

Dynamics of Heavy Rain Spells over India during 2005

S. S. Naik¹, P. S. Salvekar²

¹Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune-411007, India

²341, Narayan Peth, Pune-411030, India

Abstract: *High-impact mesoscale weather events, occurring in different parts of India in all seasons, lead to major weather and climate related disasters. In view of this, an attempt has been made in the present study to understand the dynamics of atmospheric circulation over the Indian region (50°E-100°E and EQ-30°N) during super active monsoon period 21st-30th June and 22nd-31st July 2005 using NCEP/NCAR reanalyzed daily winds (u and v), temperature (T) from surface to 200 hPa to compute the divergence (D), vorticity (ζ), vertical velocity (ω), static stability (σ) and heat source (Q_H). $\sigma^{-1}(p)$ profiles clearly indicate the unstable zone between 850 to 650 hPa. The necessary condition of barotropic instability and condition of baroclinic instability are also satisfied in the layer 850-650 hPa for all the active monsoon days. Further, zonal (u) and meridional (v) winds, are examined in the zonal (x-p) and meridional (y-p) planes. It is noticed that there exist low level cyclonic circulations in the boundary layer over major portion of the country and abnormal increase in the meridional wind in the lower and middle troposphere. Significant increase in the cyclonic vorticity upto 300 hPa and the upward motion throughout in the troposphere with maximum value around 700 to 500 hPa and positive heat source explain the possibility of highly convective and unstable mid-tropospheric zone. The study indicates that there are few mesoscale systems embedded in the synoptic scale system that are already present in the large-scale monsoon circulation.*

Keywords: Heavy rain spell, Dynamic instability, Mid-tropospheric cyclone, Cubic spline technique, Summer monsoon

1. Introduction

Onset of southwest monsoon during 2005 over Kerala coast was declared by India Meteorological Department (IMD) on 5th June and withdrawal from northwest region took place on 2nd September. The initial phase was rather weak but monsoon activity is improved by the third week of June. Due to the intense monsoon activity in the last week of June, monsoon rainfall covered entire country on 30th June i.e. two weeks prior to the normal date. As the onset date varies, atmospheric circulation pattern also differs from year to year. Many studies are available in literature, (Ananthkrishnan et al [1] & Joseph et al [2]) describing the changes that take place in the atmosphere over the Indian sub-continent at the time of onset of monsoon.

During 2005 monsoon, another occasion of heavy rainfall event was found in the last week of July. The detail discussion on the active and break spells of Indian summer monsoon given by Rajeevan et al. [3] reported the active period of monsoon 2005 as 1st- 4th July and 27th July-1st August. The GCM study by Dey et al. [4] also examined the super active monsoon period 27th July – 1st August 2005. Rajeevan et al. [3] have shown that the rainfall enhancement during active monsoon can last from a few days to beyond a week. It is important to note that the total monsoon duration of 2005 was 90 days (onset 5 August and withdrawal 2nd September) which was much less than normal 120 days. But still overall seasonal rainfall amount for the country as a whole was good for the monsoon year 2005. In fact, temporal distribution of rainfall was below normal in nine weeks in large part of the country out of seventeen monsoon weeks. Most of the subdivision reached normal rainfall only because of the abnormal monsoon behavior in the last two pentads of June (21st –30th June) and July (22nd-31st July) when there

were very heavy rain spells in the western part of the country. Due to these heavy spells, the total rainfall activity became normal over west of 80°E. On 26th July, there was abnormally intense rainfall (994 mm) at Mumbai and many west coast stations also received excessive rainfall during the last week of July.

Many observational and simulation studies are available in the literature [5-11] for understanding the record heavy rainfall events over Mumbai on 26th & 27th July 2005. Francis et al [12] examined the incidence of such events along the west coast of India and found that the belt between 14°N and 20°N is especially susceptible to such events, which occur as a result of several factors such as the large-scale strengthening of the monsoon winds over the Arabian Sea, the movement of monsoon depressions from the Bay of Bengal to central India along approximately 20–22°N, the formation of mid-tropospheric cyclones (MTCs) and the presence of active off shore troughs in the lower troposphere along central and northern parts of the coast with the possibility of an embedded mesoscale cyclonic circulation. De et al [13] have studied the role of enhancement of convective available potential energy (CAPE) and decrease in convective inhibitive energy (CINE) in the incidence of very heavy rainfall at Mumbai. Ranade et al [14] have also evaluated severity of the 26th -27th, July 2005 rainstorm over Mumbai in the backdrop of fluctuations of the spatio-temporal 1-DSG (degree square grid) extreme rainfall over the country and their investigation reveals that occurrence of unprecedented rainfall is a realization of highly significant increasing trend in the spatio-temporal extreme rainfall over the country. In the past, Ramage [15] reviewed studies of heavy tropical rainfalls and concluded that the heavy rainfalls are associated with the thunderstorms. These storms are embedded in the synoptic scale disturbances. In the

present study, dynamics of the heavy rain spells over the Indian region (50°E-100°E and EQ-30°N) have been explored for last two pentads of June and July during 21st - 30th June and 22nd -31st July of 2005 monsoon. For this purpose, dynamical (D, ζ and ω) and physical (Q_H) parameters, meridional gradient of absolute vorticity, static stability $\sigma(p)$ and meridional gradient of potential vorticity $Q_y(p)$ as well as the occurrence of strong horizontal and vertical wind shear are computed.

2. Propagation of summer monsoon during 2005

The southwest monsoon during 2005 reached south Andaman Sea and parts of southeast Bay on 26th May, with a delay of about 6 days. The Arabian Sea branch started advancing on 5th June and the onset was declared on 5th June over Kerala. Thereafter, monsoon propagation is rather weak. However, a monsoon depression formed in the Arabian Sea as well as in Bay of Bengal during last week of June that leads to the advancement of monsoon throughout the country by 30th June. During July, again monsoon activity was weakened which shows deficient monsoon activity till the 3rd week of July. Due to the occurrence of depression over Orissa coast, in the last week of July, heavy rainfall occurred in most of the sub-division over Indian region. These systems are responsible to make the all India rainfall activity as normal.

3. Data and Methodology

The unusual heavy spells of rainfall activities are studied by examining dynamical (D, ζ and ω) and physical (Q_H) parameters during the period 21st-30th June and 22nd-31st July, using NCEP/NCAR reanalyzed (Kalnay et al [16]) daily zonal and meridional wind (u and v), temperature (T) and relative humidity (q) data from surface to 200 hPa, over the region 50°E-100°E and EQ-30°N. To determine the instability characteristics of large-scale monsoon circulation, the static stability [$\sigma(p)$] and meridional gradient of potential vorticity [$Q_y(p)$] and meridional gradient of absolute vorticity $Q_y(y)$ are also computed throughout the period mentioned above. Further, wind shear in the x-p plane (15°N) and y-p plane (80°E) are also examined over the domain.

Vertical component of relative vorticity ($\zeta = \partial v/\partial x - \partial u/\partial y$) and horizontal divergence ($D = \partial u/\partial x + \partial v/\partial y$) are the two important parameters for understanding the dynamics of the system. Negative divergence i.e. $-(\partial u/\partial x + \partial v/\partial y)$ is called convergence and positive vorticity means cyclonic circulation

From the direction and magnitude of vertical velocity (ω), the atmospheric situation can be diagnosed. Therefore, vertical velocity (ω), is computed using kinematic method. This method assumes that total divergence is zero in the unit vertical column, so a correction factor as given by O'Brien [17] is introduced to get correct ω . All the computations are carried out at 50 hPa interval for which the data is interpolated using cubic spline technique [18]. Vertical

velocity contributes significantly in the heat and moisture budget during convective activity. The heat budget (Q_H) is obtained by using,

$$Q_H = C_p \left[\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + \omega \left(\frac{\partial T}{\partial p} - \frac{RT}{C_p p} \right) \right]$$

and static stability σ is obtained from

$$[\sigma(p)] = - \frac{R}{p} \left[\frac{\partial \bar{T}}{\partial p} - \frac{R \bar{T}}{C_p p} \right]$$

The meridional gradient of potential vorticity [$Q_y(p)$] for combined zonal and meridional flow [19] is computed by using.

$$[Q_y(p)] = \beta - f_o^2 \frac{\partial}{\partial p} \left\{ \frac{1}{\sigma} \frac{\partial}{\partial p} \left([u] + \frac{\ell}{k} [v] \right) \right\}$$

And the meridional gradient of absolute vorticity of zonal flow is given by

$$\bar{Q}_y(y) = \beta - \bar{u}_{yy}$$

where $R = 287$, $C_p = 1004 \text{ J kg}^{-1} \text{ K}^{-1}$, k and ℓ are zonal and meridional wave number, over the domain 50°E -100°E and EQ- 30°N respectively. f_o and β are considered for 15°N, the central latitude of the region, over bar denotes zonally averaged value and [] denotes area average values over the region.

Vertical profiles of [$\sigma(p)$] and [$Q_y(p)$] as well as meridional profile of $Q_y(y)$ are obtained for each day from 21st-30th June and 22nd-31st July. It is important to note that changing the sign of [$Q_y(p)$] in the vertical domain is the necessary condition of baroclinic instability [20] and necessary condition for barotropic instability is that $Q_y(y)$ must vanish somewhere in the meridional domain. Also we know that in a stable atmosphere [$\sigma^{-1}(p)$] decreases exponentially with height.

4. Results and Discussion

Dynamic instability characteristics are studied throughout the period from 21st- 30th June and 22nd - 31st July by analyzing the vertical profiles of zonal [u] and meridional [v] wind, inverse static stability (σ) and meridional gradient of potential vorticity [$Q_y(p)$] as well as meridional profile of ($Q_y(y)$).

4.1 Period 21st-30th June

Day to day winds throughout in the troposphere during 21st- 30th June indicate low level westerly and upper level easterly with a transition at about 500-400 hPa. The westerly maximum is about 7-8 ms^{-1} near to 900 hPa and maximum easterly value at 200 hPa is 12 ms^{-1} noticed throughout the

period. Meridional winds are weak throughout in the vertical domain except in the boundary layer (1000-850 hPa) where southerly winds have magnitude about $2-3 \text{ ms}^{-1}$.

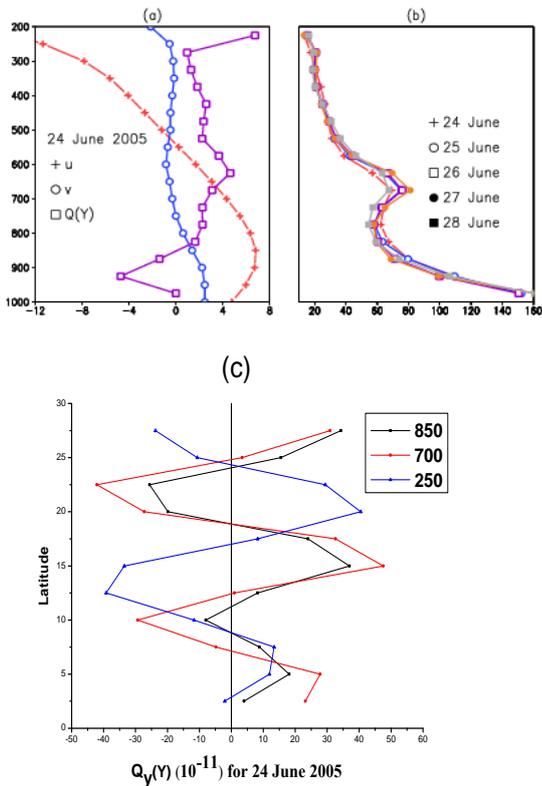


Figure 1: (a) vertical profile of $[u]$, $[v]$ and $[\bar{Q}_y(p)]$, (b) Vertical profile of inverse static stability, (c) Meridional profile of $[\bar{Q}_y(y)]$ at 850 hPa, 700 hPa and 250 hPa levels for June 2005

The existence of strong wind shear and change of sign in $[Q_y(p)]$ in the vertical domain 900-600 hPa together indicates the importance of baroclinic mechanism (Figure 1 (a)). The vertical profile of σ^{-1} indicate that the mid-tropospheric layer between 850-650 hPa is unstable for the period 24th – 28th June (Figure 1 (b)), responsible for the occurrence of synoptic system i.e. the depression during 22nd -27th June. In the past, Mak [21] found the role of baroclinic instability to explain the Mid-tropospheric cyclone. Moorthi et al [22] have shown the reasons of formation of monsoon depression as baroclinic instability mechanism with cumulus heating. Necessary condition of barotropic instability (Figure 1(c)) is found to be satisfied in the peninsular region (near 7.5N) and in the central Indian region (near 18°N to 24°N) in the lower and upper troposphere. From the observations, it is found that there exist deep depression during 22nd –24th June in Arabian Sea and 27th –30th June in Bay of Bengal. These two systems together lead the monsoon activity very intense throughout the country. From the zonal and meridional winds in the x-p (15°N) and y-p (80°E) plane (Figure 2(a) and 2(b)), it is noticed that there are small scale cyclonic circulations in the boundary layer. Maximum zonal wind of about 15 m s^{-1} is seen at 5°N-15°N belt on 24th June.

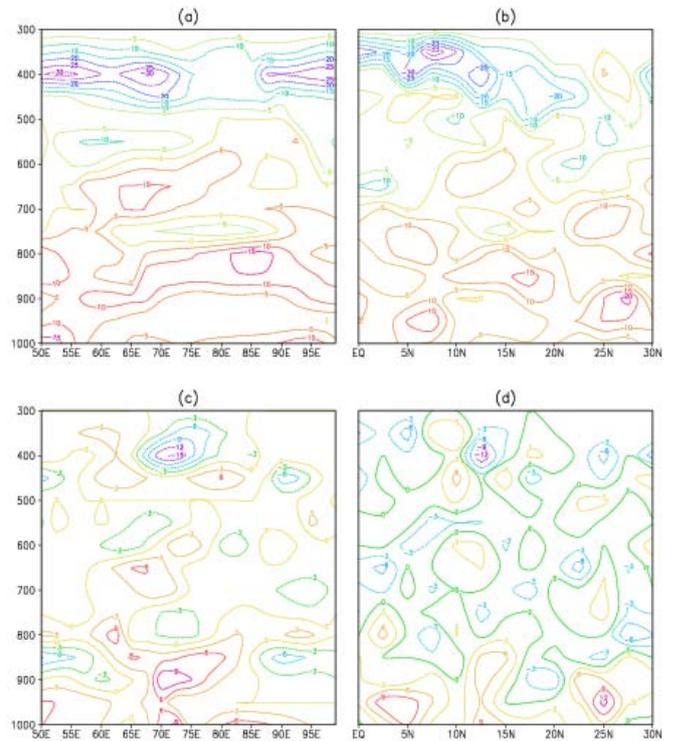


Figure 2 . Vertical distribution of horizontal wind at 15°N (x-p plane) and 80°E (y-p plane), (a) and (b) for zonal wind, (c) and (d) for meridional wind for 24th June 2005

Reduction in the wind magnitude near surface is seen, that may be due to strong surface friction. Further, careful examination of wind distribution indicates presence of inversion near west coast south of 10°N. Such situation is noticed for all the days. By examining the dynamical and physical parameters, low level convergence from surface to 700 hPa and upper level divergence is found during the period 22nd –24th June (figure not shown). In fact, the computations are carried out for every 50 hPa interval; the vorticity (ζ), divergence (D), vertical velocity (ω) and heat source (Q_H) for 24th June alone are shown for 700 hPa in

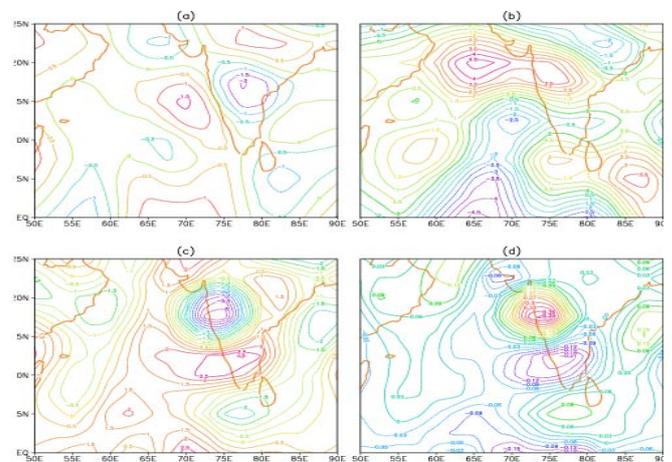


Figure 3: Horizontal distribution of (a) $D(10^{-5} \text{ s}^{-1})$, (b) $\zeta(10^{-5} \text{ s}^{-1})$, (c) $\omega(10^{-3} \text{ hPa s}^{-1})$ and (d) $Q_H(10^{-1} \text{ J Kg}^{-1} \text{ s}^{-1})$ at 700 hPa for 24th June 2005

(Figure 3). Strong upward motion ($\omega \sim -7 \times 10^{-3} \text{ hPa s}^{-1}$) significant cyclonic circulation ζ ($\sim 4 \times 10^{-5} \text{ s}^{-1}$) and positive heat source ($Q_H \sim 0.4 \times 10^{-1} \text{ J kg}^{-1} \text{ s}^{-1}$) from surface to 400 hPa gives the indication of heavy precipitation in most of the subdivision west of 80°E .

4.2 Period 22nd –31st July

Area averaged zonal and meridional wind from 22nd -31st July are examined. Low level westerly maximum ($7-8 \text{ m s}^{-1}$) at 850 hPa and upper level easterly maximum ($11-12 \text{ m s}^{-1}$) at 250 hPa is seen in most of the days. Meridional winds are weak throughout the period. The vertical profiles of $[u]$, $[v]$ $[Q_y(p)]$ and for 26th July are shown in (Figure 4(a)). The vertical profile of σ^{-1} computed for each day and it is found that the mid-tropospheric layer from 850-650 hPa are unstable for the period 24th - 28th July (Figure 4(b)). The vertical profile of $[Q_y(p)]$ also indicates that the atmosphere is unstable in the lower troposphere. Necessary condition of barotropic instability is found to be satisfied near 18°N in the lower and upper tropospheric levels. Also $[Q_y(y)]$ profile of 250 hPa changes sign in the peninsular region near 10°N (Figure 4(c)). Magnitudes of zonal wind are found upto 20 m s^{-1} at 15°N from $60^\circ\text{E}-95^\circ\text{E}$ around 850 hPa on 26th July (Figure 5(a)). Further meridional winds are found intense with magnitude ($\sim 10-15 \text{ m s}^{-1}$) upto 600 hPa east of 65°E as seen in Figure 5(c). In the y-p plane from $5^\circ\text{N}-20^\circ\text{N}$ and the zones of southerly and northerly winds are noticed at the interval of 5°N (Figure 5(d)). This suggests strong meridional shear of meridional wind. Magnitude of $\partial v/\partial y$ is large, i.e. $1.4 \times 10^{-6} \text{ s}^{-1}$. At the same time, the east-west shear of zonal wind is very small. Role of strong surface friction around $15^\circ\text{N}-20^\circ\text{N}$ and inversion at $5^\circ\text{N}-6^\circ\text{N}$ are seen in the y-p plane distribution of zonal wind along 80°E on 26th July (Figure 5(b)). It indicates that the core of westerly maximum wind is sloping from 800 hPa at 6°N to 950 hPa at 27°N . The isolines of ζ , D , ω and Q_H are presented in (Figure 6) for 26th July at 700 hPa. There exist large convergence (negative divergence) resulting significant upward motion near 15°N , 80°E at 700 hPa. This fact is clearly seen from (Figure 6(c)). By examining the isolines of ζ and ω , for different vertical levels, eastward tilt in the vertical is clearly seen from the zones of upward motion. This supports the baroclinic mechanism for the synoptic scale monsoon depression which is present during the period. In the west coast, the isolines of ζ show maximum intensity at about 700 hPa with weak circulation at surface level indicates the presence of Mid-Tropospheric Cyclone (MTC) near Mumbai and Gujarat coast during 23rd to 26th July. Combined effect of off shore vortex, monsoon depression and MTC resulted excessive rainfall in the west of 80°E .

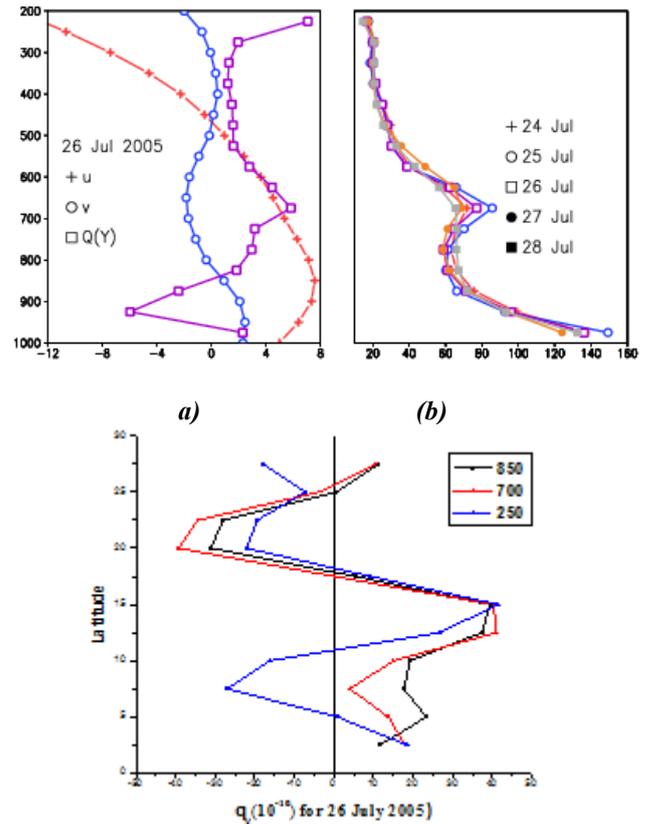


Figure 4: (a) vertical profile of $[u]$, $[v]$ and, $[\bar{Q}_y(p)]$ (b) Vertical profile of inverse static stability, (c) Meridional profile of $[\bar{Q}_y(y)]$ at 850 hPa, 700 hPa and 250 hPa levels for July 2005.

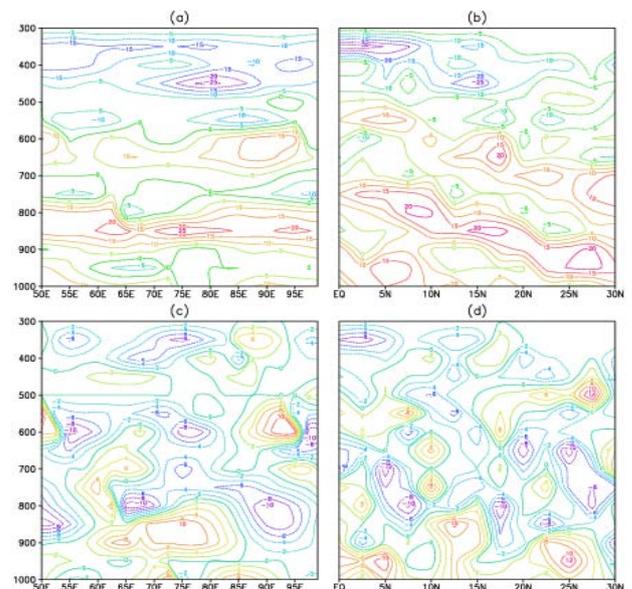


Figure 5: Vertical distribution of horizontal wind at 15°N (x-p plane) and 80°E (y-p plane), (a) and (b) for zonal wind, (c) and (d) for meridional wind for 26th July 2005.

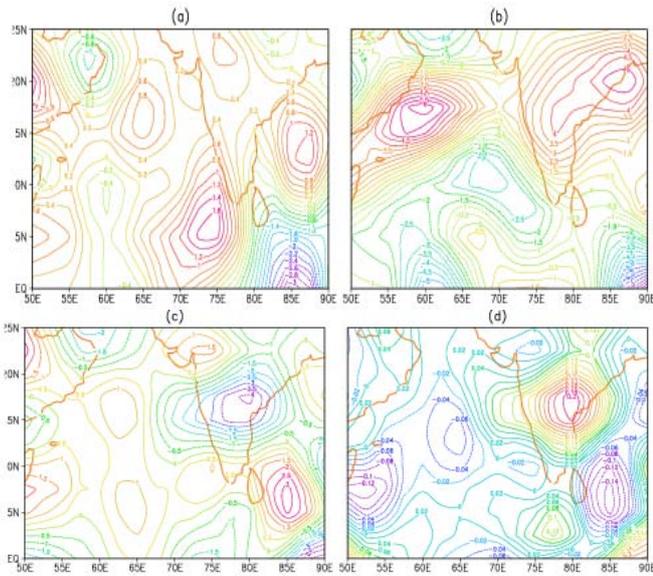


Figure 6: Horizontal distribution of (a) $D(10^{-5}s^{-1})$, (b) $\zeta(10^{-5}s^{-1})$, (c) $\omega(10^{-3} hPa s^{-1})$ and (d) $Q_H(10^{-1} J Kg^{-1} s^{-1})$ at 700 hPa for 26th July 2005.

5. Conclusions

By examining the wind distribution in the 3-dimensional domain, it is found that strong vertical shear of zonal and meridional winds are present in both the cases of June and July. In addition to this, there exists strong meridional wind shear for the case of July. Intense magnitudes of meridional wind suggest the need of examination of necessary condition of baroclinic instability for combined zonal and meridional flow. All the computation show the atmosphere is highly unstable in the middle troposphere near 850-650 hPa. Baroclinic instability condition is satisfied in the lower layer (below 800 hPa) for both June and July active monsoon days. Barotropic instability condition is satisfied by lower as well as upper tropospheric zonal flow, near peninsular region and near monsoon trough zone for the active monsoon period of June. For the case of July active period, the barotropic instability condition is satisfied near monsoon trough zone by lower and upper tropospheric flow but near peninsular region, the barotropic instability condition is satisfied only by upper tropospheric flow. Strong magnitudes of ζ , ω and Q_H for all the days in June and July are found and shown for the latitudinal belt 15N-20N in **Table 1 (a and b)**. Maximum intensity of vorticity ζ ($6.5 \times 10^{-5} m s^{-1}$) and vertical velocity ω ($-6 \times 10^{-3} hPa s^{-1}$) near 23°N, 68°E up to 400 hPa, indicates presence of active off shore trough, as a result of which very heavy rainfall occurred throughout the days. Cyclonic vorticity is significantly enhanced as compared to the climatological values. Further, it is found that cyclonic vorticity has deeper vertical extent upto 350 hPa (figure not shown) which is in the close agreement with Dey et al. [4]. In view of the strong low level convergence in the boundary layer, intense upward motion and high intensity of the heat source in the mid troposphere together result that the growth of the system is due to (CISK) mechanism. Both the cases of

Table 1(a): $\zeta (10^{-5} s^{-1})$, $\omega (10^{-3} hPa s^{-1})$ and $Q_H (10^{-1} J Kg^{-1} s^{-1})$ for the period 21st – 30th Jun 2005

Date \ Level (hPa)	21	22	23	24	25	26	27	28	29	30
500										
ζ	0.2	0.1	0.1	0.4	0.4	1.4	1.7	1.3	0.6	1.0
ω	-2	-5	-7	-7	-4	-3	-6	-6	-6	-2
Q_H	0.1	0.4	0.5	0.5	0.3	0.2	0.5	0.4	0.4	0.2
700										
ζ	4.5	5.5	5.5	4.5	4.0	5.5	5.5	5.5	6.5	5.0
ω	-3	-6	-6	-6	-2	-4	-4	-4	-4	-2
Q_H	.25	0.2	0.5	0.5	.15	0.3	0.2	0.4	0.4	0.1
850										
ζ	5.5	6.5	5.5	4.0	3.5	4.5	4.5	5.5	6.0	5.5
ω	-2	-4	-4	-4	-1	-3	-2	-2	-2	-2
Q_H	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.1

Table 1(b): $\zeta (10^{-5} s^{-1})$, $\omega (10^{-3} hPa s^{-1})$ and $Q_H (10^{-1} J Kg^{-1} s^{-1})$ for the period 22nd – 31st Jul 2005

Date \ Level (hPa)	22	23	24	25	26	27	28	29	30	31
500										
ζ	0.2	0.3	0.1	0.3	0.1	0.6	0.4	0.6	0.2	0.6
ω	-2	-3	-2	-3	-1	-3	-3	-2	-2	-1
Q_H	0.2	0.2	0.2	0.2	0.4	0.2	0.3	0.2	0.3	0.2
700										
ζ	2.5	5.5	8.5	8.0	5.0	5.0	4	7.0	7.0	6.5
ω	-2	-2	-2	-3	-4	-4	-5.5	-3	-4	-4
Q_H	0.2	0.1	0.1	0.1	.1	0.3	0.2	0.1	0.2	0.2
850										
ζ	2.0	4.0	6.0	8.5	6.0	5.0	4.5	7.5	7.0	6.0
ω	-1	-1	-2	-2	-2	-3	-2	-2	-3	-2
Q_H	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

June and July have indicated that there exists the circulation in the presence of west coast monsoon onshore trough, Mid-tropospheric Super Cyclone (MTSC) over Gujarat and low level monsoon systems in the monsoon trough zone. Finally it can be concluded that there are few mesoscale systems embedded in the synoptic scale system that are already present in the large-scale monsoon circulation.

Acknowledgements

The authors are thankful to the Director, Indian Institute of Tropical Meteorology, Pune, for providing necessary facilities to carry out this research work and constant encouragement.

References

[1] R.Ananthakrishnan, M.K.Soman, "The onset of southwest monsoon over Kerala 1901-1980," International J. Climate, (8), pp 283-296, 1988.

- [2] P.V.Joseph, J.K.Eischeid, R.J.Pyle, "Interannual variability of the onset of the Indian summer monsoon and its association with atmospheric features El.Nino and sea surface temperature anomalies," *Journal of Climate*, (7), pp81-105, 1994.
- [3] M.Rajeevan, S.Gadgil, J. Bhate, "Active and break spells of the Indian summer monsoon," *J.Earth Syst.Sci.*, (119), pp229-247, 2010.
- [4] Ayantika. Dey Chowdhury, R.Krishnan, "Dynamical response of the south Asian Monsoon trough to latent heating from stratiform and convective precipitation," *J.Atmos.Sci.*, (68), pp1347-1363, 2011.
- [5] A.K. Bohra, Swati Basu, E.N. Rajagopal, G.R. Iyengar, M. Das Gupta, R.Ashrit, B. Athiyaman, "Heavy rainfall episode over Mumbai on 26 July 2005," *Current Science*, (90), 9, pp 1188-1194, 2006.
- [6] R.K.Jenamani, S.C.Bhan, S.R.Kalsi, "Observational/forecasting aspects of the Meteorological event that caused record highest rainfall of 94.4 cm on 26-27 July 2005 in Mumbai," *Current Science*, (90), pp1344-1362, 2006.
- [7] S.S.Vaidya, J.R.Kulkarni, "Simulation of heavy precipitation over Santacruz Mumbai on 26 July 2005 using mesoscale model," *Journal of Meteor. Atmos. Phys.*, (98), pp55-66, 2007.
- [8] B. Shyamala, C.V.V. Bhadrani, "Impact of mesoscale-synoptic scale interactions on the Mumbai historical rain event during 26-27 July 2005," *Current Science*, (91), No.12, pp1649-1654, 2006.
- [9] Y.V. Rama Rao, H.R.Hatwar, A.K.Salah, Y.Sudhakar, "An experiment using the high resolution Eta and WRF models to forecast heavy precipitation over India," *Pure.Appl.Geophys.*, (164), pp1593-1615, 2007.
- [10] A.Kumar, J.Didhia, R.Rotunno, D.Niyogi, U.C.Mohanty, "Analysis of the 26 July 2005 heavy rain event over Mumbai, India using the weather research and forecasting (WRF) model," *Quar.J.R.Meteorol. Soc.*, (134), pp1897-1910, 2008.
- [11] D.R.Sikka, P.S.Rao, "The use and performance of mesoscale models over the Indian region for two high impact events," *Natural Hazards*, (44), pp353-372, 2008.
- [12] P.A Francis, S.Gadgil, "Intense rainfall events over the west coast of India," *Meteorology and Atmospheric Physics*, (94), pp27-42, 2006.
- [13] U.S.De, S.Dutta, "West coast rainfall and convective instability," *J.Indian Geophys. Union*, (9), pp71-82, 2005.
- [14] A.A.Ranade, N.Singh, "Large-scale wet spell and spatio-temporal rainfall extremes over India during 1951-2007," ISSN 0252-1075, Contribution from IITM, No. RR-126, 2010.
- [15] C.S. Ramage, "Monsoon Meteorology," *International Journal of Geophysics*, (15), Academic Press, pp 296, 1971.
- [16] E.Kalnay, M.Kanamitsu, et al., "The NCEP/NCAR 40-year reanalysis project," *Bulletin of the American Meteorological Society*, (77), pp 437-471, 1996.
- [17] J. O'Brien, "Alternative solutions to the classical vertical velocity problem," *J.Atmos.Sci.*, (USA), (9), pp192-203, 1970.
- [18] S.S.Naik, P.S.Salvekar, "Interannual variability in the dynamics and physics of the meanonset date of monsoon over Indian Region," *Indian Journal of Radio and Space Physics*. (33), pp 241-251, 2004.
- [19] P.S.Salvekar, "On the development of monsoon disturbances through baroclinic instability and other physical processes," Ph.D. Thesis, University of Pune, 1984.
- [20] P.K.Das, Monsoon, 5th IMO Lecture No. WMO No.613, 1986.
- [21] Mak Man-Kin, "The monsoonal mid-tropospheric cyclogenesis," *Journal of Atmospheric Science*, (32), pp 2246-2256, 1975.
- [22] S.Moorthi, A.Arakawa, "Baroclinic Instability with cumulus heating," *Journal of Atmospheric Sciences*, (42), pp 2007-2031, 1985.