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Variations in intensity and structure of a westward-propagating monsoon depression

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सार—इस अध्ययन में एक मानसून अवदाब पर चर्चा की गई है, जो बंगाल की खाड़ी के ऊपर विकसित हुआ और मध्य भारत को पार करता हुआ पश्चिम की ओर गतिशील हुआ। यह तत्पश्चात् अरब सागर के उत्तर-पूर्वी कोने पर मध्य क्षोभ मण्डलीय विक्षोभ (एम. टी. डी.) में परिवर्तित हो गया। बंगाल की खाड़ी के ऊपर मूल मानसून, उपोष्ण पश्चिमी द्रोणियों और बंगाल की खाड़ी के ऊपर नए अवदाब से सम्बद्ध ऊष्मीय लक्षणों के साथ इसके टकराव की जांच की गई है। स्पष्ट रूप से पता चलता है कि इसकी तीव्रता और संरचना में प्रेक्षित विभिन्नता इन तीनों तथ्यों के कारण उत्पन्न होती है। निम्न दाब प्रणाली मूल मानसून क्षेत्र के उष्ण क्षेत्रक के पुनः प्रवेश करने पर मध्य क्षोभ मण्डलीय विक्षोभ में परिवर्तित हो गई और इसके केन्द्र भी उत्तर से पश्चिम तक परिवर्तित उष्ण अभिवहन तथा मध्य क्षोभ मंडल में दक्षिण से पूर्व तक शीत अभिवहन फैल गया। तापीय अभिवहन के महत्व की पुष्टि उष्मा बजट के परिकलन से की गई है। संघनन ताप की भूमिका की भी संक्षेप में चर्चा की गई है।

ABSTRACT. The study deals with a monsoon depression which developed over the Bay of Bengal, moved westward across central India and turned into a mid-tropospheric disturbance (MTD) over the northeastern corner of the Arabian Sea. Its interactions with the thermal fields associated with the basic monsoon, subtropical westerly troughs and a new depression over the Bay of Bengal are examined. Evidence suggests the involvement of all the three factors in causing the observed variations in its intensity and structure. The low pressure system turned into a mid-tropospheric disturbance when it re-entered the warm sector of the basic monsoon field and received increased warm advection from the north to the west of its centre and cold advection from the south to the east in mid-troposphere. The importance of thermal advection is confirmed by computation of a heat budget. The role of condensation heating is also briefly discussed.

Key words—Monson depression, Westward-propagating depression, Intensity of depression, Structure of depression.

1. Introduction

Monsoon depressions which are low pressure systems of moderate intensity (for details of official classification of low pressure systems over India and adjoining sea areas, *see, e.g.,* Rao 1976, Saha *et al.* 1981) usually form over the Head Bay of Bengal during the months of June to August and move westnorthwestward into India. However, observations show that a majority of these disturbances weaken or die soon after crossing the coast and in relatively few cases only their track extends beyond 80°E longitude (Mooley and Shukla 1989). The question as to why a majority should die prematurely within a short distance of the east coast of India while others are able to move on and reach the west coast of India or a longitude even beyond has not been addressed so far, to the best knowledge of the authors. The present study deals with a Bay of Bengal monsoon depression which after crossing the east coast of India on 24 June 1979 moved across central India and emerged over the Arabian Sea three days later (Fig. 1). The specific period studied is from 25 through 27 June during which it interacted not only with the basic monsoon field over India but also with sub-tropical westerly troughs which moved eastward across northern India. Possible effect of the entry of a fresh depression over the Bay of Bengal from the east is also considered. An explosive upsurge of intensity and a change of structure of the low pressure system which occurred at 12 UTC on 27 June receive special attention.

2. Data and analysis

The depression formed during the Arabian Sea phase of the Monsoon Experiment (MONEX)-1979, and hence special observations, both surface and upper air, were available from several observing platforms such as ships, instrumented aircrafts and satellites over this sea. Unfortunately, the Bay of Bengal phase of MONEX-1979 had not started till 1 July, so no special observations, except satellite cloud imagery, were available while the depression was over the Bay. Conventional data, both surface and upper air were, of course, available over both land and sea throughout the life period of the disturbance.

Basic data for the study include, besides satellite cloud imagery, the daily 00 and 12 UTC winds and temperatures at msl, 850, 700, 500, 300, 200 and 100 hPa over domain, 08-32° N, 59-91° E, during the period 25 through 27 June 1979 and are obtained from several sources, including the synoptic maps and publications of the India Meteorological Department (IMD) and special publications of the International MONEX Management Centre (IMMC) available at the IMD Headquarters at New Delhi. Satellite cloud imagery in respect of the disturbance was obtained from Krishnamurti *et al.* (1979). Figs. 2 (a-d) present the daily 12 UTC satellite cloud imagery during the period 25 through 28 June 1979.

Available data, the coverage and quality of which were found to be satisfactory (Gupta *et al.* 1980), were plotted on maps and analysed for streamlines and isotachs and isotherms. Unfortunately, the special datasets contained few observations of dewpoints or humidity, so no moisture analysis was feasible. An example of our analysis is presented in Fig. 3 which shows: (a) the streamline-isotachs, and (b) isotherms at 500 hPa at 12 UTC on 27 June 1979, when the depression, transformed into a mid-tropospheric disturbance over the northeastern corner of the Arabian Sea, co-existed with a sub-tropical westerly trough over northern India and a fresh depression over the Bay of Bengal.

Analysed data at 2×2 latitude-longitude gridpoints were used for further analysis and computations of such derived parameters as divergence, vorticity, vertical motion, thermal advection, static stability and a heat budget. The results of some of these computations are presented in the pages that follow. Our further analysis considers the way in which the structure and intensity of the depression were affected by the basic monsoon field over India and also by sub-tropical westerly troughs that moved eastward across northern India during the period. The analysis brings out a remarkable change of structure and enhancement of intensity of the low pressure system over the northeastern corner of the Arabian Sea.

3. Computations

Some details of the computations made are as follows:

(*i*) *Divergence and vertical motion*

These were computed by using the following kinematic relationships :

$$\text{Divergence } (D) = \partial u/\partial x + \partial v/\partial y - (v/r)\tan\phi$$

$$\text{Vertical motion } (\omega) = \omega_s + \int_{p_t}^{p_s} \left(\overline{\nabla \cdot \mathbf{V}}\right) \delta p$$

where,

u, v — The eastward and the northward components respectively of the wind vector $\mathbf{V}$ at a pressure surface, p (hPa) ;

p_s — Surface pressure,

p_t — Pressure at top,

$\mathbf{V}_s$ — Surface wind vector,

ϕ — Latitude,

r — Mean radius of the earth, and

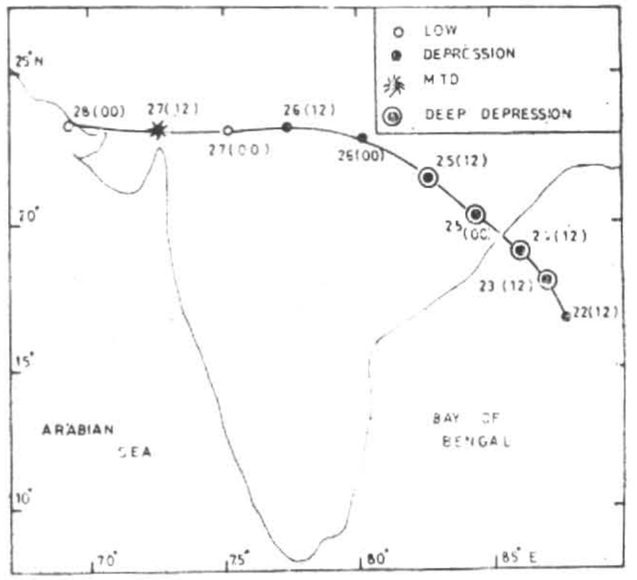


Fig. 1. Daily approximate locations of the centres of the Bay of Bengal depression with estimated intensity. Dates with time in UTC within brackets are indicated beside locations

the overbar ($\bar{\ }$) — The mean value over pressure interval.

In both the relationships, the space derivatives are evaluated by using a centred finite-differencing scheme. The equation for vertical motion is the continuity equation in which the divergence is integrated vertically from surface upward, the lower boundary condition being, $\omega_s = \mathbf{V}_s \cdot \nabla p_s$. The well-known O'Brien correction was applied to the computed vertical velocity, so as to reduce the vertical velocity at the top to zero. An example of the computed vertical velocity is presented in Fig. 4 which shows vertical motion at 500 hPa at 12 UTC on 25, 26 and 27 June.

(*ii*) *Heat budget*

The First law of thermodynamics in the following form was used to compute a heat budget :

$$Q = (c_p/g)\int(\underset{\text{I}}{\partial T/\partial t} + \underset{\text{II}}{\mathbf{V}\cdot\nabla T} - \underset{\text{III}}{\sigma\omega})\delta p$$

where,

Q — Vertically-integrated rate of diabatic heating,

T — Temperature in degrees Kelvin,

t — Time,

c_p — Specific heat at constant pressure p,

g — Acceleration due to gravity,

σ — Static stability parameter

$[= (RT/p\,c_p) - \partial T/\partial p]$

where, R is gas constant for dry air.

In the above equation, the terms I, II, III on the right hand side represent respectively the vertically-integrated local heating, thermal advection and adiabatic heating due to vertical motion. These terms are evaluated from data using a centred finite-differencing scheme for time and space derivatives and by carrying out integrations from 925 hPa to 150 hPa. Since our data were for 3 days only, the budget could be computed for 1 day, *i.e.*, for 26 June only.

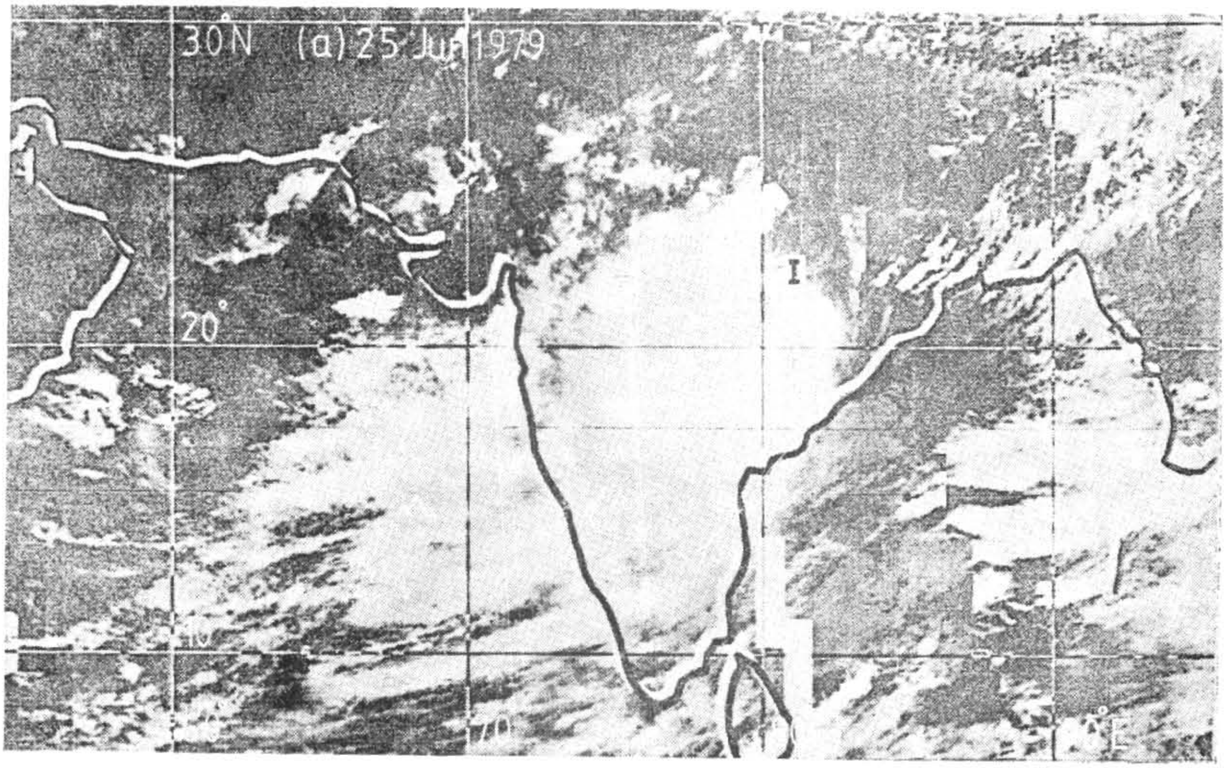


Fig. 2(a). Daily 12 UTC satellite cloud imagery on 25 June 1979

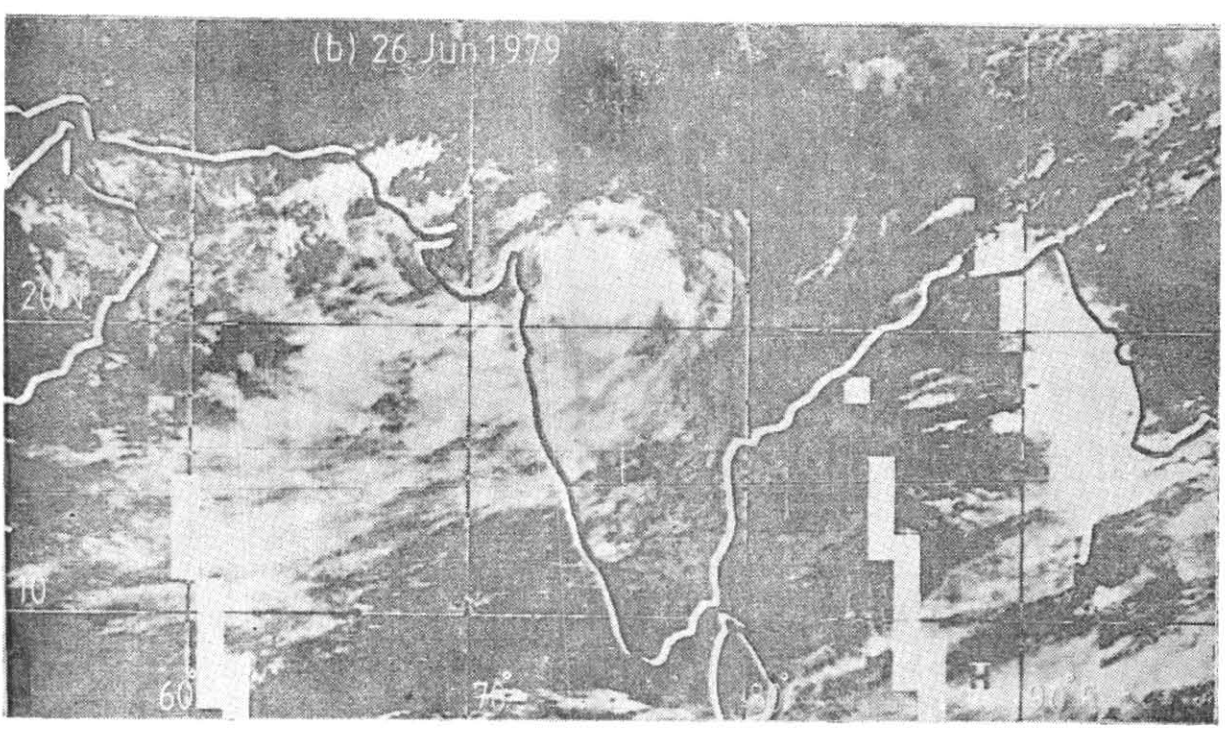


Fig. 2 (b). Daily 12 UTC satellite cloud imagery on 26 June 1979

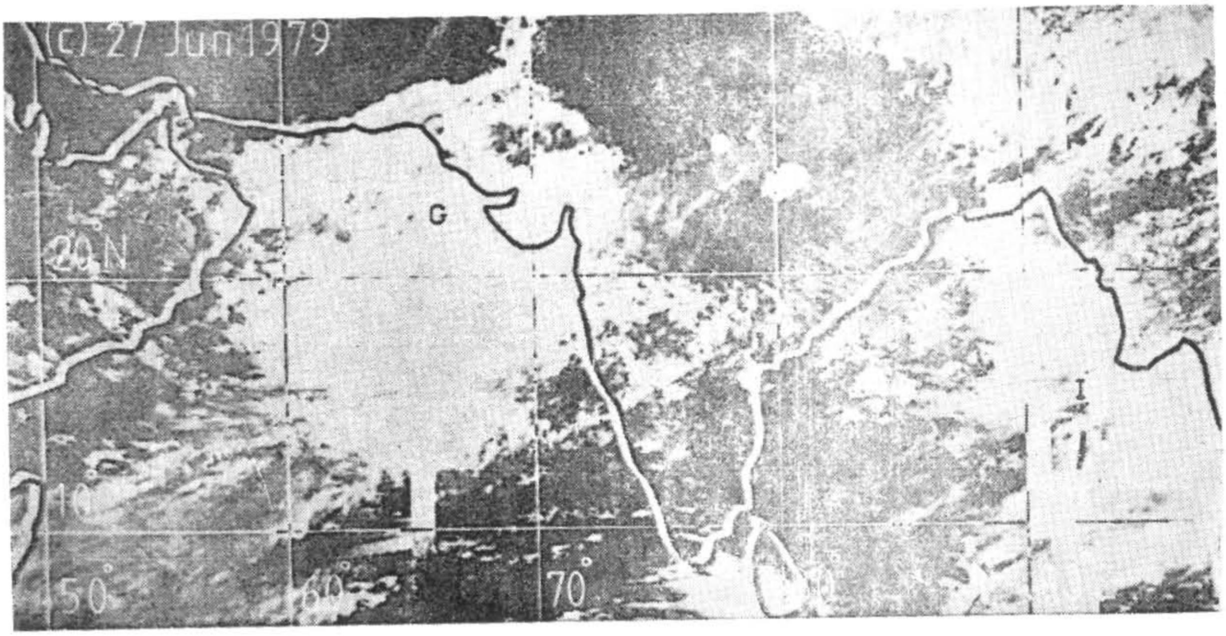


Fig. 2(c). Daily 12 UTC satellite cloud imagery on 27 June 1979

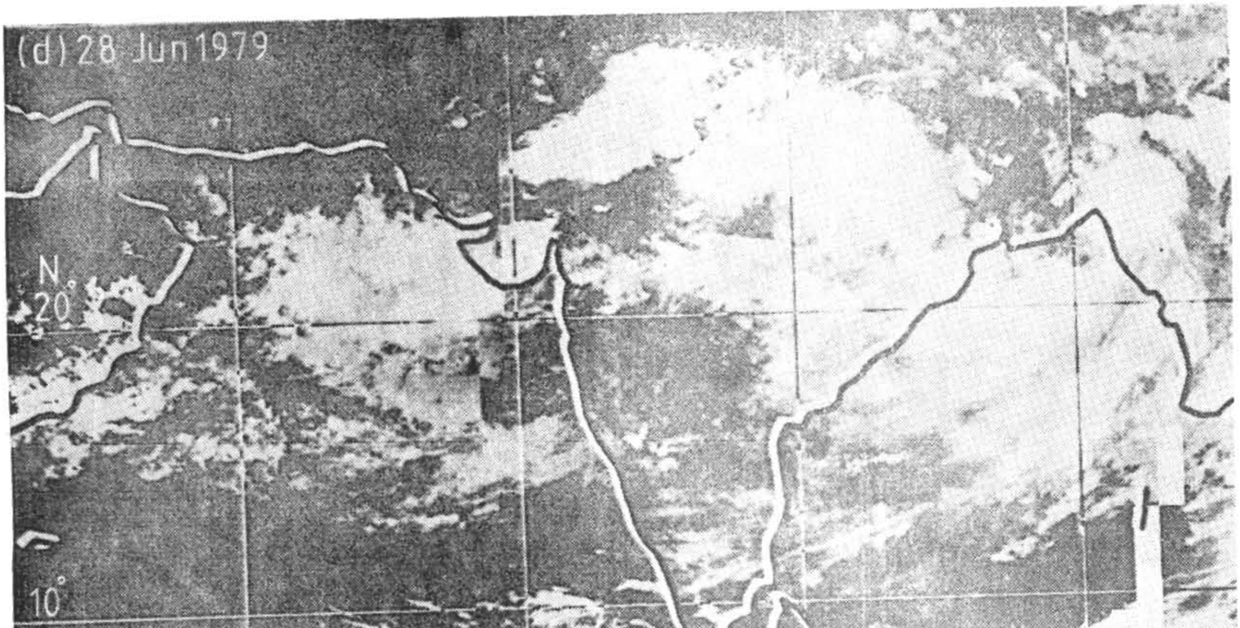
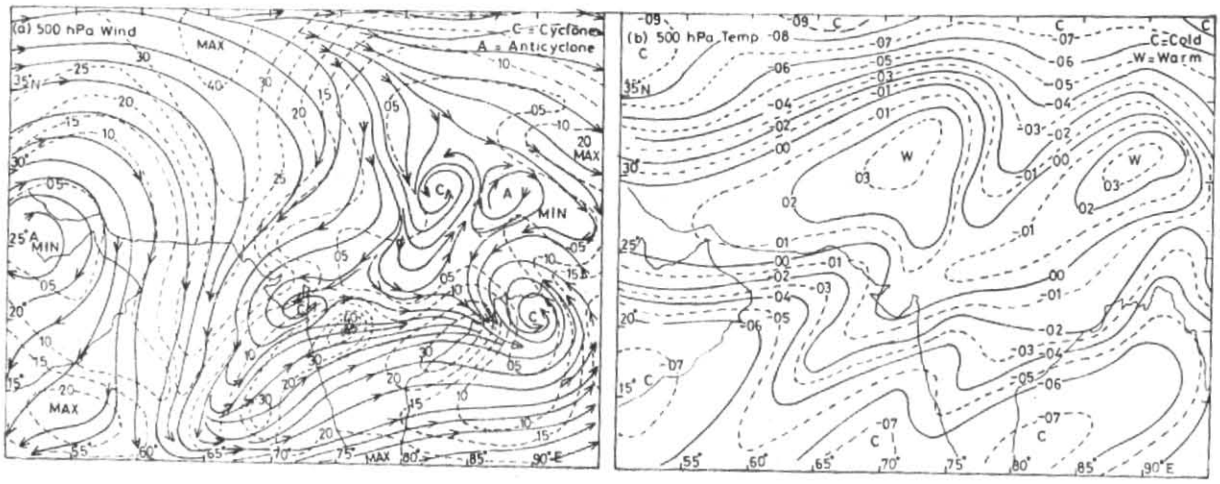


Fig. 2 (d). Daily 12 UTC satellite cloud imagery on 28 June 1979



Figs. 3 (a & b). Analyses of : (a) winds, and (b) temperatures at 500 hPa at 12 UTC on 27 June 1979. In (a), C—cyclonic, A—anticyclonic, Isotach are in kt. In (b), temperatures (°C), W—warm, C—cold

The results of the computations are presented in Figs. 5 (a-d). Fig. 5 (a) shows the distribution of local heating with extensive warming to northwest and southwest of the depression centre and extensive cooling to its south and southeast. Fig. 5(b) shows the distribution of thermal advection. Large-scale warm advection appears to occur to the northwest, west and southwest of the disturbance centre while major cold advection occurs to the south and southeast. Strong adiabatic cooling mainly to the west and southwest and mild to moderate adiabatic warming to the north and southeast of the disturbance centre are indicated in Fig. 5(c). Fig. 5(d) shows the distribution of total diabatic heating. It shows at least three large areas of diabatic warming, two to the east and one to the west, but the strongest and most extensive diabatic warming occurs to the southwest of the disturbance centre where the rate of warming reaches a value of 2750 Watts per square metre. An extensive area of mild diabatic cooling lies some distance to the north and south of the disturbance centre. It is evident that the area of strongest diabatic warming occurs where there are deep penetrative clouds and concentrated heavy precipitation over the southwestern quadrant of the depression (*see* Fig. 6; also, Fig. 2) where the upward motion is the strongest (Fig. 4). Diabatic cooling to the north of the depression centre appears to occur where there is relatively much less cloud and precipitation and vertical motion is generally downward.

4. Structure and intensity

A comparison of the daily satellite cloud pictures (Fig. 2) as well as the strength of upward motion (Fig. 4) suggests that the depression during its westward movement did suffer a reduction in its intensity on 26 June but was able to pull through and even revive, though with a change of structure, into a mid-tropospheric disturbance on reaching the west coast of India. This variation in the intensity of the disturbance becomes clear from Fig. 7 which gives a measure of the horizontally-averaged kinetic energy of the circulation at 850 and 700 hPa on the three days. Our analysis suggests that the depression came under several influences during its lifetime. Interaction with the quasi-stationary basic monsoon field over India, the influence of eastward-propagating sub-tropical westerly troughs and the entry of a new disturbance over the Bay of Bengal from the east might all have affected the structure and intensity of the depression. These are discussed here in some detail:

(i) Interaction with the basic monsoon field

The basic monsoon field over the Indian sub-continent and its adjoining sea areas is driven by differential heating between the atmospheres over the Asian continent in the north and the Indian Ocean in the south. The meridional anomaly of temperature drives the general monsoon circulation with two meridional vertical circulation cells, the monsoon cell below and the Hadley cell above with their common rising branch forming a surface of discontinuity between airmasses (warm and dry in north and relatively cool and moist in south), which slopes equatorward with height (Saha and Saha 1989, 1990). Here, in this trough zone, a steady easterly thermal wind brings about warm advection from the north through veering of the northerly wind with height and cold advection from the south through backing of the southerly wind with height. Additionally, there is a zonal differential heating between the atmospheres over the Peninsulas of Arabia, India and Indo-China and their flanking sea areas (Arabian Sea, Bay of Bengal and south China Sea). In fact, in the real atmosphere, the effects of both the meridional and longitudinal temperature anomalies are superimposed on each other and it is necessary to take into account both the effects for a proper understanding of any actual situation such as the present depression case.

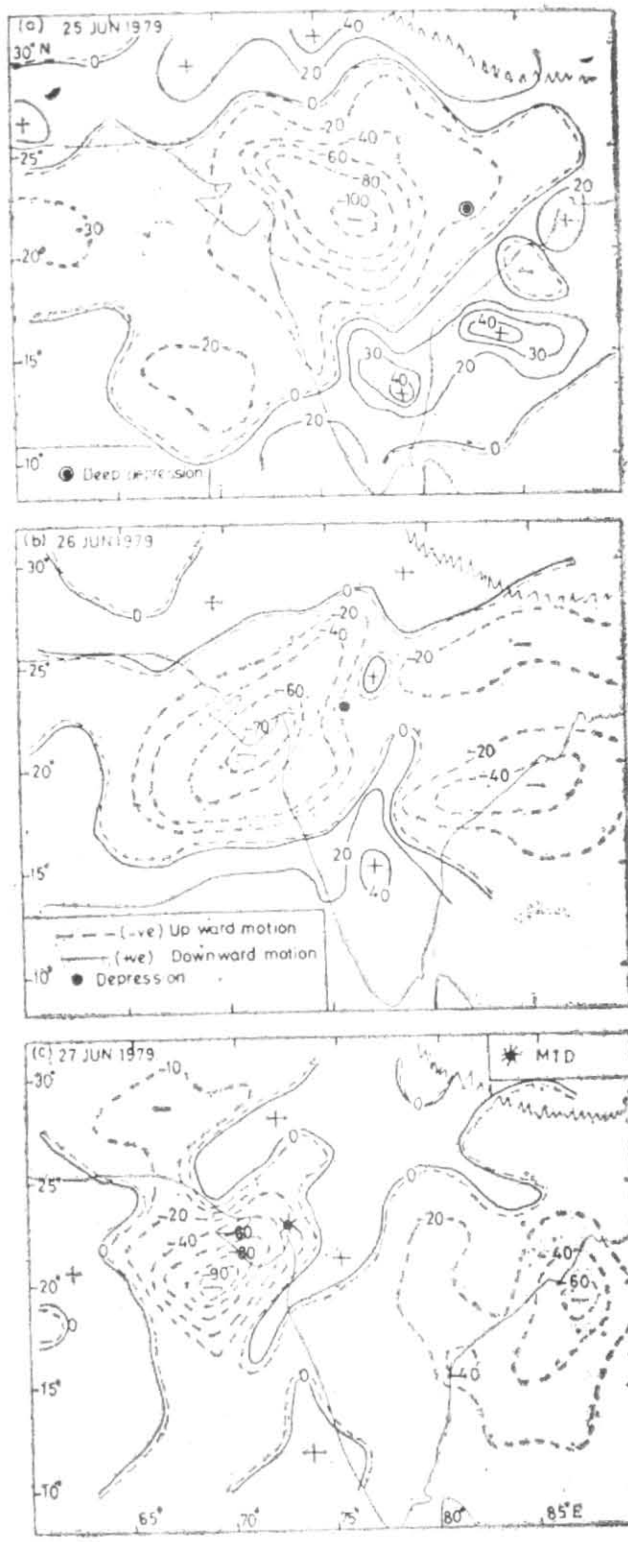
Land-sea thermal contrasts (and, perhaps, also orography) maintain a quasi-stationary wave in both the wind (or pressure or geopotential) and temperature fields, as evidenced by Fig. 8 which shows the longitudinal distribution of zonal anomalies (deviation from zonal mean) of time-mean (1963-1966) temperature and geopotential height at 850 hPa along 20°N relative to the quasi-stationary monsoon trough located at 86°E during June-August (adapted from Saha and Chang 1983). The wave structure appears to have an amplitude of about 1.2°C and a wavelength of about 2200 km in the temperature field and an amplitude of about

15-20 gpm and a wavelength of 2300-2500 km in the geopotential field. A most characteristic feature of Fig. 8 appears to be a positive phase difference between the two fields (a phase difference is regarded as positive or negative according as the warmest temperature anomaly appears to the west or the east of the trough). It is easy to see that a positive phase difference brings about warm advection from the north to the west of the trough and cold advection from the south to the east and thus helps to maintain the trough. A negative phase difference will have the opposite effect, *i.e.*, it will weaken the trough. Now, when a monsoon depression which usually develops in the trough zone moves westward, it has to move first through the warm sector and then through the cold sector which lies farther to the west and then a second warm sector which lies still farther to the west. Fig. 9 presents the longitudinal distribution of zonal anomaly of temperature relative to the centre of the present depression at 700 hPa on 25, 26 and 27 June. It shows that on 25 June the centre of the depression more or less coincides with the longitude of the warmest temperature anomaly. In this position, the depression is in a neutral state, *i.e.*, it is neither developing nor dissipating. The situation appears to have changed by 26 June when it appears to have the warmest temperature anomaly to the east of the centre and the coldest temperature anomaly to the west. This marks a dissipating stage. However, the situation changes rapidly on 27 June when a pronounced warmest temperature anomaly appears to the west of the centre ensuring fresh warm advection from the north for re-development of the system. The re-development process may, perhaps, be explained as follows :

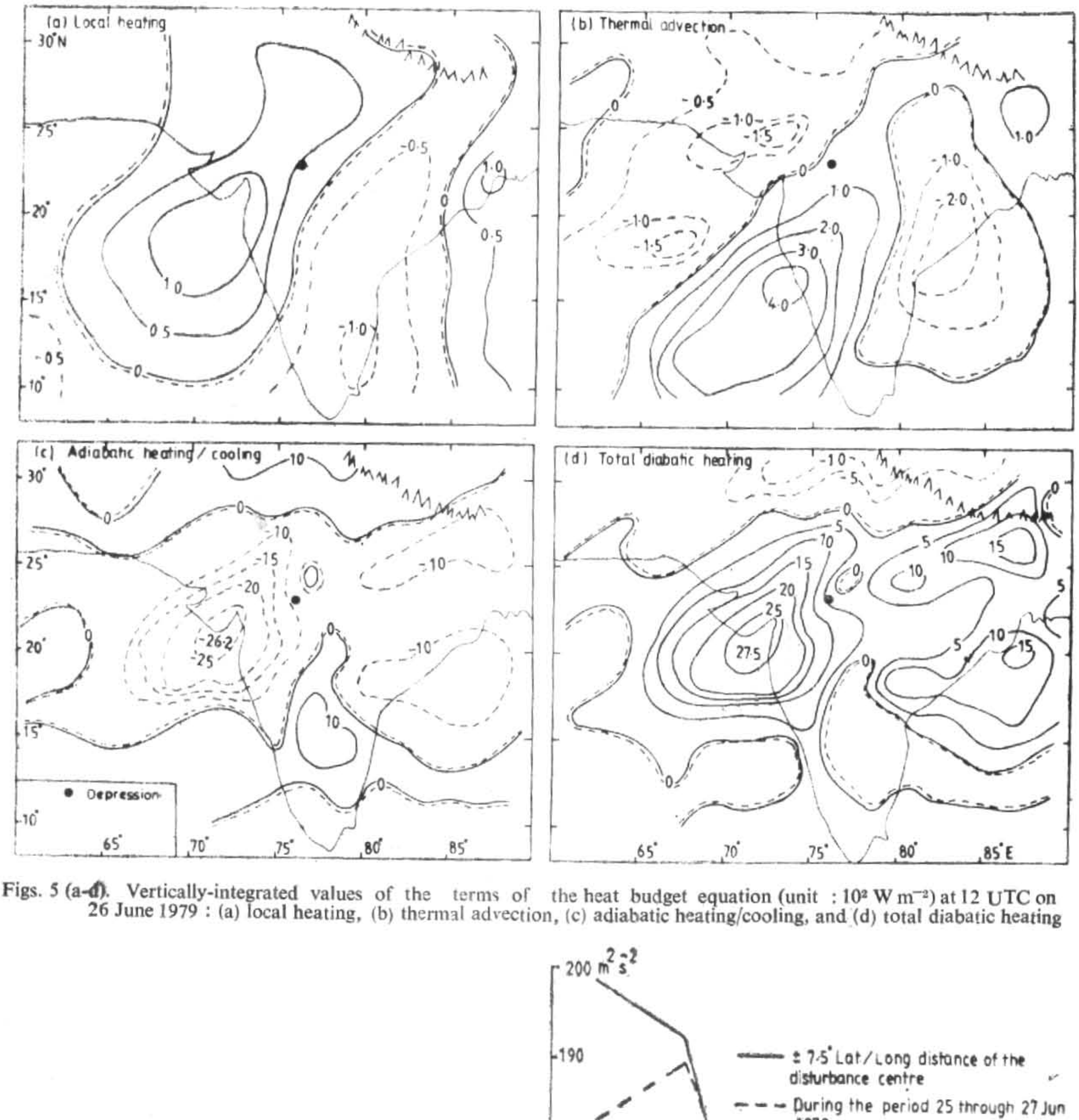
On 27 June, when the warmest temperature anomaly was on the west of the centre with warm advection due to the northerlies in the western half of the depression and cold advection due to the southerlies in the eastern half, there is an increase of differential heating in either half of the depression (east-west direction). This strengthens the depression on 27 June. However, on 26 June, with the warm anomaly being to the east of the centre of the depression, the differential heating decreases due to thermal advection inhibiting the growth or even weakening the system.

(*ii*) *Influence of sub-tropical westerly troughs*

It is well-known (*see, e.g.*, Saha and Chang 1983) that sub-tropical westerly troughs that move eastward across northern India and adjoining Tibetan region occasionally interact with westward-propagating monsoon depressions over the Indian region if any present. As it would be evident from Fig. 3, a sub-tropical westerly trough with its associated cold and warm sectors interacted with the present depression and when the warm sectors of both the disturbances merged with each other, there was strong warm advection from the north to the west of the monsoon disturbance on all the days, as evident from Figs. 10 (a & b) which show the vertically-integrated total thermal advection in the field of the depression on 25 and 27 June respectively and Fig. 5(b) which shows the advection on 26 June. The daily distribution shows warm advection to the west of the disturbance centre and cold advection to the east/southeast on all the days, though the magnitude of both warm and cold advection gets reduced somewhat on 26 June compared to the other two days. It is our inference that it is this continued warm advection to the west of the disturbance centre that helped the disturbance to materially overcome the weakening effect of the cold sector of the basic monsoon field on 26 June and led it to a warm zone on 27 June.



Figs. 4 (a-c). Distribution of vertical velocity (unit : 10^{-4} hPa s^{-1}) at 500 hPa at 12 UTC on:(a) 25, (b) 26 and (c) 27 June 1979. Upward motion by negative (- - -) downward motion by positive (——)



Figs. 5 (a-d). Vertically-integrated values of the terms of the heat budget equation (unit : 10^2 W m^{-2}) at 12 UTC on 26 June 1979 : (a) local heating, (b) thermal advection, (c) adiabatic heating/cooling, and (d) total diabatic heating

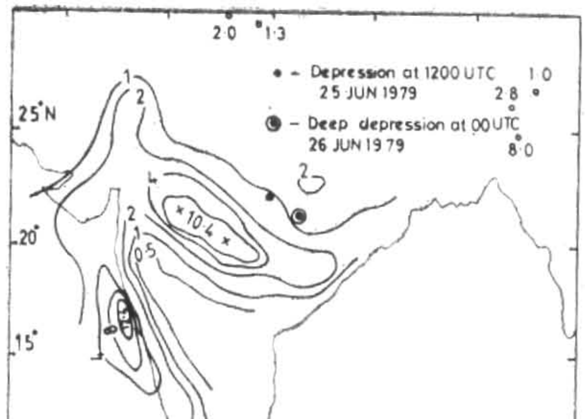


Fig. 6. Distribution of 24 hours rainfall (cm) measured at 03 UTC on 26 June 1979

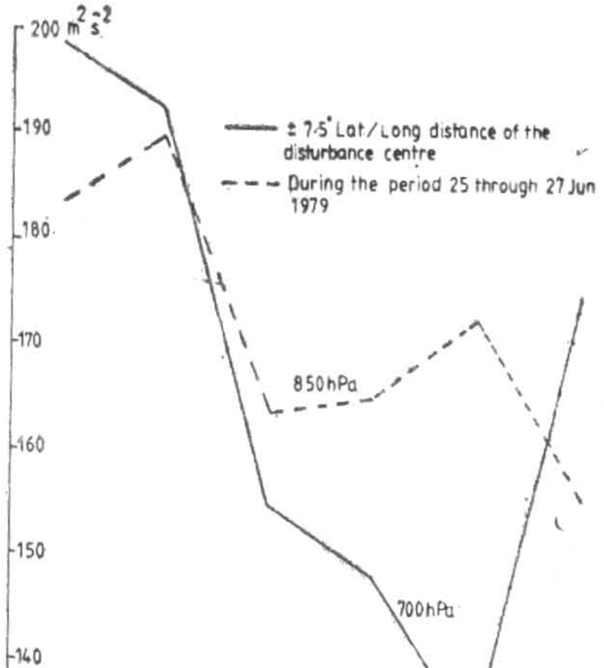


Fig. 7. Daily values of mean square velocity (unit : m^2 s^{-2}) of winds over area within ± 7.5° Lat.-Long. distance of the disturbance centre at 700 hPa(———)and 850 hPa (- - - -)during the period 25 through 27 June 1979

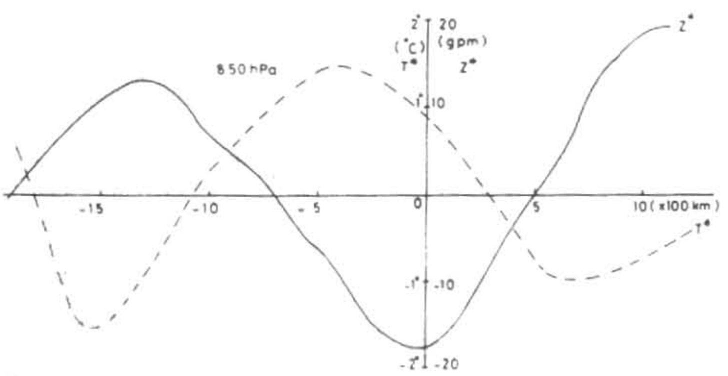


Fig. 8. Longitudinal distribution of zonal anomaly (deviation from zonal mean) of time-mean (1963-1966) summer monsoon (June-August) temperatures and geopotential heights at 850 hPa along 20° N relative to the mean monsoon trough located at 86° E

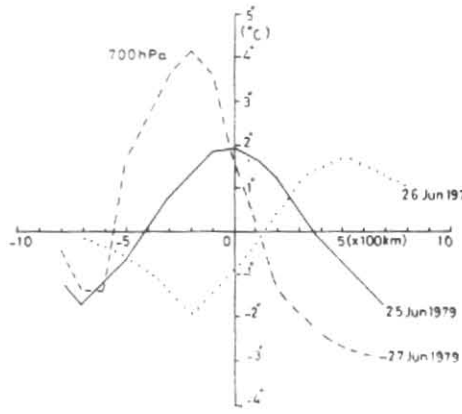
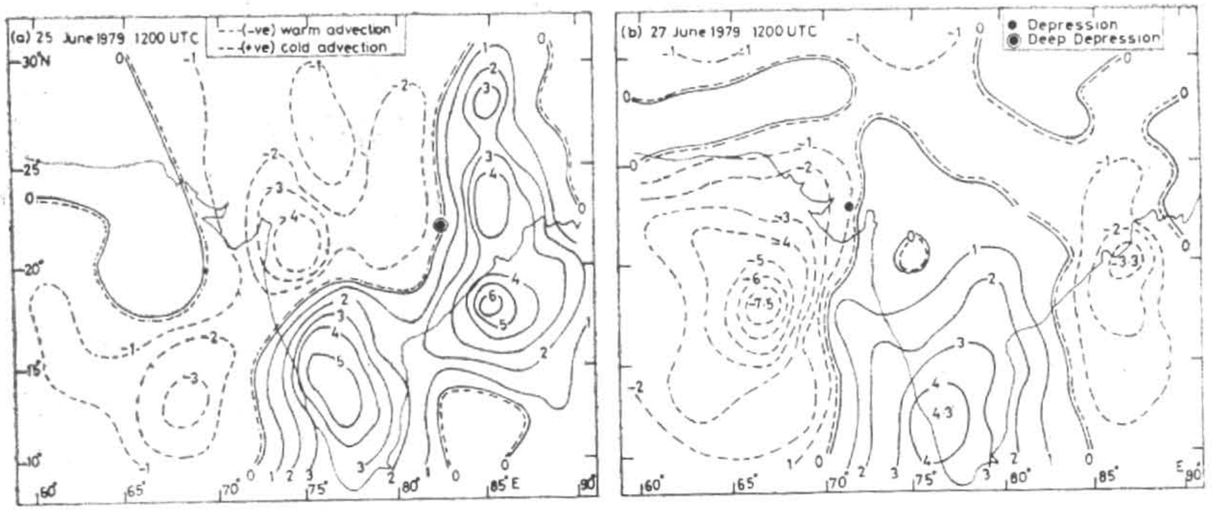


Fig. 9. Longitudinal distribution of zonal anomaly (deviation from zonal mean) of temperature (°C) at 700 hPa relative to the depression centre at 12 UTC on 25-27 June



Figs. 10 (a & b). Distribuion of vertically-integrated total thermal advection (unit : 10^2 W m^{-2}) at 12 UTC on : (a) 25, and (b) 27 June 1979. Negative values (— — —) warm advection and positive values (———) cold advection

(*iii*) *Interaction with a new Bay depression*

A new low pressure system entered the Bay of Bengal from the land area to the east on 26 June and its presence over the Bay on 27 June is clearly seen in Fig. 3. In what way, did the new comer interact with the depression over India ? Our analysis suggests that it had a debilitating influence on the depression in two ways : (*i*) the low-level westsouthwesterly moist winds which were converging onto the depression were partially diverted towards the Bay of Bengal, and (*ii*) the warm advection from the north (from the warm sector of the sub-tropical westerly trough) was now divided between the two disturbances. These are clearly shown in Fig. 3.

Current thinking emphasizes the role of condensation heating in intensification of tropical disturbances via a cooperative mechanism between the disturbance field and its ensemble of cumulus clouds, which has been called Conditional Instability of the Second Kind (CISK) (Charney and Eliassen 1964). However, the exact manner in which intensification occurs is not clear. If it is due to condensation heating, it should occur over the southwestern quadrant of the depression where diabatic heating is the maximum. But observations show that the rate of surface pressure fall is maximum over the western or the northwestern quadrant where the atmosphere is adiabatically warmed by subsidence in the descending branch of the Hadley circulation. It thus seems likely that the intensification due to condensation warming is not effected directly over the condensation zone where diabatic heating is almost totally compensated by adiabatic cooling due to penetrative convection but occurs over the subsidence warming zone of the Hadley circulation which is forced by condensation heating. Thus, alongwith horizontal thermal advection, the role of condensation heating in the intensification process may prove to be quite important.

5. Transformation into a mid-tropospheric disturbance

Following a pioneering observational study of a mid-tropospheric disturbance over the Arabian Sea by Miller and Keshavamurthy (1968) who called it a mid-tropospheric cyclone, there have been several theoretical studies (*e.g.*, Mak 1975, 1983; Carr 1977, Brode and Mak 1978) into the origin of this kind of disturbances in which the maximum kinetic energy resides not at low levels as in conventional monsoon depressions but at a mid-tropospheric level, near 700 hPa. Sharma *et al.*

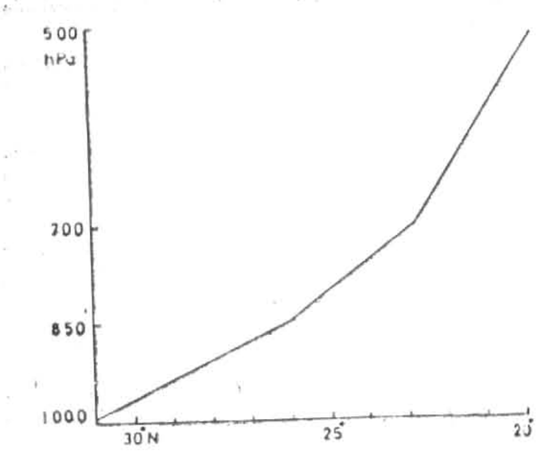


Fig. 11. Latitudinal positions of the time-mean (1963-1966) monsoon trough at different pressure surfaces along 70°E longitude during July (*after* Boogaard 1977)

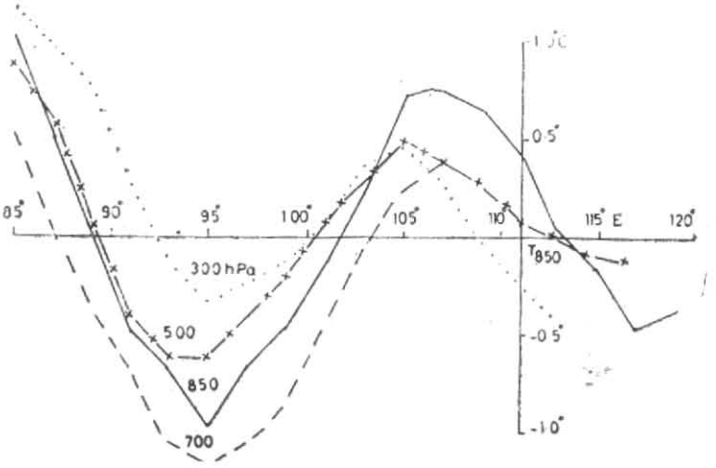


Fig. 12. Longitudinal distribution of zonal anomaly (deviation from zonal mean) of ten-year (1976-1985) mean July temperature (°C) along 20°N at different pressure surfaces relative to the location of the mean monsoon trough at 111°E

(1980) who studied some aspects of the present depression stated that it filled up over central India on 26 June under the weakening influence of a new depression over the Bay of Bengal and that the formation of an MTD over the Arabian Sea was quite a separate phenomenon, which grew out of a pre-existing disturbance over this sea during the period 22 through 26 June. According to them, the new depression over the Bay of Bengal, while it helped to weaken the depression over central India, might have been responsible for the development of the MTD by strengthening the zonal wind over the Arabian Sea. The present study does not support this view of the formation of the MTD over the Arabian Sea on 27 June. No evidence is found, either from synoptic data or satellite cloud imagery, of the pre-existence of a disturbance during period 22 through 26 June which might have developed into an MTD. On the other hand, our study clearly establishes the continuity of the MTD with the present depression (Figs.1 and 2). According to the present authors, the formation of the MTD on 27 June was favoured by two distinct factors : (*i*) the entry of the centre of the present depression into the warm sector of the basic monsoon field over northeastern Arabian Sea (Figs. 8 & 9), and (*ii*) the coupling of the warm sector of an eastward-propagating sub-tropical westerly trough in middle and upper troposphere with the warm sector associated with the westward-propagating monsoon depression [Fig. 3(b)]. Fig. 11, adapted from Boogaard (1977) (*see*, also, Saha and Saha 1990), shows that the monsoon trough over the northeastern corner of the Arabian Sea appears at an elevated surface around 700 hPa, thus facilitating the formation of an MTD at this mid-tropospheric level. In the case of the present depression, Fig. 3 testifies to occurrence of strong warm and cold advections by the meridional components of the winds at 500 hPa on 27 June. Theoretical studies, referred to earlier, have also emphasized the importance of the meridional components of the wind in the formation of mid-tropospheric disturbances over the Arabian Sea.

With the sub-tropical westerly trough and the monsoon depression moving in opposite directions, the coupling of their warm sectors ended rapidly and the MTD weakened and became unimportant from 28 June onward.

6. Variations at other longitudes

Situations similar to the present case may arise at some other longitudes, *e.g.,* over southeast Asia where westward-propagating low pressure system from the monsoon trough zone over south China Sea or typhoons drifting from areas farther to the east cross the Vietnam-coast and move inland. As over the Indian region, a majority of these disturbances weaken and die within a short distance of the coast but some (about 20-25%) are able to get through and emerge over the Bay of Bengal where they may develop into new depressions (*see, e.g.,* Iyer 1931, Koteswaram and Bhaskara Rao 1963, Ramanna 1969, Saha *et al.* 1981). Here also, it seems that the variations in the intensity of the disturbances are determined by the characteristics of the basic monsoon field and thermal advections from the warm and cold sectors associated with the sub-tropical westerly troughs which move eastward across China, in the same manner as over the Indian region. Hilly and rough terrain of southeast Asia can be expected to have a general weakening influence on the westward movement of monsoon low pressure systems.

The thermal structure of the basic monsoon field over southeast Asia is shown in Fig. 12 which presents the longitudinal distribution of zonal anomaly of 10-year (1976-1985) mean July temperature at 850, 700, 500 and 300 hPa along 20°N relative to the quasi-stationary monsoon trough at about 111°E over south China Sea. It bears close resemblance to that in Fig. 8 which relates to a shorter period of climatology and to 850 hPa only.

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