Cyclogenesis in the Bay of Bengal and Arabian Sea

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ABSTRACT

In the paper the author studied the position of development of 413 depressions/cyclones in the Bay of Bengal and 53 depressions/cyclones in the Arabian Sea, formed during 1924 to 1952. He found that the 200 mb level warm pool formed in the mean charts is connected with the cyclogenesis in the Bay of Bengal and Arabian Sea. Eight depressions of 1964, seven in the Bay and one in the Arabian Sea, were also found to have warm pools at the 200 mb level one or two days before cyclogenesis took place over the sea. He further studied one depression in detail and found the formation of a warm pool at the 200 mb level three to four days before the development of the depression below at sea level. The 200 mb level warm pool that forms generally three to four days earlier was attributed to be one of the causes of cyclogenesis of tropical storms/depressions.

1. Introduction

1.1. Cyclogenesis of tropical storms has not yet been completely understood, but these storms develop over five major zones in the Northern hemisphere. Bay of Bengal and the Arabian Sea are two such zones.

Cyclones, tropical disturbances of all intensities with reference to wind speed greater than 33 m.p.h. form in the Bay of Bengal and in the Arabian Sea almost throughout the year. They are most frequent during the summer (June–September) over the northern part of the Bay of Bengal and over Eastern parts of Arabian Sea. They are more frequent in the Bay and in Arabian Sea in the region between latitude 6° N to 15° N during the pre-monsoon (March–May) and post-monsoon (October–November) seasons and are least frequent during the winter (December–February) when they are generally concentrated to the region between latitude 6° N to 11° N, as shown in Table 1.

The position of origin of all the above storms and depressions have been shown by Anantha Krishnan & Bhatia (1960) on the map.

Figs. 1*a–c* have been constructed on the basis of the original data mentioned above. The legends shown below Fig. 1 are self-explanatory.

1.2. It will be noticed from the four figures that during the summer (June–September) the occurrence of cyclogenesis in Bay of Bengal is most frequent in the area between latitude 20° N and 21° N bounded by longitude 88° and 90° E. The frequency of cyclogenesis in the Bay of Bengal and north-western parts of adjacent land area decreases as the distance from the area of maximum cyclogenesis increases. In the Arabian Sea the concentration of cyclogenesis is between latitude 20° N to 14° N and to the East of longitude 65° E.

1.3. During the pre-monsoon season the occurrence is almost scattered in the whole of the Bay. The same is the position in the Arabian Sea lying to the North of latitude 7° N and East of longitude 68° E. The position during the post-monsoon season is almost identical to the pre-monsoon, but the frequency is slightly concentrated in the Bay of Bengal between latitude 7° N and 10° N. There is another concentration in the Bay between latitude

Table 1. *Storms and depressions formed in the Bay of Bengal and Arabian Sea during 1924–1952*

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Bay of Bengal	7	2	3	14	26	33	77	66	62	54	46	23	413
Arabian Sea	2	1	1	3	8	12	2	Nil	4	10	9	1	53

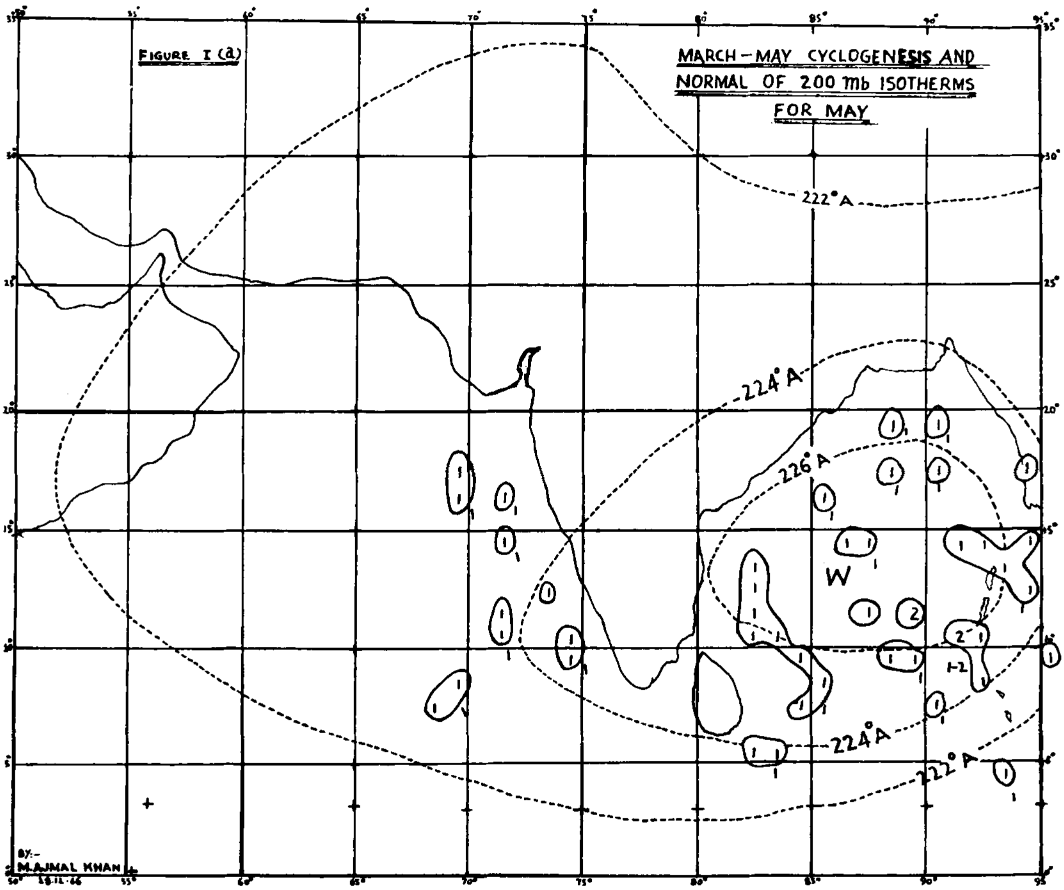

Fig. 1a. ——, Frequency of cyclones formed in a degree square (area bounded by one deg. lat. and 1 deg. long.) during March–May. ---, 200 mb normal isotherms for May.

13° N and 15° N along 95° longitude East. In the Arabian Sea, the frequency of concentration of cyclogenesis is between latitude 11° N and 13° N, East of longitude 71° E.

1.4. During winter the frequency centre shifts slightly to the south and is more concentrated between latitude 9° and 11° N and longitude 86° and 92° E.

1.5. If we look carefully at the isocyclogenesis lines, it will be noted from Figs. 1*a*–1*d* that there is a tendency for cyclogenesis to concentrate in certain areas during each season.

(i) According to Anantha Krishnan (1960) the zone of cyclogenesis undergoes a periodical oscillation following the northward and southward movement of the sun in the Bay and in the Arabian Sea.

(ii) The frequency of storms and depressions in the Bay of Bengal increases steadily from February to July and decreases from August to January.

(iii) The frequency of disturbances in the Arabian Sea shows a double maximum, one in June and the other in October, as can be seen from Table 1.

2. The 200 mb level warm pool and sea level cyclogenesis

2.1. It has been noticed that normal isotherms of 200 mb level over the sea area bear some remarkable similarity with the isocyclogenesis lines in the Bay of Bengal and Arabian Sea pertaining to the same season. In this connection normal charts showing temperature distribution at 200 mb level for May, June and Novem-

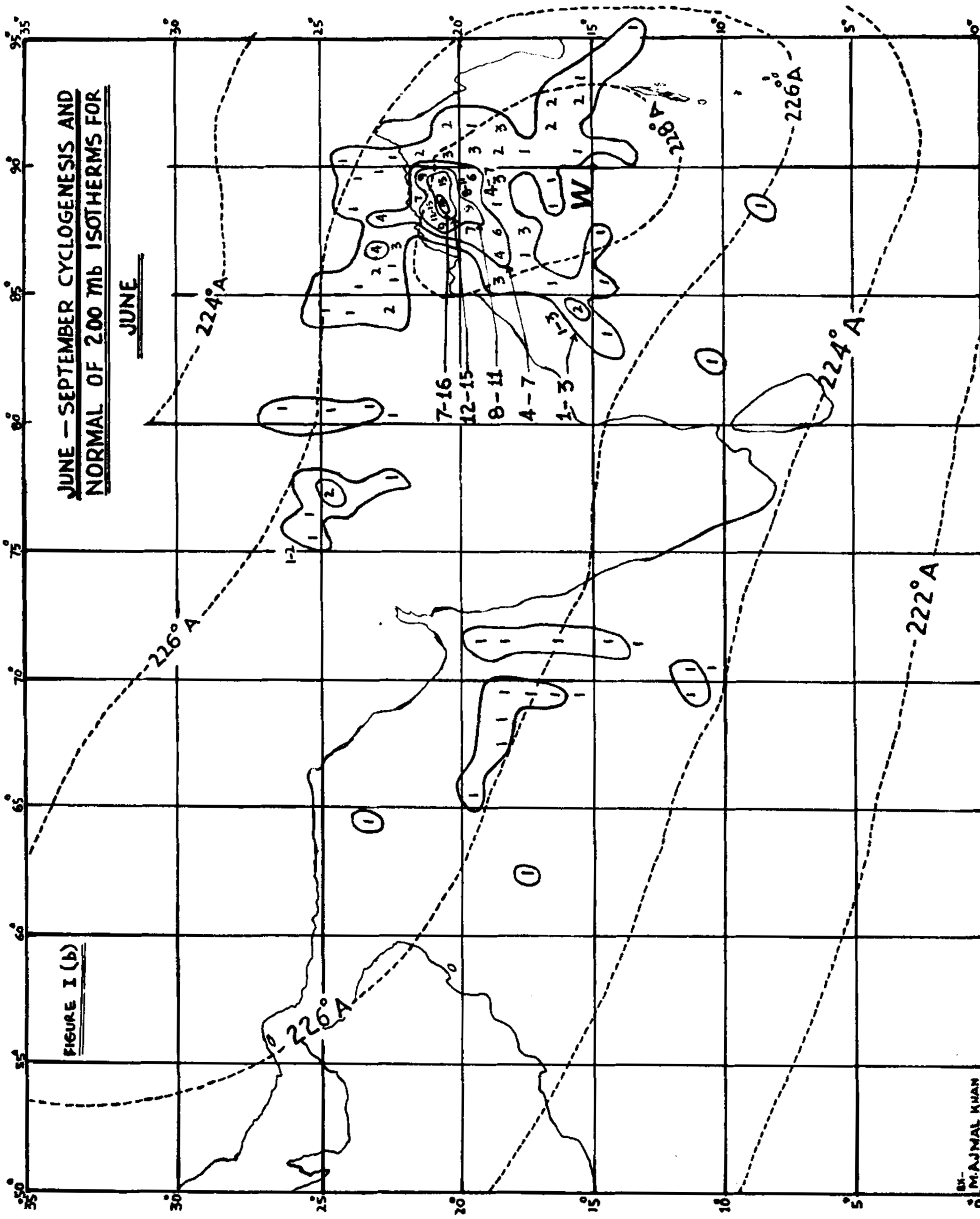

Fig. 1b. ——, same as Fig. 1*a* for cyclones formed during June–September. – – –, 200 mb normal isotherms for June.

ber, as published by Rama Krishanan (1960), are superimposed on Figs. 1*a–c* and for July reproduced in Fig. 2. The normal temperature distribution at 300 mb for the winter is superimposed from Kotes Waram (1953) on Fig. 1*d*.

2.2. A comparison of the various normal isotherms superimposed in Figs. 1 and 2 side by side with the frequency of cyclogenesis in the same figures clearly brings out the following fact.

The cyclogenesis at sea level over the Bay of Bengal and the Arabian Sea (and even over the

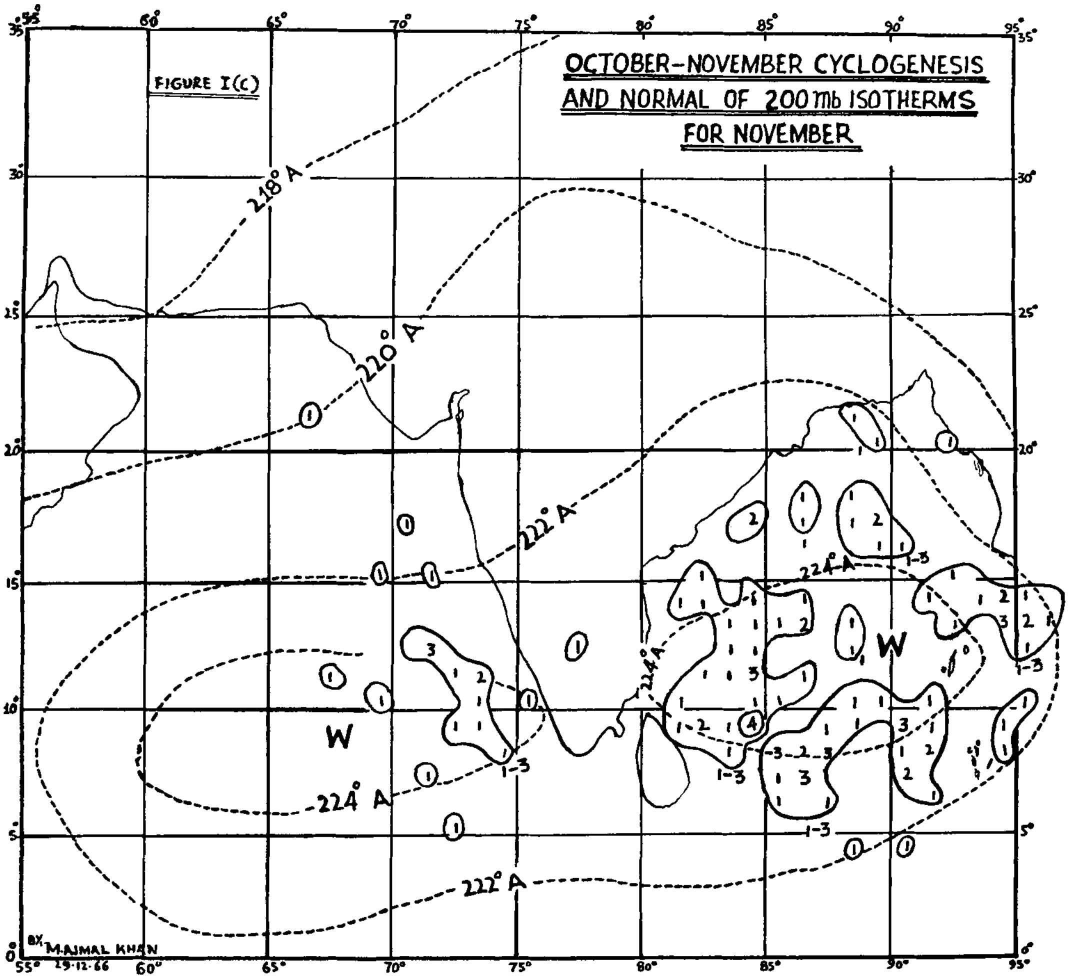

Fig. 1c. ——, same as Fig. 1*a* for cyclone formed during October–November. – – –, 200 mb normal isotherms for November.

land area of the Indo-Pakistan sub-continent) tends to occur over the area where a warm pool forms at the 200 mb level. These warm pools are generally bounded by some 226° A isotherms and more. In the winter season, however, it appears that the warm pool comes down at a lower level (300 mb) and is more or less bounded by 240° A, i.e. Fig. 1*d*.

3. Eight cases of cyclogenesis and 200 mb level warm pools 1964, in the Bay of Bengal and the Arabian Sea

3.1. The above conclusion of para 2 showing a tendency of forming storms and depression in the Bay of Bengal and Arabian Sea in the region having a warm pool at 200 mb level has been investigated in the case of 8 storms and depressions that formed in the same area during June to September 1964. The charts are not reproduced here to minimise the number of figures. The warm pool at the 200 mb level each connected with a storm or a depression formed at sea level in the sea area (shown in Table 2) has lent support to the above conclusion.

In Table 2 row No. 1 the values are shown of the isotherms which surrounds the warm pool at the 200 mb level associated with the formation of the storm or depression.

Row No. 2 shows the intensity of the warm pool one day before the formation of the storm or depression.

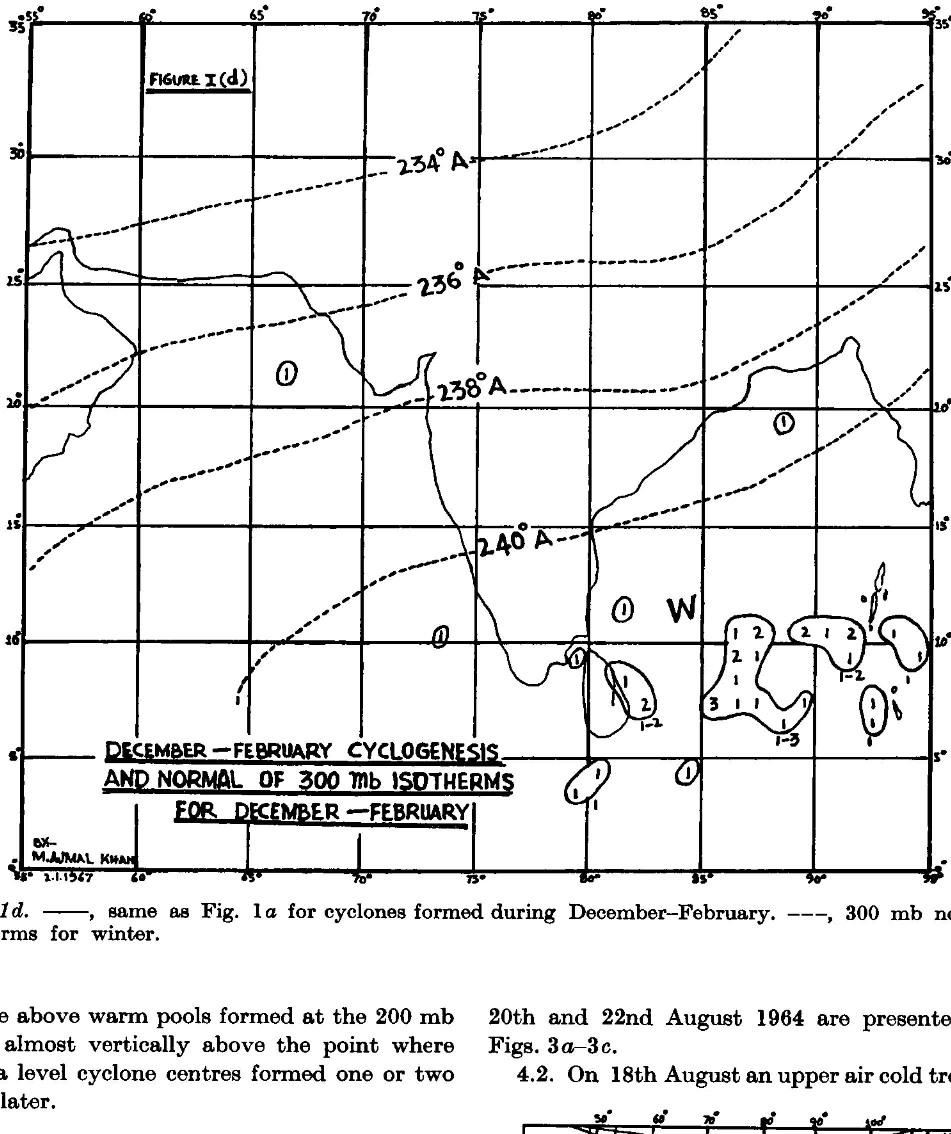

Fig. 1d. ——, same as Fig. 1*a* for cyclones formed during December–February. ---, 300 mb norma isotherms for winter.

The above warm pools formed at the 200 mb level almost vertically above the point where at sea level cyclone centres formed one or two days later.

4. A particular cyclogenesis and associated 200 mb warm pool

4.1. The case has been further studied on the basis of a depression that formed in the Bay of Bengal on 22nd August 1964. The detail of the case-study is presented below:

Isotherms at intervals of 2°C were drawn for 850, 500, 300 and 200 mb levels for 18th, 19th, 20th, 21st, 22nd, 23rd and 24th August 1964, on the basis of radio sonde data of 0000 G.M.T. Only charts for the 200 mb level for 18th, 20th and 22nd August 1964 are presented as Figs. 3*a*–3*c*.

4.2. On 18th August an upper air cold trough

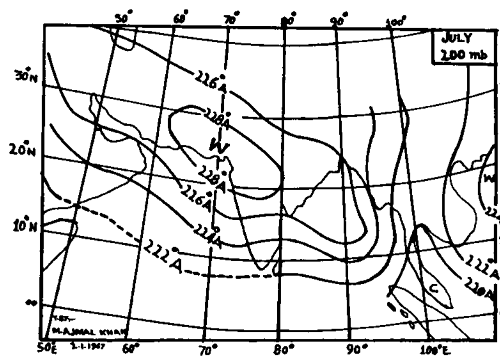

Fig. 2. ---, Normal isotherms for July for 200 mb levels.

Table 2. *The June depression formed in the Arabian Sea and all others in the Bay of Bengal (Measures in °A.)*

	9th June	3rd July	4th Aug.	10th Aug.	15th Aug.	22nd Aug.	7th Sept.	22nd Sept.
(1)	226	233	227	227	229	233	230	229
(2)	227	226	233	233	229	233	229	227

at the 200 mb level from the westerlies was passing across the north of the country. The trough was extending up to latitude 29° N in the vicinity of longitude 85° E. Another cold trough moving along with the Easterlies moved from the south across latitude 24° N along longitude 90° East.

A warm pool was lying to the east along longitude 95° E and latitude 26 to 34° N. The surface synoptic situation was the normal monsoon condition with an ordinary monsoon trough extending up to the Bay of Bengal along the Gangetic Valley. 1004 mb isobar was passing across north Bay lying to the north of latitude 20° N.

On 19th August 1964 the two cold troughs at the 200 mb level became less prominent but the southern cold trough came almost along longitude 90° E and reached as far north as latitude 26° N. The cold trough associated with the westerlies was moving almost along the same longitude across latitude 28° N. The warm pool of 18th August further intensified. The cold trough of the north and south weakened considerably. The whole area warmed up by about 4° C.

Position of the sea level remained unchanged. As a matter of fact, the trough over the Bay of Bengal across 20° N latitude even weakened.

On 20th August, the area at the 200 mb level was further warmed up and both the cold troughs of North and South almost disappeared and the entire area above the North Bay of Bengal and adjoining areas of Bengal and Orrisa was filled up by a well marked warm pool with the highest temperature of −42° C. In all appearance the shape of the isotherm of the 200 mb level and their locations in the warm pool are almost giving the sameshape and pattern of the surface isobars just below which we shall encounter after two days, i.e. on 22nd August 1964. The surface condition on the 20th in the Bay of Bengal and adjoining areas remained almost identical. There has been, however, one peculiarity which showed the appearance of a trough of low pressure over the Arabian Sea.

On 21st August the strength of the warm pool further intensified and it was enclosed by a −40°C isotherm with its centre at the 200 mb level approximately at latitude 22° N and longitude 89° E. The condition of the surface chart changed appreciably this day. A definite trough formed over the head of the Bay. Against this change at the mean sea level, the upper air at 200 mb had undergone a change of about 10°C of temperature. There was no cyclogenesis over the Bay of Bengal up to the 20th. The formation of the trough over Head Bay at 0300Z on 21st August 1964 showed the sign of cyclogenesis. It might have started on 20th as was seen from the trough over Arakan Coast. But up to 21st August, no closed sea level isobar appears over Bay of Bengal. It appears that cyclogenesis started over the Bay of Bengal on 21st August 1964 whereas the warm pool formed at the 200 mb level over the same area on 20th August.

On 22nd August the warm pool above Head Bay at 200 mb level was enclosed by −40°C. Side by side a low formed at 0300Z on 22nd August at Head Bay enclosed by the 998 mb isobar, with its centre approximately at latitude 21½° N and longitude 88½° E on the same sea level chart.

4.3. The 500–1000 mb thickness above Calcutta from 17th to 21st August shows that it increased from 5810 gpm on 17th August to 5870 gpm on 21st August and that for 200–500 mb column, the increase was from 6550 gpm to 6800 gpm. This shows that a warming took place in the air column during 17th to 21st August above Calcutta!

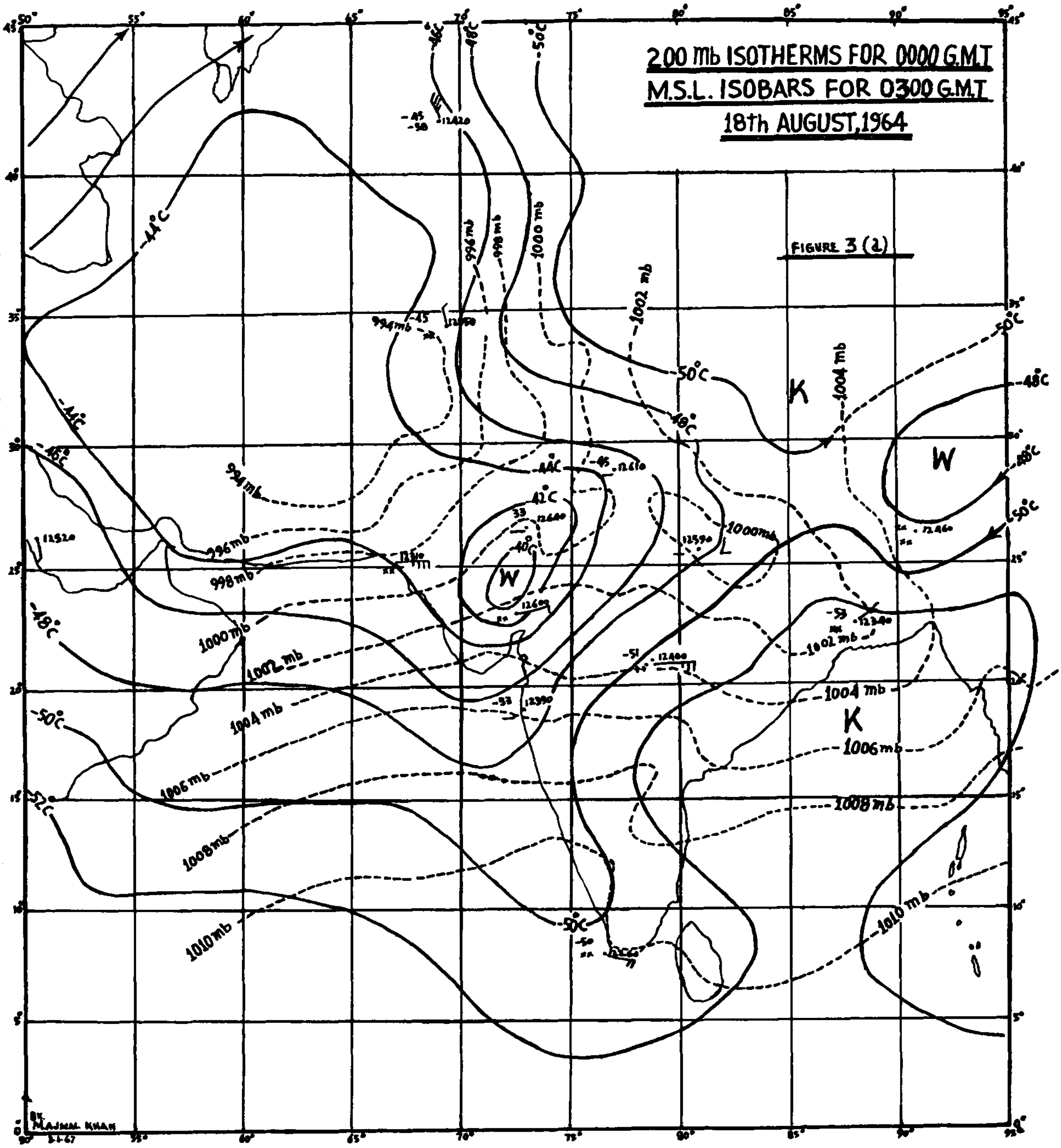

Fig. 3a. ——, 200 mb isotherms for 18th August 1964 – – –, Mean sea level isobars for 18th August 1964.

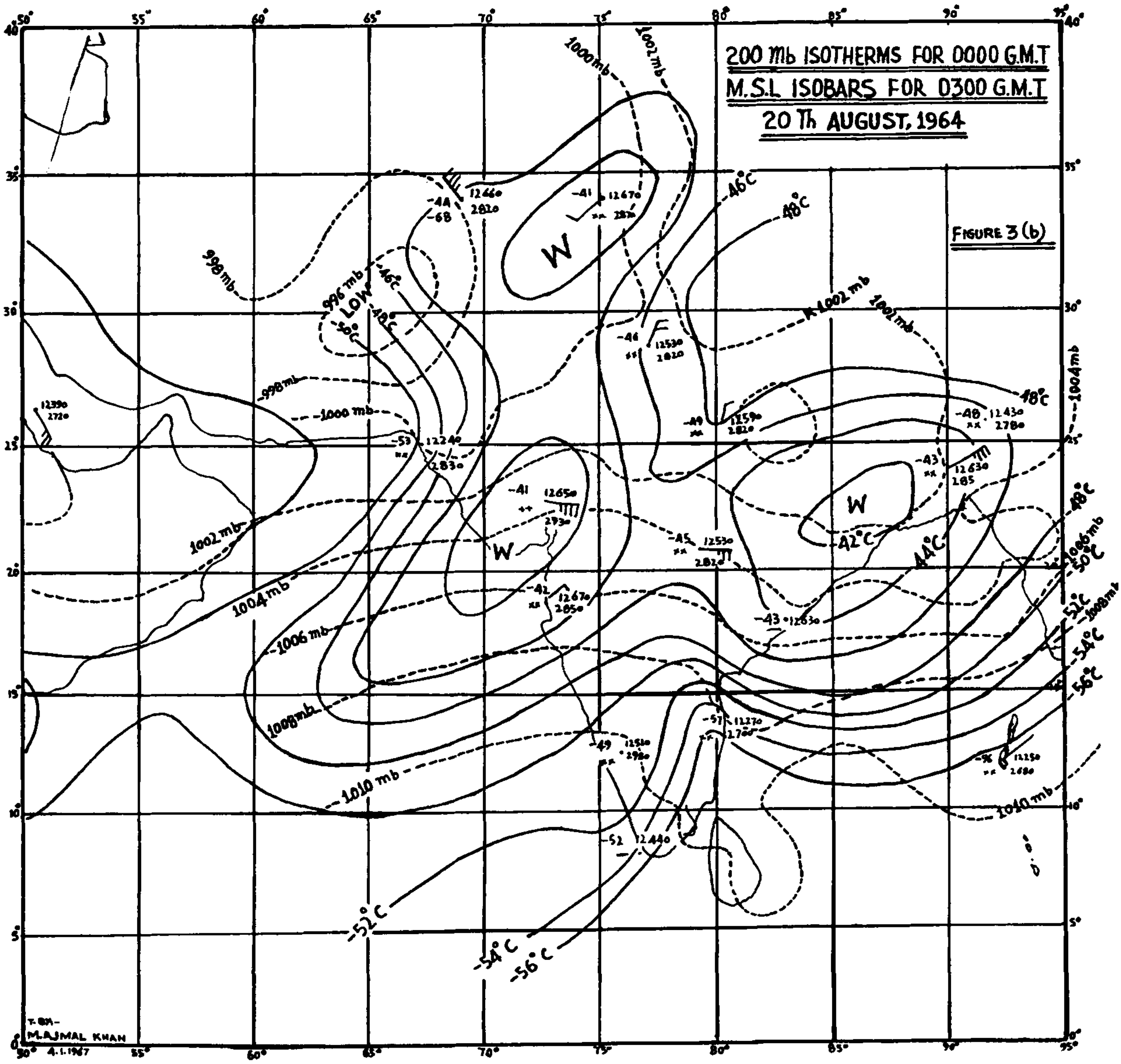

Fig. 3b. —— and – – –, same as Fig. 3*a* for 20th August 1964.

5. Discussions

5.1. Our present day knowledge on the cyclogenesis of tropical storms are, following Petterson (1958), as follows:

(i) Due to a weak coriolis factor, generally in the Northern hemisphere, the tropical cyclone forms between 5 to 25° N although Palmer (1952) has once located a storm at 1.8° N in the Marshal Islands.

(ii) Tropical storms form over ocean and sea with temperatures about 27°C (80°F). Some investigators put it as 78°F.

(iii) All tropical storms generally begin at sea and there is a tendency to dissipate over land.

(iv) Although these conditions are necessary, Petterson states that the above three conditions are not enough to produce a tropical cyclone. In the Bay of Bengal all the above three conditions are satisfied.

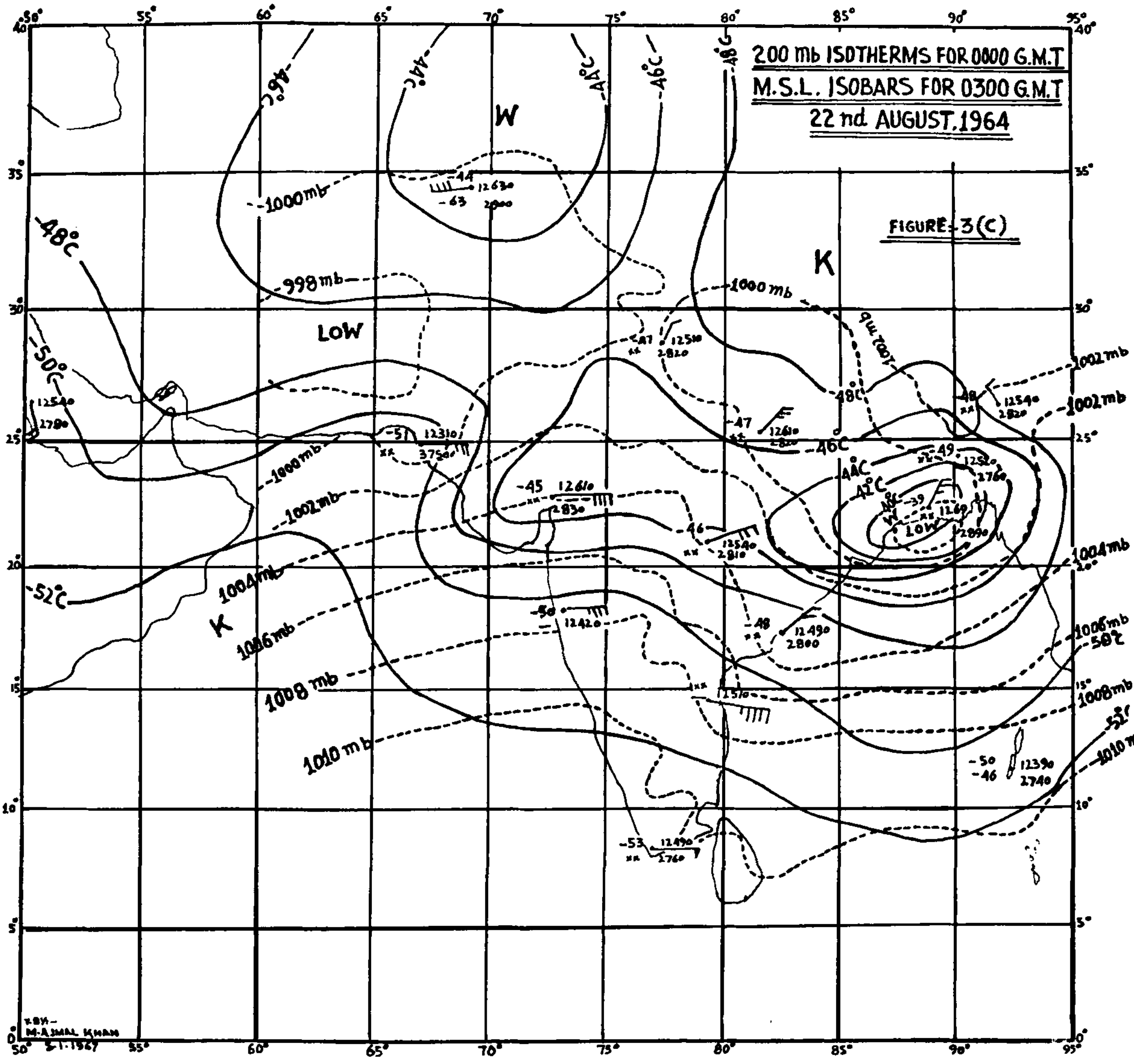

Fig. 3c. Same as Fig. 3*a* for 22nd August 1964.

5.2. Kotes Waram (1958) has shown that an easterly jet stream is invariably present with the cyclogenesis of a storm in the Bay and the Arabian Sea. Easterly jets, to me, appear to be an accidental co-existence, rather than a cause of cyclogenesis in these two areas. In the North Atlantic and North Pacific, off the West Coast of Mexico, there are no easterly jet streams, yet tropical storms form. In the North Pacific, west of 170° E, there is practically no easterly jet stream in the high troposphere, yet the frequency of tropical storm formation in that area is the greatest in the Northern Hemisphere.

5.3. Fig. 4 showing a time section for Calcutta (18–22 Aug., 1964) also indicates that the Easterly jet stream weakened when cyclogenesis was taking place below at sea level over the Bay of Bengal. It appears as if the Easterlies were sinking from 200 mb to the surface where the centre of the depression formed on 22nd August, 1964.

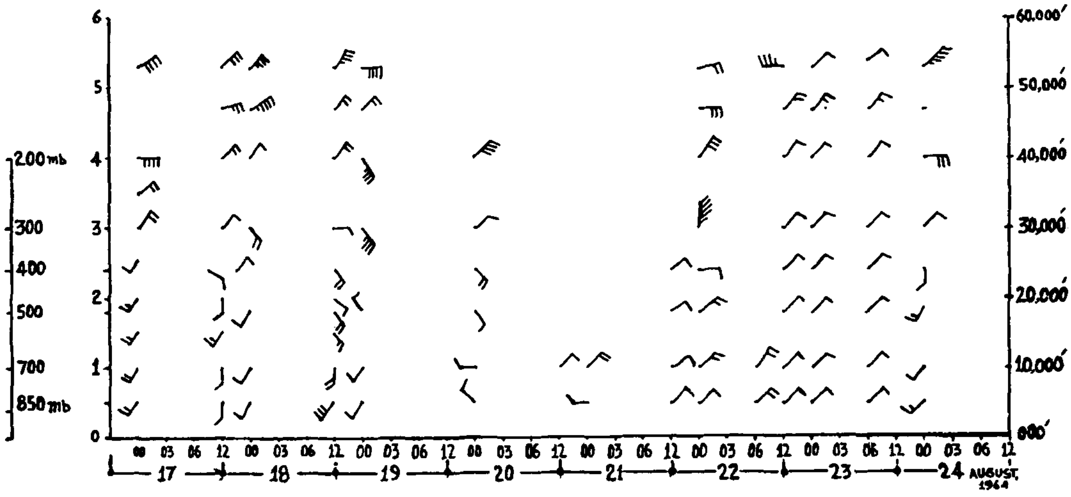

Fig. 4. Time Section for Calcutta from 17th to 24th Aug., 1964.

5.4. It appears that the formation of a warm pool at the 200 mb level, other conditions being favourable, is likely to lead to the formation of a tropical depression or a storm in the Bay of Bengal and in the Arabian Sea. When such a warm pool forms at the 200 mb level above a land area, there is tendency to form a land depression as well, as will be evident from Fig. 1*b* for June to Sept.

5.5. *Relationship of convergence in the lower level with divergence aloft*

Assuming a uniform convergence in the lower layer say with a pressure depth Δp_{10} and a uniform divergence with pressure defect Δp_{20} the equations for horizontal convergence and divergence are:

$S_0 \Delta p_0 = S\Delta p$ (law of conservation of mass)

$\eta_0/\Delta p_0 = \eta/\Delta p$ (conservation of potential vorticity)

Where S—cross sectional area of air column & η—absolute vorticity, the suffix 0 denoting initial state.

The increase of vorticity in the lower layer is

$$\eta_1 = \eta_0 \frac{\Delta p_0}{\Delta p_{10}} = \eta \frac{S_0}{S_1}; \ \frac{S_0}{S_1} > 1$$

and the initial surface pressure.

$$p_0 = \Delta p_{10} + \Delta p_{20} + \Delta p_{30}$$

There being no change in depth in the middle layer, the pressure depth changes in the other layers are:

$$\Delta p_1 = \Delta p_{10} \frac{S_{10}}{S_1} = \Delta p_{10} \frac{\eta_1}{\eta_{01}}$$

$$\Delta p_3 = \Delta p_{30} \frac{S_{30}}{S_3} = \Delta p_{30} \frac{\eta_3}{\eta_{03}}$$

The surface pressure therefore becomes

$$p = \Delta p_1 + \Delta p_2 + \Delta p_3 = \Delta p_{10} \frac{S_{10}}{S_1}$$

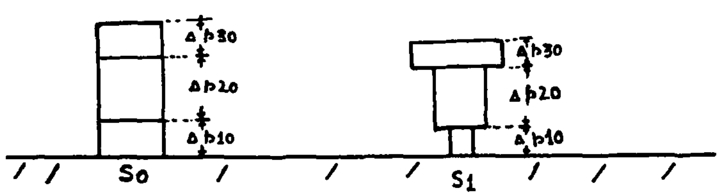

Fig. 5

If $Po > p$, the pressure decreases in spite of the increase of the vorticity in the lower layer and therefore

$$\Delta p_{10} + \Delta p_{30} > \Delta p_{10}\frac{S_{10}}{S_1} + \Delta p_{30}\frac{S_{30}}{S_3}$$

or

$$1 - \frac{\Delta p_{10}}{\Delta p_{30}}\left(\frac{S_{10}}{S_1} - 1\right) > \frac{S_{30}}{S_3}$$

These are then the criteria that the surface pressure decreases with divergence aloft.

Table 3 shows that a sufficiently large amount of divergence aloft is a necessary condition for the development of cyclones and this divergence aloft can be classified into the following:

(i) Caused by the structure of the general shower field in which the cyclone is embodied.

(ii) Caused by a self-exciting mechanism of tropical cyclones the energy source of which is the release of latent heat.

5.6. In an extra-tropical cyclone, a cold trough is invariably present in the upper troposphere over the rear of a mature sea level cyclone (p. 302, S. Petterssen Weather Analysis & Forecasting, 1956 Vol. I). But it is noticed that a warm pool exists in the upper troposphere over the sea level tropical cyclone in this case.

Yanai (1961) analysed the formation of Typhoon Doris 1958 which appeared in the Marshall Islands area. Yanai's analysis revealed that the warming of the ascending air was the result of liberation of latent heat of condensation. This, coupled with cooling of surrounding air due to evaporation, created a horizontal temperature gradient of a warm core type. He observed that a rapid fall of sea level pressure took place after completion of the warm core-structure.

According to Yanai, the formation of a typhoon takes place in three stages i.e. (1) the first stage consists of an easterly wave having a cold core, (2) the second stage is the transient stage of formation of the warm core due to liberation of latent heat by condensation and cooling due to evaporation in the subsiding air around it. The reason for a first formation of a warm core in the upper troposphere was stated by Yanai to be due to the upward turbulent transport of heat by penetrative cloud towers and (3) the third is the stage of rapid development of an incipient vortex after the establishment of a warm core structure.

Table 3. *Critical values of upper air divergence*

$\frac{S_{10}}{S_1}$		2	1.5	1.2
$\frac{\Delta p_{10}}{\Delta p_{30}}$	1	0	0.5	0.80
	$\frac{1}{2}$	0.05	0.15	0.90
	$\frac{1}{3}$	0.66	0.83	0.93

5.7. Yanai (1963) also discussed the necessity for having an upper anticyclone over the easterly wave in order to have a typhoon formation. In 17 wave examples, Yanai found only two that were not characterised by anticyclonic vorticity aloft. In every wave that developed the upper anticyclone was also accompanied by warming as shown by positive 400 mb temperature anomalies. However, on the basis of his data Yanai could not conclude that upper anticyclone and upper warming were dependent phenomena.

Fett (1966) concluded from his study of satellite pictures of Typhoon, Bess, July 1963, Hurricane, Alma, August 1962, and Guatemalan Storm, October 1962 that the upper anticyclone and upper warming were dependent phenomena. He reasoned that the warming is the forced result of internal heat released through convection. Space sections published by Fett also demonstrate the same fact.

5.8. Petterssen (1956), while discussing extratropical cyclones, has shown that development (cyclonic) at sea level comes out as an imbalance between the vorticity advection at the level of non-divergence and the Laplacians of three thermal components i.e. advection of thickness, stability and heat terms.

In the case of the Bay of Bengal storms where the sea level temperatures varied from 28° to 30°C from August 18 to August 22 Laplacians of the heat term are negative. The same appears to be the case with the Laplacians of the stability term, as, in the major part of the air column, the motion is upward and thus the velocity is negative and the air is unstable. The movement of the warm air towards the area where a later cyclone developed shows the Laplacian of thickness advection is also negative.

Hence, it appears that all the three Laplacians will individually contribute positively to the vorticity advection in the case of these tropical storms. In the case of extra tropical cyclones any or more of the three Laplacians may be positive as well. The stability term works as a brake there.

This appears to be one of the substantial differences between the development of tropical cyclones and extra-tropical cyclones.

6. Conclusion

The warm pool observed in the present study thus appears to have a definite influence upon the development of tropical storms in the Bay of Bengal and Arabian Sea. As mentioned above, Yanai also holds the same opinion for typhoons of the Pacific Ocean, and Fett for hurricanes formed in the Atlantic Ocean.

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REFERENCES

Fett, R. W. 1966. *Monthly Weather Review* (Washington D.C.) *94*, No. 1, Jan. 1966, 9–18.

Krishanan, Rama. 1960. *Monsoon of the World.* Report of the Symposium on India Met. Dept., New Delhi, 10–21.

Krishnan, Anantha & Batia. 1960. *Monsoon of the World.* Report of the Symposium on India Met. Dept., New Delhi, 156–172.

Palmer, C. E. 1952. *Quarterly Journ. Royal Met. Society 78*, 126.

Petterssen, S. 1956. *Weather Analysis and Forecasting I*, McGraw-Hill, New York, 320–325.

Petterssen, S. 1958. *Introduction to Meteorology*, McGraw-Hill, New York, 246–248.

Riehl, H. 1954. *Tropical Meteorology*, McGraw Hill, New York, 331–337.

Waram, Kotes. 1953. India, *J. Met. Geophy. 4*, No. 2.

Waram, Kotes. 1958. India, *J. Met. Geophy. 9*, No. 1.

Yanai, M. 1961. *Journal Met. Soc. Japan Series II, 39*, No. 4, 187–213 and No. 5, 282–309.

Yanai, M. 1963. "A preliminary survey of large-scale disturbances over the tropical Pacific region", *Geofisica International 3*, Nos. 3–4 July–Dec. 1963, 73–84.

ЦИКЛОГЕНЕЗ В БЕНГАЛЬСКОМ ЗАЛИВЕ И АРАВИЙСКОМ МОРЕ

В данной статье автор изучил положение и развитие 413 депрессий или циклонов в Бенгальском заливе и 53 депрессий или циклонов в Аравийском море, формировавшихся в 1924–1952 гг., и нашел, что образующаяся на уровне 200 мб теплая область на средних картах связана с циклогенезом в Бенгальском заливе и Аравийском море. Найдено, что в случае восьми депрессий 1964 г. (семь в заливе и одна в Аравийском море) также формировались теплые области на уровне 200 мб за один или два дня до того, как циклогенез имел место над морем. Далее автор детально изучил одну депрессию и обнарупил формирование теплой области на уровне 200 мб за три–четыре дня до развития депрессии ниже, на уровне моря. Теплая область на уровне 200 мб, которая формируется обычно на три–четыре дня раньше, рассматривается как одна из причин циклогенеза в тропических бурях или депрессиях.