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Formation and structure of a monsoon revival depression over the Bay of Bengal during a 'break' monsoon period

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सार — संयुक्त भारत-सोवियत मानसून अभियान में भाग लेने वाले सोवियत रूस के चार समुद्र वैज्ञानिक अनुसंधान जहाजों में बहुभुजीय द्वारा छह घंटेवार राविनसोन्दे उड़ानों की सहायता से अगस्त 1977 के मानसून 'व्यवधान' के दौरान बंगाल की खाड़ी के ऊपर मानसून पुनः प्रवर्तन अवदाबों (मा.पु.अ.) की उत्पति और बनावट का अध्ययन किया गया है। यह देखा गया है कि बर्मा के अराकान तट को पार करते हुए पश्चिम दिशा में बढ़ते हुए उच्च स्तरीय पूर्वी लहरें (उ. पू. ल.) के प्रभाव के कारण पूर्व मध्यवर्ती खाड़ी (पू. म. खा.) के ऊपर प्रारम्भ में एक मध्य क्षोम मण्डलीय चक्रवात (म. क्षो. च.) विकासित हुआ और म. क्षो. च. के उत्तर पूर्व दिशा में चले जाने के चौबीस घंटे से अधिक समय बाद वह भूमि पर एक मा. पु. अ. के रूप में उत्तरा। उच्च स्तरीय पूर्वाओं और मानसून पछुवाओं के बीच पश्चिम-पूर्व अंतपृष्ठ (प. पू. अं.) पर एक म. क्षो. च. उत्पन्न हुआ और उ. पू. प. में उच्च स्तरीय चक्रता अभिवहन के प्रभाव के कारण वह ऊपर की ओर और नीचे की ओर विकसित हुआ। समुद्र स्तर पर उतरने से थोड़े पहले तक यह दोलनाकारी था जिसका ऊर्ध्वाधर विस्तार 200 मिलीबार तक एक संकड़े क्रोड के रूप में था। मध्य क्षोममंडल में म. क्षो. च. निम्न क्षोममण्डल में मा. पु. अ. के दक्षिण-पश्चिम में स्थित था और इसका क्रोड कोष्ण था जबकि मा. पु. अ. का क्रोड शीतल था। यह अभिधारणा है कि सभी मानसून अवदाब समरूप उद्गम और बनावट के होते हैं।

ऊर्ध्वाधर में व्यवधित मानसून कोशिका की बनावट और म. क्षो. च. तथा उ. पू. ल. के आपसी अंगीकार द्वारा मा. पु. अ. के निर्माण की विधि के नियमानुसार दर्शाया गया है। यह दिखाया गया है कि व्यवधान के बाद मानसून का पुनःप्रवंतन दक्षिण खाड़ी से उतर की ओर चलने वाले नए महासागरीय अन्तः भूमध्यरेखीय कटिबन्ध (म. अ. भू. क.) के संघनन के कारण न होकर एक उ. पू. ल. के प्रभाव में महाद्वीपीय म. अ. भू. क. के बर्मा से उतरी खाड़ी में वापसी द्वारा होता है।

ABSTRACT. Formation and structure of a monsoon revival depression (MRD) over the Bay of Bengal during the monsoon 'break' of August 1977 are studied with the aid of six hourly rawinsonde ascents made by a polygon of four oceanographic reasearch vessels of the USSR participating in the joint Indo-USSR Monsoon '77 expedition. It is found that a mid-tropospheric cyclone (MTC) initially developed over the East Central Bay (ECB) under the influence of an upper easterly wave (UEW) moving westwards across the Arakan coast of Burma and descended to the surface as MRD after the MTC had moved northwestwards for more than 24 hours. The MTC formed at the west-east interface (WEF) between the monsoon westerlies and the upper easterlies and developed upwards and downwards under the influence of the upper vorticity advection in the UEW. It was oscillatory, reaching its maximum vertical extent upto 200 mb (as a narrow core) just before it descended to the sea level. The MTC in the mid-troposphere was located to the southwest of the MRD in the lower troposphere and was warm cored while the MRD was cold cored. It is postulated that all monsoon depressions have similar origins and structures.

The structure of a break mosoon cell in the vertical and the mechanism of the formation of the MRD by superposition of the MTC and UEW are postulated schematically. It is pointed out that monsoon revival after a break takes place not by northward movement of a fresh oceanic intertropical zone of convergence (OITC) from the south Bay but by the return of the continental OITC from Burma to the north Bay under the influence of a UEW.

1. Introduction

When the monsoon trough (MT) over north India shifts to the Himalayas, there is a general cessation or 'break' in monsoon rains over the plains of India although heavy rains continue over the foot hills, flooding the Himalayan rivers. The major synoptic features indentified in the break monsoon are : the southwards extension over Pakistan of a westerly trough (WT) in the extratropical westerlies (Ramaswamy 1962) and westward moving lows or mid-tropospheric cyclones (MTC) over the south Bay and the south Peninsula causing showers there (Koteswaram 1950). The mechanisms for the revival of monsoon activity over the Bay are westward moving low pressure waves across Burma, intensification of MTC to a monsoon depression (MD) over the central Bay (Koteswaram 1950) and extension of a WT in the upper troposphere from China to the northwest Bay (Prasad and Rao 1974). We call the monsoon depressions (MD) reviving the monsoon activity over the Bay as monsoon revival depressions (MRD) analogous to the monsoon onset depressions (MOD) over the southeast Arabian Sea.

In a monsoon break in the joint Indo-USSR Monsoon '77 experiment, four oceanographic research ships of USSR obtained six hourly rawinsonde observations upto 30 km a. s. l. in a stationary polygon over the central Bay during the formation and movement of a MRD there. Raman *et al.* (1978) who analysed these observations found a drop in the vertical wind shear (VWS) between the zonal winds at 850 mb and 200 mb before the formation of the MRD and considered such a decrease as a precondition for the generation of a MD and gives advance intimation of it. Koteswaram and George (K. G. 1958) had postulated that when the upper vorticity advection (UVA) or divergence ahead of an upper easterly wave (UEW) is superimposed on the MT over the Bay, the latter intensified into a MD. Since zonal wind speed decreases in wave troughs, the observed drop in VWS is a corollary of the hypothesis of K. G. (1958) and not contrary to it.

We, however, make a detailed four dimensional analysis of available observations in the MRD of August 1977 and investigate the mechanism of its formation and intensification.

2. History of the MRD and data used

2.1. *Abbreviations used*

Monsoon trough	MT
Monsoon depression	MD
Monsoon onset depression	MOD
Monsoon revival depression	MRD
Intertropical convergence zone	ITC
Continental intertropical convergence zone	CITC
Oceanic intertropical convergence zone	OITC
ITC (Lower)	LITC
ITC (Upper)	UITC
Mid-tropical cyclone	MTC
Mid-tropical anticyclone	MTA
Upper tropospheric ridge	UTR
Upper tropospheric anticyclone	UTA
Tropical easterly jet	TEJ
Upper easterly wave	UEW

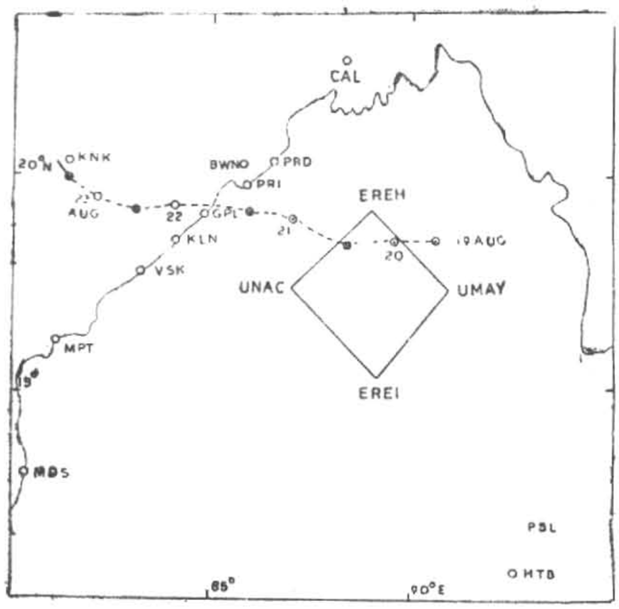


Fig. 1. Track of the monsoon revival depression and location of the USSR research vessels (call signs)

Upper vorticity advection	UVA
Vertical wind shear	VWS
Westerly trough	WT
Heavy rainfall zone	HRZ

A—Anticyclone, W—Warm, K—Cold.

2.2. A monsoon break started over India on 12 August with the usual shift of the MT to the Himalayas and continued for about a week. On the night of 17th a MTC formed over the east central Bay (ECB), moved northwestwards over the ship polygon and descended to the sea level off the Arakan coast of Burma at 00 GMT of 19th (19/00GMT) as MRD. Moving westwards over the northern-half of the polygon for a day, the MRD turned westnorthwestwards and crossed the Orissa coast near Gopalpur on the night of 21st. The four USSR ships took 6 hourly rawinsonde and oceanographic observations from 13th to 20th after which they moved away. The positions of the ships with call signs UMAY, EREH, EREI and UNAC as well as the track of the MRD are shown in Fig. 1. The upper air observations over these ships and 5 coastal observatories of the India Meteorological Department (IMD) and six hourly synoptic charts over the Asian monsoon area have been used in this investigation.

3. Vertical time sections

Vertical time section over the ships from sea level upto 100 mb, during 17/00GMT-20/06GMT are presented in Figs. 2 (a-d). Stratospheric data have been omitted as there were no significant changes there relevant to the MTC or MRD. Isotachs, isohumes and UEWs are marked on the figures. The

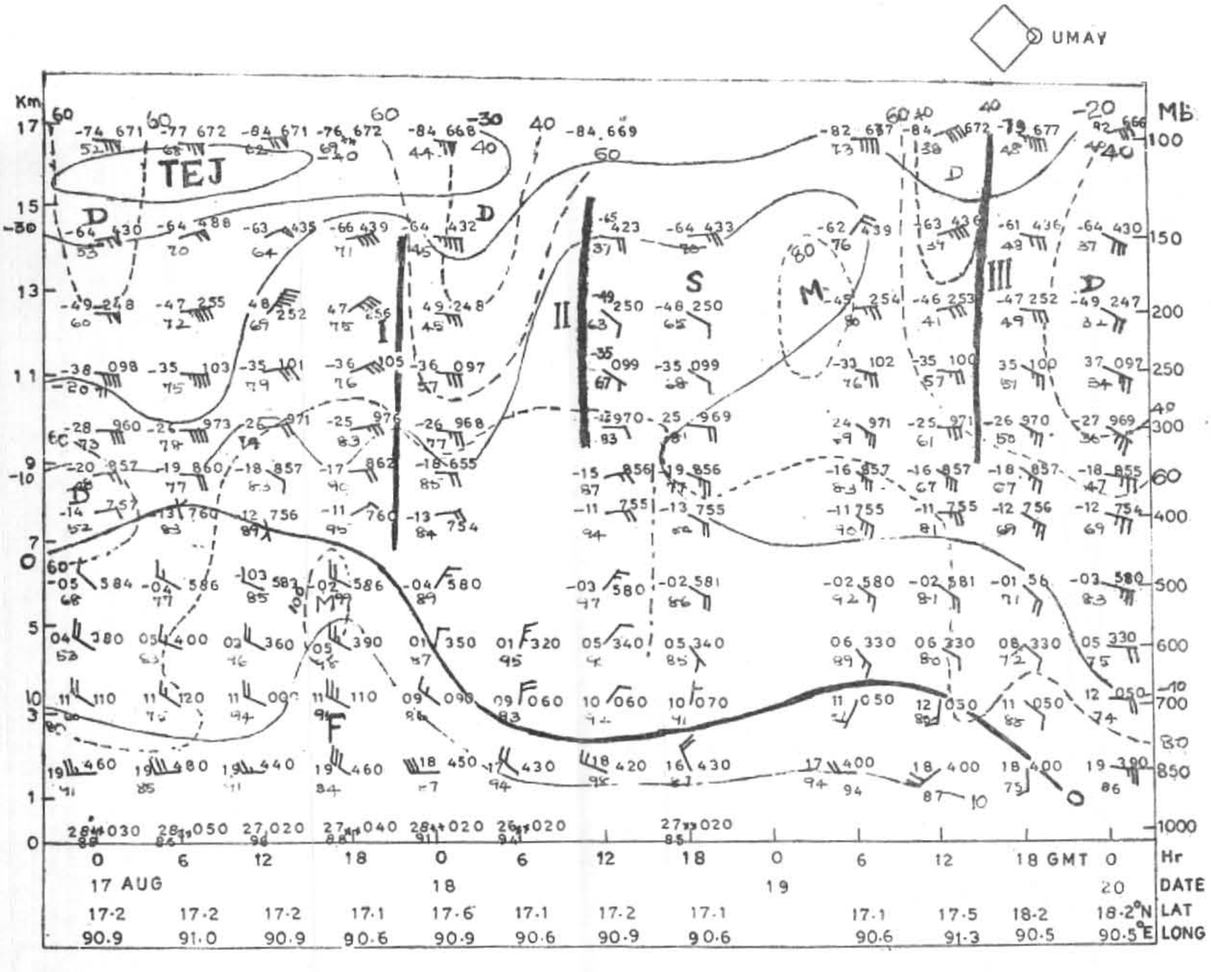


Fig. 2(a). Vertical time section over the USSR research vessels. Full lines—isotachs (m/s); dash lines—isohumes(%); Thick vertical lines—axes of UEWs; dash dot vertical lines—axes of MTC, F—fast, S—Slow, M—Moist, D—Dry.

zero isotach indicates the west-east interface (WEF). Dash-dot lines are axes of the cyclonic vortices.

3.1. *Ship UMAY* (17°N, 90°E— *Fig. 2a*)

The ship was the easternmost in the polygon and was located about 150 km south of the developing MRD. The wind flow from 17/00GMT to 17/18GMT was westerly upto 500 mb and easterly aloft with the WEF near 400 mb. The monsoon westerlies veered from W to NW and weakened with height while the tropical easterlies strengthened to about 40 mps at the Tropical Easterly Jet (TEJ) near 125 mb (15 km) (Koteswaram 1958). UEW-I passed over the ship between 400-150 mb at 17/21GMT and easterly isotachs rose in it. Wind speeds at 200 mb fell from 30 mps at 17/00GMT to about 15 mps at the wave trough. The WEF descended thereafter to about 800 mb at 18/06GMT indicating the passage of the Intertropical Convergence Zone (ITC) over the ship and the formation of a MTC to its southeast. The axis of the MTC passed over the ship between 600 and 350 mb at 18/15GMT. The MRD formed at 19/00GMT to the north of the ship and extended from sea level to about 700 mb. As the MRD moved to the west of ship after 17/21 GMT the WEF descended to sea level by 19/21GMT.

The rawin ascent at 17/06GMT was short but the weak southeasterlies at 250-200 mb during 17/12-18 GMT indicated the general weakening of the winds in the upper troposphere and the passage of UEW-II at about 17/12GMT. The easterlies between 400-200 mb instead of strengthening with height as usual, weakened during 17/12-18GMT indicating the reversal of thermal wind due to the warm core of the MTC south of the ship. The TEJ also weakened after 18/00GMT and wind speeds at 100 mb fell to about 20 mps from 19/06 GMT onwards.

Isohumes are used to trace the transport of moisture in the atmosphere. 80% relative humidity (RH) isohume rose from about 800 mb at 17/00GMT to 300 mb at 17/12GMT ahead of UEW-I indicating ascent of moist air from the lower to the upper troposphere. Behind UEW-I there was a sharp drop of RH above 300 mb due to descending currents there and when UEW-II approached the ship the 60% isohume rose to 150 mb. The 80% isohume remained near 300 mb and RH was 65-68% to the rear of UEW-II due to descent in the upper troposphere during the formation of MRD at 19/00GMT. With the approach of UEW-III there was a rise of RH to about 80% near 200 mb and decrease to less than 60% during and after the passage of the wave. The 80% isohume lowered to 650 mb at 19/18GMT and 800 mb at 20/00GMT as the MRD moved away to the west of the ship. The configuration of the 80%

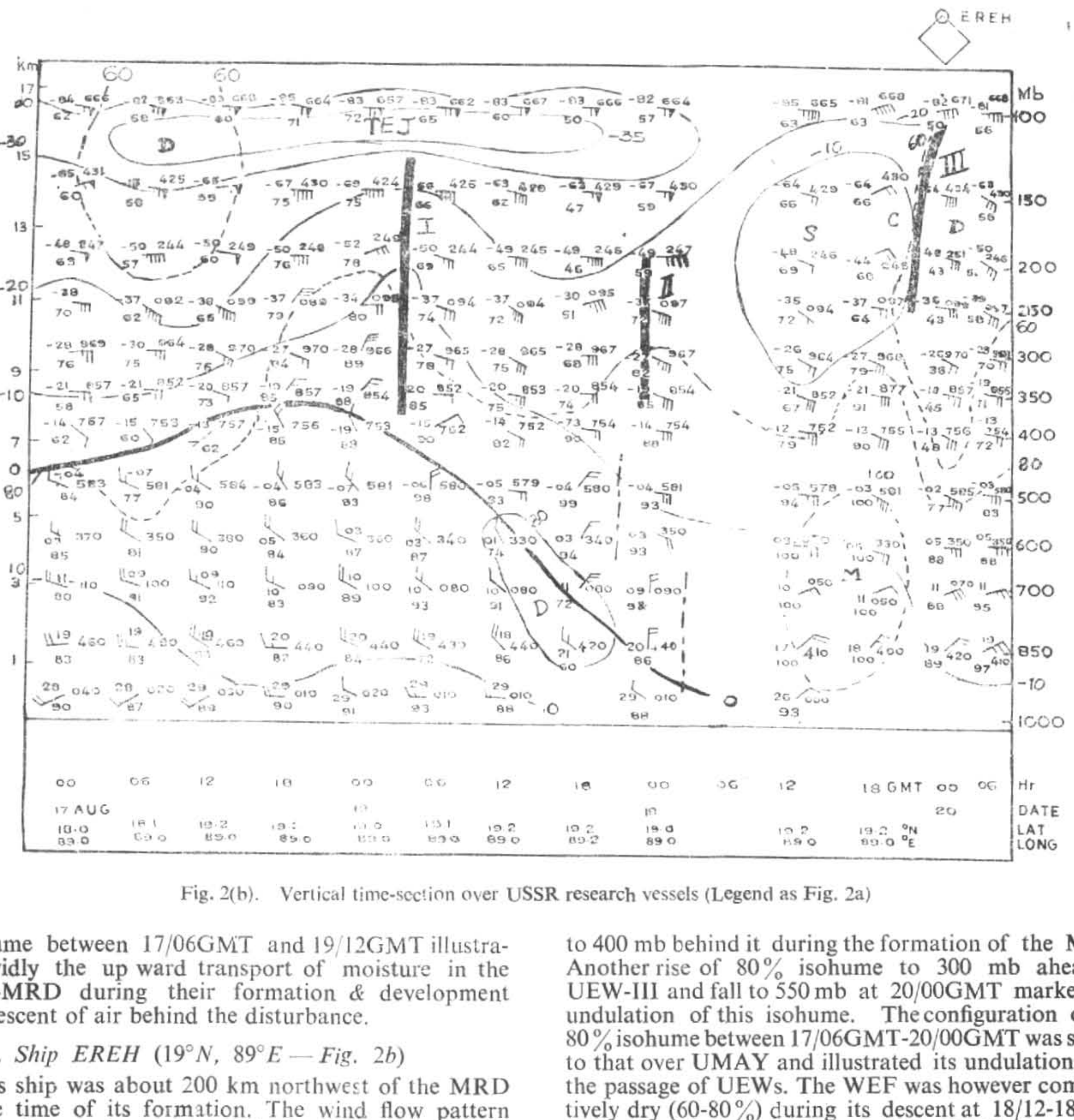


Fig. 2(b). Vertical time-section over USSR research vessels (Legend as Fig. 2a)

is ohume between 17/06GMT and 19/12GMT illustrates vividly the up ward transport of moisture in the MTC-MRD during their formation & development and descent of air behind the disturbance.

3.2. *Ship EREH* (19°*N*, 89°*E* — *Fig.* 2*b*)

This ship was about 200 km northwest of the MRD at the time of its formation. The wind flow pattern was similar to that over UMAY. UEW-I passed over the ship at 18/03GMT between 400-150 mb. WEF descended thereafter to sea level at 19/06GMT after the MRD had formed. The ITC passed over the ship between 18/03GMT and 19/00GMT. The MTC moved westwards to the south of the ship between 600-400 mb at 18/21GMT when UEW-II between 350-200 mb also passed over. There were no observations at 19/06GMT but the northerlies between 850-700 mb at 19/00GMT indicated that the MRD extended from the sea level to 700 mb. Upper tropospheric winds weakened after 19/00GMT and thermal wind between 400-200 mb reversed was over UMAY due to the location of the warm core of the MTC south of the ship. UEW-III passed over at 19/21GMT between 200-100 mb. TEJ (30-35 mps) persisted till 19/00GMT after which it weakened to 20 mps at 100 mb. 80% isohume rose from 550 mb at 17/06GMT to 200 mb in UEW-I and fell to 400 mb at 19/12GMT in the rear of UEW-I. It again rose to 300 mb in UEW-II and lowered to 400 mb behind it during the formation of the MRD. Another rise of 80% isohume to 300 mb ahead of UEW-III and fall to 550 mb at 20/00GMT marked the undulation of this isohume. The configuration of the 80% isohume between 17/06GMT-20/00GMT was similar to that over UMAY and illustrated its undulations with the passage of UEWs. The WEF was however comparatively dry (60-80%) during its descent at 18/12-18GMT as the ship was located in the MTA (Mid-tropospheric anticyclone) over the Bay with descent in the mid-troposphere. In the northern sector of the MRD, RH was 100 % during 19/12-18GMT from sea level to 500 mb with comparatively drier air (60-80%) in the upper troposphere.

3.3. *Ship EREI* (15.2°*N*, 89.1°*E* — *Fig.* 2*c*)

This ship sampled the westerly monsoon current in the MRD in the lower troposphere and the structure of the MTC which came over it in the upper levels. UEWs I, II and III passed over at 18/06GMT, 18/21GMT and 19/21GMT respectively. The WEF rose from about 450 mb between 17/00-18GMT to 350 mb in UEW-I, 300 mb in II and 350 mb in III. The undulations of the WEF responded to the ascent and descent of air before and after the passage of each UEW and indicated the level of the top of the MTC after its formation at 17/18GMT. At 18/21GMT the MTC reached about 300 mb with a narrow core extending upto 200 mb as inferred from the

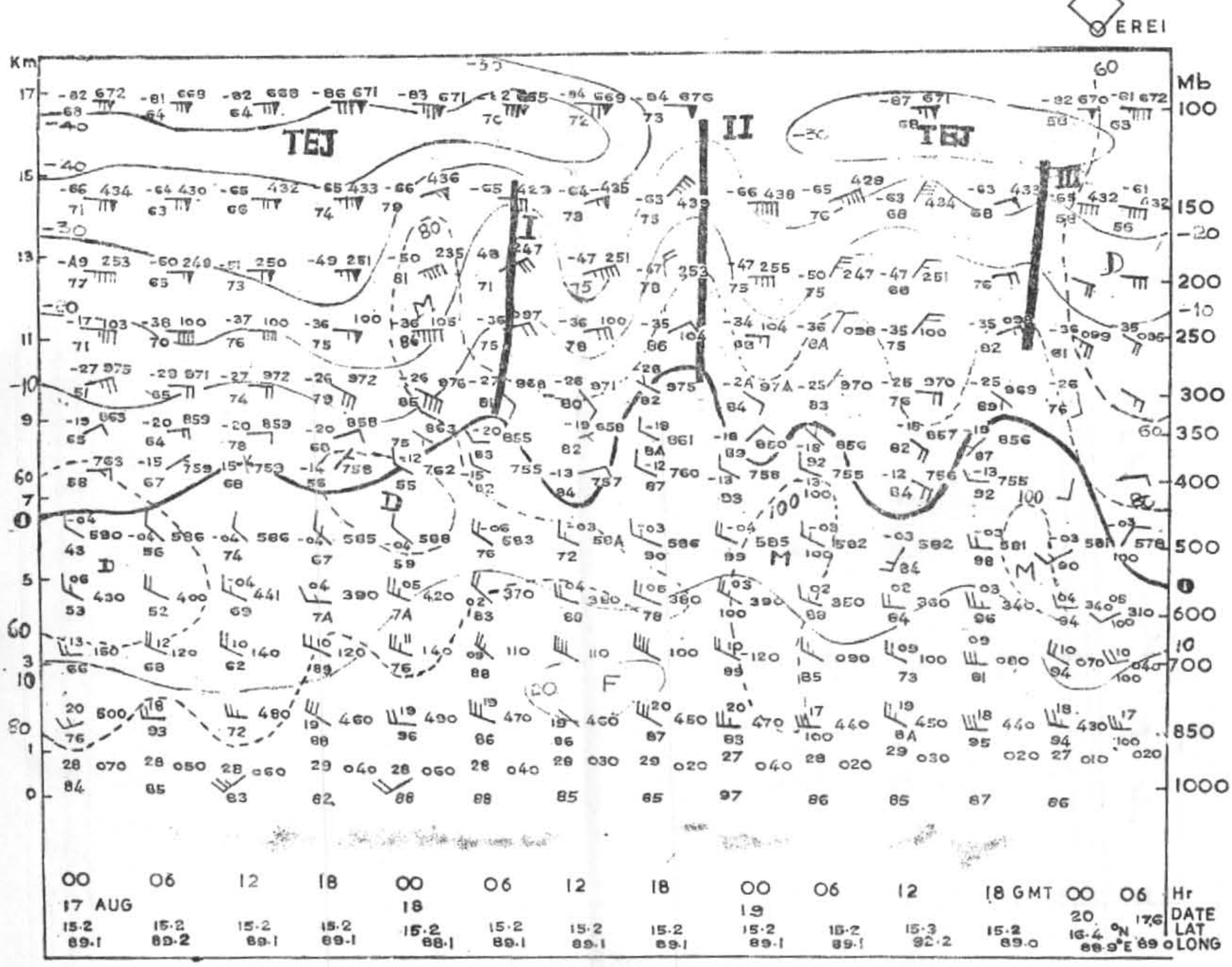


Fig. 2(c). Vertical time-section over USSR research vessels (Legend same as Fig. 2a)

northerly wind at this level. TEJ (30-40 mps) persisted over the ship except at 18/18GMT when the MTC reached its highest vertical extent and the winds in the upper troposphere below 150 mb weakened to less than 10 mps during the formation of the MRD as over other ships.

The 80% isohume was confined to about 850 mb upto 17/12GMT after which it rose gradually to 600 mb at 18/18GMT. The WEF however was comparatively dry (RH less than 60%) due to descent in the MTA. The upper troposphere was more moist (65-70%). As at other ships the 80% isohume rose at 18/00GMT ahead of UEW-I in the upper troposphere and oscillated between 300-200 mb in response to the passage of the upper waves. 100% RH at 19/00-06GMT between 850-400 mb in the SW sector of the MRD is significant as this is generally the heavy rainfall zone (HRZ).

3.4. *Ship UNAC* (17.3°*N*, 87°*E—Fig. 2d*)

This ship was westernmost in the polygon being about 400 km westsouthwest of the developing MRD. The wind flow pattern was similar to that over the other ships. UEW, I, II and III passed over at 18/09GMT, 19/00GMT and 20/00GMT respectively. Winds in the upper troposphere below 150 mb weakened to 10 mps and less between 18/00GMT and 19/06GMT during the passages of UEWs I & II and below 200 mb at 19/18GMT in UEW-III. The WEF lowered from about 400 mb at 18/21GMT to 650 mb at 19/18GMT and fell to sea level by 20/06GMT indicating the passage of the ITC. A relatively dry layer (RH less than 60%) existed in the MTA at the WEF till 17/18GMT. The 80% isohume rose from 800 mb at 18/00GMT to 200 mb in UEW-I and oscillated between 300-250 mb thereafter. TEJ of 30-40 mps persisted over the ship till 20/00GMT.

4. Vertical wind shears

VWS between the monsoon westerlies at 850 mb and the tropical easterlies in the TEJ at 200, 150, 100 mb respectively are plotted in Fig. 3. The VWS was maximum at 100 mb near the core of the TEJ but its variations were more pronounced at 200 mb where the wind speeds were less. As the variations in the westerly speeds below were small, the changes in VWS were mainly due to the variations in the wind speeds in the TEJ. The times of passage of UEWs over each ship and those of formation of MTC and MRD are marked in Fig. 3 as C and D.

The VWS at 200 mb fell over each ship with the approach of UEW-I but the lowest values were reached at D due to reversal of the thermal wind in the warm core of the MTC. Over EREH at 19/12GMT the VWS fell below zero and the thermal wind reversed in the whole layer 850-200 mb . There was some rise in VWS after the passage UEW-I on account of the increase in the speed of the upper easterlies behind it but VWS

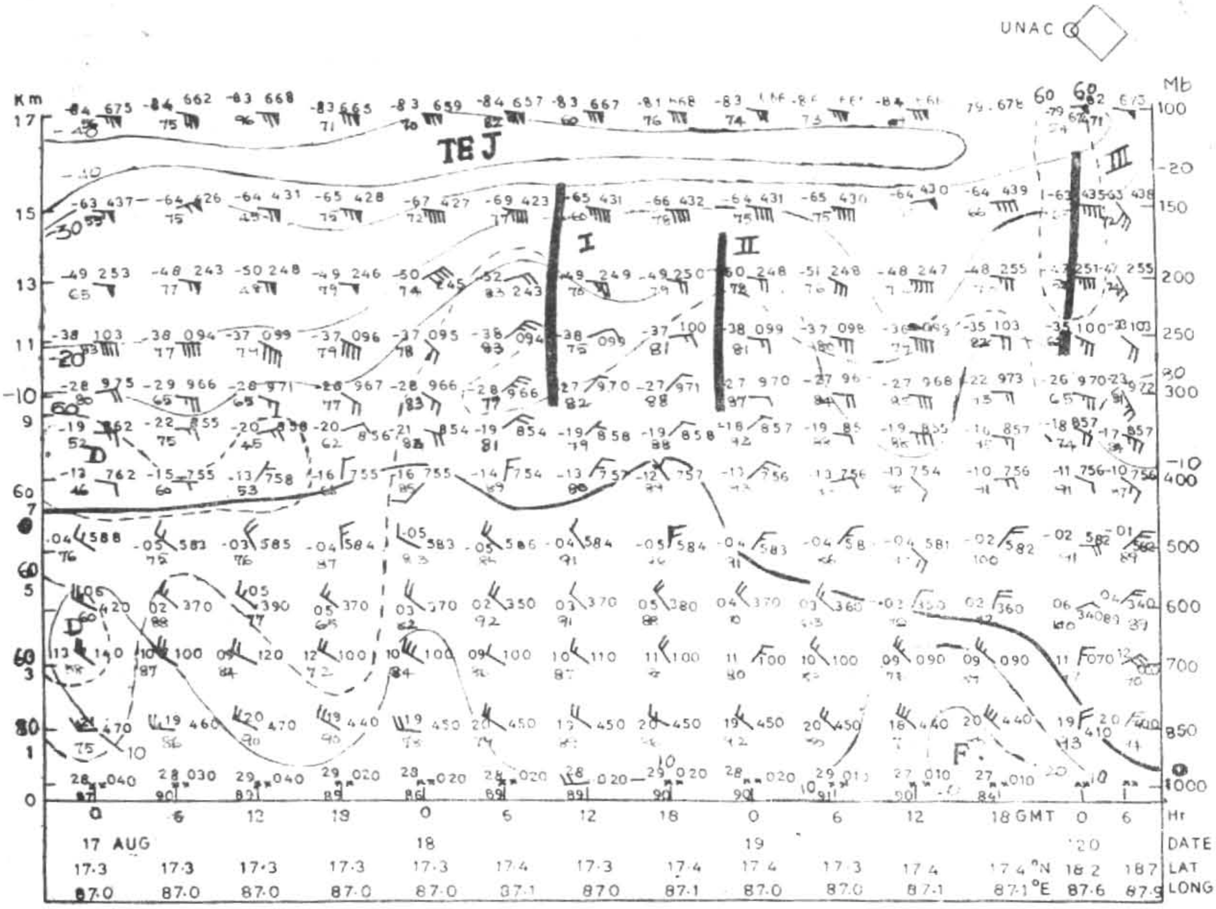


Fig. 2(d). Vertical time-section over the USSR research vessels (Legend same as Fig. 2a)

fell after II and in D. A similar rise after I and fall in II and III occurred over other ships except over EREI where the strengthening of the low level westerlies between 18/00-06GMT compensated for the weakening of the upper easterlies and the VWS remained constant between 18/00-06GMT.

The fall of the VWS before the formation of the MRD was contributed both by the weakening of upper winds in the UEWs and the warm core of the MTC. The fall of the UWS however does not always lead to the formation of a MD. For example a UEW passed over the polygon on 13 Aug soon after the ships started observations and VWS fell over all the ships. The UEW induced a MTC between 700-300 mb which however did not descend to the surface as there was no MT there as required by the mechanism of K.G. (1958). In the present case UEWs I and II induced the shift of the ITC over the Bay and subsequent formation of the MRD.

5. Structure of the cyclonic vortex

Fig. 4 presents streamlines and isotherms at standard isobaric levels (850-100 mb) over the polygon at 12 hourly intervals during 17/00GMT-20/00GMT. As the ships started moving out on 20 Aug, observations at 20/06GMT have been composited with those at 20/0CGMT. Maps of intermediate hours have been omitted except that of 18/18GMT just before the formation of the MRD.

5.1. *The wind vortex*

The wind flow over the polygon at 17/00GMT was W/WNW from 850-500 mb and easterly aloft. As UEW-I approached from the east, the flow at the WEF at 400 mb got perturbed from 17/06GMT onwards and the MTC formed at this level to the southeast of the polygon at 17/18GMT. UEW-I came over the eastern half of the polygon between 350-150 mb at 18/00GMT and the MTC extended between 600-400 mb. By 18/06GMT its top rose to 350 mb and was linked with UEW-I aloft and the base lowered to 700 mb. UEW-I moved over the western-half of the polygon by 18/12GMT and the top of the MTC lowered to 500 mb under the convergent (subsident) rear sector of UEW-I. UEW-II came over the eastern-half of the polygon by 18/18GMT when the MTC also moved over it between 600-300 mb. It was nearly vertical and a narrow core protruded upward to 200 mb with UEW-II aloft. By 19/00GMT, UEW-II moved over the western-half of the polygon and the descent in its convergent rear sector transported cyclonic vorticity downwards to the sea level to form the MRD. The top of MTC also lowered to 400 mb. The MRD in the lower troposphere below 700 mb was generated in the northeast sector of the polygon and the MTC located to the southwest of the MRD indicated the well-known southwestward tilt of the cyclonic vortex of a MD with height.

As UEW-III approached the polygon, the top of the vortex rose to 350 mb by 19/06GMT. By 19/12GMT

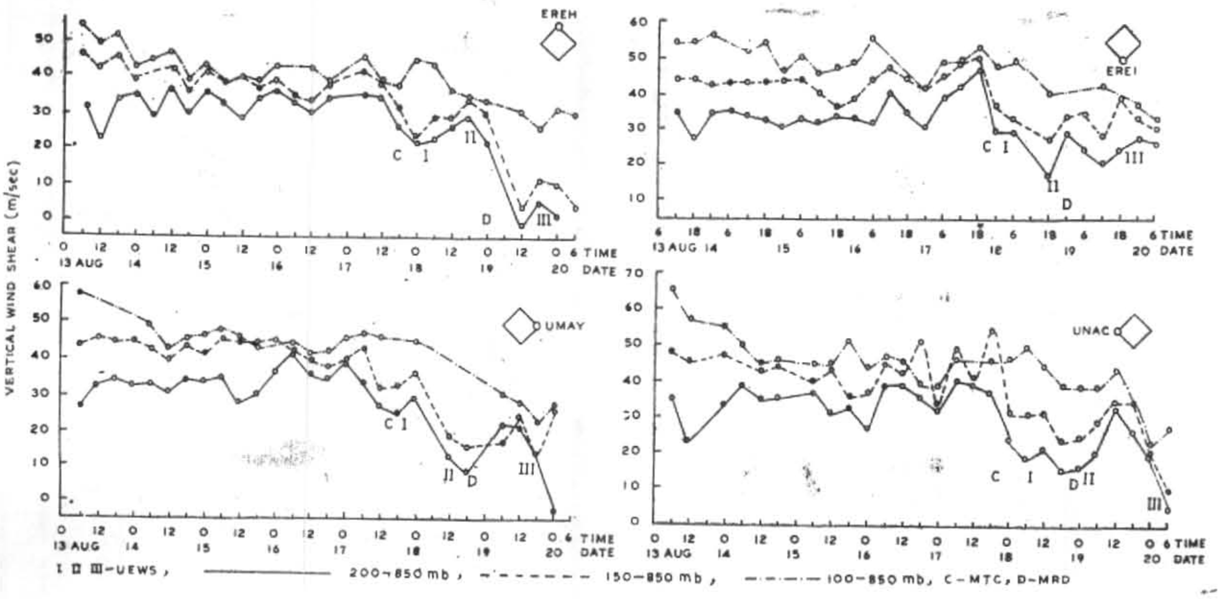


Fig. 3. Variation of vertical wind shear over the ships : I, II, III– UEWs : C—MTC, D—MRD. Abscissa– Date/Time, Ordinate– VWS (m/s)

MTC formed off the N. Andhra coast at 500 mb under the influence of UEW-II. C linked up with it and its circulation weakened over the polygon was hardly perceptible. The combined vortex rose to 300 mb (Fig. 5) judged by the southeasterly winds over UNAC at this level. UEW-III came over the polygon at 19/18GMT and C rose again to 350 mb. By 20/00GMT UEW-III moved to the western-half of the polygon. The top of C rose to 300 mb and was well to the southwest of D.

The vertical extents of MTC-MRD and UEWs are marked schematically in Fig. 5. The vertical oscillations of the MTC in response to the UVA in the UEWs are illustrated in the diagram. A striking feature was the maximum vertical extent of MTC upto 200 mb just before it descended to sea level. Whether such upwards protrusion precedes the formation of every MD or not is not known and needs to be investigated. Although the tilt of the over-all vortex was southwestwards the axes of the MRD and MTC were nearly vertical, the latter being displaced to the southwest of the former as seen in Fig. 4. Cyclonic vorticity seems to have been propagated vertically through a linkage of UEW-MTC-MRD the transport being upward ahead of each UEW and downwards behind it.

5.2. *Thermal structure*

The MTC started with a warm core at the WEF (400 mb) and remained throughout its existence the warm core extended into the UEWs aloft. In the lower troposphere below 700 mb, the MRD had a cold core of 16°-18°C at 850 mb. The warm core was caused by the release of latent heat in the cloud towers in the circulation of MTC as in other tropical cyclones. Similar thermal structures were observed by earlier workers (Krishnamurti 1975, Godbole 1977, Choudhury and Rao 1976, Chaudhury and Gaikwad 1983) in the mean monsoon depression over land. Although the condensation heat from the warm core of the MTC was transported into the upper troposphere, it did not form an upper anticyclone as in other tropical cyclones as the TEJ aloft transported the heat westwards.

6. Vergence and vorticity

Time sections of divergence and relative vorticity at the centre of the polygon computed from the 6 hourly wind vectors reported by the four ships during 17/00-20/00GMT are given in Figs. 6 and 7. As the ships were about 400 km apart, the computed magnitudes of divergence and vorticity are crude estimates at the centre of the polygon. However, their variations with height and time with respect to the locations of the MTC and MRD should be illustrative of the development of vergence and vorticity in the cyclonic vortex.

6.1. *Divergence (Fig. 6)*

At 17/00GMT there were alternating layers of convergence and divergence of small magnitude of about 1 unit (10^{-5} sec^{-1}) over the polygon. During 17/12-18 GMT upper divergence of 2-4 units between 200-150 mb occurred ahead of UEW-I and the MTC formed in the WEF (400 mb). Convergence was induced over the polygon between 400-250 mb and descended to sea level by 18/06GMT. The level of non divergence (LND) was near 250 mb on 18th and lowered to 300 mb on 19th after the MRD had formed. Divergence of 4-6 units continued above the LND on 18th-19th over the MTC. After the MRD came over the polygon the convergence in the lower troposphere at 19/18GMT and 20/00GMT was about 4 units. Mid-tropospheric convergence of 2-4 units occurred between 500-250 mb on 18th when the MTC came over the polygon. Upper divergence and lower convergence were involved in the formation of the MTC-MRD.

6.2. *Vorticity (Fig. 7)*

Anticyclonic relative vorticity of -2 to -6 units occurred in the upper troposphere upto 18/00 GMT atter which cyclonic vorticity set in upto 200 mb till 18/12GMT extending over the entire troposphere at 18/18GMT. The maximum cyclonic relative vorticity in the MTC between 600-500 mb at 19/00GMT was about 8 units. As the MRD came over the polygon from 19/12GMT onwards the cyclonic relative vorticity rose to 6-9 units

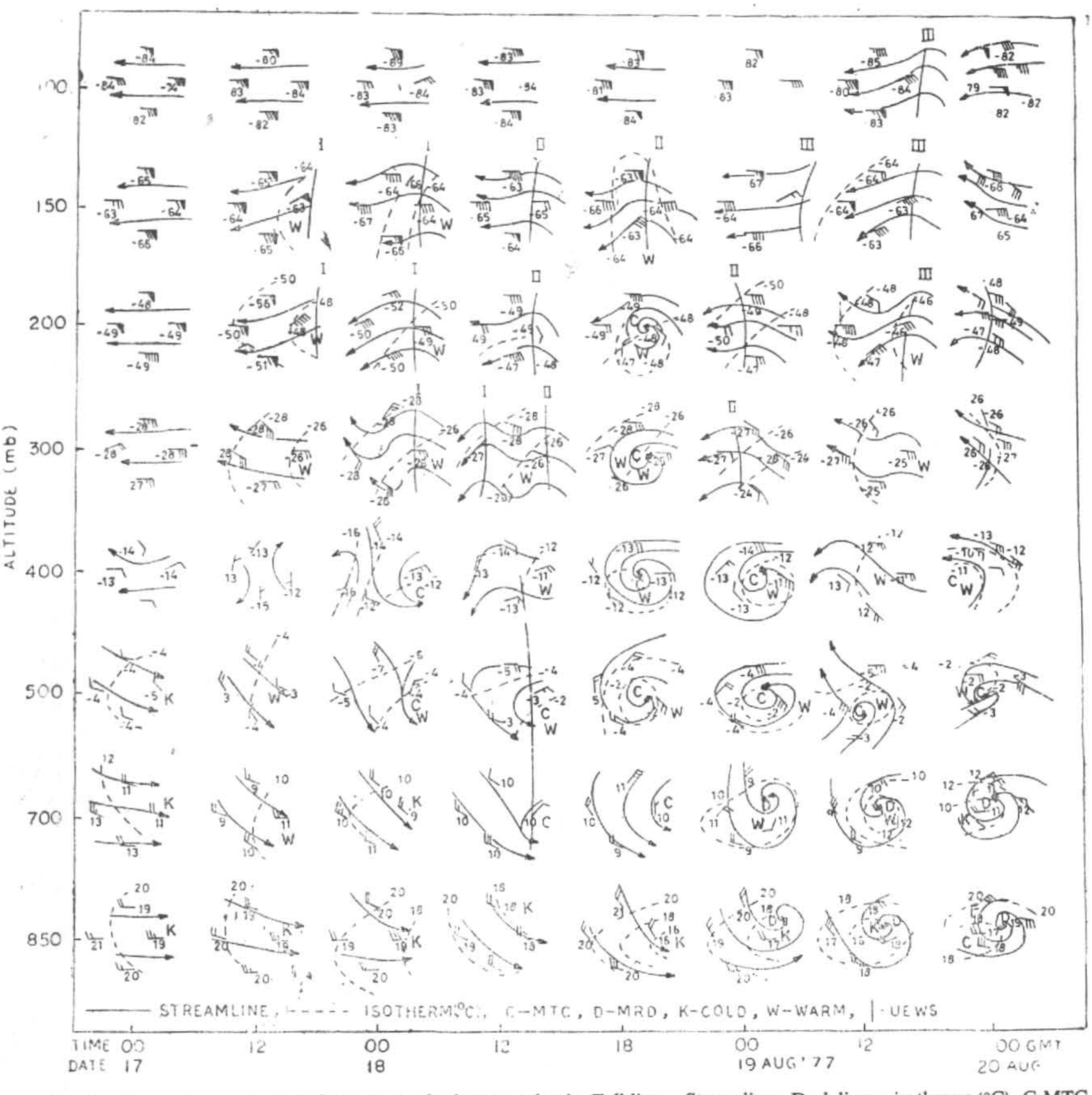


Fig. 4. Flow patterns over the polygon at standard pressure levels. Full lines– Streamlines, Dash lines—isotherms (°C), C-MTC, D-MRD, K-Cold, W-Warm, Vertical lines-UEWs.

and decreased rapidly aloft. The numerical values of the average vergence and vorticity over the polygon generally support the qualitative conclusions drawn in Sec. 5.

7. Synoptic developments

Figs. 8&9 contain synoptic maps of stream lines and isotherms over the Bay of Bengal and neighbourhood at 00GMT of 17-20 August at 850, 500 and 200 mb representing the lower, middle and upper troposphere respectively. Intertropical convergence zones (ITC) are indicated by double dash lines.

7.1. *Initial conditions* (17/00GMT — *Figs. 8a-c*)

The initial conditions before the formation of the MRD were typical of the prevailing break monsoon. The monsoon ridge (MR) extended northwards from the equator to the Himalayas at 850 mb (Fig. 8a) and the northwesterly flow over north and central India was relatively warm due to land heating. Temperatures rose over Orissa to 26° C from the initial temperature of 16°-18°C in the fresh monsoon current. The modified equatorial maritime (NEm) air streaming off the Orissa coast backed to west in a shallow trough over the northwest Bay (NWB) and cooled to 18°C over ECB after sea travel. A similar downstream decrease of temperature of 26°-19°C at 850 mb from the Orissa coast to ECB was observed by Joseph (1980) during a research aircraft flight in a break monsoon situation in MONEX 1979. The MT over Burma was flanked by the MR to its west and the Pacific Ocean Ridge (PR) across China to its east and was indeed the lower tropospheric continental ITC (CITC-L) with an active low pressure area (LPA)

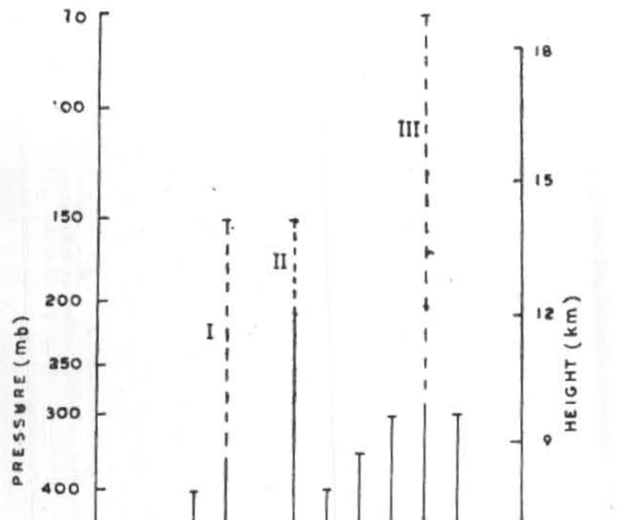


Fig. 5. Variation of the vertical extent of the cyclonic vortex

embedded in it over north Burma. A low level oceanic ITC (OITC-L) between the NEm air across India and fresh Em air across the equator extended from the southeast Bay (SEB) to the south Andaman Sea (SAS).

At 500 mb (Fig. 8b) a mid-tropospheric anticyclone (MTA-I) was located over the Bay and the Peninsula with its central region over the west central Bay (WCB). MTA-I was cut-off from the supply of fresh Em air across the equator and consisted of subsident NEm air. Westerlies to the north of MTA-I extended upto the Himalayas and a deep WT protruded over Pakistan. The PR extended westwards over north Burma and Assam with MTA-2 over north Burma. MTA-2 was thermal in origin due to cloud heating in the LPA over north Burma. CITC-U between MTA-1 and 2 extended from north Bengal to NE Bay (NEB) and thence southeastwards across lower Burma. The easterlies south of MTA-1 and southwesterlies across the equator converged to form the OITC-U which extended from SEB to Vietnam across the SAS/MTA-1 was warm (-4°C) due to subsidence and MTA-2 was warmer (-2° to 0°C) due to cloud heating. OITC-U was cold (-8° to -9°C) due to forced ascent of relatively dry air in the mid-troposphere.

At 200 mb (Fig. 8c) the subtropical ridge (STR) had shifted south of its normal *position* over Tibet and was located at 25°N between 75°E and 110°E with two-subtropical anticylones (STA 1 and 2) over West Bengal and north Burma. STA 2 was thermal being an upper extension of MTA-2. UEW-I lay over the Arakan coast.

7.2. *Formation of MTC* (18/00 *GMT — Figs. 8d-f*)

By 18/00GMT CITC-L shifted westwards and extended from Assam to NEB and thence southeastwards across lower Burma (Fig. 8d). The low level trough over NWB moved west and a well marked LPA formed over ECB off the Arakan coast. Warm advection to its west continued and temperatures at 850 mb decreased from 22°C over Orissa to about 18°C over the ECB.

At 500 mb (Fig. 8e) MTA-1 shifted southwards to the southwest Bay (SWB). MTA-2 protruded westwards over Bangladesh and CITC-U between the two anticyclones extended from Bihar to ECB where a MTC was formed at the intersection of CITU-U with OITC-U extending from SEB to NAS and thence eastwards. MTA-1 and 2 continued to be warm (-4°C and -2°C respectively). MTC-I was warm due to cloud heating and OITC-U continued to be cold (—6° to —9°C). In the upper troposphere at 200 mb UEW-I moved westwards past UMAY (Fig. 8f). STAs 1 and 2 merged to form a single STA over Bangladesh.

7.3. *Generation of MRD* (19/00 *GMT—Figs. 9 a-c*)

At 18/00GMT the LPA over ECB off the Arakan coast concentrated into a MRD with its central region D near 18.5°N, 91°E and surface pressure of nearly 996 mb. CITC-L at 850 mb (Fig. 9a) extended from north Bengal to the MRD and then southeastwards across lower Burma. The MRD had a cold core of 17°-18°C with warm advection to its west. Monsoon activity revived over Bangladesh and West Bengal in CITC-L. The MRD vortex was nearly vertical from sea level upto 700 mb.

In the mid-troposphere at 500 mb (Fig. 9b) the MTC moved over the ship polygon and was centred near 17.5° N, 89°E about 200 km southwest of D at the surface. MTA-I shifted southwards towards the equator. MTA-2 protruded west to Bihar and CITC-U extended from northeast Madhya Pradesh to the MTC and eastwards thereafter. The anticyclonic circulation over the north and central Bay was replaced by a cyclonic circulation which was larger than that of the MRD below. OITC-U shifted south to SAS. MTC-I was warm (-2°C) due to cloud heating and was flanked by a cold pool (-8°C) to its south. MTA-2 continued to be warm (-2° to 0 °C).

At 200 mb (Fig. 9c) the STR shifted slightly eastwards and was located between 80°E and 115°E with STA over Arunachal Pradesh. UEW-I moved over the Andhra coast, UEW-II was over the western-half of the polygon and UEW-III was over Burma.

7.4. *Intensification and movement* (20/00 *GMT— Figs. 9d-f*)

The MRD moved westwards and was centred at 20/00GMT near 18.5°N, 89.5°E. Its cyclonic circulation at 850mb (Fig. 9d) expanded and covered the north and central Bay. CITC-L extended from NE Uttar Pradesh (UP) to the MRD and thence eastwards. Monsoon activity revived over Bihar and Orissa in CITC-L.

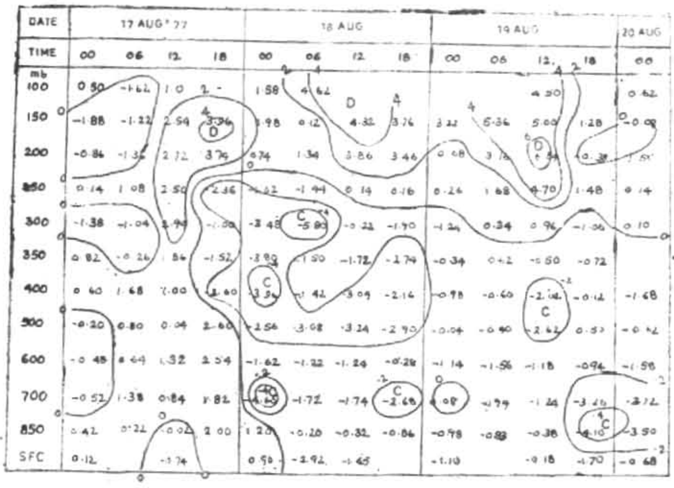


Fig. 6. Vergence over the polygon at standard pressure levels

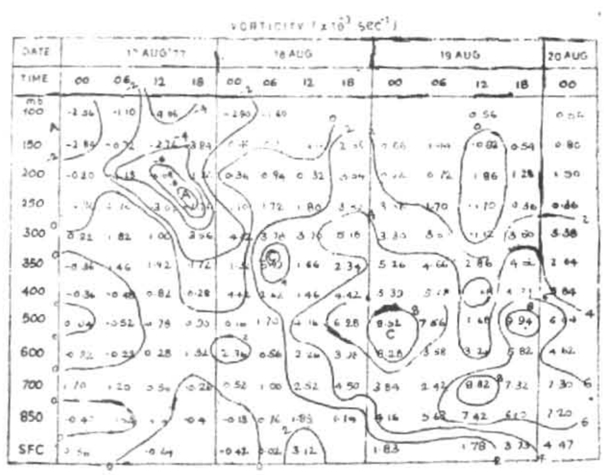


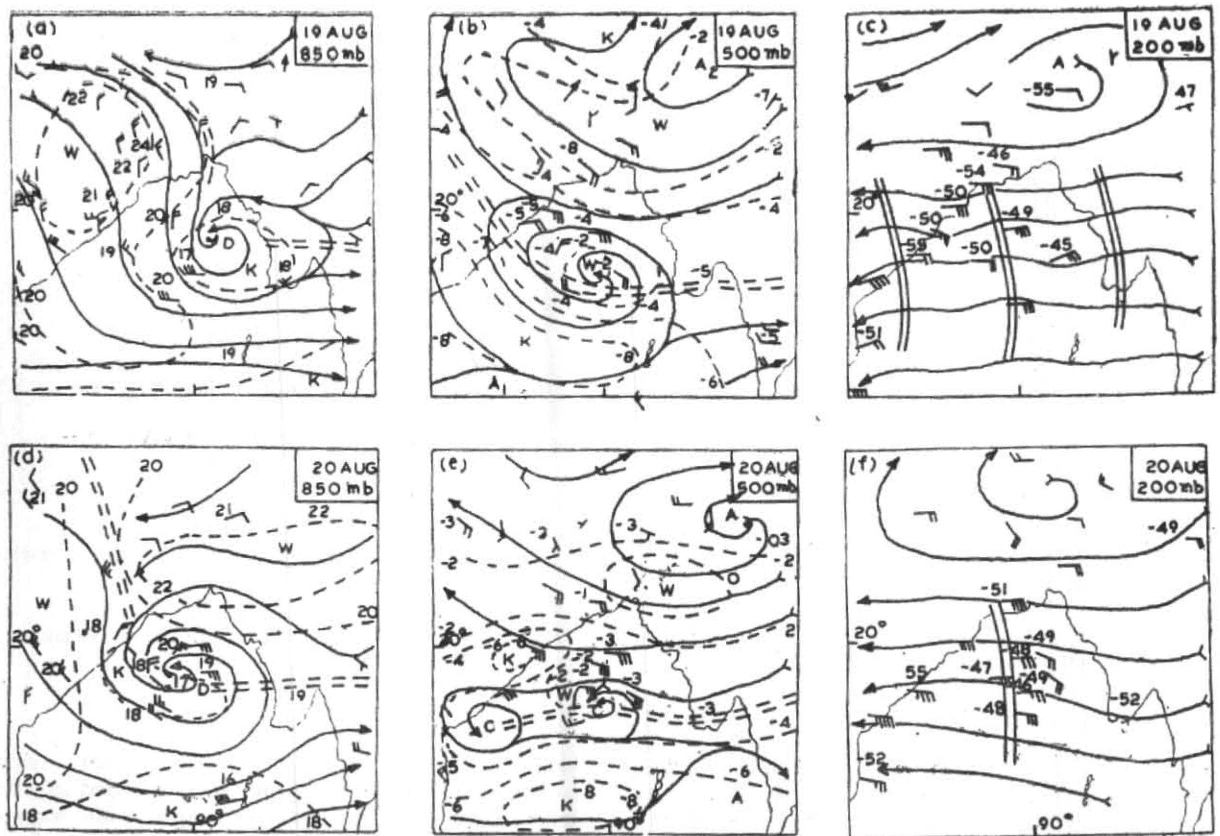
Fig. 7. Rel. vorticity over the polygon at standard pressure levels

——— STREAM LINES, - - - - ISOTHERMS(°C), = = = = ITC, C–MTC, D–MRD, A–ANTICYCLONE W–WARM, K–COLD

Figs. 8(a-c). 17 August (00 GMT)—Upper

Figs. 8 (d-f). 18 August (00 GMT)—Lower

Figs. 8 (a-f). Synoptic weather maps at 850, 500 and 200 mb for 17 & 18 August. Full lines—streamlines, Dash lines—isotherms (°C), Double dash lines—ITC, C—MTC, D--MRD



STREAM LINES,— - - - ISOTHERMS(°C), = = = ITC, C—MTC, D—MRD, A—ANTICYCLONE
W—WARM, K—COLD

Figs. 9 (a-c). 19 August (Upper) Figs. 9 (d-f). 20 August (Lower)

Figs. 9 (a-f). Synoptic weather maps at 850, 500 and 200 mb for 19 & 20 August

At 500 mb (Fig. 9e) the MTC was centred near 17.5° N, 89°E but its circulation was feeble. Another MTC formed off the Andhra coast and the cyclonic circulation of both covered the whole Bay reversing the initial anticyclonic circulation that had existed at 17/00 GMT. The MTC had a warm core of (-2°C). MTA-1 shifted south to the equator. A-2 was over Arunachal Pradesh and continued to be warm (-2°C). It protruded westwards to west U.P. CITC-U extended from SW upto north Andhra coast and thence eastwards over the Bay. In the upper troposphere at 200 mb (Fig. 9f) the STR shifted over Nepal and Arunachal Pradesh and UEW-III moved over 87°E. The MTC rose upto 300 mb.

7.5. *Landfall*

The Russian ships moved out of the polygon after 20/00GMT. The MRD moved westnorthwards and was centred at 21/00GMT at 19°N, 87°E with central pressure of about 992 mb. The centre of the MTC at 500 mb was near 16°N, 85°E about three degrees SW of the MRD. The MRD crossed the Orissa coast at 21/21GMT.

8. Discussion

8.1. *Mechanism of the monsoon break*

The northward extension of the MR from the equator to the Himalayas in the lower troposphere and the corresponding shift of the MTA from the equator to about 15°N over the Bay and the Peninsula in the mid-troposphere are the main features of the monsoon break resulting in the cessation of monsoon rains over the plains over India. The ridge and the anticyclone are stable configurations and last for some days extending to one or two weeks sometimes. The SW monsoon current is sinusoidal and attains its maximum wavelength (about 60 degrees longitude—6000 km) between the coasts of Arabia & southwest Asia and its maximum amplitude (about 30 degrees latitude—3000 km) during the break monsoon. The westerlies to the north of the MTA rise to about 7 km a.s.l. and the easterlies to its south lower to nearly 3 km. The WEF over India and the Bay slopes upwards from the equator to the Himalayas reversing the usual downwards slope from the equator to the MT (ITC) during normal monsoon. Westerly waves move eastwards in the NEm current over the Himalayas foot hills causing heavy rains there. MTCs over the south Bay cause showers over the south Peninsula. While the MR remains stationary except for westerly troughs moving eastwards, MTAs are migratory and move east to west in the wake of MTCs. MTA-I in the present case moved on to the Bay from the east on 15 August in the wake of a MTC. Koteswaram and Bhakskara Rao (1963) had characterised the monsoon break as the state of maximum development of the SW monsoon current over the Indian subcontinent.

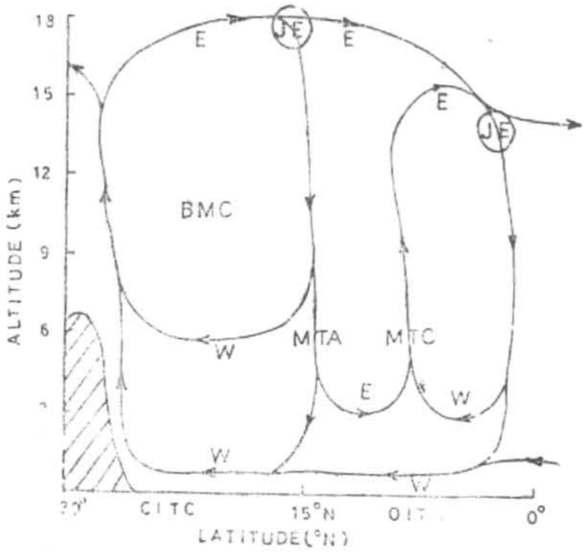


Fig. 10. Postulated structure of the meridional monsoon cell during break monsoon

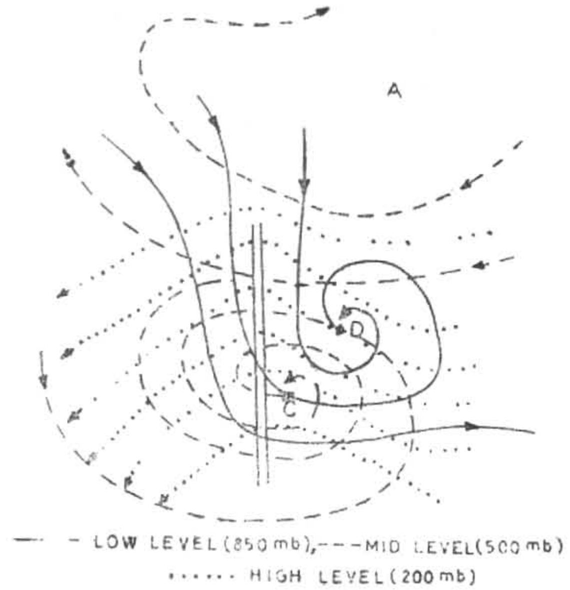


Fig. 11. Formation of monsoon depression — Schematic flow pattern

The vertical circulation in the meridional plane is significantly modified during the break monsoon. The ascending limb of the meridional monsoon cell (MMC) of the reverse Hadley type postulated by Koteswaram (1960) shifts slightly southwards from Tibet to the heavy rainfall zone (HRZ) over the eastern Himalayas that provides the main heat source for the break monsoon cell. The descending limb over the equator and the return westerly current in the lower troposphere are maintained. The strong low level jet (LLJ) also persists over the SW Arabian Sea during break and weak monsoon conditions (Jambunathan and Ramamurthy 1974). Significant changes, however, occur in the mid-troposphere where the descending limb of the MMC shifts northward to about 15°N with consequent shift of the MTA there. The return westerly current in the mid-troposphere converges into the CITC over the Himalayas foot hills and the easterly current south of the MTA forms the OITC-U at about 10°N with embedded MTCs moving westwards. The MMC is thus subdivided into three cells during the break monsoon as illustrated schematically in Fig. 10. Two TEJs over 15°N and the equator are characteristics of the mean monsoon circulation (Koteswaram 1969).

8.2. *The monsoon trough and the intertropical convergence zone*

We have identified the MT over Burma and SE Asia as the ITC between the MR and PR. There is no clear-cut temperature discontinuity in the ITC as in extra-tropical fronts since the temperatures of the converging airmasses do not differ much. They are, however, modified by land heating in the lower troposphere, cloud heating in the mid and upper troposphere and mountain-heating over the Himalayas and Tibet. There are well marked shear lines which can be traced on daily weather maps except in the lower troposphere where the air streams (*e.g.*, Em and NEm) flow parallel to each other. Cyclonic vortices ranging from weak lows to MDs and tropical cyclones lie embedded in the ITC with cold cores in the lower troposphere and warm cores aloft. In general, the ITC is a broad zone of varying widths with embedded cyclonic vortices.

When the ITC shifts to the north Bay and NE India the box effect of the Arakan mountains of Burma and the Himalayas produces a MT in the lower levels with embedded cyclonic vortices (Simpson 1921, Banerji 1929). In the mid-troposphere, however, the PR extends to Burma & north India and the MT at this level can be identified as CITC-U. Malurkar (1950) traced the easterlies north of the MT as of Pacific Ocean origin and called it as Tr (Transitonal) air.

The western branch of the ITC along and off the Arabian coast is distinguished by the wind shear as well as the strong temperature gradient. The SW monsoon current is anticylconic and although the continental air north of the ITC gains cyclonic vorticity during its southward travel, it is dry and MTCs do not develop into MDs.

During active monsoon conditions there is a single CITC over India. In the break monsoon the CITC shifts to the Himalayas and the OITC appears over the south Bay in the mid-troposphere. The monsoon activity over India revives when the CITC shifts back to the Bay and the OITC moves south to the equator and disappears.

8.3. *Formation and structure of the MRD*

The MRD is important to revive the monsoon activity over the Bay and India. It is basically similar to the MD in its formation and structure but for the fact that there is no pre-existing MT (ITC) over the north Bay for its formation according to the mechanism postulated by K.G. (1958). In the present case UEW-I induced the shift of the ITC to the Bay from Burma and generated the MTC over ECB. The MTC-I moved northwest over ECB for a day when UEW-II came over it and built it up to 300 mb with a narrow core upto 200 mb. As UEW-II moved away westwards, descent in its convergent rear transported cyclonic vorticity to the sea level to form the MRD as we have discussed in Section 5. The MTC was about 200 km southwest of the MRD producing the well-known HRZ in the southwest sector of the MRD. We consider that the formation of the MTC at the CITC at first and its descent after sometime to the sea level to form a MD to the northeast of the MTC is a feature common to all MDs. It has been often observed that cyclonic circulations generally start in the upper levels above 700 mb and descend to the surface after some time (Desai 1977 and Rao 1976).

Another important aspect is that the initial MTC is formed in the easterlies to the south of an MTA over Burma and Assam as they gain cyclonic vorticity during their southward travel. Earlier workers (Roy and Roy 1930, Malurkar 1950) considered that the northwesterlies over India were tropical continental (Tc) and postulated that this dry air mass was necessary for monsoon cyclogenesis. The gain of cyclonic vorticity of the air streams moving southwards and converging in the UITC and LITC respectively seem to be necessary to wind them up into MTCs and MDs under the influence of UEWs aloft.

The present investigation has also revealed that the top of the cyclonic vortex of the MTC-MRD oscillates up and down in the troposphere in response to the UVA in the UEWs. This feature was observed from the time of of formation of the MTC and it reached its maximum vertical extent just before it descended to sea level. Such vertical oscillations probably occur in all MDs since they are triggered by UEWs.

The MTC is warm cored from its inception and contributes to its intensification by CISK process as in other tropical cyclones. However in the MD warm advection in the lower troposphere generates cyclonic vorticity ahead of the cold core there and extension of the cyclonic circulation. In the mid-troposphere the warm core is the dominant feature and the UVA in the UEWs aloft generate the cyclonic vorticity in this layer.

Apart from the southwest displacement of the MTC with respect of the MD, sometimes a second MTC is formed at some distance to the southwest of the MD and causes a second HRZ. In the present case a MTC was induced by UEW-I off the Andhra coast at a distance of about 500 km from the MRD. Chaudhary *et al.* (1983) observed a second HRZ at a distance of about 800 km from the centre of the mean MD over land.

A schematic representation of the formation of a MD by off-centred superposition of a MTC and a UEW is illustrated in Fig. 11. Cyclonic vorticity and kinetic energy are transported from the TEJ aloft to the MD below as seen in Fig. 4. Since the TEJ is baroclinic we consider that baroclinic instability plays a role in initiating a MD.

8.4. *Lateral displacement of ITC*

Sikka *et al.* (1986) traced the movement of the ITC during MONEX '79 from its onset north of the equator to its break over the Himalayas and found that the time-interval between the active CITC phase at 20°N and the break phase over the hills is about 30-50 days. They considered that the OITC that forms over the south Bay during the monsoon break shifts northward to revive the monsoon. The present investigation has however revealed that the revival of the monsoon over India takes place by the shift of the CITC from Burma to the north and central Bay and not by the northward movement of the OITC from the south Bay. The latter, on the other hand, shifts back to the equator and disappears. The ITC basically follows the sun's movement and is located near 10°N after the vernal equinox (21 Mar) near the Tropic of Cancer after the summer solstice (22 June) and back to 10°N after the autumnal equinox (23 Sep). The double ITCs (CITC and OITC) are special features of the break monsoon, being located on either side of the MTA over 15°N is illustrated in Fig. 10. The period of 30-50 days is that of the oscillation of the CITC about its mean position near 20°N.

9. Conclusions

The following are our main conclusions :

1. The monsoon break is caused by the northward extension of the MR from the equator to the Himalayas and the corresponding northward shift of the MTA and the downward limb of MMC in the mid-troposphere to about 15°N.
2. The MT is the CITC between the MR and the PR and slopes southwards with height. When the CITC shifts north to the Himalayas an OITC forms over the south Bay.
3. The monsoon activity over the Bay during the monsoon break is revived by the westward movement of UEWs across the Arakan coast of Burma and consequent shift of the CITC to the Bay and formation of MTC and MRD in it. The OITC moves south to the equator and disappears.
4. Since the MTC and MRD are formed at CITC-U and CITC-L repectively at intervals of 24 hours or more, the former is located southwest of the latter producing the well known HRZ in the southwest sector of MDs.
5. The MTC starts at the WEF and propagates vertically downwards and upwards in response to the UEWs transitting in the upper troposphere and is oscillatory in nature. It grows upto 300 mb in UEWs and even to 200 mb before it lowers to sea level in some cases.
6. The MD is formed by baroclinic instalibility and transport of cyclonic vorticity and kinetic energy from the TEJ in the upper troposphere to the monsoon westerlies in the lower levels.
7. The above conclusions for MRD should be applicable for all MDs forming in a bi-directional flow pattern as in the Asian summer monsoon.

Acknowledgements

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