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## ON THE DEVELOPMENT AND STRUCTURE OF MONSOON DEPRESSIONS IN INDIA

BY

B. N. DESAI

*(Received on the 30th September 1948)*

*(The Editor does not hold himself responsible for the opinions expressed by the author in this paper.)*



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BY

B. N. DESAI.

CORRIGENDA IN MEMOIRS, VOL. XXVIII, PART 5

Page	Line	Correction
220	25 } Under 500 26 } mbs. level.	<i>Read</i> $-10^{\circ}$ <i>for</i> $10^{\circ}$
"		<i>Read</i> 'warmer' <i>for</i> 'colder' between the words 'relatively and air'.
223	16 } 17 }	<i>Delete</i> the portion 'and having caused rain over the west coast being drier'.
225	14 } 15 } 16 }	<i>Delete</i> the sentence 'There is still. . . . . in the lower levels.'
"	21	<i>Add</i> the word 'of' between the words 'most' and 'northeast'
226	5	<i>Add</i> the word 'level' after the word '4 Km'.

38 DGO

It is known that a very large portion of the rainfall in the plains of India during the monsoon months June to September occurs in connection with the depressions which pass inland from the North Bay of Bengal; a majority of these depressions move in a westerly to northwesterly direction, while a few move in a northwesterly to northerly direction and curve later to northeast. In view of the association of a considerable amount of the monsoon rainfall with these depressions, a number of papers have been written by the Indian Meteorologists (1, 2, 3, 4, 5) with an idea to understand their structure and direction of movement. During the last few years Radiosonde ascents at selected stations all over the country are being made daily and upper air temperature and humidity data have become available. It is proposed to discuss in this paper the structure of a monsoon depression during July 1947 with the help of available surface and upper air data with a view to find out, if any new points are brought out by the Radiosonde data, which can enable us to understand the structure of the monsoon depressions more clearly than hitherto.

ers in connection papers have been ut, structure and ore attempt, but weather situation de ascents which

erally such that, if Bengal at the ble condition for of the fresh cold : equator and its gong hills, Khasi ran-belt usually ges after the cold of the depression. nly one effective westerly air mass und Central India

### Discussion of weather conditions from the 8th to 13th July 1947.

On the 8th morning the seasonal trough of low pressure on the surface chart was at the foot of the Himalayas and rain was confined to the hills and sub-montane districts from the east U. P. to Assam. The upper winds in the morning were mainly westerly over Port Blair and the Arakan coast.

The upper air charts for 850, 700 and 500 mbs. levels for the 8th evening are given in *Figs. 1 to 3*. The temperature and humidity data were obtained from the Radiosonde ascents made at different stations in the evening. Clock-type instruments were sent from Delhi, Allahabad, Jodhpur and Peshawar and Fan-type from other stations. In the absence of details, it is not possible to say to what degree of accuracy these data should be accepted; but one can accept them to be sufficiently accurate to give a general trend, particularly if one considers the day to day changes at the same stations. The station model used is given below —

TT hhh  
 O  
 HH m<sub>1</sub>m<sub>2</sub>

where '**hhh**' stands for height above sea level in feet of the particular isobaric surface,

**m<sub>1</sub>m<sub>2</sub>** stands for specific humidity in gms. per kgm. of dry air,

TT stands for temperature in 0°C

and HH stands for percentage humidity.

Thin lines are contour lines

Thick lines are isotherms

The charts for 850, 700 and 500 mbs. level also contain afternoon upper wind data for 1.5, 3.0 and 6.0 km. respectively.

The following points may be mentioned regarding *Figs. 1 to 3* :—

**850 mbs. level**—Temperature is decreasing from north to south. Contour lines and isotherms have similar trend. Winds are mainly westerly over the east coast of Madras, Orissa, South Bengal and the Andamans.

**700 mbs. level**.—Temperature is generally lower over the Bay of Bengal than over Northern India and the Peninsula. The air is warmest over and around Sind. Upper winds are mainly westerly over the east coast of Madras, Orissa and South Bengal.

**500 mbs. level**.—Temperature is lowest over the South Bay. There is relatively warmer air over the area extending from Kathiawar to Bihar. There are signs of a trough over the Central and North Bay. There was how ever no cyclonic circulation over the north Bay at least up to 3 km.

The synoptic chart for the 0800 hrs. IST of 9th July 1947 is given in *Fig. 4*. The following station model has been used:—

TT PPP  
  
 T, T<sub>d</sub>

where

PPP is M. S. L. pressure in mbs., R rainfall in previous 24 hr. in inches (rainfall upto 9 cents being represented as ‘. . .’ and from 10 to 16 cents as ‘—’), TT is D. B. temperature in degrees F, T<sub>d</sub>, T<sub>d</sub> dew point in degrees F and ww present weather remarks in international symbols.

Shading in the circle represents amount of cloud irrespective of kind.

Continuous lines are isobars and broken lines are significant wind discontinuities.

It will be seen from *Fig. 4* that on 9th July 1947 the axis of the seasonal trough of low pressure was still near the hills and widespread and locally moderate to heavy rain had fallen in Bihar, North Bengal and Assam. The Arabian Sea branch was fairly active or weak over the west Coast of the Peninsula, but there were signs of the monsoon strengthening over the South Bay, as could be seen from the winds over Port Blair backing slightly and becoming stronger than on the previous day. As could be judged from the upper winds of the 9th morning, there was no sign of arrival of any fresh easterly or southeasterly air over the North Bay, the Arakan Coast and south Bengal.

The upper air charts of the 9th evening are given in *Figs. 5 to 7*. The following points are seen from the same.—

*850 mbs. level.*—There are signs of a trough over the North Bay, the upper winds over the head of the Bay being under its influence. 20° isotherm has apparently moved northwards over the Bay since the previous evening, thus indicating movement of colder air northwards from the south.

*700 mbs. level.*—There is a trough over the north Bay and winds over Chittagong Coast are under its influence. Temperatures continue relatively low over the Bay.

*500 mbs. level.*—There is a trough over the North Bay and relatively cold air over the South Bay. The air is warmest over and around Sind.

3" of rain had fallen at Port Blair between 0800 and 1700 hrs. of the 9th, thus showing that the monsoon had strengthened over the South and Central Bay of Bengal.

By 0800 hrs of the 10th (see *Fig. 8*), a trough of low pressure, which was apparently concentrating into a depression, had appeared over the North Bay. Port Blair had further 3" of rain since the previous evening *i e.*, a total of 6" of rain in the preceding 24 hrs.; moderate to heavy rain had also fallen on the Tennesserim Coast and in Pegu; Bassein had 3" of rain in the previous 24 hrs. It was thus clear that the fresh monsoon current had extended further northwards. The morning upper winds on the 10th did not show any easterly to southeasterly winds over the South

and Central Bay, Tennasserim and Central Burma at least upto a height of 2 km., thus indicating that the low pressure area over the North Bay did not result due to movement of any low from the south along or across Tennasserim Coast or through the Andaman Sea, and that it might probably have developed under the combined influence of the northward extension of the cold fresh monsoon air and of the Arakan hills. Winds over Sandoway were light southerly to south-southwesterly up to 5,000 ft., but over Akyab they were moderate to strong southeasterly up to that height.

The following points may be mentioned in connection with the upper air charts (*Figs. 9 to 11*) of the 10th evening:—

**850 mbs. level.**—The trough lay over the North Bay. 20° isotherm had apparently moved slightly northwards towards the head of the Bay; temperature had fallen by 3° and specific humidity decreased at Madras and the same trend was also noticed at Trivandrum, thus showing that colder and less moist air had arrived over the south of the Peninsula when compared with the previous day. Upper winds at Chittagong veered from E to SSE and at Calcutta from NE to E.

**700 mbs. level.**—The trough had moved slightly northwards since the previous day. Warmer air had apparently arrived over Assam and North Bengal (appearance of 15° isotherm) and over Delhi, Veraval and Poona; this led to the appearance of a relatively colder pool of air over Central India. Temperature had slightly fallen at Trivandrum. Chittagong winds veered from E to SE. Upper winds over Calcutta were light Ely and over Asansol light Nly.

**500 mbs. level.**—Temperature had fallen at Madras (correction of +5° applied) but had slightly risen over Trivandrum and the 10° isotherm had moved northwards. There was relatively colder air over the region from Bihar, the U. P. and the East Punjab to Sind, Kathiawar and the North Konkan. Temperature had fallen by as much as 7° over Karachi since the previous evening. The trough had moved northwards since the previous day.

By the 11th morning a deep depression had formed (see *Fig. 12*) with central region near Lat. 19°N and Long. 87°E. Upper winds over the Arakan Coast were under its influence, Sandoway winds having backed to SE and strengthened since the previous day. The monsoon had also strengthened in the north Konkan as could be judged from moderate to heavy rain which had fallen there during the previous 24 hours.

The upper air charts for the 11th evening (*Figs. 13 to 15*) show some significant changes:—

**850 mbs. level.**—Temperature had fallen by as much as 4° and winds had veered and strengthened over Calcutta since the previous day, showing arrival of cold air from south. Temperatures have also slightly fallen at Nagpur, Poona, Madras and Trivandrum, while they have risen over the region from the U. P. to Sind and Kathiawar; the rise of temperature might be due to arrival of Ely air from Assam and North Bengal in the case of the East U. P., and of the air from the West U. P. and the North Punjab

in other cases. These temperature changes produced a steep temperature gradient over the region from Orissa-Bengal Coast to the central parts.

*700 mbs. level.*—Temperature has fallen by  $5^{\circ}$  at Calcutta, showing arrival of cold air as at 850 mbs. level; winds have strengthened and have been generally from E to SE over north-east India and there is cyclonic circulation. There was no appreciable change in temperature over the Peninsula, the C. P., Kathiawar and Sind, but it appeared that relatively warmer air from North Bengal had come to the South Punjab and Rajputana. Temperature gradient has developed over South Bengal, Orissa and the east and south of the Peninsula.

*500 mbs. level.*—Temperature has fallen over the west and north Peninsula and the C. P. It has however apparently risen over North-east India and from the U. P. to Kathiawar. Temperature gradient has also developed over North-east India and the C. P. Cyclonic circulation is well marked even at this level.

In *Fig. 16* is given the thickness chart between 20,000 and 5,000 ft. for the 11th evening. The contour lines drawn will give idea about virtual temperature isotherms in the layer of 15,000 ft. thickness. There is colder air over the most of the Peninsula and warmer air to its north. This would show that the depression might move skirting the periphery of the colder air *i.e.*, westwards.

From *Fig. 17* in which the synoptic chart for 0800 hrs. IST of the 12th is given, it would be seen that the depression moved about 250 miles westwards since the previous morning. It will also be seen from this figure that a well defined rainbelt in the southwest quadrant of the depression had developed on the 12th morning. This type of rainfall distribution only on one side of the front is observed in the case of warm front type occluded depressions of the middle latitudes. The upper air charts for the 12th evening are given in *Figs. 18 to 20*. The following points might be noted in connection with these charts:

*850 mbs. level.*—Temperatures had risen over the region from the Konkan to southeast Bengal (compare the position of  $20^{\circ}$  isotherm on the 11th and the 12th). This would indicate that westward movement of the cold fresh monsoon air had stopped; over Bengal the rise of temperature might be due to replacement of cold SEly to Sly air by warm Ely to SEly air, and over the Konkan due to the arrival of the continental air. Temperature has fallen over the U. P., the South-east Punjab and the adjoining parts of Rajputana presumably due to north-westward movement of the cold fresh monsoon air which was over South Bengal and neighbourhood on the previous day. There was a fall of temperature over Veraval and rise over Karachi; the latter was probably due to arrival of warmer and drier air from the West Punjab and areas towards its west. Upper winds have lost northerly component over the Southeast Arabian Sea and south of the Peninsula. The trough is over the east C. P.

*700 mbs. level.*—Temperature had risen from the C. P. to Southeast Bengal and fallen over the U. P. ; temperature had also slightly risen over Kathiawar and the Peninsula. The causes of those changes might be the same as those mentioned for 850 mbs. level. As a result of these temperature changes, the  $10^{\circ}$  isotherm shifted southward. The trough is over the east C. P. and the Circars—Orissa Coast.

*500 mbs. level.*—Temperature has fallen over the region from the U. P. to Kathiawar probably due to westward movement of cold fresh monsoon air which was further east on the previous day. There is a general rise of temperature over the Peninsula, the C. P. and North-east India and the  $-5^{\circ}$  isotherm has shifted southwards.

The depression weakened further as will be seen from the synoptic chart for 0800 hrs. IST of the 13th (*Fig. 21*). The easterly current weakened by the 13th evening and the depression became unimportant by the 14th morning.

### Conclusions from Analysis.

The following conclusions can be drawn from the points discussed above regarding the formation, movement and weakening of this particular depression :—

1. The monsoon strengthened over the Bay Islands and Tennasserim and Pegu with the arrival of south-westerly to westerly air.
2. The fresh monsoon air as it advanced northwards got deflected from SW to SE under the combined influence of the seasonal trough of low pressure and of the Arakan hills and began to move northwestwards. As seen from the temperature changes over Calcutta with the arrival of SEly air, the fresh monsoon air was colder than either the Wly to NWly air which was originally there or NEly to Ely air which replaced it. With this movement of the cold fresh monsoon air northwestwards and further backing of winds from SE to E under the influence of the Khasi hills and the eastern Himalayas, wave formation favourable for the generation of cyclonic circulation took place ; fresh monsoon front of the cold front type thus came into existence.
3. The northeasterly to easterly air taking part in the cyclonic circulation and constituting the warm sector was in the lower levels up to about 2 km. at least, probably the mixture of the old monsoon air over Bengal and Assam and the upper easterly air of the general circulation which had subsided down the hills to the east of Assam and East Bengal. In the upper air above about 2 km. the easterly air was probably that which was a part of the general circulation. The cold monsoon air advancing northwards undercut the warm NEly to Ely air.
4. The partition between the NEly to Ely warm air and the westerly air over the North-west Bay, which was a part of the circulation over the Peninsula, was of the warm front type. This westerly air was probably a mixture of the continental air and the Arabian Sea Monsoon Air which after giving precipitation over the west coast had travelled over the Deccan plateau.

The westerly air was colder than the north-easterly to easterly air and the latter could rise over it, causing warm front type rain. The slope of this partition increased as the depression intensified and with this the rainbelt became better defined and more extended.

The partition between the moist Ely air and dry NWly continental air would be of a peculiar type, the latter being warmer overrunning the former upto about 3 km., and above that height the former being warmer overrunning the latter, this is due to the difference in the lapse rates in the two air masses, near dry adiabatic in the continental air and near saturation in the easterly air (2, 6, 7, 9). The partition between the moist westerly Arabian Sea Monsoon Air and the dry NWly continental air would also be expected to be of the same type.

5. The partition between the westerly Arabian Sea Monsoon Air which has travelled over the Deccan plateau and the fresh Westerly to South-westerly Bay Monsoon Air would be of warm front type, the former having travelled over land being warmer and having caused rain over the west coast being drier than the latter.
6. The depression having formed, the cold front dissipated either due to mixing of air near the centre or due to supply of fresh cold monsoon air in the Bay having not been maintained due to the current weakening or withdrawing, or due to replacement of SEly fresh cold monsoon air by Arabian sea monsoon air which had travelled over the Peninsula or due to any two or all the three of these causes. The warm front type partition between NEly to Ely air and Wly air with rainbelt on the westerly air side however continued.
7. The setting up of cyclonic circulation stimulated the easterly current.
8. The depression moved along the warm front type partition and weakened when the easterly warm current weakened.

### Seasonal Characteristics.

It is now proposed to examine the above conclusions from the point of view of the normal conditions during the monsoon months to see if any mechanism of formation and generalised structure of the monsoon depressions can be suggested.

July can be taken as a typical monsoon month. In *Fig. 22* are given the boundaries (as determined from upper winds (?)) between the air masses having their sources in different regions. Characteristics at different levels can be summarised as under :

*Surface level.* -- There are south-westerly to westerly winds over the Peninsula, the central parts, Orissa, South-west Bengal and Lower Burma, the Arabian Sea about south of Lat. 25°N and the Bay of Bengal. This south-westerly to westerly air has as its source region the 'High' in the South Indian Ocean. Due to winter conditions in the southern hemisphere, the air at the source will be cold. As this cold air moves north to warmer latitudes, it gets warmer and humidified; the amount of moisture

and the depth up to which it penetrates will depend upon the length of sea travel. This air mass has been designated (<sup>9</sup>) as "Equatorial maritime-Em". When this air reaches coast it gives plenty of precipitation as a result of orographic features ; it gets heated as it moves over land and some moisture might be added due to evaporation from wet ground as it travels over it ; it may be considered as transitional when moving over land and called "NEm".

The SEly to Ely air over and near the Arakan-Chittagong Coast and East and North Bengal, Bihar and the U. P. is a mixture of the transitional equatorial maritime air of the Indian Ocean origin (NEm) and of the subsiding transitional tropical maritime air. The tropical maritime air (Tm) has its origin in the "High" over the north Pacific Ocean ; it will not be able to reach India in the lower levels due to the hilly regions over Assam, Burma and China, although in the higher levels it can flow freely as it does as an easterly current. However Tm air from the higher levels can subside along the hills on the Chittagong-Arakan Coast and in Assam and reach the ground level and this subsided Tm air mass is designated as "TmS". This air mass mixture of NEm and TmS- will be warmer than Em.

The air over Northwest India is dry tropical continental air (Tc), having its origin over land ; it is driest. Tc air mass is warmest at the surface.

There is no easterly air of the north Pacific Ocean origin over Burma or Indo-China although there will be TmS air mass as a result of subsidence of easterly Tm air from higher levels as mentioned above.

*1 km. level.*—The boundary between the Tc and NEm has shifted southwards and that between Tc and mixture of NEm and TmS has shifted eastwards ; this would show that Tc is warmer than the NEm or its mixture with TmS from the ground to 1 km. From the results of sounding balloon ascents (<sup>9</sup>), it is seen that Tc is warmer and drier than Em or the mixture of NEm and TmS at this height ; the mixture of NEm and TmS is found to be warmer and more moist than Em. It is assumed here that in the data given by A. K. Roy (<sup>9</sup>) those for Hyderabad and Madras can be taken to represent SWly to Wly NEm in the lower levels (2-3 km.) and Em higher up ; those for Calcutta can be taken to represent Ely mixture of NEm and TmS in the lower levels and Tm in the higher levels. Data for Tc over Agra can be taken to be representative of Tc air mass generally. The boundary between NEm and the mixture of NEm and TmS has shifted slightly eastwards presumably due to a difference in the orographic features between surface and 1 km. level.

There is no Ely air of the north Pacific Ocean origin over Burma or Indo-China even at this level.

*2 km. level.*—What has been said above for 1 km. level generally holds good also for 2 km. level.

*4 km. level.*—It can be presumed that at this height there is Em instead of NEm as the effect of orography and heating due to travel over land would be mostly absent. There is Em air from the Peninsula to at least Indo-China. The position of the boundary between the Tc and Em would show that at 4 km. the former is still warmer than the latter. From the data given by A. K. Roy (<sup>9</sup>) it would appear that Tc is slightly warmer and drier than Em at 4 km. level.

The mountains of Assam and Burma and China being lower than 4 km., the Ely equatorial maritime air (Tm) from the north Pacific Ocean 'High' is able to spread over North-east India at that height. From the position of the boundary between the Tc and Tm over the Northern Burma and China, it would appear that Tm is warmer than Tc when compared with lower levels. This has presumably occurred due to a difference in the lapse rate of the two air masses—Tc air having near dry adiabatic lapse rate and Tm near saturation lapse rate (2, 6, 7, 9). It may be mentioned here that Tm having its origin in the north Pacific Ocean 'High', will be warmer than Em having its origin in the South Indian Ocean 'High'. It will also probably have higher moisture content than Em when it arrives over India. From the data given by A. K. Roy (<sup>9</sup>) it is seen that Tm is warmer and also more moist than Em at 4 km. level.

*6 km. level.*—It would appear that between 4 and 6 km., Tm is warmer than Tc, the boundary between the two air masses having shifted westwards. There is still Tc over a portion of the Peninsula and from the position of the partition it would appear that it is warmer than Em between 4 and 6 km. also as in the lower levels. Tm is warmer than Em between 4 and 6 km. as the boundary between the two is displaced southwards when compared with the position of the same at 4 km.

When there is a break in the monsoon and the seasonal trough is in the hills, the whole Northern India right up to the head of the Bay has Tc or a mixture of Tc and NEm air masses; under such circumstances, the Ely winds over most northeast India are absent up to 3 to 4 km. or even higher up.

From what has been stated above about characteristics of Em, NEm, TmS and Tm air masses, it would appear that the partition between the SWly to Wly air and Ely air is of the warm front type as it is displaced southwards with height. This explains why widespread rain falls near the partition at the ground level on the NEm air side when the seasonal trough of low pressure is active or well-marked; rainfall near the partition will be heavy if the inclination of the partition is steep.

### **Suggested Mechanism of formation and Structure of Monsoon Depressions.**

It is generally observed that depressions form in the North Bay of Bengal in the monsoon months either with a strengthening of the monsoon in the Bay or with the passage of a low pressure wave into the Bay from the east across Burma, which stimulates the activity of the monsoon current. As the Em air is cold and Tm air warm, it was suggested by Pettersen (see report of discussions in the Poona Met. Office in Feb. 1948) that the initial wave may develop when the Tm air meets Em air and that this may move N or NW-wards and intensify into a depression at the head of the Bay. Such initial wave formation can take place only above about 3 km. level as the Tm air is found over North-east India, the head of the Bay, North Burma and China at a height of about 4 km. as mentioned above and over Indo-China, Lower Burma and east and north Bay at about 6 km. In this connection it may also be mentioned that it is generally the experience of the Indian Meteorologists that during the monsoon season cyclonic circulation prior to appearance of a depression at the surface is frequently found to set in, above about 2 km. The same cannot however be said about the setting up of cyclonic circulation in the first 2 to 3 km. as the Tm

air is confined only to Malaya and to its east and to the east of Indo-China in those levels. Further, according to observations of pilots flying across fronts in connection with the monsoon depressions and from the wind partitions drawn on the basis of pilot balloon observations, it is seen that most of the depressional rainfall falls from below about 4 km. It is therefore necessary to understand the nature of the factors responsible for setting up of cyclonic circulation in the first 2 to 4 km.

It is generally noticed that every time, a fresh pulse of Em air moves northwards into the Bay of Bengal, heavy rain first occurs in the Bay Islands and on the Tenasserim coast and the belt of heavy rain gradually moves northwards with the monsoon current; cyclonic circulation in the lower levels does not however begin to get established till the cold fresh monsoon air and heavy rain reach about the southern tip of the Arakan hills (Stage I in *Fig. 23(a)*). When this occurs, under the combined influence of the Chittagong-Arakan hills and of the seasonal trough of low pressure, the cold SWly to Wly Em air advances North-westwards and SEly moderate to strong winds develop along and off the Arakan-Chittagong Coast, thus leading to the formation of a wave (Stage II in *Fig. 23 (a)*) favourable for the development of a depression. The mixture of NEm and TmS air which is originally over the north Bay being warmer than the fresh Em, a partition of the cold front type is established between the two air masses. As the fresh Em air moves northwestwards, it gets deflected westwards under the influence of the Khasi hills and the eastern Himalayas to the north, and a complete cyclonic circulation is set up and a depression forms (Stage III in *Fig. 23 (a)*). In *Fig. 23(b)* are shown the three stages with reference to the air masses over the region. With the setting up of cyclonic circulation in the lower levels, movement west to north-westwards of the Tm air in the higher levels will also be stimulated; a discontinuity will develop between Tc (warmer) and mixture of NEm and TmS (warm) from the ground level to the reversal level (*i.e.*, the level above which Tc becomes colder than mixture of NEm and TmS) and between Tc (cold) and Tm (warm) above the reversal level; or if Tc is not at the head of the Bay or is further north-westwards, the discontinuity will develop between NEm (warm) and mixture of NEm and TmS (warmer) or Tm (warmer) in the higher levels. The structure at the surface in the two cases would be as in *Fig. 24*. In the case of structure as in *Fig. 24 (a)*, Tc would lose its identity near the centre in a short time, due to rain falling through it, and the structure near the centre would become almost as in *Fig. 24 (b)*, Tc being much further away from the centre. The fresh Em supply may not however be maintained for long and the current either weaken or withdraw. As a result, the cold front would become ineffective and only the warm front remain; rain would occur mostly in the south-west quadrant of the depression on the NEm side of the warm front type partition, it being very heavy near the centre if the partition is steep. The depression will move west or north-westwards more or less along the partition and gradually weaken.

It may also be mentioned that even if the fresh Em does not advance into the Bay, a depression can still form at the head of the Bay, if the fresh Em advances on the west coast of the Peninsula (Arabian Sea Monsoon current); on such occasions, NEm when it reaches the North Bay after crossing the Peninsula will still be colder

than the mixture of NEm and TmS over Northeast India, and NEm over the North Bay would take the place of fresh Em. In such a case the structure at the surface will be similar to that in *Fig. 24(a)* or *(b)* with the exception that the partition between NEm and fresh Em will not be there. It should however be mentioned that the depression will form in this case only if the NEm coming from the Arabian Sea side across the Peninsula is colder than the mixture of NEm and TmS over Bengal.

Once the supply of fresh cold monsoon air (Em) from the Bay stops or weakens, there would be left in association with the depression only one effective partition of the warm front type with the mixture of NEm and TmS air masses on the northern side and the less warm air mass NEm on the southern side, all the rain falling on the NEm side of the partition, and depression would appear to be similar to the warm front type occlusion; the slope of this partition may be as small as one in three hundred in which case the rainfall is not heavy or it may be as much as one in fifty in which case rainfall near the front is very heavy. It should however be mentioned that the processes which lead to the development of a warm front type occlusion in the case of depressions of the middle latitudes are not operative in the case of monsoon depressions; the similarity is only regarding the distribution of rainfall on the colder NEm air side of the partition after the fresh Em current has either withdrawn or weakened and the cold front type partition disappeared. As stated above the peculiar distribution of precipitation on the NEm air side is due to the partition between the NEm air mass and the mixture of NEm and TmS air masses in the lower levels and NEm and Tm air masses in the higher levels, being of the warm front type.

Pramanik and Rao<sup>10</sup> have recently stated that there was no existence of any front with temperature contrast either during the formation stage of a depression or later when it developed into a storm in the North Bay of Bengal during June-July 1945. The upper air temperature readings which they have quoted however fit in with the ideas developed in this paper. They have mentioned presence of cold air over Akyab on the 29th June. As this cold air moved north-westwards temperature fell over Chittagong and Calcutta and a depression formed by the first July morning with centre about 200 miles to the east of Cuttack. The rise of temperature over Cuttack noticed on the 1st was apparently due to the pulling up of Tm air mass as result of the formation of the depression and the fall of temperature there in the lower levels on the 2nd was due to the arrival of cold air. The supply of fresh cold air from Akyab side was however not maintained for long as temperatures rose at Akyab between 1st and 2nd. The conclusion of Pramanik and Rao that the zone of the heavy rain in the southwest quadrant cannot be due to the upglide of air is not clear because an upglide surface between the south-westerly to westerly air and easterly air is ordinarily found to be associated with the seasonal trough of low pressure as mentioned earlier in this paper.

### Summary and Concluding Remarks.

It will be seen from what has been stated above, that conditions during the monsoon months are generally such that if favourable circumstances develop, a depression can form in the North Bay of Bengal at the south-eastern end of the seasonal

trough of low pressure. The essential favourable condition for the formation of a depression is the extension northwards in the Bay of Bengal of the fresh cold monsoon air from the south and its deflection north-westwards under the combined influence of the Chittagong—Arakan hills—Khasi hills—Eastern Himalayas and of the seasonal trough of low pressure. The rainbelt in the southwest sector of the depression ordinarily develops only in the later stages, after the cold Em air current weakens or withdraws after the depression has already formed, the only effective partition (warm front type) remaining, being that between south-westerly to westerly cold NEm air mass and easterly warm mixture of NEm and TmS air masses in the lower levels and between south-westerly to westerly cold NEm and easterly warm Tm air masses in the higher levels.

NOTE ADDED ON THE 2ND JULY 1951.

Regarding development of rain-belt in the southwest sector in the later stages of the depression referred to in the last but one sentence of the "Abstract" on p. 217 and in the last sentence on p. 228 of the "Summary and concluding remarks" section, it may be mentioned that Desai and Koteswaram (paper on "Air masses and fronts in monsoon depressions" in course of publication in the *Indian Journal of Meteorology and Geophysics*) have observed in a subsequent study of a monsoon depression in the beginning of July 1945, which formed nearer the coast and for which more radiosonde data are available than the July 1947 depression, that heavy rain occurs in the southwest sector both during the initial and later stages of the formation of the depression and even when the partition between the easterly and westerly air masses is getting established. They have also amplified the mechanism of heavy rain proposed in the present paper.

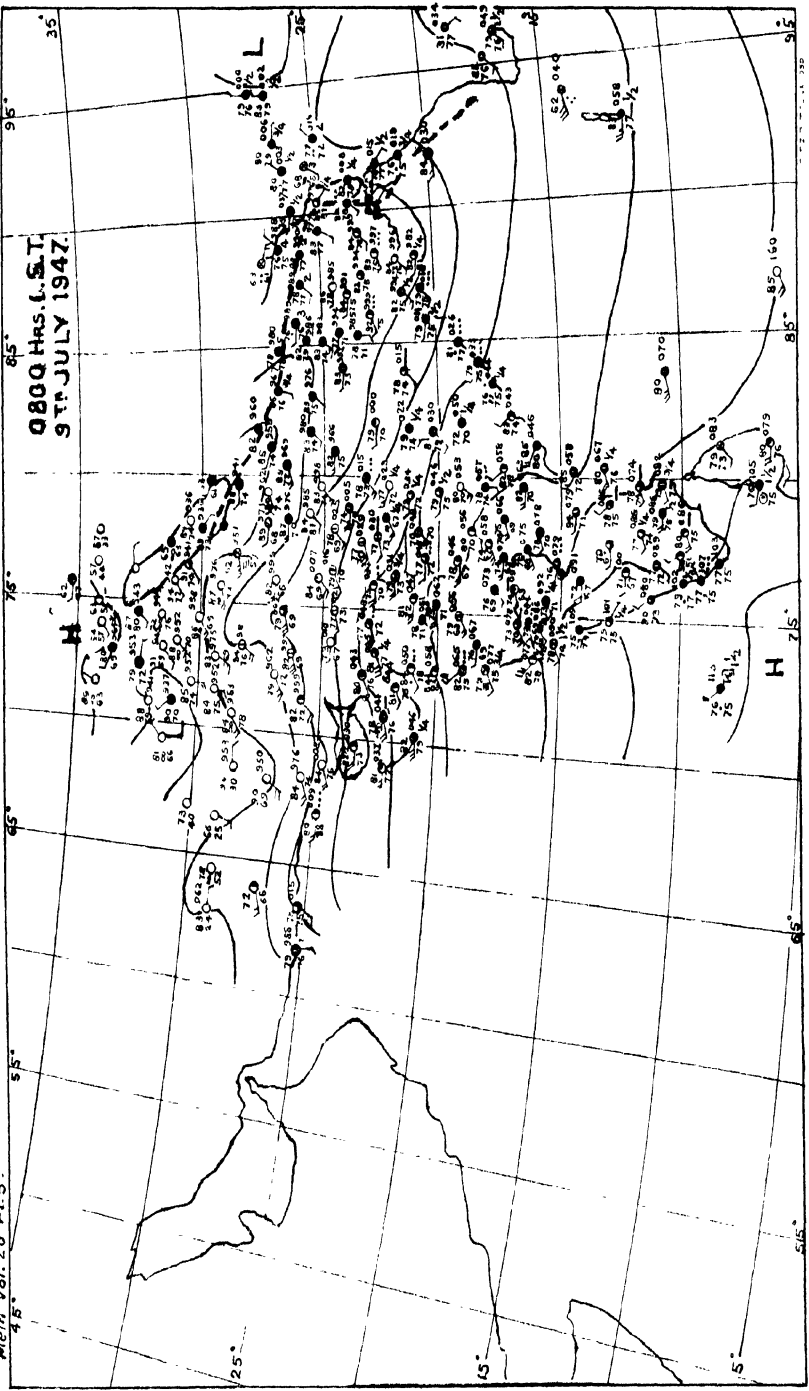
In the last paragraph on p. 225 of the section "Seasonal Characteristics" it is stated that the partition between the SWly to Wly air and Ely air is of the warm-front type as it is displaced southwards with height. In this connection it may also be mentioned that in the paper referred to above, Desai and Koteswaram have amplified the ideas given in the present paper regarding the displacement of the partition southwards with height. They have stated that during the monsoon season when the depth of the westerly current increases with height from north to south, the northern boundary of the westerly current should be considered as a quasi-stationary sloping surface and that when the easterly air current strikes this sloping surface, it is forced to rise and give precipitation which will be found to occur on the NEm air side of the partition at the surface level; conditions under which the extent and intensity of rainfall should be expected to vary have also been discussed by them.

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0800 Hrs. L.S.T.  
9th JULY 1947.

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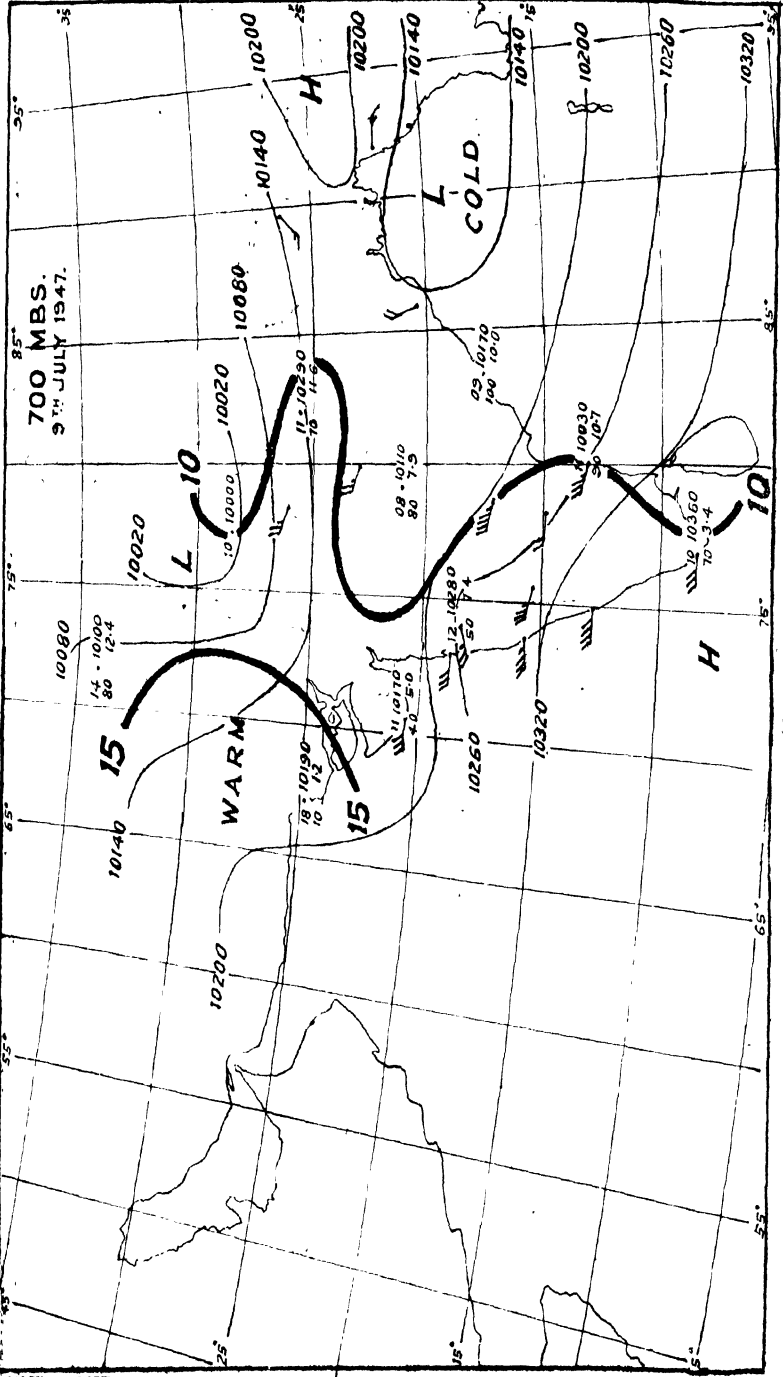
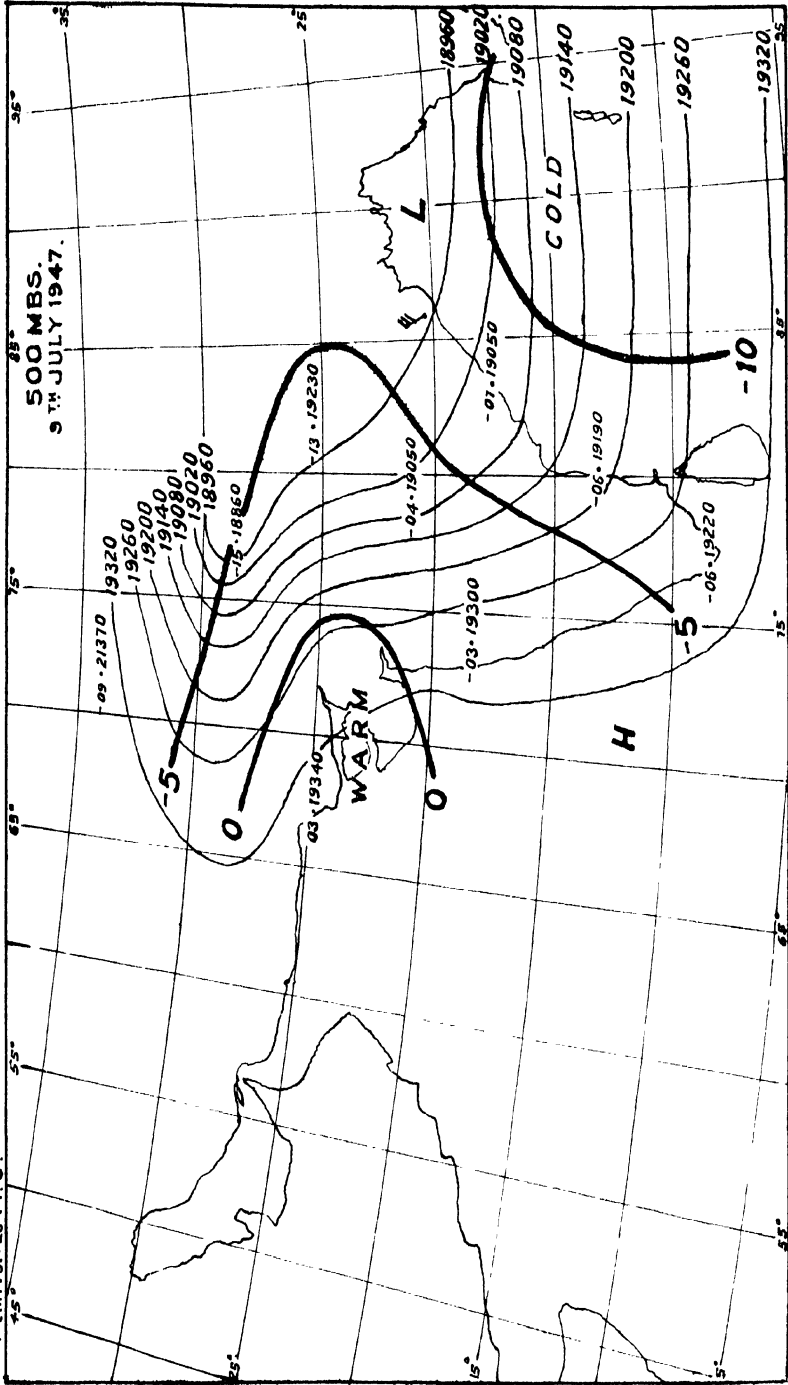


FIG. 6.









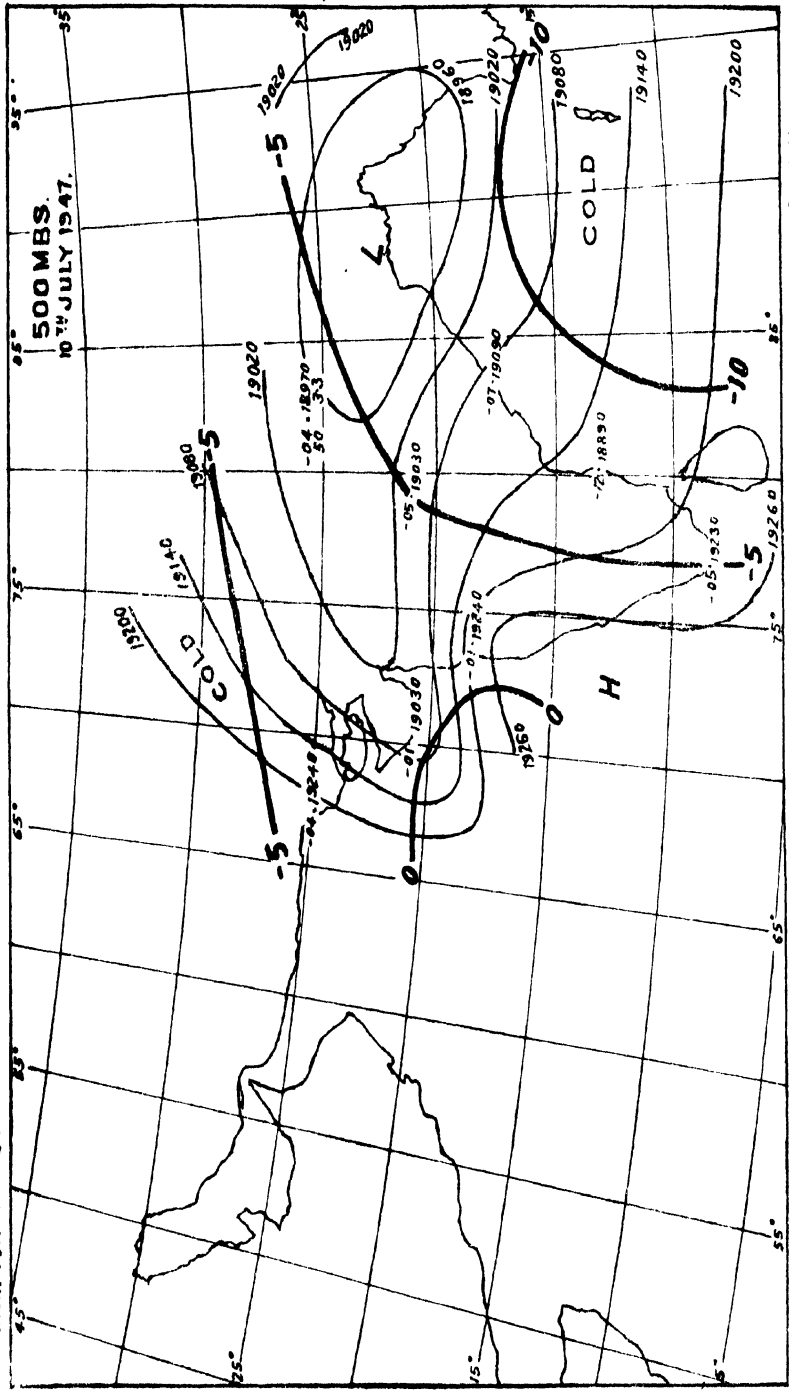


FIG. 11.

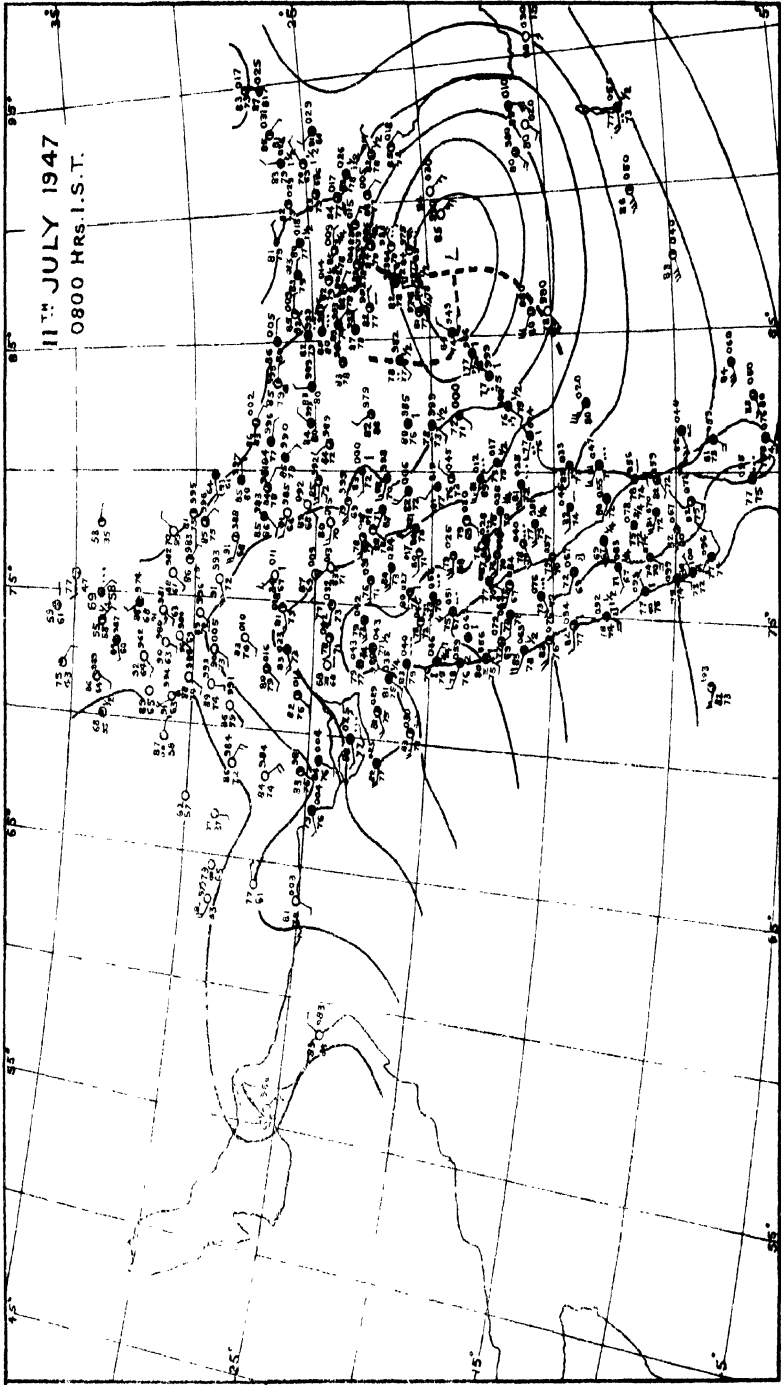
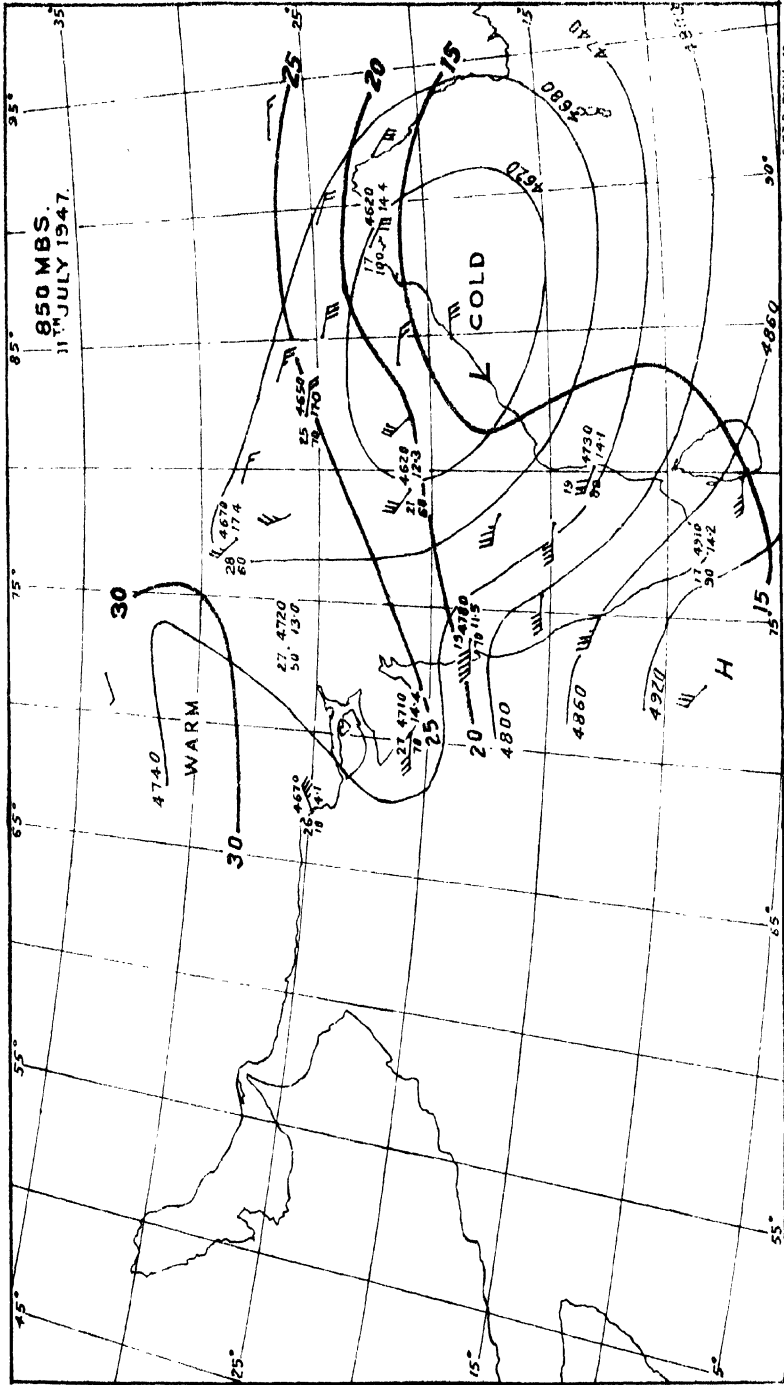
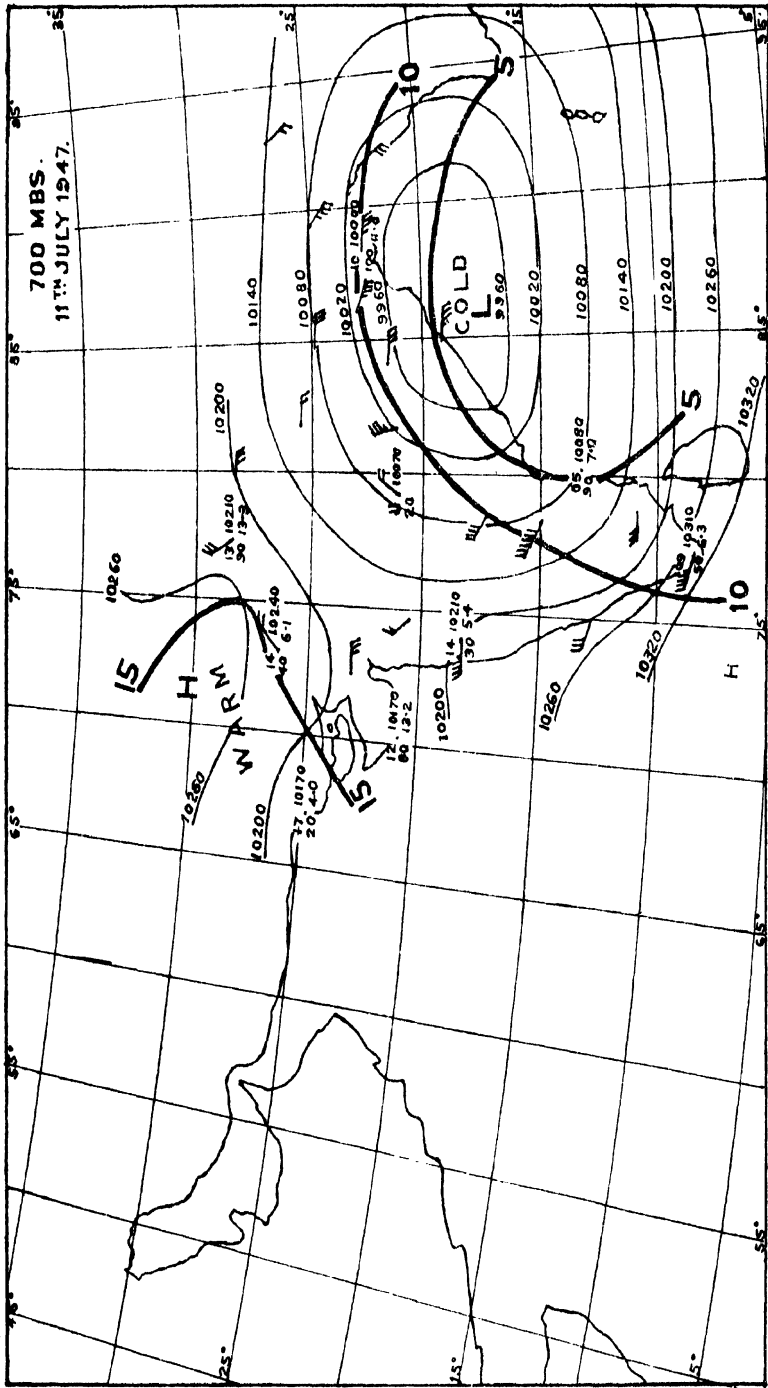


FIG. 12.





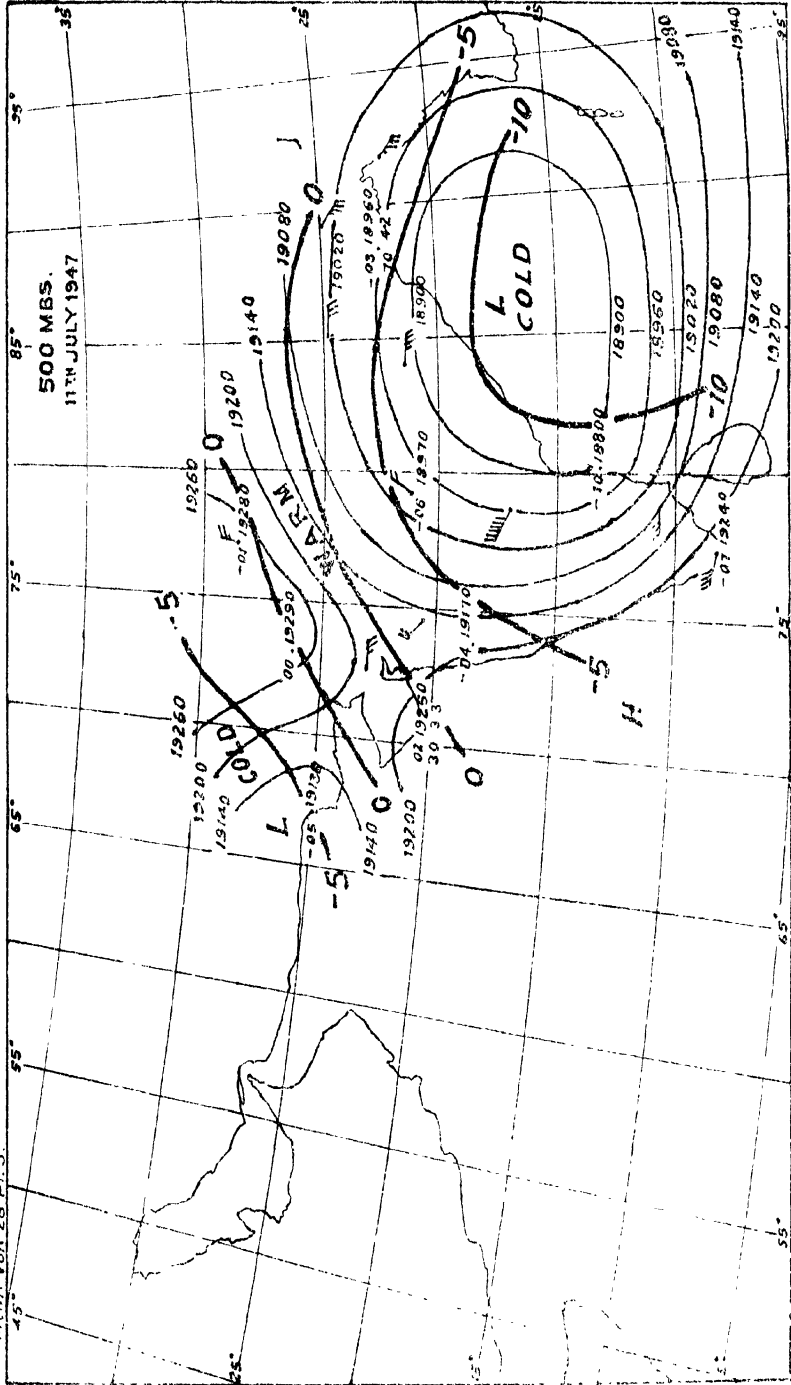


FIG. 15.

THICKNESS CHART  
(850 TO 500 MBS.)

Mem. Vol. 28, Pt. 5

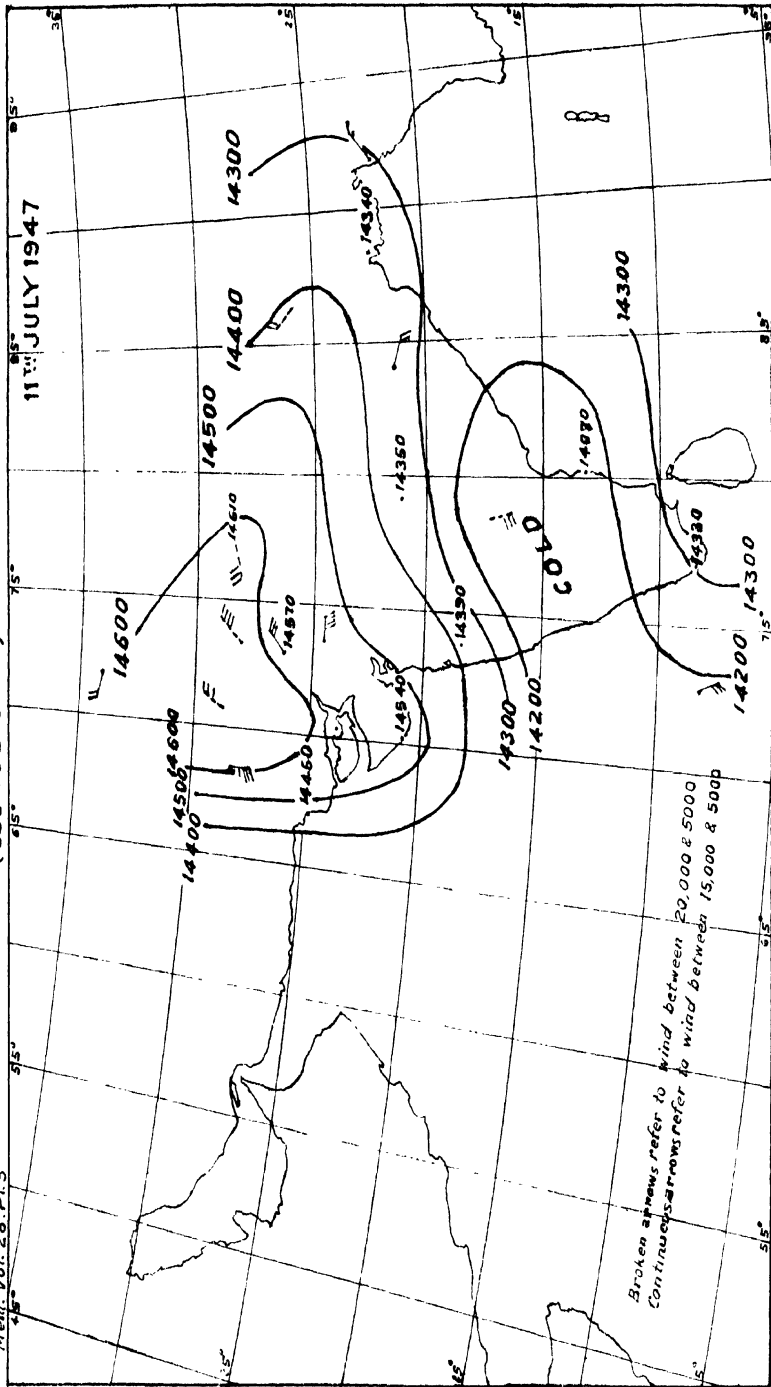
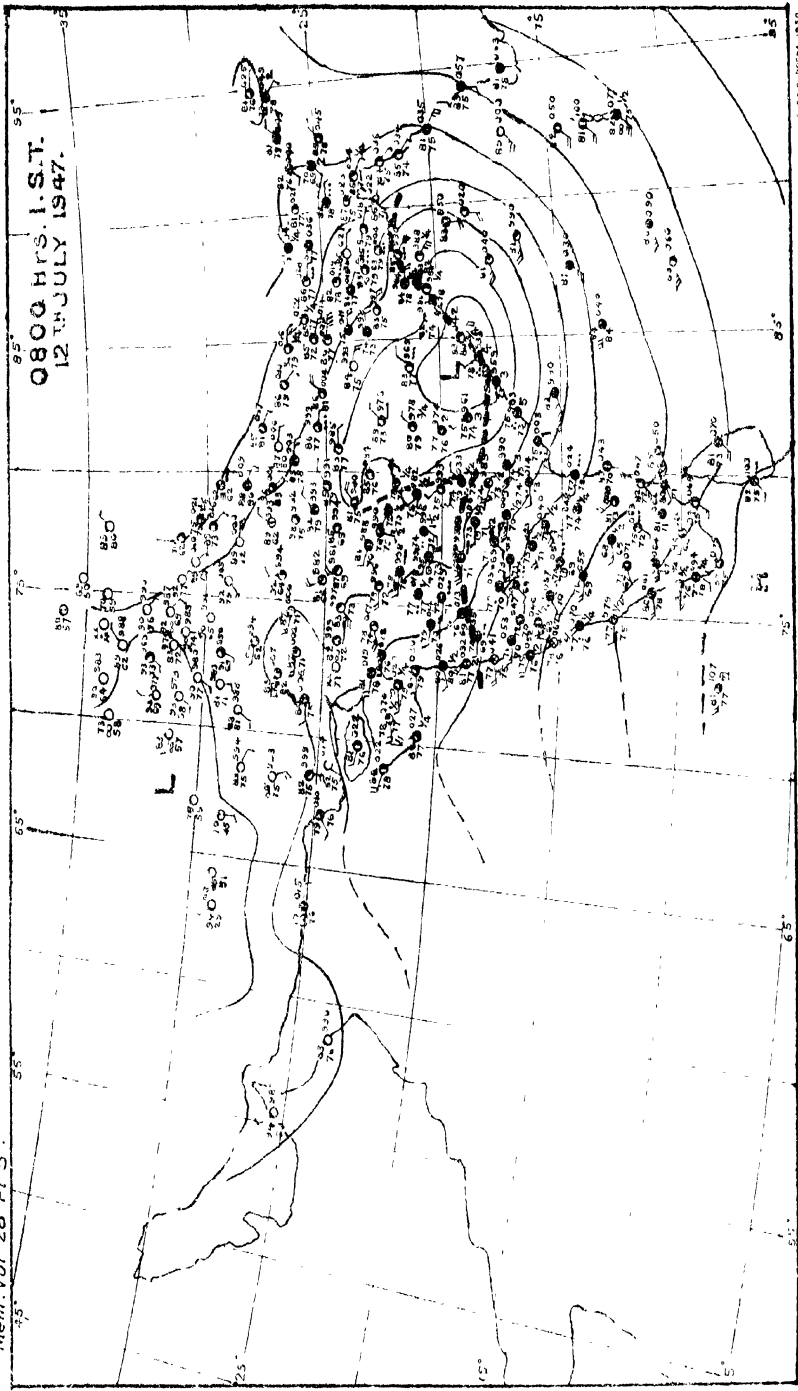


FIG. 16.



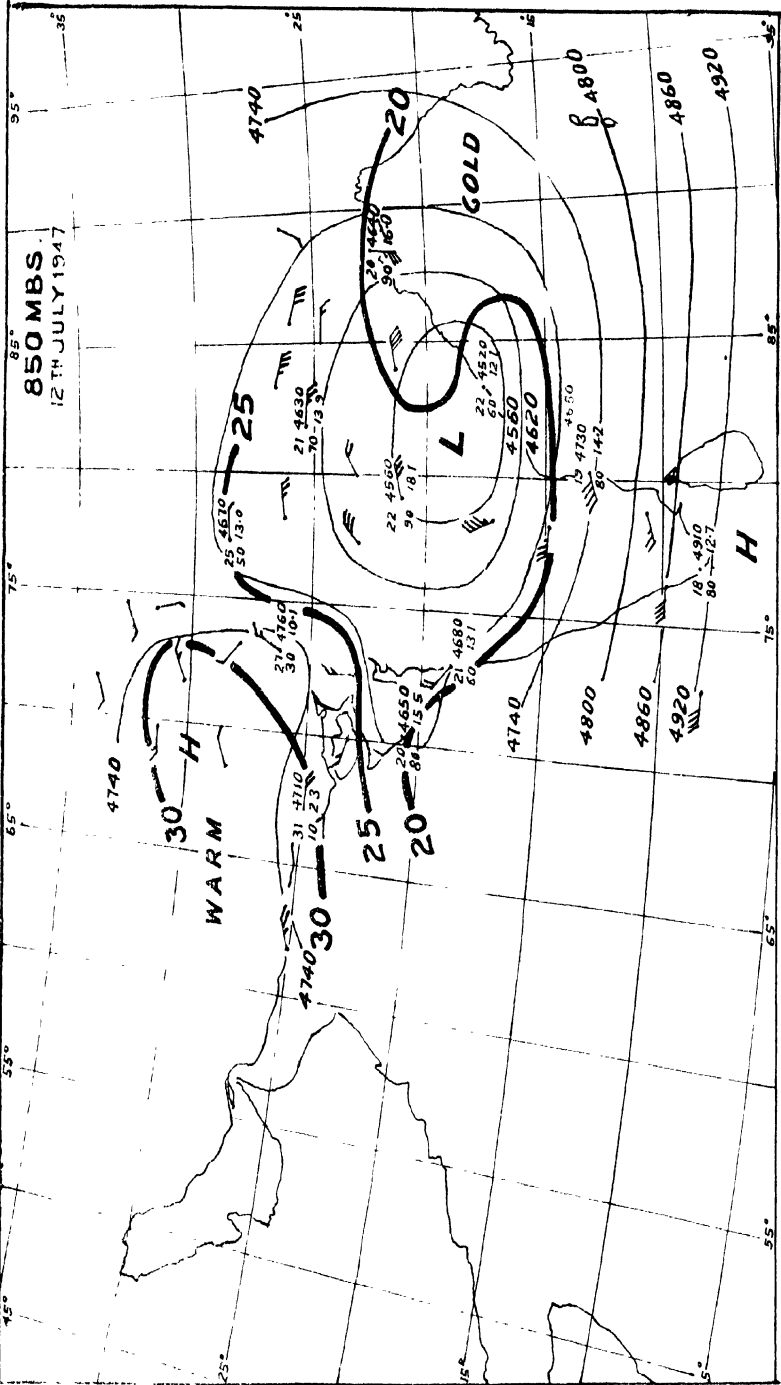


FIG.18.

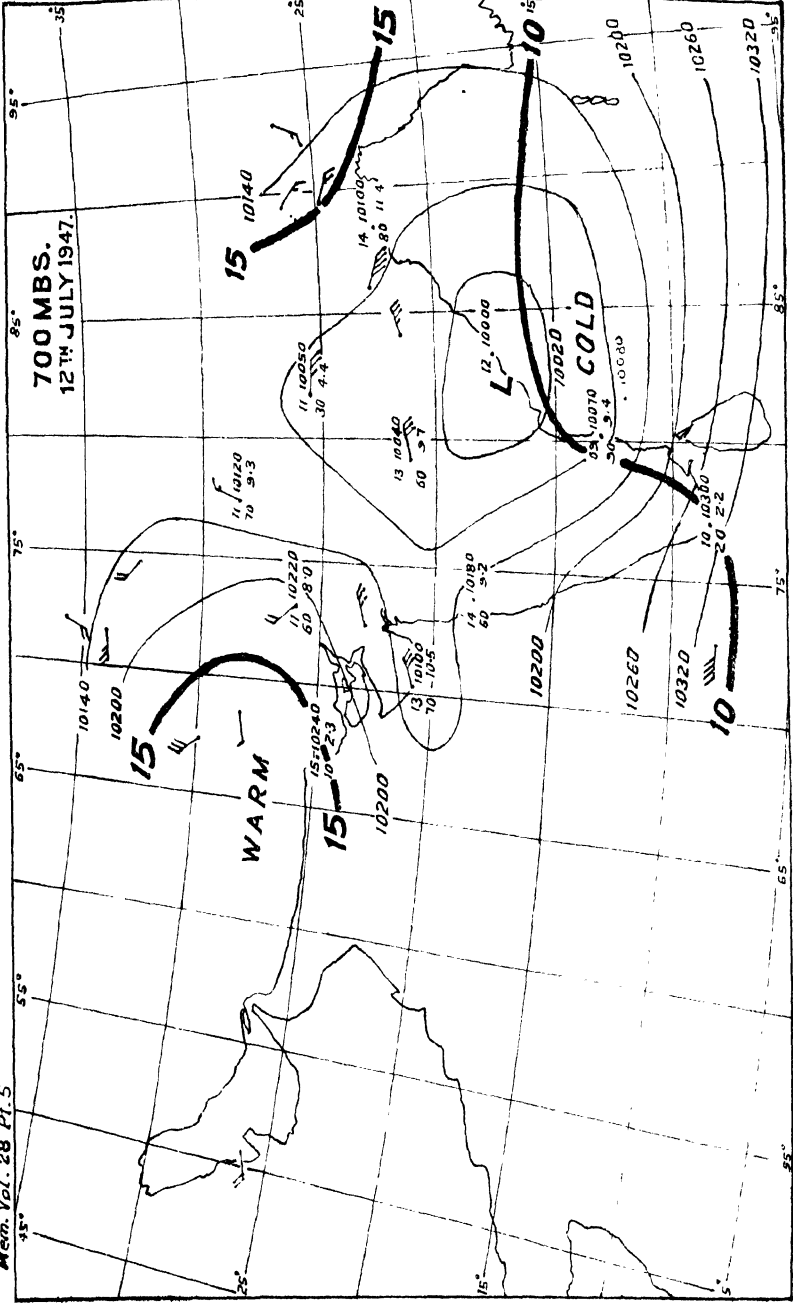
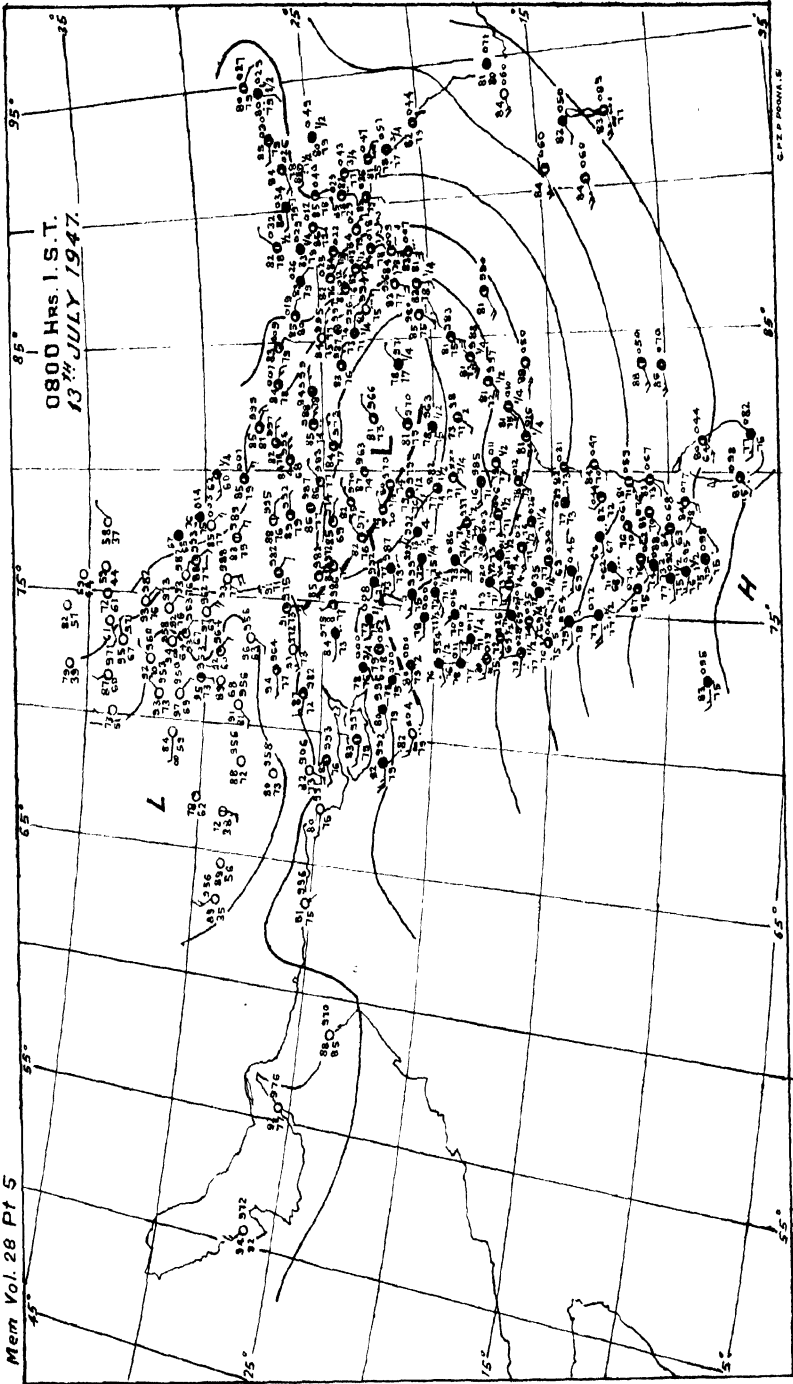


FIG. 19.





0800 Hrs. I.S.T.  
13<sup>th</sup> JULY 1947.

FIG. 21.

G.P.F. MONNA, 16

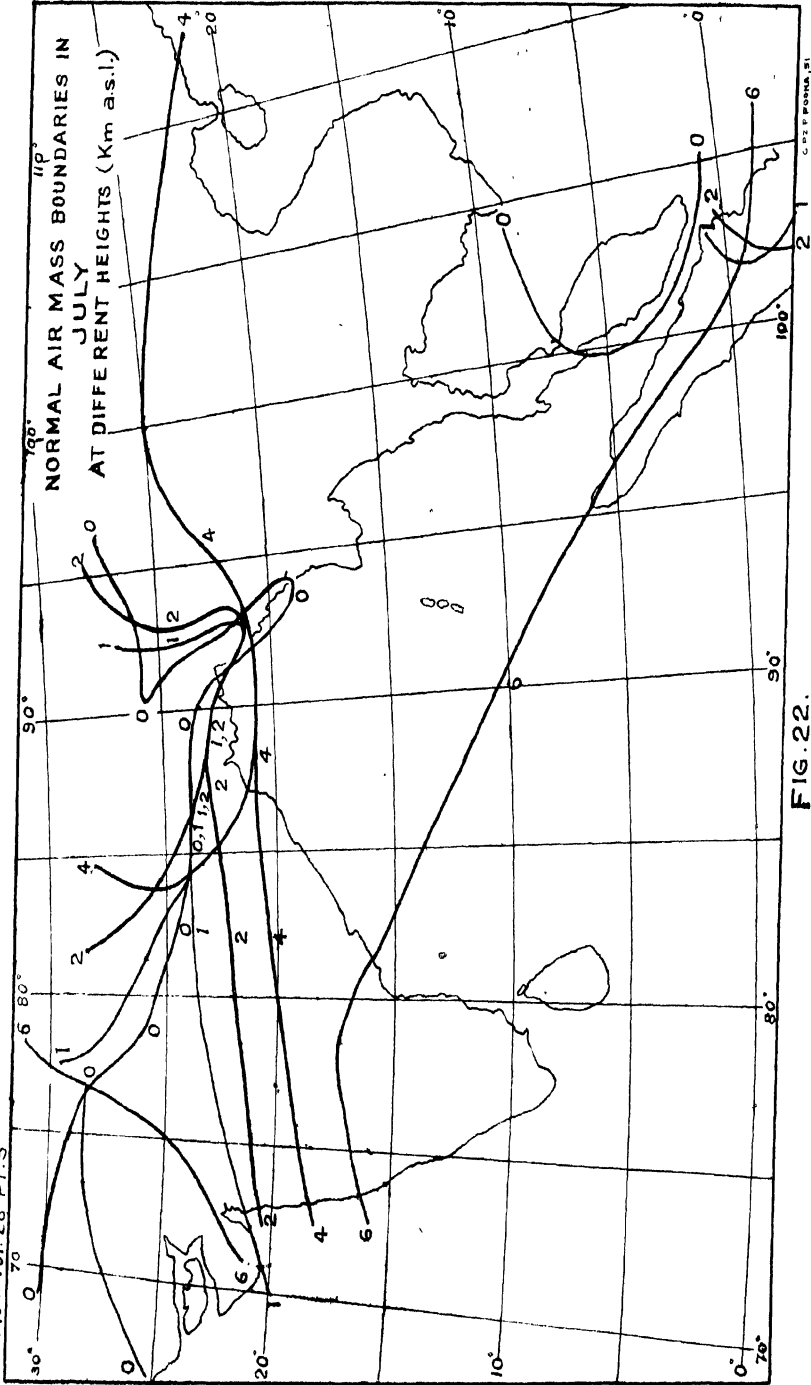


FIG. 22.

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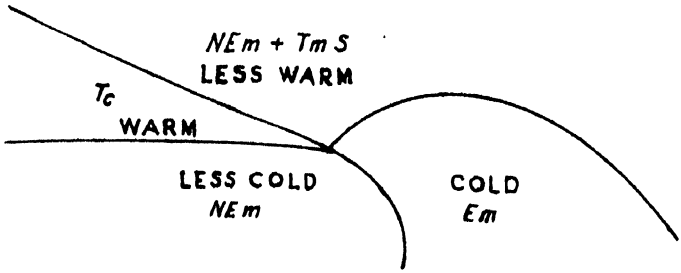


FIG. 24 (a).

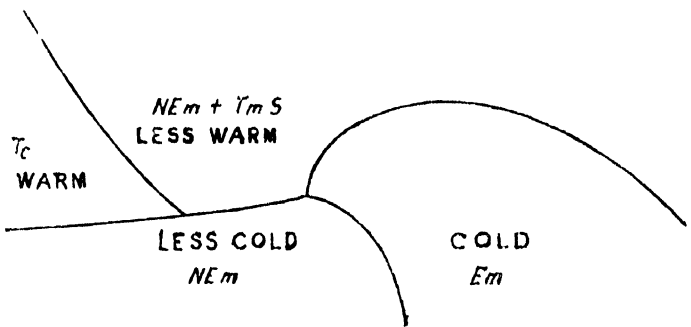


FIG. 24 (b).

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[Continued from Inner side of the front cover.]

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