.4	15.8	11.9	64	311.0
804	18.6	13.6	10.5	61	312.0
774	16.4	11.7	9.5	62	313.0
745	14.2	9.9	8.4	61	314.0
716	11.9	7.8	7.5	61	314.5
664	7.3	4.3	6.5	64	316.0
615	2.9	1.1	5.5	71	318.0
566	-0.9	-1.9	5.5	87	321.5
522	-4.3	-5.4	4.5	88	324.5
483	-7.8	-8.6	3.9	89	327.5
446	-10.9	-11.7	3.3	87	331.5

Figure 46

Wp=1.62

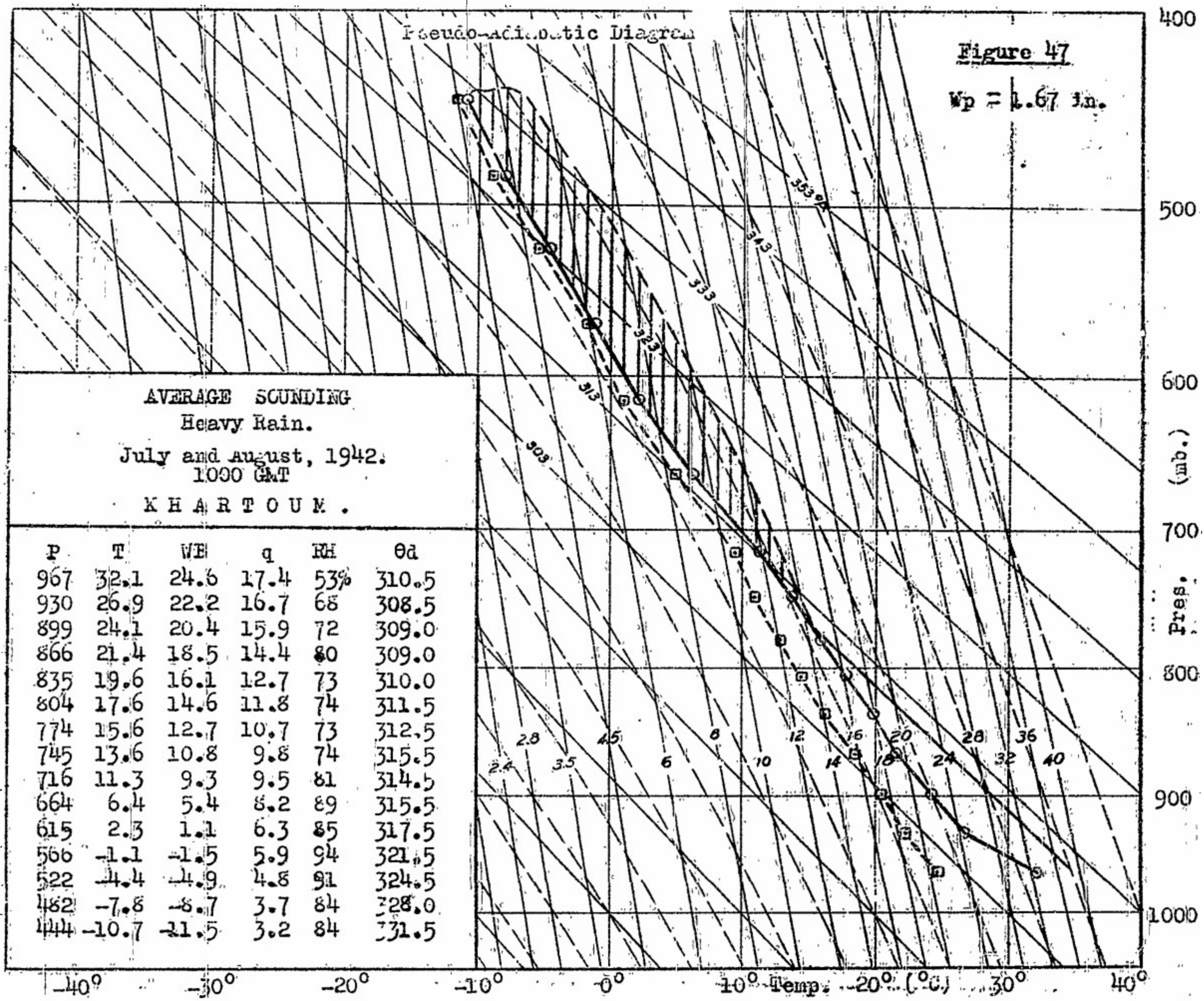


AVERAGE SOUNDING
Light Rain

July and August, 1942
1000 GMT

K H A R T O U M .

P	T	WB	q	RH	θd
966	32.6	24.7	17.6	53%	310.0
930	27.7	22.3	15.6	61	309.0
899	24.8	20.4	15.6	69	309.5
866	22.4	18.6	14.4	71	310.0
835	20.1	16.4	12.6	71	310.5
804	18.1	14.3	11.4	69	312.0
774	16.1	12.6	10.4	69	313.0
745	13.8	10.6	9.4	70	313.5
716	11.2	8.6	8.9	76	314.0
664	7.1	4.9	7.3	76	316.5
615	3.0	1.6	6.3	81	318.5
567	-1.4	-1.6	5.9	97	321.0
523	-4.3	-5.3	4.4	83	324.5
483	-7.8	-8.8	3.7	84	327.5
443	-11.1	-11.9	3.2	86	331.5



AVERAGE SOUNDING
Heavy Rain.
July and August, 1942.
1000 GMT
KHARTOUM.

P	T	WB	q	RH	θd
967	32.1	24.6	17.4	53%	310.5
930	26.9	22.2	16.7	68	308.5
899	24.1	20.4	15.9	72	309.0
866	21.4	18.5	14.4	80	309.0
835	19.6	16.1	12.7	73	310.0
804	17.6	14.6	11.8	74	311.5
774	15.6	12.7	10.7	73	312.5
745	13.6	10.8	9.8	74	315.5
716	11.3	9.3	9.5	81	314.5
664	6.4	5.4	8.2	89	315.5
615	2.3	1.1	6.3	85	317.5
566	-1.1	-1.5	5.9	94	321.5
522	-4.4	-4.9	4.8	91	324.5
482	-7.8	-8.7	3.7	84	328.0
444	-10.7	-11.5	3.2	84	331.5

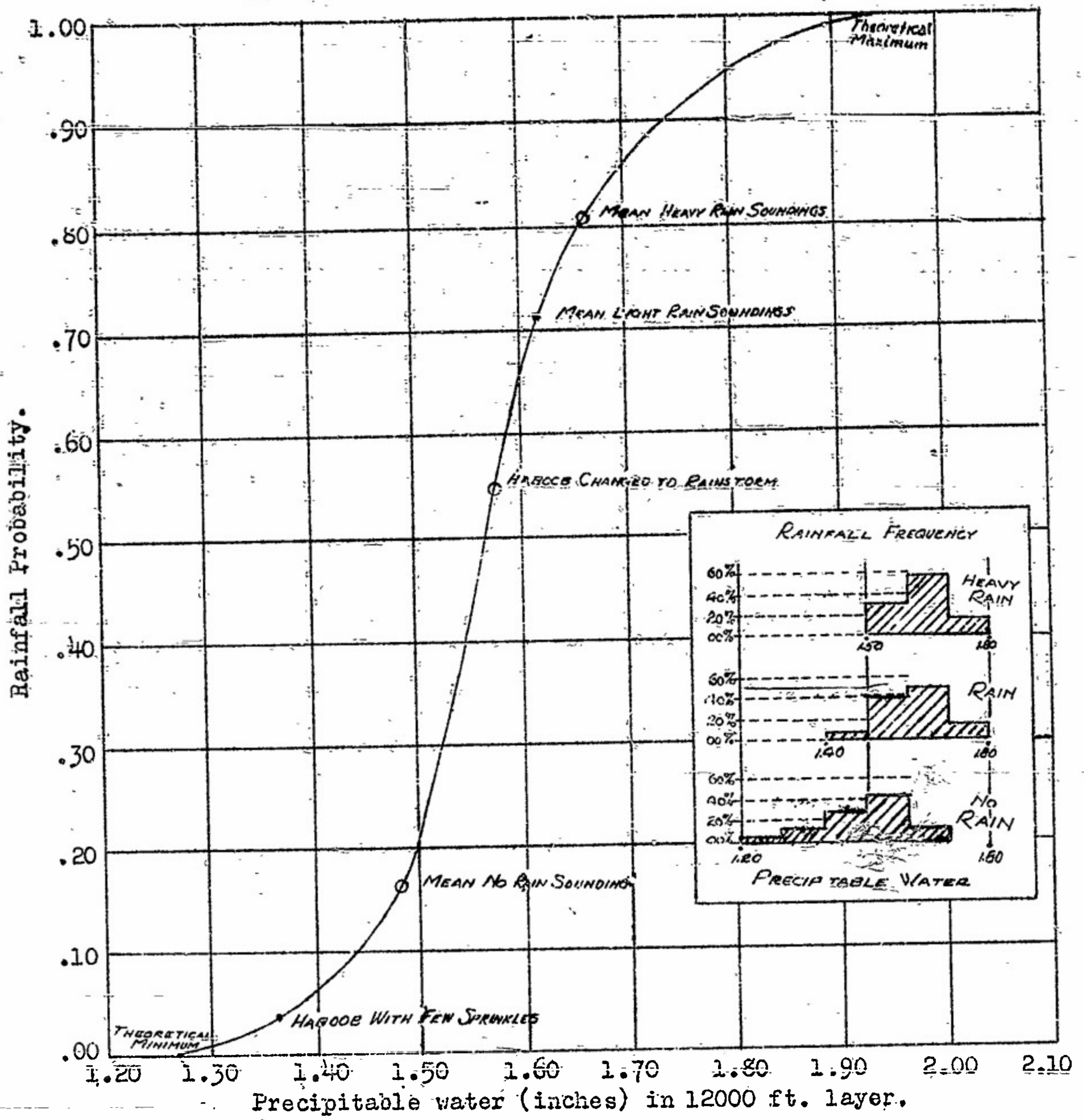


Figure 48 - Rainfall Probability Chart-Khartoum Area.

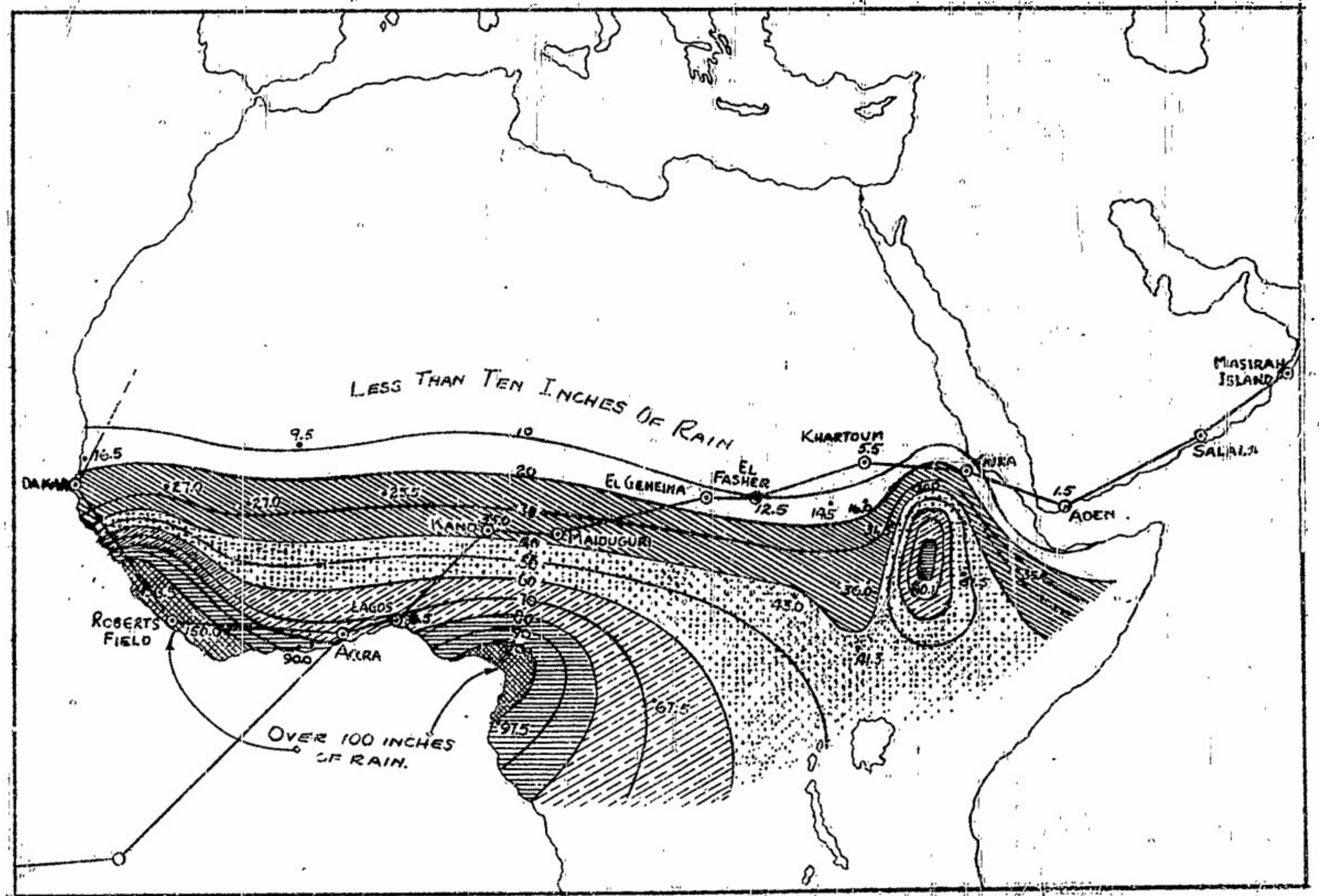


Figure 49 - Annual Rainfall Central Africa.

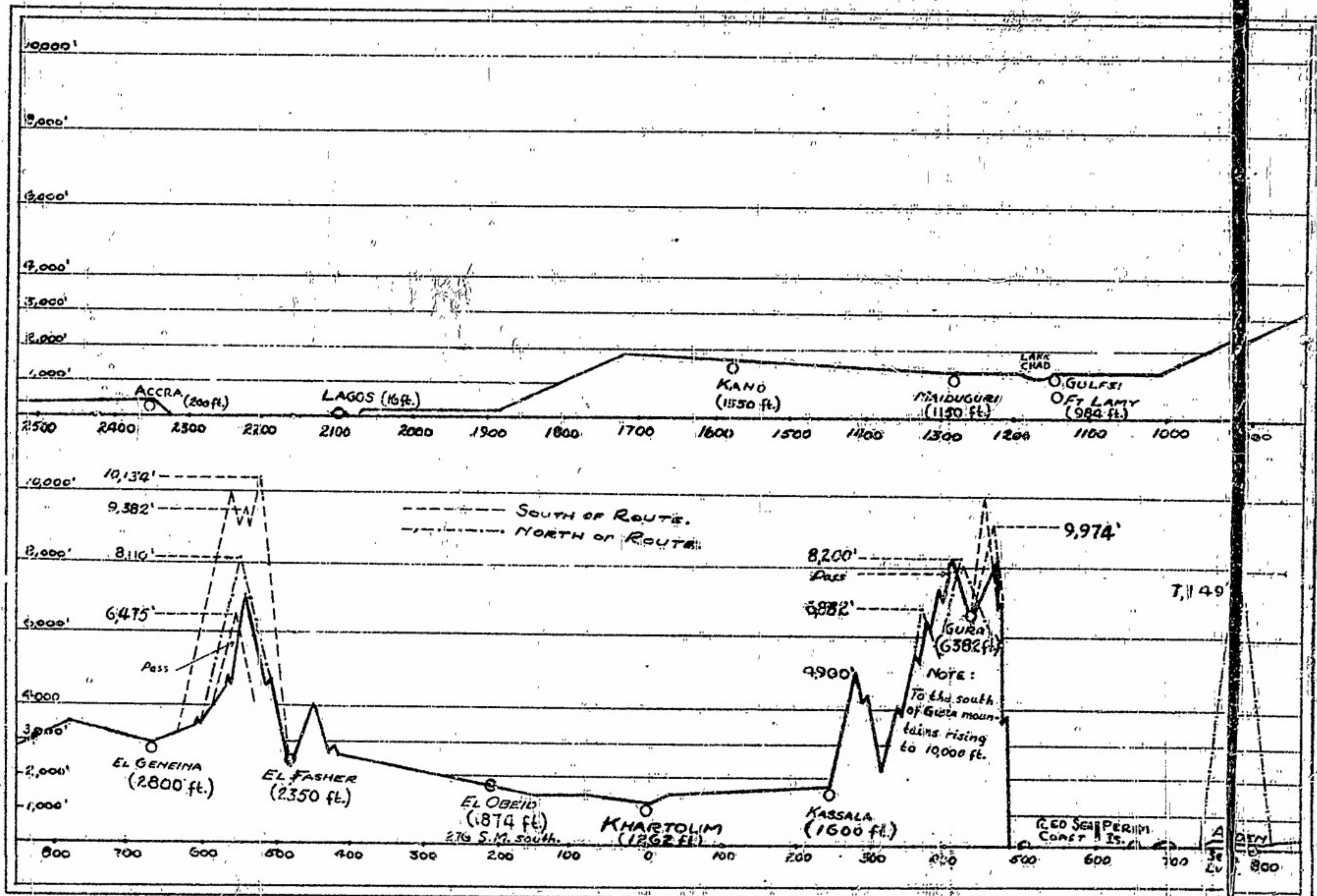


Figure 50 — Cross Section.

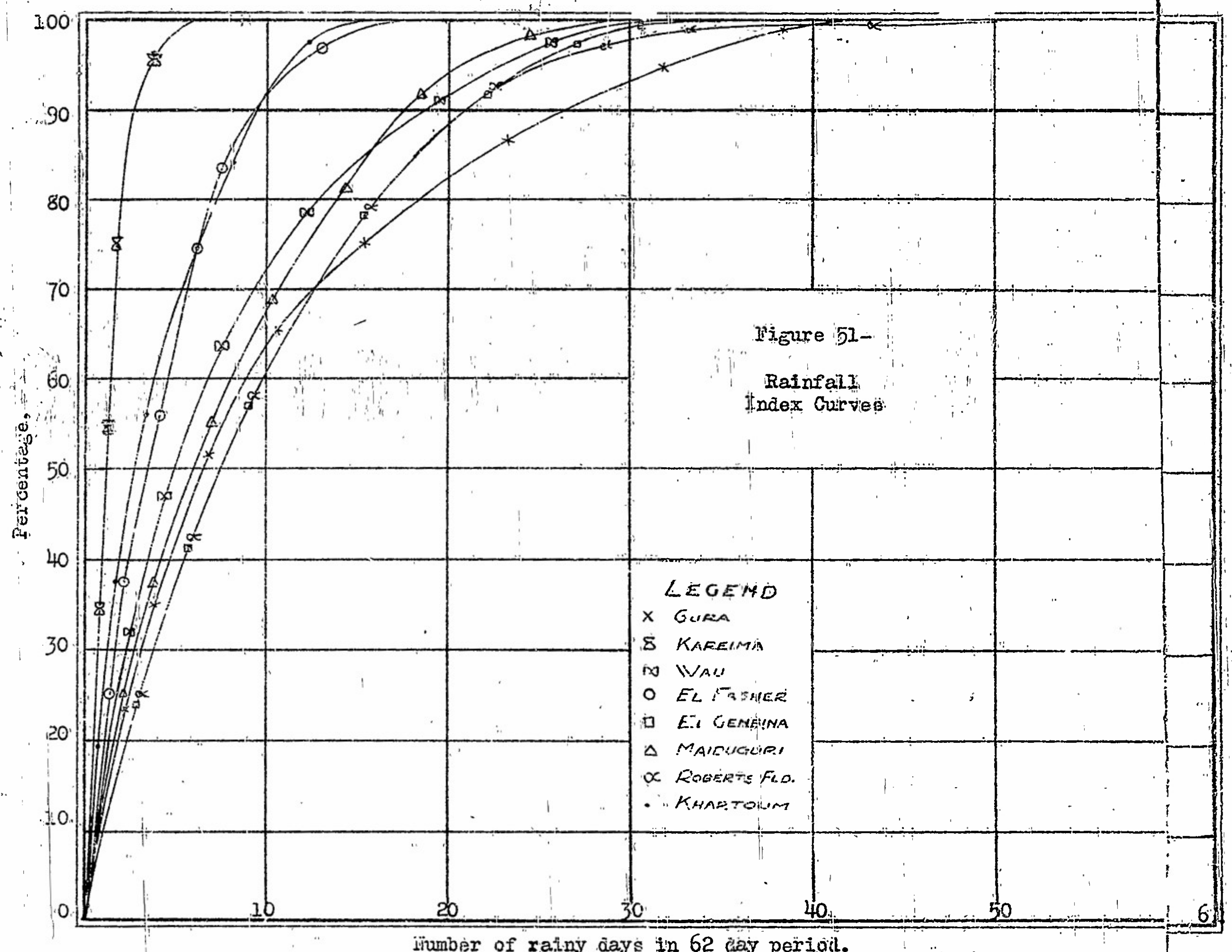


Figure 51–
Rainfall Index Curves

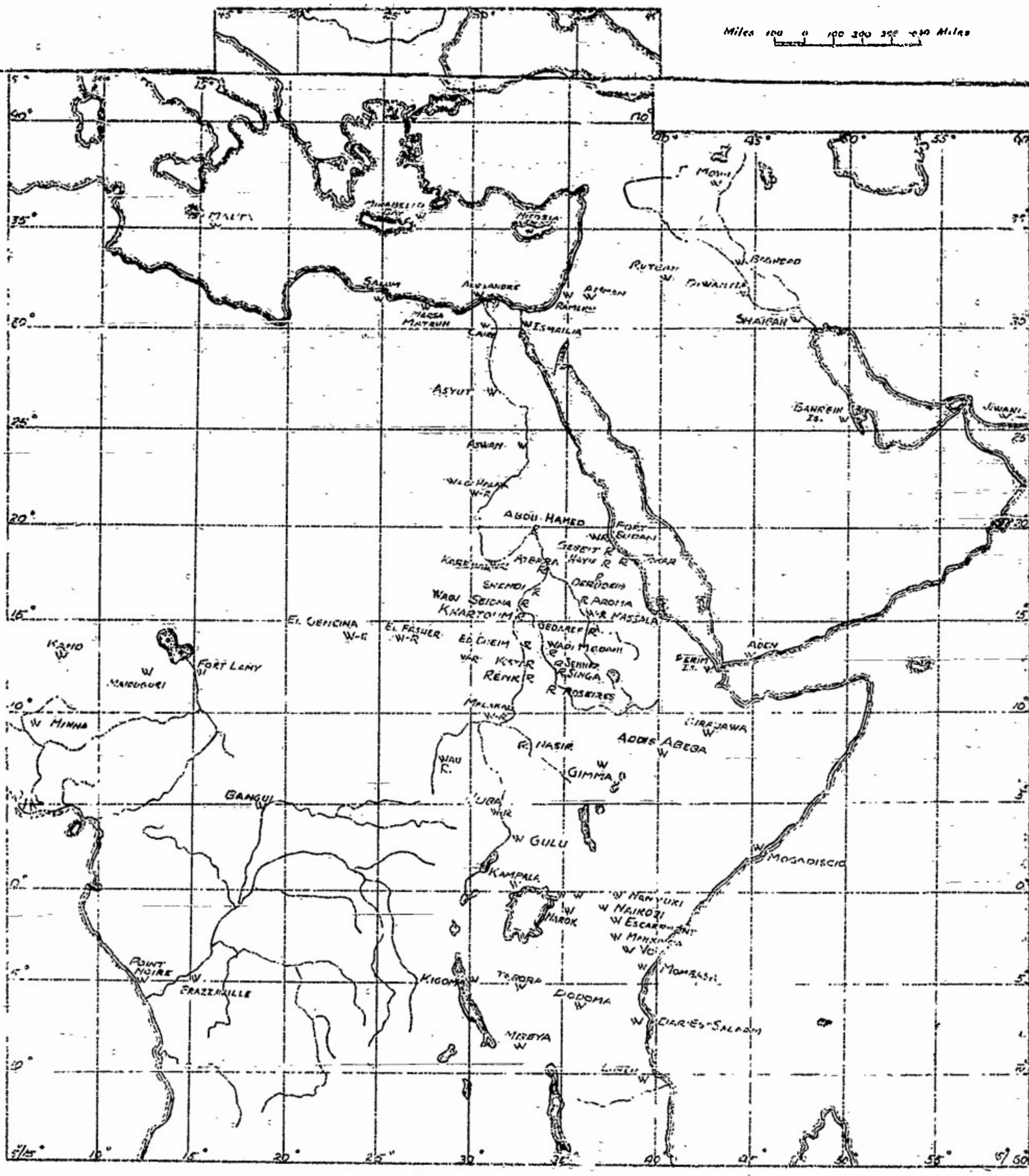


Figure 52 - Wind and Rainfall Stations.

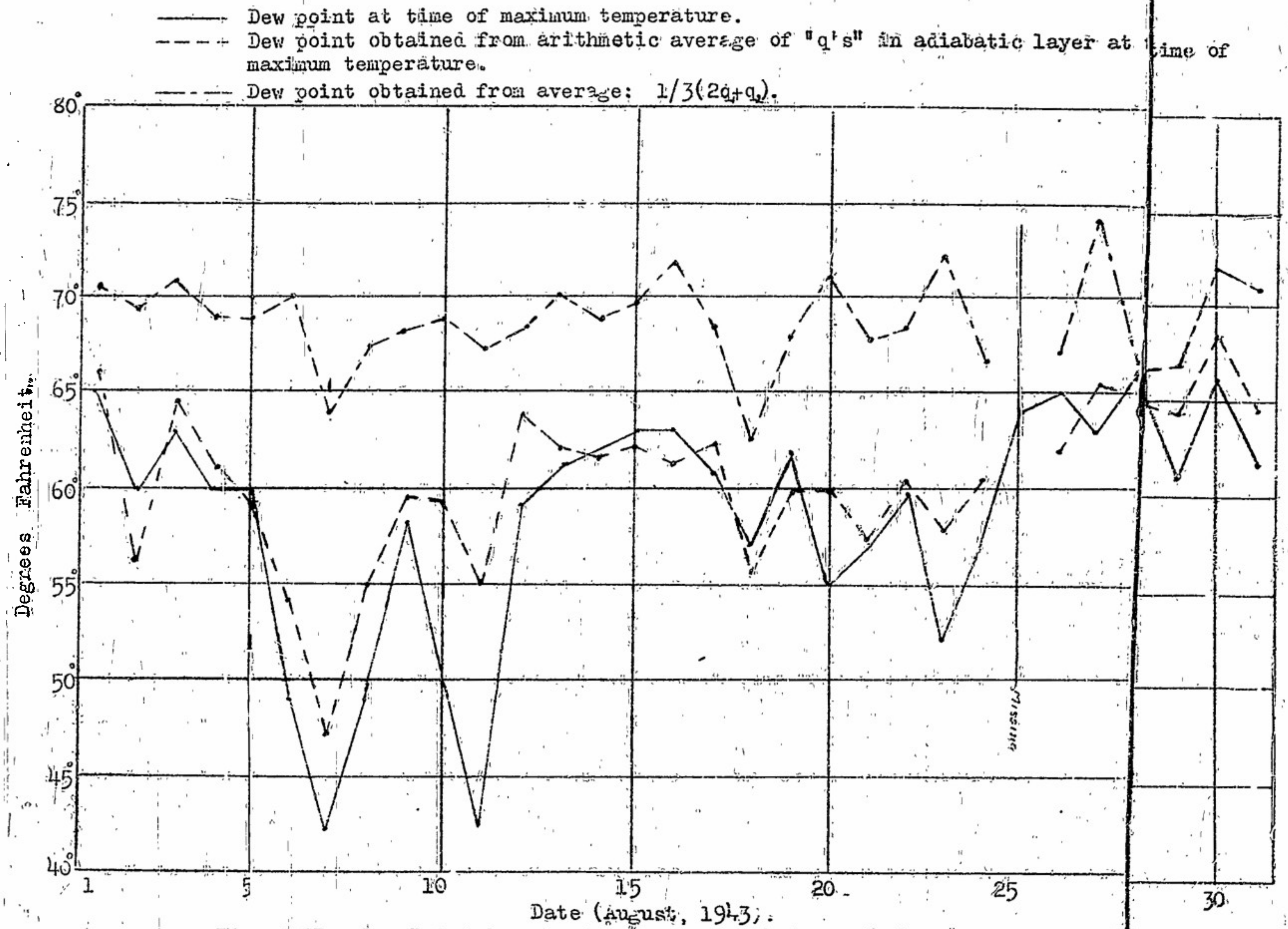


Figure 53 - Dew Point Correlation (based on Khartoum 0400 GMT RAOB's)

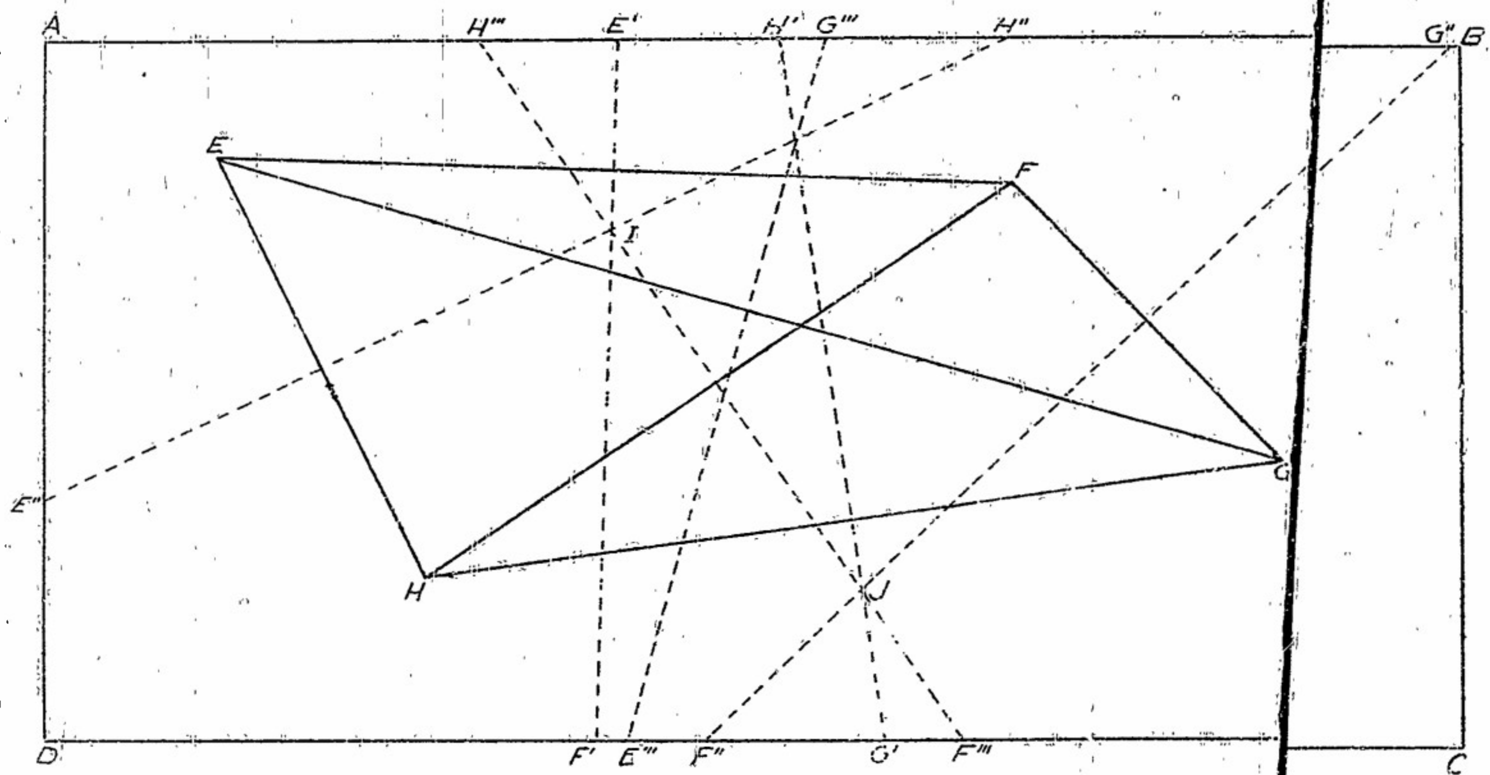


Figure 54 - Example of Thiessen Network.

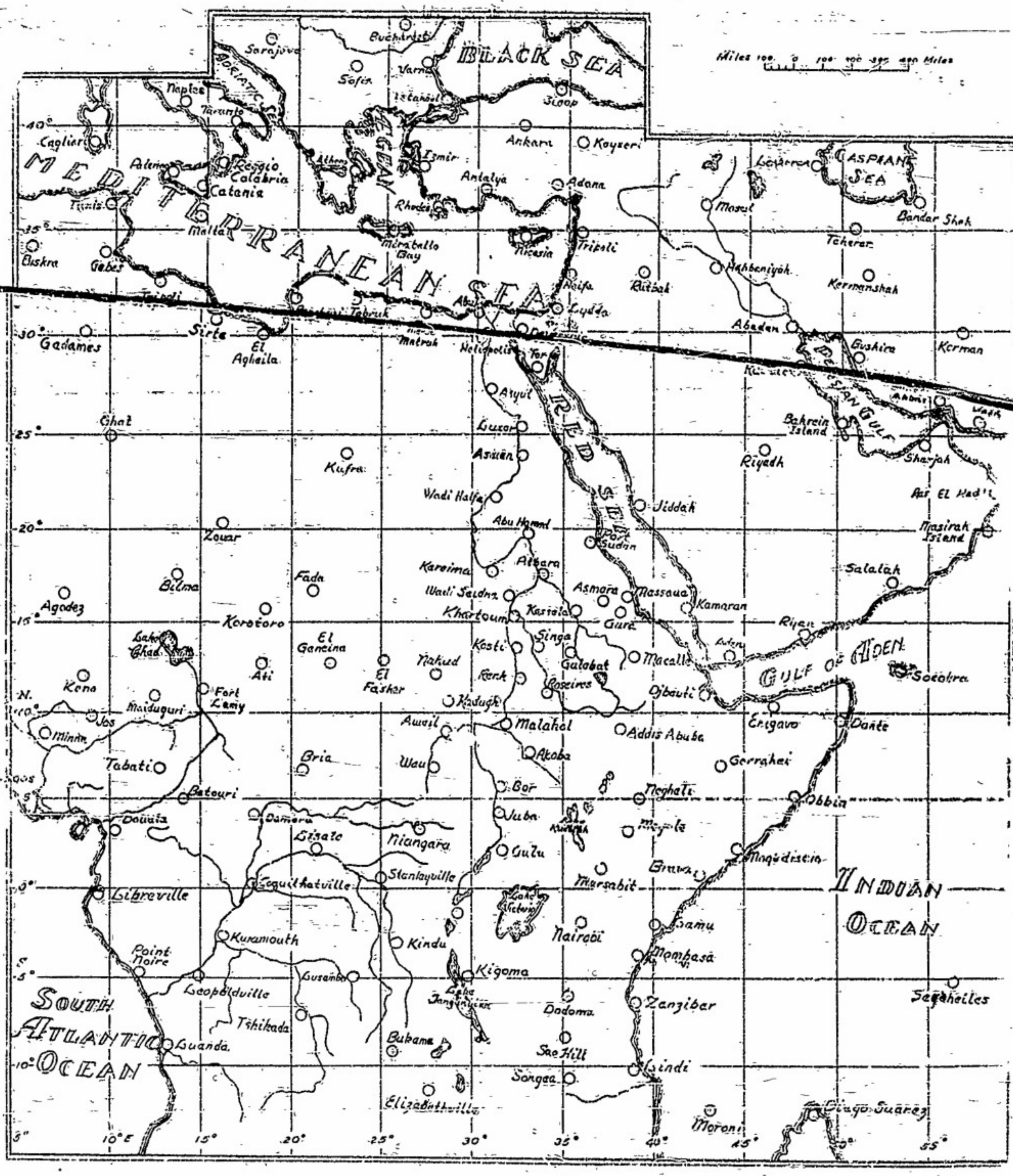


Figure 55 - Location of Weather Stations.