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Fields of vorticity, divergence and vertical velocity associated with break and strong monsoon

D. S. DESAI

Meteorological Office, Pune

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सार — भ्रमिलता, अपसारिता और ऊर्ध्वाधर गति के क्षेत्रों द्वारा 'व्यवधानित' मानसून और संपुष्ट मानसून में विपरीत वर्षा वितरण को स्पष्ट किया गया है। (*ii*) मानसून ऋतु में भारी वर्षा की पेटी सामान्य: मानसून द्रोणिका की भूपृष्ठीय स्थिति के दक्षिण में होती है। संपुष्ट मानसून में भारी वर्षा की पेटी भूपृष्ठ और 700 मिलीबार तल वाली मानसून द्रोणिका की स्थिति के बीच सीमित रहती है। (*iii*) ग्रहीय पैमाने के "वाकर परिसंचरण" की भांति भारतीय मानसूनी क्षेत्र के ऊपर पूर्व-पश्चिम सिनॉप्टिक पैमाने का क्षेत्रीय परिसंचरण की उपस्थिति प्रेक्षित की गई है। मानसून ऋतु के दौरान उत्तर भारत के साथ-साथ प्रायद्वीपीय भारत के ऊपर अलग से और/या एक साथ सिनॉप्टिक पैमाने का पूर्व-पश्चिम क्षेत्रीय परिसंचरण प्रेक्षित किया जाता है। उत्तर भारत के ऊपर संपुष्ट मानसून ऋतु के दौरान उत्तर-पश्चिम भारत के ऊपर आरोही गति और उत्तरपूर्व भारत के ऊपर अवरोही गति होती है तथा प्रायद्वीपीय भारत के ऊपर पश्चिम तट के साथ-साथ आरोही गति और दक्षिणपश्चिम खाड़ी एवं समीपवर्ती क्षेत्र के ऊपर अवरोही गति होती है। मानसून में "व्यवधान" के दौरान यह सिनॉप्टिक पैमाने के पूर्व-पश्चिम क्षेत्रीय परिसंचरण या तो क्षीण हो जाता है अथवा विपरीत हो जाता है, मानसून की क्षमता इस सिनॉप्टिक पैमाने की पूर्व-पश्चिम क्षेत्रीय परिसंचरण पर आधारित है।

ABSTRACT. Contrasting rainfall distribution in break and strong monsoon is explained by the **fields of vorticity, divergence and vertical motion.** (*ii*) **Heavy rainfall belt in monsoon, is generally** south of the surface position of the monsoon trough. In strong monsoon, the heavy rainfall belt is confined between surface and 700 mb (hPa) monsoon trough position. (*iii*) The presence of an *east-west synoptic scale zonal circulation* is observed over the Indian monsoon region similar to the **planetary scale 'Walker's circulation'. The synoptic scale east-west zonal circulation is observed** over north India and as well as over Peninsular India during the monsoon season, separately and/or simultaneously. During strong monsoon, over north India, there is an ascending motion over northwest India and descending motion over northeast India. And over Peninsular India, there is ascending motion along the west coast of Peninsular India and descending motion over southwest Bay and neighbourhood. During break monsoon, this synoptic scale east-west zonal circulation either weakens or reverses. **The strength of monsoon depends upon this synoptic scale east-west zonal circulation.**

1. Introduction

Strong and break monsoon spells exhibit contrasting features in respect of associated rainfall and flow patterns. As is well known, in strong monsoon, there is a well distributed and heavy rainfall over the entire Indian region outside sub-montane districts of Himalayas and northeast India and also over southeast Peninsular India. While, during the break monsoon period, there is heavy and well distributed rainfall along the sub-montane districts of Himalayas, northeast India and southeast Peninsular India and no rainfall activity over other parts of the country. Thus, it is interesting to note that the area which gets heavy rain in strong monsoon, does not get rainfall in break monsoon and *vice-versa*. These phases of monsoon are found to be associated with intensity of the monsoon trough, which controls the distribution of monsoon rainfall. The monsoon trough, normally extends upto 500 hPa level, tilting southwards with height. It is a warmer region with strong low level convergence with vertical velocity and strong convection. In strong monsoon, it is very active and intense with embedded vortices and is south of the normal position over the plains of north India. In contrast, in break monsoon, the monsoon trough moves north to the foot hills of Himalayas over north India and not seen many times up to 850 hPa level. It is, therefore, thought worthwhile to study the dynamics of the associated flow pattern in strong and break monsoons. For that, the fields of divergence, vorticity and vertical velocity for break and strong monsoon period are studied here.

From the study of the intensity and position of the monsoon trough and also its tilt with height (up to 500 hPa) it is observed that the heavy rainfall belt is confined between surface and 700 hPa positions of the monsoon trough.

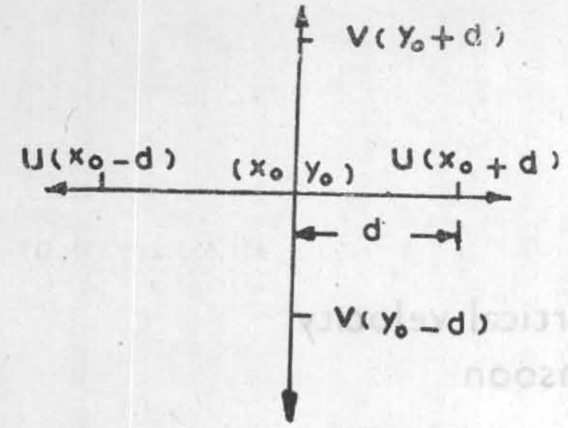


Fig. 1. Grid

Further, two synoptic scale east-west zonal circulations one over north India and another over Peninsular India are observed over the Indian monsoon region. Over north India during strong monsoon period, there is an ascending motion over northwest India and descending motion over northeast India. Similarly, over Peninsular India in strong monsoon, there is ascending motion along west coast of India off Arabian Sea and descending motion over southeast Peninsular India off southwest Bay of Bengal. During break monsoon, these two east-west zonal circulations become weak or reverse. Thus, the characteristic distribution of rainfall during strong and break monsoon period mainly depend upon the nature, intensity and position of these east-west zonal circulations.

2. Data used

A period of break monsoon 17-28 July 1972 and another period of strong monsoon 1-12 July 1977 are selected on the basis of rainfall and associated synoptic situation. Vorticity and divergence at grid points of 5° interval were calculated for the area 5°N 35°N and 45°E-105°E for the levels: surface, 850 hPa, 700 hPa, 500 hPa and 200 hPa by using finite difference method. The vertical velocity field for (surface-850 hPa), (850-700 hPa), (700-500 hPa) and (500-200 hPa) levels are calculated by using the equation of continuity in pressure coordinate system.

Indian Daily Weather Reports were consulted for identifying the strong and break monsoon spells and delineating the axis of the monsoon trough at various levels. The study of five break and strong monsoon spells was done and only one typical spell is reported here to keep the diagrams to the minimum.

3. Method of calculation

3.1. *Field of vorticity and divergence*

Divergence and vorticity are two important and basic parameters of a wind field. Horizontal divergence (henceforth called divergence) is defined as the amount of flow of fluid across a unit cross sectional area per unit time. The relative vorticity (henceforth called vorticity) is defined as vertical component of the rotaion of a fluid per unit area per unit time. Mathematically, we can express vorticity and divergence in local co-ordinate system as :

$$D = \text{Divergence} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \tag{1}$$

$$\zeta = \text{Vorticity} = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \tag{2}$$

We have used the finite difference method to calculate D and ζ at each grid point, where partial derivatives $\partial u/\partial x$, $\partial v/\partial y$, $\partial u/\partial y$ and $\partial v/\partial x$ are approximated by the finite differences. For example, at a given grid point (x_0, y_0) in Fig. 1, we calculate the D and ζ as :

$$D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = \frac{u(x_0+d)-u(x_0-d)}{2d} + \frac{v(y_0+d)-v(y_0-d)}{2d}$$

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \frac{v(y_0+d)-v(y_0-d)}{2d} - \frac{u(x_0+d)-u(x_0-d)}{2d}$$

where u and v are components of wind along x and y axis and d is the grid length. The values of D and ζ are expressed in units of 10^{-5} sec^{-1}.

As suggested by O'Brien (1970), the horizontal divergences calculated by this method are subjected to errors due to the uncertainties in the wind observations. As we calculated vertical velocity at only four levels (*i.e.*, surface-850 hPa, 850-700 hPa, 700-500 hPa and 500-200 hPa) for spells of strong and break monsoon, it was found that the adjustments in vertical velocity were marginal (*i.e.*, less than 4%) only in magnitude and did not cause the change of direction. As this served the required purpose here, we did not apply the corrections, for vertical velocity calculated here.

3.2. *Field of vertical velocity*

Vertical velocity is calculated by using the equation of continuity in isobaric coordinates which is given as :

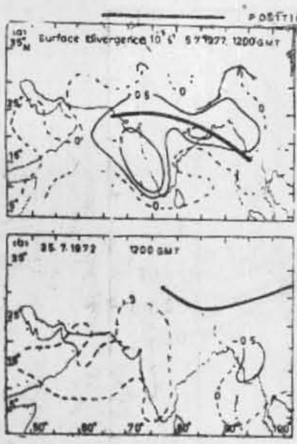
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial p} = 0. \text{ By integrating,}$$

$$w(P_1) - w(P_0) = -\int_{P_0}^{P_1} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)\partial p \tag{3}$$

$$w(P_1) = w(P_0) + (P_0 - P_1)\left(\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y}\right)_p \tag{4}$$

The term $[(\partial\bar{u}/\partial x) + (\partial\bar{v}/\partial y)]$ gives the mean divergence between the two pressure surfaces P_1 and P_2 separated by ∂p. The details are given by Holton (1979, p. 72). The values of vertical velocity are expressed in units of 10^{-3} hPa per second.

Charts of divergence, vorticity and vertical velocity were prepared for all the days of break monsoon and strong monsoon period. On examination of the charts, it was found that main features on all the break monsoon



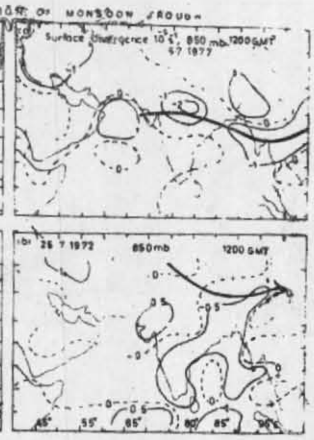


Fig. 2 Fig. 3

Fig. 2 : Surface fields of divergence (10^{-5} s^{-1}), 12 GMT for (a) Strong monsoon (5 July 1987) and (b) break monsoon (25 July 1972) and Fig. 3: Field of divergence at 850 hPa for (a) break and (b) strong monsoon

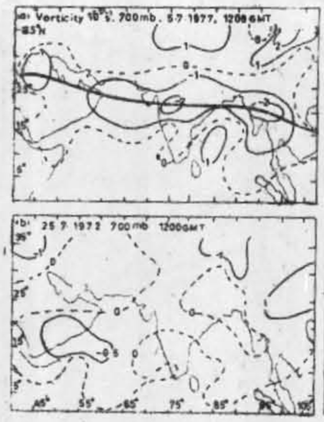
days (as well as strong monsoon days) were similar to each other. Therefore, it was thought to compare only two days charts, one representing break monsoon and other representing strong monsoon. Therefore, charts of 25 July 1972 (representing break monsoon) are compared with charts of 5 July 1977 (representing strong monsoon).

4. Discussion

4.1. *Fields of divergence*

Figs. 2 (a & b) show the surface fields of divergence for strong monsoon day (*i.e.*, 12 GMT of 5 July 1977) and for the break monsoon day (*i.e.*, 25 July 1972) respectively. We find on the strong monsoon day, convergence field covers the whole of India outside the foot of the Himalayas. The maximum convergence of the order of 1×10^{-5} sec^{-1} occurs along the west coast of India, from Kerala coast to Saurashtra coast and also along the axis of the monsoon trough, over the plains of north India. On break monsoon day, there is a weak field of convergence to the west of longitude 78°E over India, which extends westwards to cover north Arabian Sea and also to the east of longitude 90°E which covers north Bay of Bengal. The belt in between these two, is the region of weak divergence. Field of divergence on break monsoon day is very weak.

Figs. 3 (a & b) give 850 hPa level, field of divergence for break and strong monsoon day. On strong monsoon day (5 July 1977) the region of strong convergence lies over the plains of north India and extends southeastwards up to Burma and neighbourhood across north Bay of Bengal. It also extends northwestwards up to Iraq across Afghanistan and west Pakistan. The Bay of Bengal is a region of convergence. The region of strong divergence is northeast India and north Arabian Sea. On break monsoon day (25 July 1972), a belt from south Peninsula to northeast India across Orissa, is region of convergence and also north Bay of Bengal. A belt from north Madhya Pradesh to north Iran across west Pakistan is a region of divergence. Also, Indian Ocean region from 60°E to 75°E is belt of divergence and region 80°E to 90°E is a belt of convergence.



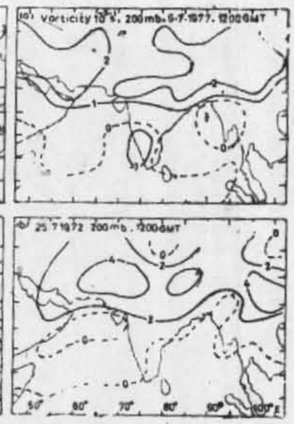


Fig. 4 Fig. 5

Fig. 4 : 700 hPa level field of vorticity for strong and break monsoon day and Fig. 5 : 200 hPa level field of vorticity on strong and break monsoon days

At 700 hPa level, on strong monsoon day (5 July 1977) there is convergence along the monsoon trough and also over Bay of Bengal.

An area of strong convergence lies near 30°-35°N and 50°-60°E and also near 20°-25°N and 100°-110°E. In contrast on break monsoon day (25 July 1972) there is divergence over entire north India north of Lat. 15°N and also over north and central Bay of Bengal.

At 500 hPa level, on strong monsoon day (5 July 1977), there is convergence over central Peninsular India and extends eastwards to south Burma across Bay of Bengal. In contrast, on break monsoon day (25 July 1972) this area has divergence.

At 200 hPa level, on strong monsoon day (5 July 1977), there is divergence over India outside Gujarat and Rajasthan. There is also convergence between 25°-35°N and 95°-110°E. On break monsoon day, there is convergence over India outside Uttar Pradesh and northeast India. Strong field of convergence also lies off west coast of India. Strong field of divergence lies between 20°-35°N and 95°-110°E.

4.2. *Field of vorticity*

At 850 hPa, on strong monsoon day (5 July 1977), negative vorticity lies over India between latitudes 15°N and 20°N and the values of vorticity are of the order of -2×10^{-5} sec^{-1}. On break monsoon day (25 July 1972), negative vorticity lies over India outside south Peninsula and the values of negative vorticity are very small. Over north Bay, there is positive vorticity.

Figs. 4 (a & b) give 700 hPa level field of vorticity for strong (5 July 1977) and break (25 July 1972) monsoon day. On strong monsoon day (5 July 1977) a belt between 15°N-30°N and 40°E-100°E along the monsoon trough is a region of positive vorticity. On either side of this belt, is a region of negative vorticity with the maximum value of negative vorticity (2.0×10^{-5} sec^{-1}) over eastern Tibet. On break monsoon day (25 July 1972), a belt from west Pakistan to north Arabia and another belt from northeast India to north Bay are the regions of negative vorticity. On either side of this belt, is a region of positive vorticity.

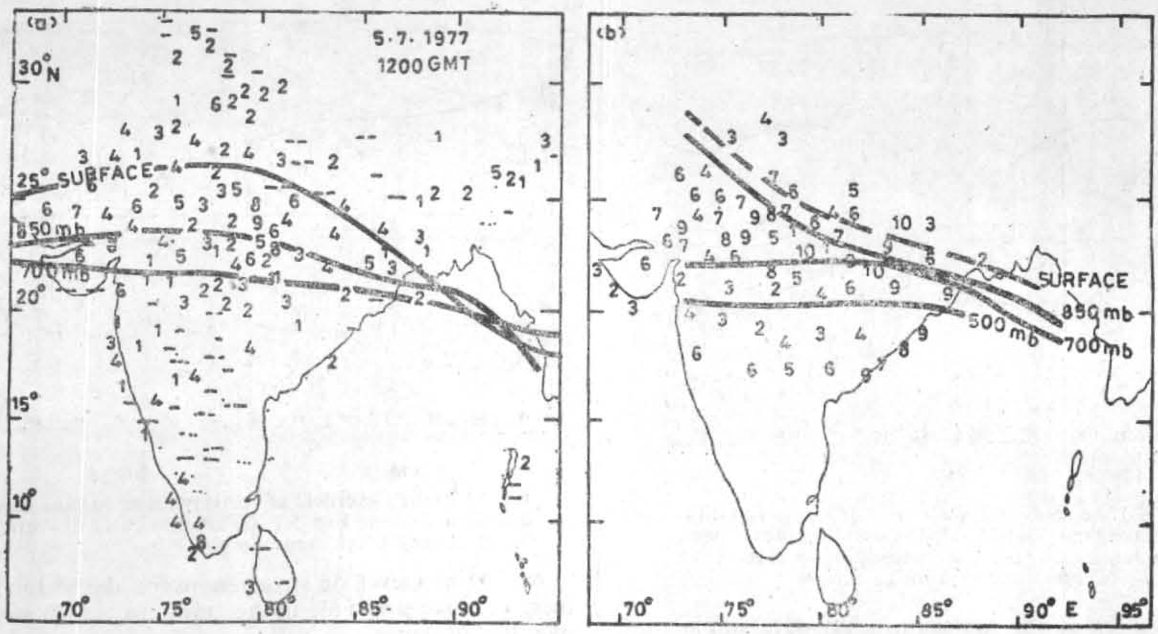


Fig. 6(a). Rainfall next day

Fig. 6(b). Five spells rainfall

Figs. 6(a & b). Mean position of monsoon trough with height and the rainfall realised : (a) the next day and (b) five spells

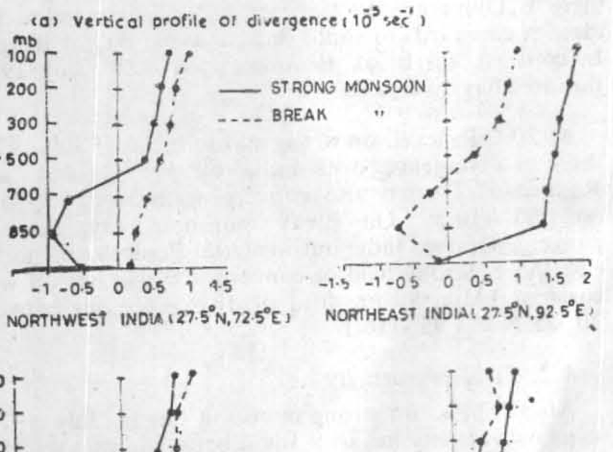


Fig. 7(a). Vertical profile of divergence (10^{-5} sec^{-1})

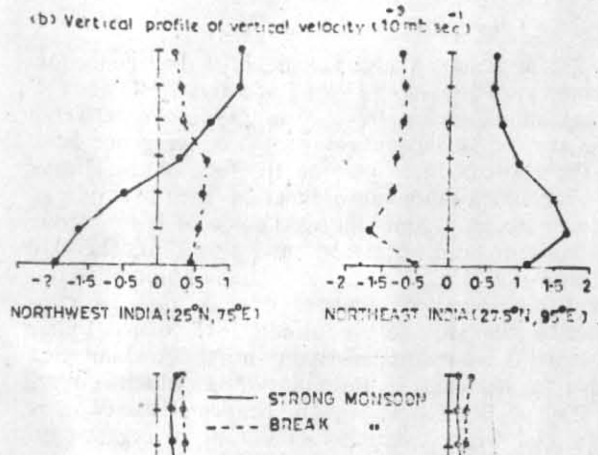


Fig. 7(b). Vertical profile of vertical velocity (10^{-3} mb sec^{-1})

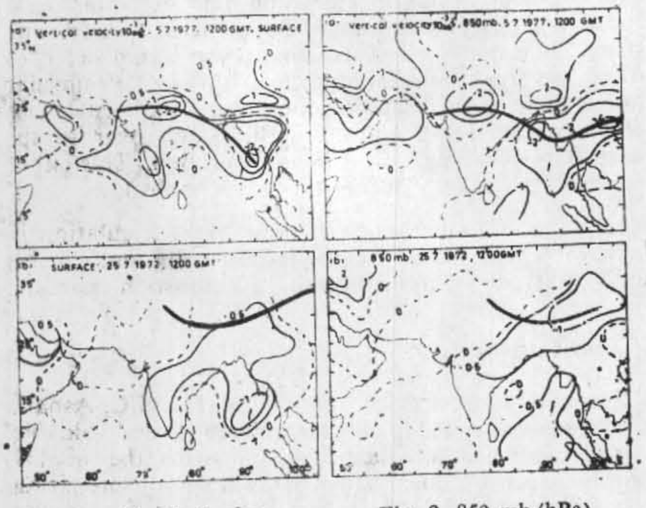


Fig. 8. Surface Fig. 9. 850 mb (hPa)

Figs. 8&9. Field of vertical velocity on strong and break monsoon days

At 500 hPa level, the vorticity field on both the days, namely on strong and break monsoon days is similar. In that, along latitudinal belt between 15° N and 20°N there is negative vorticity on both days. The values of vorticity on break monsoon days are between —0.5 & —1.0 while they are between —2.0 & —2.5 on strong monsoon day.

Figs. 5 (a & b) give 200 hPa level field of vorticity on strong (5 July 1977) and break (25 July 1972) monsoon days respectively. Negative vorticity field lies over south Peninsula over India on both the days and on strong monsoon day the values are stronger of the order of —1.0 along west coast. Positive vorticity field to the north of 16°-18° N of latitude lies on both the days. On break monsoon day, the values of the vorticity of the order of 4, lies between 25° N & 30° N and on strong monsoon day they are of the order of 2 over the same latitudinal belt.

4.3. *Field of vertical velocity*

Figs. 8 (a & b) show at surface the field of vertical velocity on strong (5 July 1977) and break (25 July 1972) monsoon day respectively. On strong monsoon day, there is upward motion over the entire country outside northeast India and southeast Peninsular India. Magnitudes of upward motion are of the order of —2 near north Andaman Sea and Arakan coast, north India and along the west coast of India. There is downward motion over northeast India (+ 1.0) and also over northwest Arabian Sea off Saudi Arabia coast. On break monsoon day, the Peninsula and northeast India have smaller values of upward motion and over northwest India, smaller values of downward motion. Upward motion is more over north Andaman Sea off Burma coast on strong monsoon day than on break monsoon day. There is subsidence over west central Bay off Andhra coast on both the days.

Figs. 9 (a & b) show the vertical velocity field on *strong and break monsoon* day. On strong monsoon day, the axis of the strong upward motion passes through (30°N, 50°E), (25°N, 80°E), (20°N, 90°E) and (20°N, 105°E). The upward motion of the order of—2 to -3×10^{3} mb/sec lie over south Iran, central India, north Bay and Burma. There is downward motion over northeast India +2 mb/sec and Peninsular India. On break monsoon day, there is downward motion over India outside the belt from Peninsular to northeast India when there is upward motion. The upward motion over northeast India is of the order of (-1×10^{-3}) mb/sec. There is also downward motion over north Iraq and adjoining Caspian Sea.

5. Heavy rainfall and monsoon trough

The position, intensity and tilt of the monsoon trough with height are important in governing the spatial and intensity distribution of the monsoon rainfall. In figures the position of the monsoon trough, whenever available, have been shown. It could be clearly seen that fields of divergence, vorticity and vertical velocity are most conducive for the contrasting distribution of monsoon rainfall for the strong and break monsoon spells. Figs. 6 (a & b) show the position of monsoon trough with height and also rainfall realised the next day. It could be seen that during strong monsoon spell, the belt of heavy rainfall is confined between the surface monsoon trough and 700 hPa monsoon trough. This has been verified in all the five spells of strong monsoon studied here. This finding can be used to forecast the belt of heavy rainfall in strong monsoon situation.

6. Synoptic scale east-west zonal circulation

We could see in Figs. 2-5, 8&9 in strong monsoon, there is low level convergence, positive vorticity and vertical motions over northwest India and there is corresponding low level divergence, negative vorticity and downward motion over northeast India. Thus, there is an east-west zonal circulation with its ascending limb over northwest India and descending limb over northeast India, similarly over Peninsular India, second east-west zonal circulation whose ascending limb is over and along the west coast of Peninsular India and descending motion over southwest Bay and neighbourhood. In break monsoon, this east-west zonal circulation reverses or weakens considerably. Figs. 7 (a & b) show the vertical profile of divergence and vertical motion for the strong and break monsoon day. The east-west zonal circulation is very clearly seen here in strong and break monsoon periods.

Walker (1920) found a quasi-periodic oscillation of sea level pressure between the Pacific and the Indian Ocean which he called as Southern Oscillation (S.O.). He described S.O. as "when pressure is high in the Pacific Ocean, it tends to be low in the Indian Ocean from Africa to Australia". Walker (1920) was the first to show that S.O., which is essentially an oceanic phenomena, is intimately related to the Indian monsoon. Bjerknes (1969) suggested that the El-Nino (sudden warming of sea surface temperature) is closely associated with the S.O. discovered by Walker. Bjerknes (1969) further postulated an east-west zonal circulation in the equatorial Pacific and called it "Walker's circulaion" as the physical mechanism for the S.O. discovered by Walker (1920). Over the Asiatic monsoon region, we can extend the idea of Walker's circulation (east-west zonal circulation) and study its variation in relation to the fluctuations of the monsoon rainfall.

Walker's (1920) circulation over the tropical Asiatic monsoon region is mainly a planetary scale circulation. Whereas, the east-west zonal circulation which we have observed over Indian monsoon area is a synoptic scale circulation. It is observed in the study of five spells of break and strong monsoon that the synoptic scale east-west zonal circulation is an associated feature of strong and break monsoon. We know that the strong and break monsoon conditions are characterised by contrasting rainfall distribution in association with the position, intensity and tilt of the monsoon trough. Now, we can add that the position and intensity of the synoptic scale east-west zonal circulation is also an important associated feature of monsoon which can be used for forecasting monsoon rainfall. As no two spells of strong monsoon (or break monsoon) are identical and differ in many respects, this synoptic scale east-west zonal circulation also fluctuates and can be used for forecasting monsoon rainfall.

7. Conclusions

(*i*) Contrasting rainfall distribution in spells of break and strong monsoon, can be explained by the fields of divergence, vorticity and vertical motion.

(*ii*) In strong monsoon, heavy rainfall belt lies between the positions of monsoon trough in surface and 700 hPa. This can be used for heavy rainfall forecast.

(*iii*) Two synoptic scale east-west zonal circulation are observed over the Indian monsoon region. The one over north India has an ascending limb over northwest India and descending limb over northeast India during strong monsoon spell. This either reverses and becomes weak in break monsoon. Similarly, over Peninsular India, there is an ascending limb along the west coast of Peninsular India and descending limb over southwest Bay of Bengal and neighbourhood. This either reverses or weakens during the break monsoon.

(*iv*) This synoptic scale east-west zonal circulation is a characteristic feature of Indian monsoon and can be used to study the fluctuations in monsoon rainfall.

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