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On the presence of upper air divergence in relation to pre-monsoon and monsoon weather systems of the MONEX period 1979

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सार — जी ओ ई एस-1 उपग्रह पवन अभिवाह के आंकड़ों की सहायता से बंगाल की खाड़ी में चक्रवाती झंझा की उत्पत्ति और मानसून से पहले की अवधि में भूमध्यरेखीय द्रोणी के तीव्रीकरण की कुछ घटनाओं का अध्ययन किया गया है। इससे पहले यह निष्कर्ष निकला है कि इन घटनाओं में अपसरण अधिकांशत: प्रणाली जनित था और किसी पूर्व विद्यमान अपसरण प्रणाली की गतिशीलता के बिना ऊपर से विकसित हो गया। उपरोक्त पवन प्रवाह के आंकड़ों के आलोक में पश्चिम तट की दिशा में दक्षिण-पश्चिम मानसून की शुरूआत के साथ-साथ अरबसागर में चक्रवाती झंझा की उत्पत्ति तथा बंगाल की खाड़ी में बने अवदाबों की तीन घटनाओं की जांच की गई है। लगता है कि इन प्रणालियों का विकास उपरितन वायु अपसरण प्रणाली की उपस्थिति में हुआ है।

ABSTRACT. A case of formation of a cyclonic storm in the Bay of Bengal and some cases of intensification of equatorial trough during pre-monsoon period were studied with the help of GOES-1 satellite wind flow data. It could be inferred that divergence in these cases was mostly generated and the development took place without the movement of any pre-existing divergent system aloft. Onset of the southwest monsoon along the west coast, together with formation of a cyclonic storm in the Arabian Sea and three other cases of formation of depression in the Bay of Bengal were examined in light of the above wind flow data. The development of these systems took place in the presence of upper air divergence systems.

1. Introduction

Koteswaram and George (1958) advanced the following hypothesis for the formation of monsoon depression in the Bay of Bengal 'Cyclonic development at sea level occurs when and where an area of positive vorticity advection in the upper troposphere becomes superimposed upon a pre-existing trough at sea level'. Koteswaram (1960) and then George (1970) observed that given a pre-existing lower tropospheric feature causing convergence at sea levels along and near the Kerala coast, upper divergence in the western portion of an advancing trough in the easterlies or the left exit portion of an accelerating easterly wind maximum in the upper levels usually precedes and causes the onset of the monsoon over the Kerala coast. The above observations, however, had the limitation of depending upon the network of land stations only whereas there was complete absence of upper air observations, over sea. These theories again related only to the vortices forming in the summer monsoon regime with typical westerly flow in the lower levels and easterlies with embedded waves and jet stream aloft. Similar studies on the formation of cyclonic disturbances in a pre-monsoon field over the Indian region are, however, lacking. During summer MONEX 1979 a sub-programme of First Global GARP Experiment there was for the first time, the facility of a geostationary satellite positioned at 58 deg. E to continuously view the monsoon circulation. In addition, special observations such as drop-sonde soundings from the aircraft, radiosonde ascents from ships, enhanced network of world weather watch stations, constant level balloons and special collections of commercial aircraft wind reports, TIROS-N cloud imageries complimented the standard observational data base between May and July.

It was, therefore, for this year that a case of the formation of a cyclonic storm in the Bay of Bengal and some cases of intensification of equatorial trough during pre-monsoon period, onset of monsoon along the west coast along with the formation of a cyclonic storm in the Arabian Sea and three other cases of formation of depressions in the Bay of Bengal were examined using the derived wind flow data (analysed for direction and speed) from GOES-1 (Young *et al.* 1980), upper air charts (850, 700 and 200 mb) from the quick look Summer Monsoon Atlas (Krishnamurti *et al.* 1979, 80) and the analysed charts of Weather Central (India Meteorological Department), Pune, in order to verify whether upper air divergence was

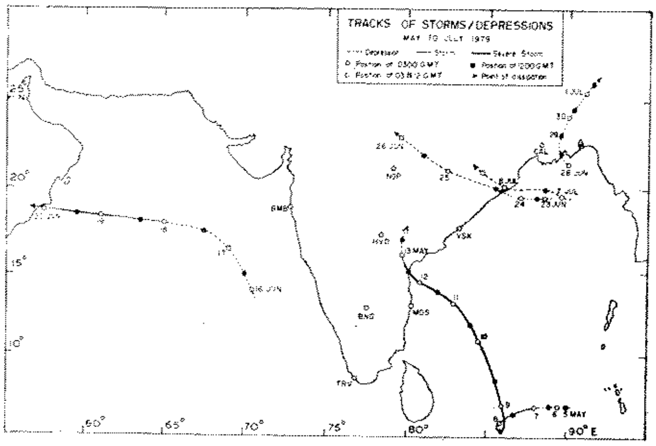
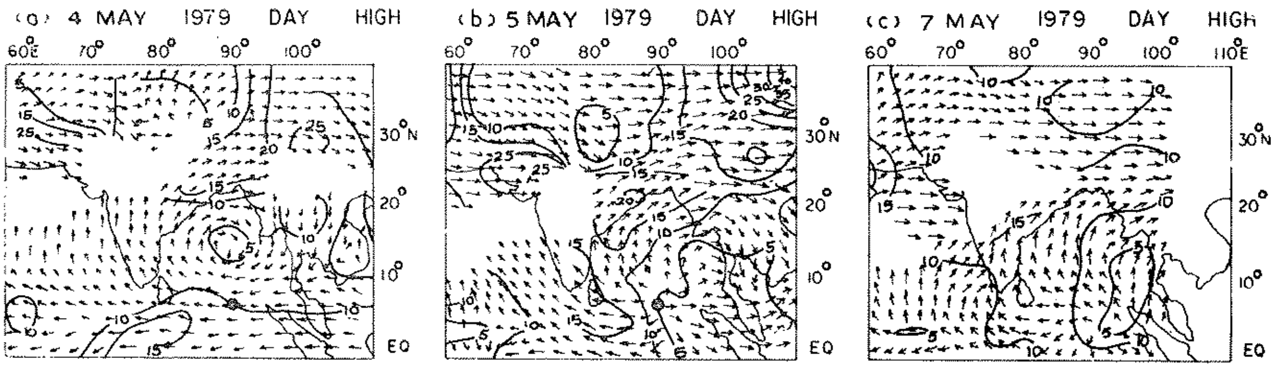


Fig. 1. Tracks and life history of depressions and cyclonic storms formed over the Arabian Sea and the Bay of Bengal between May and July 1979



Figs. 2 (a-c). Satellite derived wind flow patterns at 200 mb on 4, 5 & 7 May 1979 respectively (solid lines are isotachs)

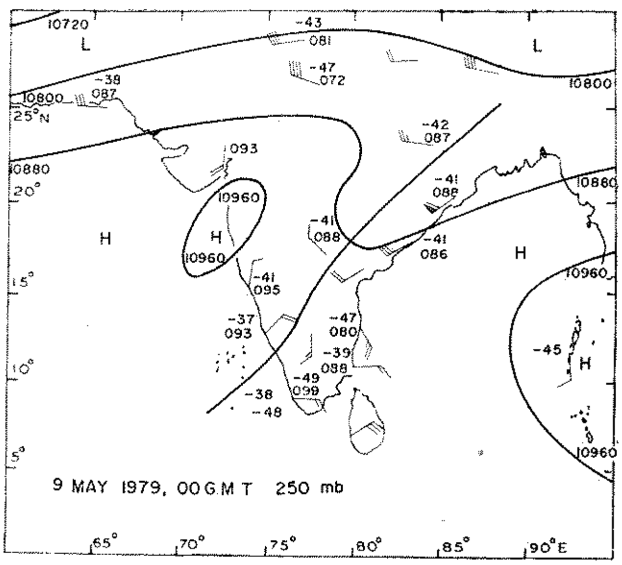


Fig. 2 (d). Constant pressure chart, 250 mb at 00 GMT

TABLE 1

Computation of divergence by Bellamey's method for the triangular area with vertices at 8° N, 89° E; 4° N, 86° E and 4° N, 92° E

Vertices (deg.)	Wind (°)	Wind (m sec^{-1})	Div. in units of 10^{-5} sec^{-1}	Vort. in units of 10^{-5} sec^{-1}	Wind (°)	Wind (m/sec^{-1})	Div. in unit of 10^{-5} sec^{-1}	Vort. in units of 10^{-5} sec^{-1}
				4 May 1979				
8 N 89 E	090	09	0.000	2.313	170	7	1.6962	0.257
4 N 86 E	110	14	+1.542	—2.57	090	12	2.1074	—1.542
4 N 92 E	090	11	—1.8504	—1.285	300	4	1.028	0.1028
For the area			—0.3084	—1.542			+4.83	—1.1822

necessary for the evolution of these phenomena. While investigating these, Gray's views (1968) that upper air divergence is not necessary for the formation of tropical storms and Ranjit Singh's observation (1981) on the occurrence of tornadoes in the absence of upper air divergence as indicated by the advection of positive vorticity were kept in view.

2. Pre-monsoon systems

2.1. *Cyclonic storm of* 5-12 *May* 1979

A depression formed in the Bay of Bengal on 5th evening with centre near 7 deg. N and 90 deg. E. It intensified into a deep depression on the 6th morning and into a cyclonic storm on 7th morning with centre near 7 deg. N and 88 deg. E. Moving slowly westward the system further intensified into a severe cyclonic storm on 8 May. The satellite picture indicated an eye on this day. The track of the cyclonic storm from 5 May onward till it crossed the coast near Nizampatnam by the afternoon of 12 May is given in Fig. 1 along with those of other depressions and cyclonic storms studied. Some of the salient features noted from the satellite derived wind flow patterns (Figs. 2 a, b, c, d) are discussed below.

On 4 May, a day before the formation of the depression, weak easterlies formed in upper air circulation over the region, south of the subtropical ridge. A closed anticyclonic vortex was centred near 15 deg. N and 90 deg. E on the 4th (day) high level chart of Young's Atlas. This circulation was disturbed on the 4th (night) high level chart in response to the development associated with the formation of a well marked low pressure area on 5th morning. With the formation of the depression on 5th evening, a centre of divergence formed around 6 deg. N, 89 deg. E on the 5th (day) high level chart (Fig. 2b). The flow diverges in all directions over the system in a manner depicted in Fig. 2.6.1 E on page 34 of Petterssen (1956), turns anticyclonically in response to the environmental flow and covers an extensive area. There was a weak westerly trough north of 22 deg. N and east of 84 deg. E at 200 mb.

2.1 (*a*). *Computation of divergence and vorticity*

Since the wind direction at 2 degree grid points and isotachs are available in Figs. 2(a) & (b) extracted from Young's Atlas, divergence and vorticity maps are prepared by finite difference method for the area 4 deg. S-16 deg. N, 80 deg.-100 deg. E (Figs. 2 e-h). There is moderate upper air divergence on 4 May over the area and to its south. Divergence increases in the southwest sector and also extends in north-northwest direction. However, the distribution of anticyclonic vorticity (Fig. 2 g) and divergence (Fig. 2 e) on 4 May is in conformity with the wind distribution south of the subtropical anticyclone. Four to eight times increase in divergence with the formation of depression on 5 May (Fig. 2f) and displacement of anticyclonic vorticity maximum to the west (Fig. 2h) is in response to the explosive *Cb* convection below and subsequent modification of the existing circulation by the large-scale outflow at this level.

The upper air divergence and vorticity are also computed by Bellamey's method for the triangular area with vortices at points 8 deg. N, 89 deg. E, 4 deg. N, 86 deg. E and 4 deg. N, 92 deg. E on 4 and 5 May. The values are given in Table 1. Southerly component of 4.8 m sec^{-1} at point 4 deg. N, 86 deg. E may have been responsible for the moderate convergence noticed in the triangular area. Thus the development started in an upper air easterly circulation south of the subtropical anticyclone and no other divergent system like the trough or the accelerating wind maxima in the easterly field could possibly be identified over the region.

The southerly flow over the Indian Peninsula on 7 May high level chart (Fig. 2c) was caused by the system-induced divergence when it intensified into a cyclonic storm. We see similar types of pictures till the morning of 8 May. On 12 GMT of 8th and 00 GMT of 9 May there was a deep westerly trough over Indian Peninsula running parallel to the east coast (Fig. 2d). This trough is generated independently on the westerly flow in the northern latitudes by an eastward displacement of the subtropical anticyclonic cell over the Bay under the combined influence of divergent outflow over the system and northwesterlies north of 22 deg. N.

2.1 (*b*). *Outflow jet*

An outflow jet (Gray 1981) can be inferred, embedded in this trough from the 60 kt wind at Bhubneswar and 35 kt wind at Vishakapatnam to account for horizontal shear. These two winds can be explained

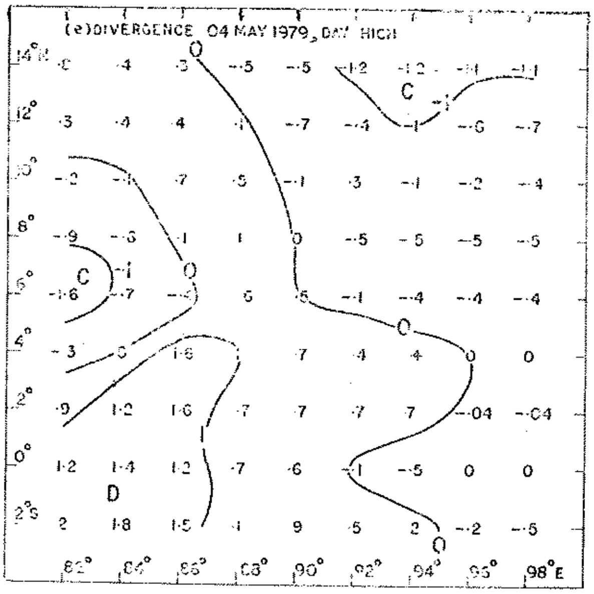


Fig. 2 (e)

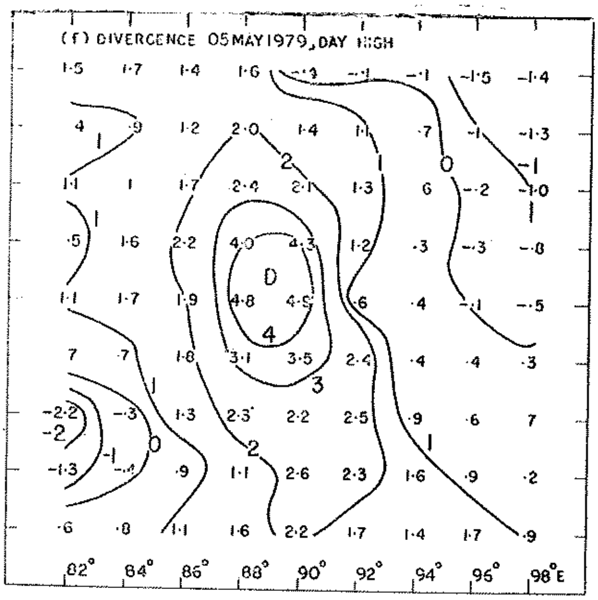


Fig. 2 (f)

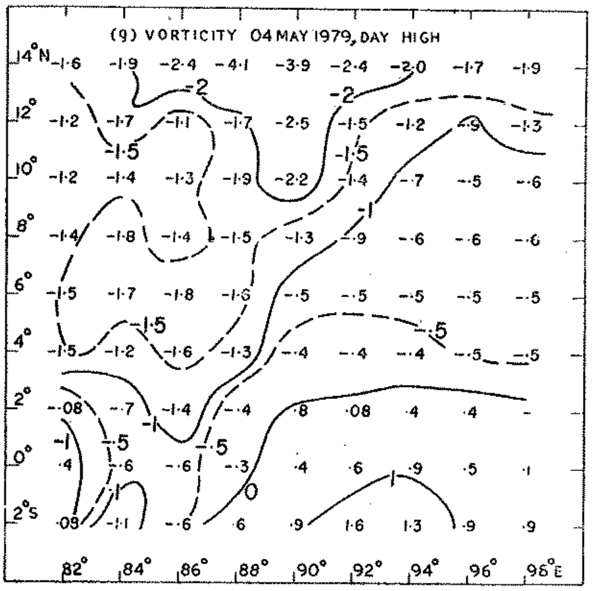


Fig. 2 (g)

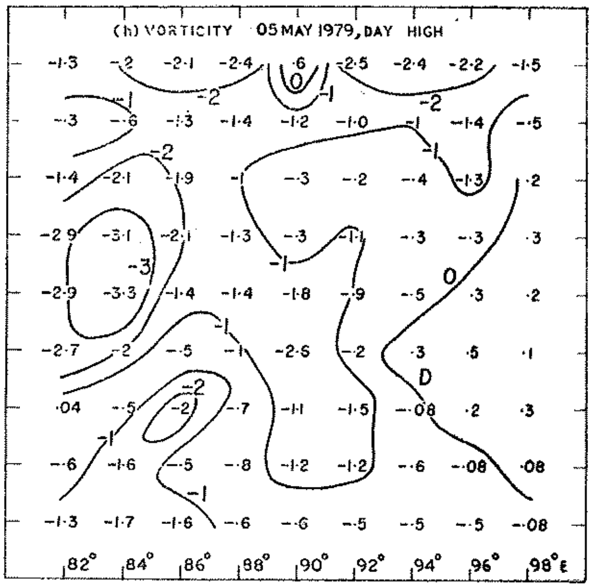


Fig. 2 (h)

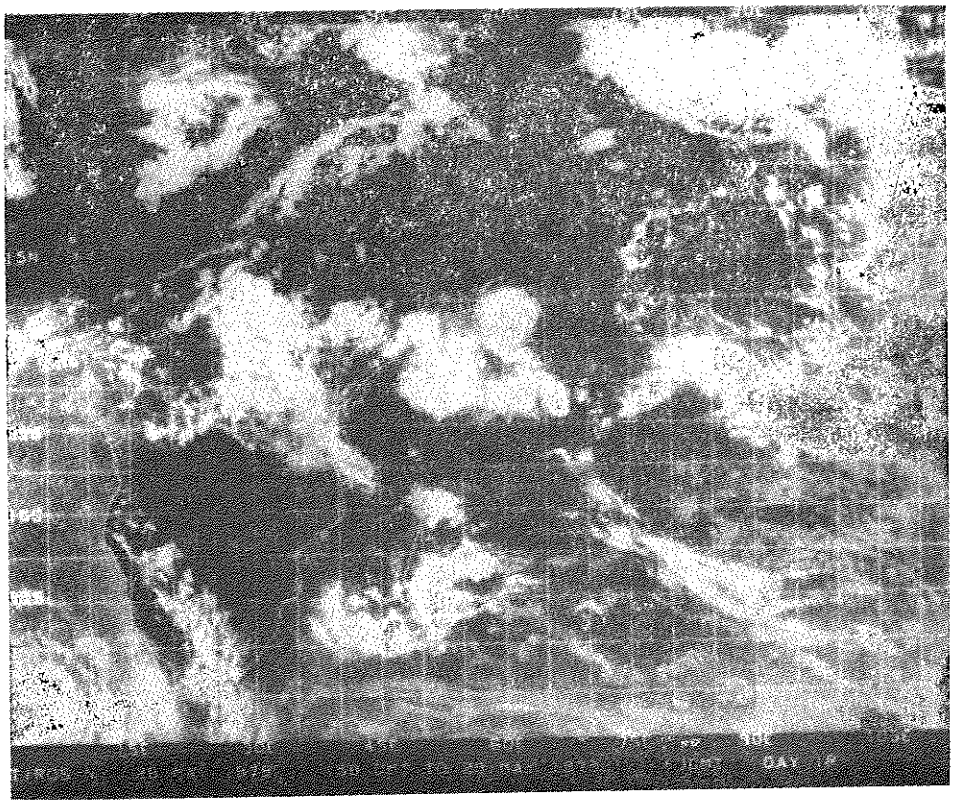


Fig. 3 (a)

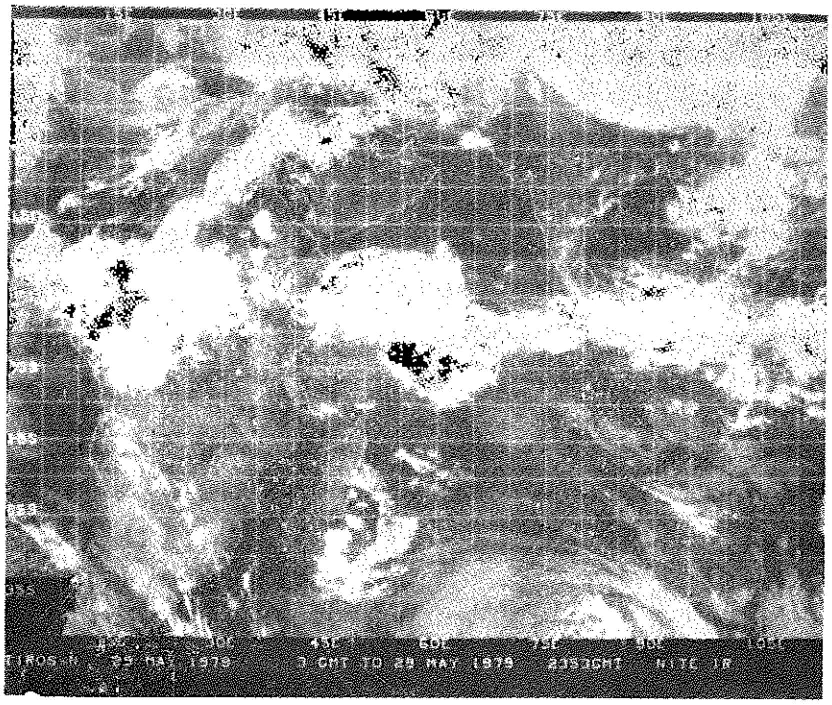


Fig. 3 (b)

TABLE 2

Computation of winds at 250 mb on 00 GMT, 9 May 1979

	Initial wind at 9° N (m sec^{-1})	Additional zonal velocity (m sec^{-1})	Computed wind (m sec^{-1})	Observed value wind (m sec^{-1})
Visakhapatnam (17.75° N)	—10	33.7	23.7	18
Bhubneswar (20° N)	—10	45.9	34.9	30

to form from the outflow with the help of conservation of angular momentum equation :

$$\triangle V = \Omega R (\cos^2 \phi_1 - \cos^2 \phi_2)/\cos \phi_2$$

where, $\triangle V$ is an additional zonal velocity relative to the earth's surface when an air particle moves from ϕ_1 to ϕ_2, R is the earth's radius $\sim$ 6370 km and $\Omega = 7.29 \times 10^{-5}$ radian sec^{-1} (Reiter 1973).

The computations are made from an arbitrarily chosen latitude 9 deg. N. The computed and observed values are given in Table 2. The observed values fall short of the computed values. It is likely that *Cb* convection plays an important role in reducing the outflow circulation to values less than those specified by angular momentum conservation (Gray *loc. cit.*). This jet lies in the northeast sector of the cyclonic storm. Similar strengthening of the easterly wind is observed in the southwest sector of the cyclonic storm. In the present case of a pre-monsoon cyclonic storm, the jet in the northeast sector is stronger than the wind maxima in the southwest sector. In another similar sudy, it has been shown that easterly jet maxima form in the southwest sectors from the outflow over monsoon depression (Ranjit Singh *loc. cit.*).

2.2. *Cloudiness of the equatorial zone*, 28 & 29 *May* 1979

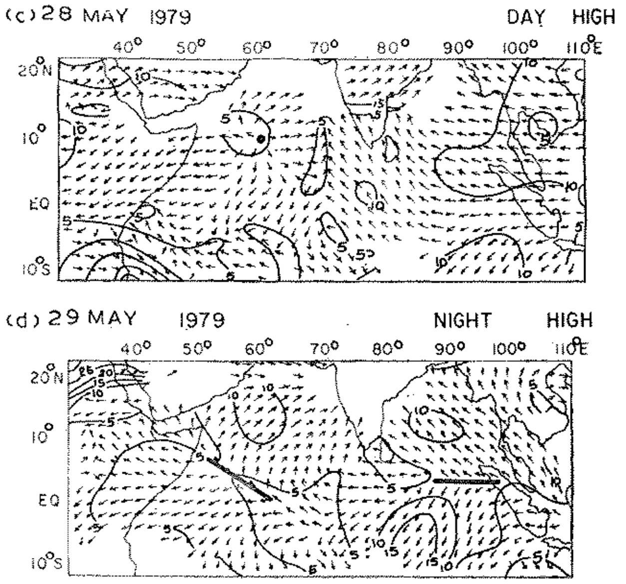
On the TIROS-N satellite picture of 28 and 29 May well defined circular cloud patterns are observed associated with mid-tropospheric vortices embedded in the equatorial trough (Figs. 3a, b). Some of the identified vortices were approximately centred at 02 deg. N, 58 deg. E; 07 deg. N, 62 deg. E on 12 GMT of 28 May and 04 deg. N, 53 deg. E; 03 deg. N, 95 deg. E on 00 GMT of 30 May. On the derived cloud wind charts for the level 200 mb (Figs. 3c, d) it is the system induced divergence over the convective cloud regions which is noticed around 60 deg. E and 90 deg. E. The outflow centres and lines of diffluence are marked by thick dots and lines in the figures. The northerly and northeasterly flow over the equatorial west Indian Ocean on 26 and 27 May, however, signify the presence of upper air divergence before the formation of cloud clusters on 28 May. Inspite of this, two distinct types of cloud effects on the upper tropospheric easterly circulation are noticed here : (1) radical outflow, in which the air mass lifted up convectively diverges out in all directions as observed at 10 deg. N, 60 deg. E on 28 May (Fig. 3c), (2) cloud barrier effect, in which cloud acts as an obstacle and deflects the flow generating thereby diffluence effect. This is obvious along equator between 80 deg. E and 90 deg. E on 29 May (Fig. 3d).

3. Onset of monsoon and the formation of Arabian Sea cyclone

The southwest monsoon advanced into south Kerala as a feeble current on 11 June. At 700 mb the trough which extended from the east Bay of Bengal across Sri Lanka and westward over the southeastern Arabian Sea showed a northward shift and strengthening thereafter, as indicated by westsouthwesterly winds of 20 to 30 knots reported by the USSR ships on 13 June. Figs. 4 (a-c) show the flow patterns at 850, 700 and 200 mb respectively on 12 GMT of 13 June. Winds were relatively weak in the eastern half of the Arabian Sea approaching towards coast in comparison to these over the western Arabian Sea at 850 mb level. This suggests the conditions of low level convergence at the time of onset of the monsoon. Mid-level cyclonic vortices are observed at 700 mb. Northeasterlies were noticed at 200 mb from 12 June onward which suggested the presence of upper air divergence at the time of onset of the monsoon. The upper air northeasterlies formed the part of cross-equatorial flow east of 60 deg. E on 13th. These strengthened downwind and spread westward upto 50 deg. E south of the equator on 14 June and further west upto 40 deg. E on 16 June. On 14 June, the mid-tropospheric cyclonic circulation descended downward and appeared as a low on sea surface centred around 11 deg. N, 70 deg. E with westerly wind of upto 50 knots in the southern quadrant at 700 mb level. At 850 mb the Somali jet makes it's appearance from this day. It appears that the Somali jet and strong southwesterly flow across the equator over the western half of the Arabian Sea was a compensatory current in response to the upper air northeasterly flow over the eastern half of the Arabian Sea. From 16 June onward when the low concentrated into a depression in the Arabian Sea, the system induced divergence began to shape the upper air flow at 200 mb (Fig. 4d). However, to the south of the system the presence of strong northeasterlies indicated an upper air easterly trough over the region.

4. The Bay depressions of 23-24 June, 28-30 June & 7-8 July 1979

A depression formed in the Bay of Bengal on 23 June with centre near 19.5 deg. N, 88.5 deg. E. It became deep on 24 June and crossed coast near Puri in Orissa. Fig. 5 (a) shows the satellite derived flow pattern at 200 mb on the night of 22 June.



Figs. 3 (c & d). Satellite derived wind flow patterns of 200 mb on 28 (day composite) and 29 May 1979 (night composite). The positions of centres of vortices and lines of difference are marked by big dots and thick lines

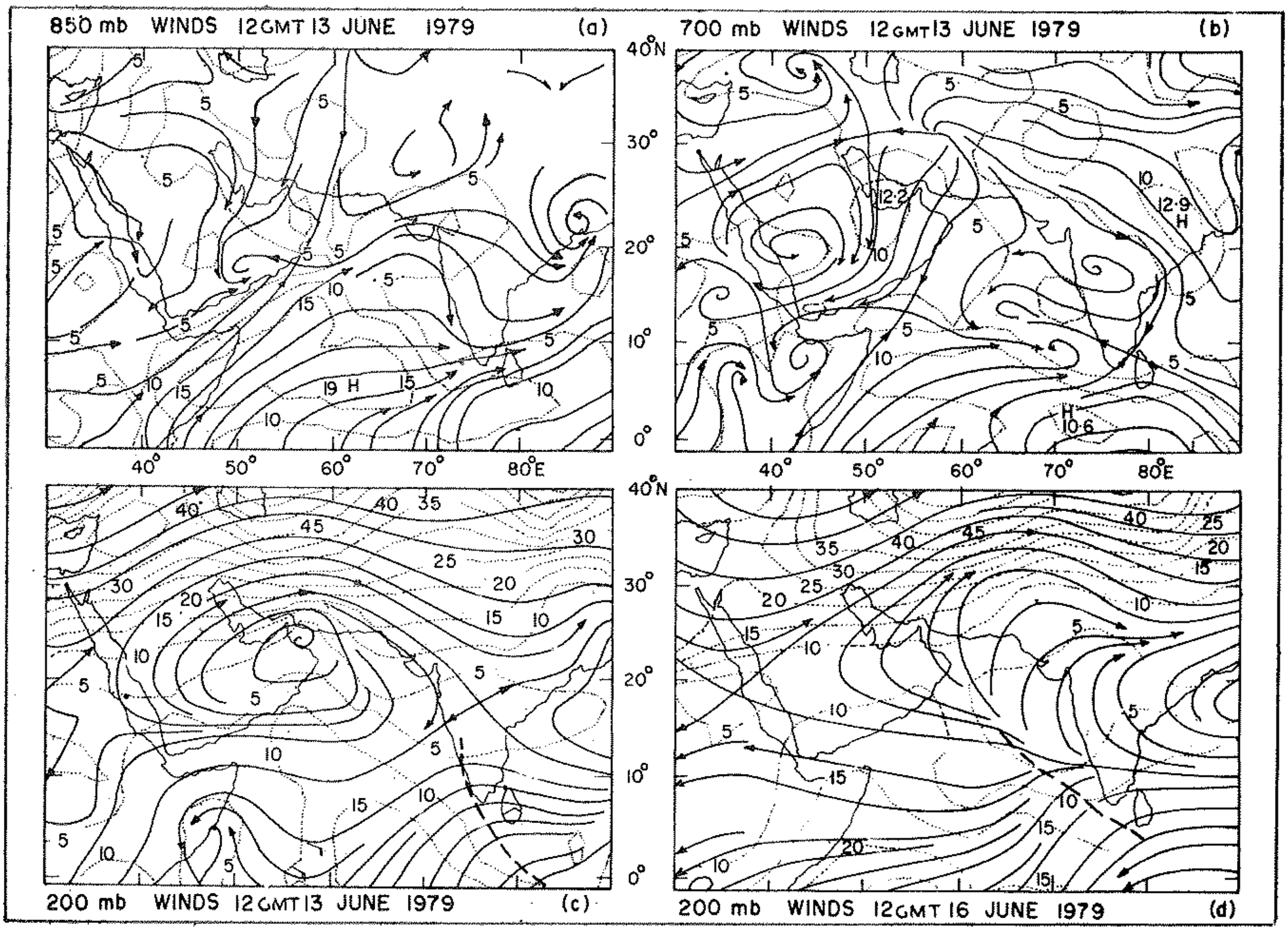
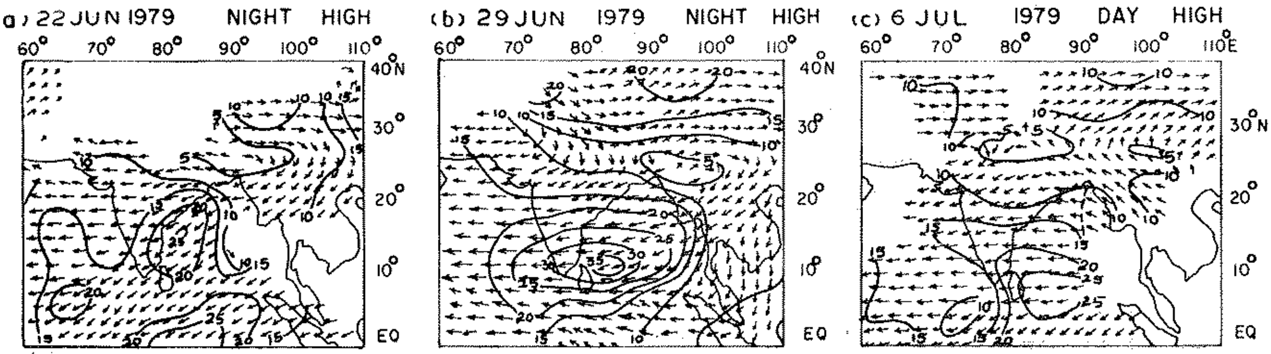


Fig. 4 (a-d). The wind flow patterns at 850, 700 and 200 mb on 1200 GMT, 13 June 1979 and at 200 mb on 1200 GMT, 16 June 1979



Figs. 5 (a-c). Satellite derived wind flow patterns at 200 mb on 22 and 29 June 1979 (night composite) and 6 July 1979 (day composite).

Another depression formed over the north Bay of Bengal off Bangladesh coast on 28 June. Moving northward it became deep over Bangladesh on the morning of 30 June. Subsequently, it weakened and dissipated over north Assam by 2 July. Fig. 5 (b) gives the flow pattern at 200 mb on the night of 29 June prior to the further intensification of depression into deep depression over land.

Both these depressions developed and further intensified under the influence of upper air northeasterlies emanating from the subtropical anticyclone located further north. These northeasterlies at 200 mb increasing in speed downwind indicate the presence of upper air divergence over the region of development.

A third depression formed on the morning of 7 July with centre about 400 km eastsoutheast of Paradip. It crossed north Orissa coast near Paradip on the afternoon of 8 July. Fig. 5 (c) gives the flow pattern at 200 mb on 6 July. The western sector of an advancing easterly trough was the source of upper divergence in this case.

A thermal anticyclone forms over the Tibetan Plateau between 500 & 300 mb during the monsoon season from the vertically lifted airmass (Flohn 1958, Koteswaram 1958). The subtropical anticyclone which forms from subsidence over the northern periphery of Hadley cell is also displaced over this region during monsoon. Both merge and form a highly divergent system at 200 mb and above. The east-westward displacement of this anticyclone because of the latent heat release from precipitation occurring in different sectors to it's south (Kanamitou and Krishnamurti 1978) provides a significant perturbation input to the strong easterly flow over southeast Asia resulting into the formation of eastward travelling divergent systems like the troughs and jet maxima. These features are lacking during the pre-monsoon season when the subtropical anticyclone located much south is lesser divergent with mainly a weak to moderate easterly flow to its south.

5. Discussion and conclusion

In this paper an attempt has been made to study the tropical disturbances formed in Indian region during the pre-monsoon and monsoon seasons. The observational evidence leads to the conclusion that the presence or movement of an upper air divergent system as inferred from the positive vorticity advection is not a necessary condition for the development of these disturbances during the pre-monsoon season. The lower level development occurs south of the subtropical anticyclone and can be explained by ITCZ forcing (Mc Bride and Gray 1980) or by the mechanism of CISK (Charney and Elliassen 1964). The presence of an upper air divergent system in the form of an easterly trough or an accelerating easterly jet maxima was, however, confirmed during the period of the onset and advance of monsoon along the west coast when a cyclonic storm also formed in the Arabian Sea. It was also present in the case of other three depressions which formed in the Bay of Bengal during the established phase of monsoon.

Although the upper air circulation features in the pre-monsoon and monsoon seasons are naturally different, the dynamics of the formation of low level cyclonic circulation, however, seem to have been the same, *viz.*, upper air divergence and Dines compensation. The low level system no doubt interacts with the upper circulation, but the interaction depends upon the intensity of the developing system depending on whether it is a severe tropical cyclone or a monsoon depression or a weak mid-tropospheric cyclone vortex. In the pre-monsoon season such interactions seem to cause distinct outflow centres and modify the upper air circulation at meso and synoptic scale of motions while in monsoon season the system outflow is carried off by the pre-existing strong easterlies aloft and the outflow centre is obliterated.

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