

Does the Western-Ghats play any dynamical role in the distance effect of vortex over the Bay of Bengal on the enhancement of monsoon rainfall over Pune?

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सार – इस शोध पत्र में दक्षिण-पश्चिम मानसून ऋतु (एस.डब्ल्यू.एम.एस.) के दौरान बंगाल की खाड़ी में उठे बवंडर के दूरवर्ती प्रभाव के फलस्वरूप पुणे में वर्षा में हुई वृद्धि में पश्चिमी घाट (डब्ल्यू.जी.) की गत्यात्मक भूमिका (यदि कोई हो तो) की जाँच करने का प्रयास किया गया है। इसकी जाँच करने के लिए मध्य मापक्रम अवरोध के ऊपर वायु-प्रवाह के एक गत्यात्मक मॉडल का उपयोग किया गया है। छः घटनाओं के अध्ययन से यह ज्ञात हुआ है कि बंगाल की खाड़ी में बवंडर उठने की स्थिति में पुणे में हुई वर्षा में वृद्धि देखी गई है। इन छः घटनाओं में से चार घटनाओं में यह देखा गया है कि गत्यात्मक मॉडल पुणे में वर्षा की प्रेक्षित घट-बढ़ (कमी-बेशी) का पता लगाने में गुणात्मक रूप से सफल रहा है। इन चारों घटनाओं में पश्चिमी पवनें पश्चिम तट के किनारे उर्ध्वाधर में अपेक्षाकृत काफी तीव्र थीं। अन्य दो घटनाओं में से एक घटना में यह मॉडल वर्षा की अधिकता को, कम से कम गुणात्मक रूप में, पता लगाने में सफल रहा है परन्तु वर्षा में कमी का पता लगाने में असफल रहा है। एक अन्य घटना में यह मॉडल पुणे में वर्षा की घट-बढ़ ज्ञात करने में गुणात्मक रूप से भी पूर्णतया असफल रहा है। अंतिम दो घटनाओं में पश्चिम तटीय स्टेशन पर पश्चिमी पवन कमजोर एवं सतही थी।

ABSTRACT. An attempt has been made to examine the dynamical role (if any) played by the Western Ghats (WG), in the distance effect of vortex over the Bay of Bengal (BOB) on the rainfall enhancement over Pune, during southwest monsoon season (SWMS). To examine it, a dynamical model of airflow over a meso-scale barrier has been used. Six cases have been studied, in which enhancement of rainfall over Pune in presence of vortex over the Head Bay are noticed. Out of these six cases, in four cases it is found that the dynamical model can capture, at least qualitatively, the observed fluctuation (rise and fall) of rainfall over Pune. In these four cases westerly along west coast was strong with considerable depth in vertical. In one of the other two cases, the model has been able to capture, at least qualitatively, the observed rise in rainfall but failed to capture the observed fall in rainfall. In the other case the model has failed completely to capture, even qualitatively, the fluctuation in observed rainfall over Pune. In the last two cases, westerly along west coast station was weak and shallow.

Key words – Distance effect, Orographic rainfall.

1. Introduction

Qualitatively much has been discussed about orographic effect of the Western Ghats (WG) in enhancing precipitation. Generally orographic enhancement of rainfall due to the WG is more over its windward side. Rainfall enhancement on the windward side of western ghats is mainly due to forced orographic lifting (Sarker 1966, 1967). It is known that besides lifting, the WG plays another crucial role by producing lee waves under favourable conditions of the south-westerly (SW'ly) moist air stream during SWMS. Sometimes updraft associated with these lee waves may cause an

enhancement of rainfall on the lee side under favourable condition of moisture supply. Sarker (1967) has shown that lee waves produced by the WG can give good rainfall on the leeward side.

It has been observed that whenever a vortex forms over Head Bay during southwest monsoon months, the west coast experiences heavy rainfall. Observations show that, not only the west coast, in many occasions a vortex, formed over the head-Bay of Bengal during southwest monsoon season (SWMS), causes an enhancement in rainfall over Pune also. This has been termed by earlier workers as 'Distance effect'.

TABLE 1

Selected cases for rainfall enhancement over Pune in the presence of a vortex over the Bay of Bengal

Case No	Period of rainfall	Period of RS/RW data
1	From 14 June 2004 to 16 June 2004	From 13 June 2004 to 15 June 2004
2	From 6 June 2004 to 8 June 2004	From 5 June 2004 to 7 June 2004
3	From 27 July 2003 to 29 July 2003	From 26 July 2003 to 28 July 2003
4	From 31 July 1997 to 2 August 1997	From 30 July 1997 to 1 August 1997
5	From 22 August 1990 to 25 August 1990	From 21 August 1990 to 24 August 1990
6	From 16 August 1990 to 18 August 1990	From 15 August 1990 to 17 August 1990

There are many qualitative and synoptic studies addressing the distance effect of vortex over the Bay of Bengal on the enhancement of rainfall over Pune. Mukherjee and Sinha Ray (1983) studied the characteristics of July rainfall, over the districts in Madhya Maharashtra adjoining the WG. In this study, the observed difference of rainfall characteristics between the western and eastern parts of the above districts were attributed to the orographic influence. In the study of Mukherjee & Shyamla (1985), the increased rainfall activity over Konkan - Kerala coasts was attributed to a monsoon depression over northwest Bay along with an active trough line at 850-700 hPa level. Saxena *et al.* (1988) attributed the strengthening of monsoon activity over Madhya Maharashtra and Marathwada to the monsoon depressions over Bay and north-south troughs in the monsoon westerlies.

Sen and Sunder (1994) have attributed the heavy rainfall over Pune to the combined effect of the system from head bay moving over the central peninsula and north-south trough off the west coast during the monsoon months.

Lal and Sunder (1998) used easterly wave model to study the effect of monsoon depressions on the rainfall enhancement at some distant region in the west. Their study inferred that depending on the intensity of the system over Bay and easterly wave's extended position, the quantity of rainfall over the region varies from moderate to heavy and from scattered to widespread.

From the foregoing discussions, it appears that though there are many studies addressing the distance effect of vortex over the Bay of Bengal on the enhancement of rainfall over Pune, but there may be hardly any study to investigate the dynamical effect of the

western ghats on the rainfall enhancement over Pune, in presence of a vortex over the Bay of Bengal (BOB).

Objective of the present study is to examine the dynamical role (if any) played by the western ghats (WG), in the distance effect of vortex over Bay of Bengal (BOB) on the rainfall enhancement over Pune, during southwest monsoon season (SWMS).

2. Data

For the present study, cases are selected when enhancement in rainfalls are observed over Pune in presence of a vortex over BOB during SWMS. The six cases selected are shown in Table 1. For these cases daily rainfall data of Pune and corresponding RS/RW data of Santacruz (SCZ), a station far upstream of the WG, have been collected from the National Data Centre (N.D.C), India Meteorological Department, Pune.

3. Methodology

To examine the dynamical effect of the WG on the above mentioned 'Distance effect', a 3-D meso-scale linear dynamical model for orographic rainfall as developed by Dutta (2005) has been used.

This orographic rainfall model has two parts, *viz.*, a dynamical part and a thermo dynamical part. In the dynamical part the model computes the vertical velocity (w') due to perturbation induced by the orographic barrier and in the thermo dynamical part it computes the rainfall intensity, using the perturbation vertical velocity (w'), basic state density (ρ) and basic state saturation mixing ratio (q).

The model considers a saturated adiabatic, non-rotational, Boussinesq and laminar basic westerly flow under a steady-state condition. Under the above assumptions the linearised governing equations are given below :

Linearised u -momentum equation :

$$U \left(\frac{\partial u'}{\partial x} \right) + w' \left(\frac{dU}{dz} \right) = - \left(\frac{1}{\rho_0} \right) \left(\frac{\partial p'}{\partial x} \right) \quad (1)$$

Linearised v -momentum equation :

$$U \left(\frac{\partial v'}{\partial x} \right) = - \left(\frac{1}{\rho_0} \right) \left(\frac{\partial p'}{\partial y} \right) \quad (2)$$

Linearised w -momentum equation :

$$U \left(\frac{\partial w'}{\partial x} \right) = - \left(\frac{1}{\rho_0} \right) \left(\frac{\partial p'}{\partial z} \right) - g \left(\frac{\rho'}{\rho} \right) \quad (3)$$

Linearised continuity equation :

$$\left(\frac{\partial u'}{\partial x} \right) + \left(\frac{\partial v'}{\partial y} \right) + \left(\frac{\partial w'}{\partial z} \right) = 0 \quad (4)$$

Linearised saturated adiabatic equation :

$$U \left(\frac{\partial \theta_e'}{\partial x} \right) + w' \left(\frac{d\bar{\theta}_e}{dz} \right) = 0 \quad (5)$$

The above equations are subjected to 2-D Fourier transformation. The Fourier transformed equations, after some algebraic simplification, are reduced to the following vertical structure equation :

$$\frac{\partial^2 \hat{w}}{\partial z^2} + \frac{1}{\rho_0} \frac{d\rho_0}{dz} \frac{\partial \hat{w}}{\partial z} + \left[\frac{N_m^2 (k^2 + l^2)}{(Uk)^2} - \frac{1}{U} \frac{d^2 U}{dz^2} - \frac{1}{\rho_0} \frac{d\rho_0}{dz} \frac{1}{U} \frac{dU}{dz} - (k^2 + l^2) \right] \hat{w} = 0 \quad (6)$$

Using the substitution,

$$\hat{w}(k, l, z) = \sqrt{\frac{\rho_0(0)}{\rho_0(z)}} \hat{w}_1(k, l, z) \quad (7)$$

Equation (6) is further simplified to :

$$\frac{\partial^2 \hat{w}_1}{\partial z^2} + \left[\frac{N_m^2 (k^2 + l^2)}{(Uk)^2} - \frac{1}{U} \frac{d^2 U}{dz^2} - \frac{1}{\rho_0} \frac{d\rho_0}{dz} \frac{1}{U} \frac{dU}{dz} - (k^2 + l^2) + \frac{1}{4\rho_0^2} \left(\frac{d\rho_0}{dz} \right)^2 - \frac{1}{2\rho_0} \frac{d^2 \rho_0}{dz^2} \right] \hat{w}_1 = 0 \quad (8)$$

Here, $\hat{w}(k, l, z)$ is the 2-D Fourier transformation of perturbation vertical velocity $w'(x, y, z)$,

$$N_m^2 = \frac{g}{\beta \theta_e (1 + q_s)} \frac{d\bar{\theta}_e}{dz} \quad \text{and} \quad (9)$$

$$\beta = 1 - \frac{Lq_s}{C_p T} \left(\frac{\varepsilon + \gamma q_s}{\varepsilon + q_s} \right) \quad (10)$$

Here, γ is the ratio between two specific heats of gas, ε is the ratio between dry and moist gas constants and q_s is the basic state saturated mixing ratio of water vapour. Sarker (1966, 1967) had shown that the basic southwesterly flow during the SWMS across the WG is almost neutral with respect to saturated adiabatic lapse rate, *i.e.*, $\frac{d\bar{\theta}_e}{dz} \approx 0$. Hence, $N_m^2 \approx 0$.

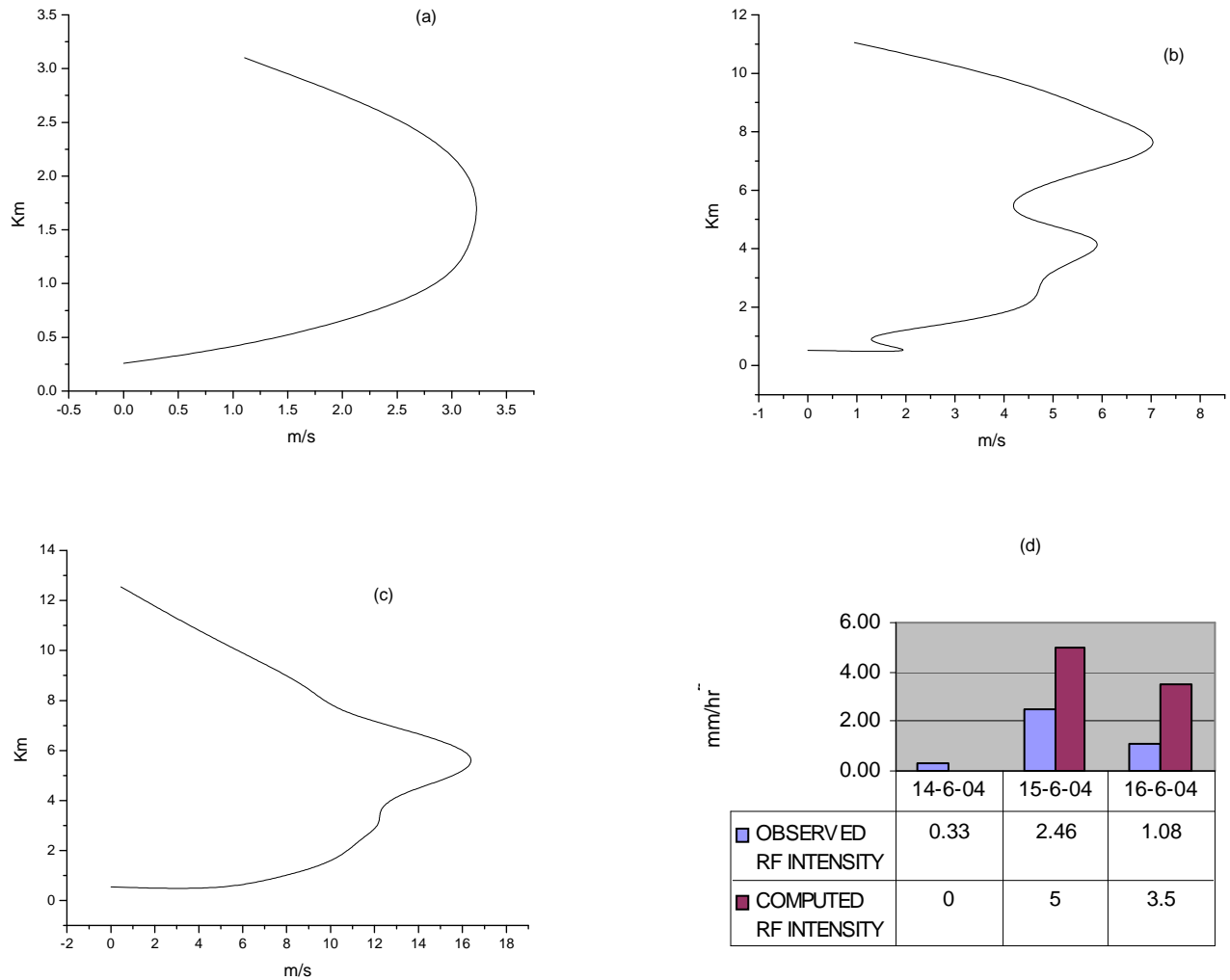
Following Dutta (2003, 2005), the Eqn. (8) is solved, quasi numerically for $\hat{w}_1(k, l, z)$, at each grid level (separated by 0.25 km) for a given (k, l) , using the following boundary conditions:

(i) At the lower boundary *i.e.*, at the surface, airflow is tangential to the ground surface. So, at $z = 0$

$$w'(x, y, 0) = U(0) \frac{\partial h}{\partial x}$$

Therefore, $\hat{w}(k, l, 0) = \hat{w}_1(k, l, 0) = ikU(0)\hat{h}(k, l)$. In the dynamical model the barrier has been approximated by a 3-D elliptical barrier with following analytical expression :

$$h(x, y) = \frac{H}{1 + (x/a)^2 + (y/b)^2}$$



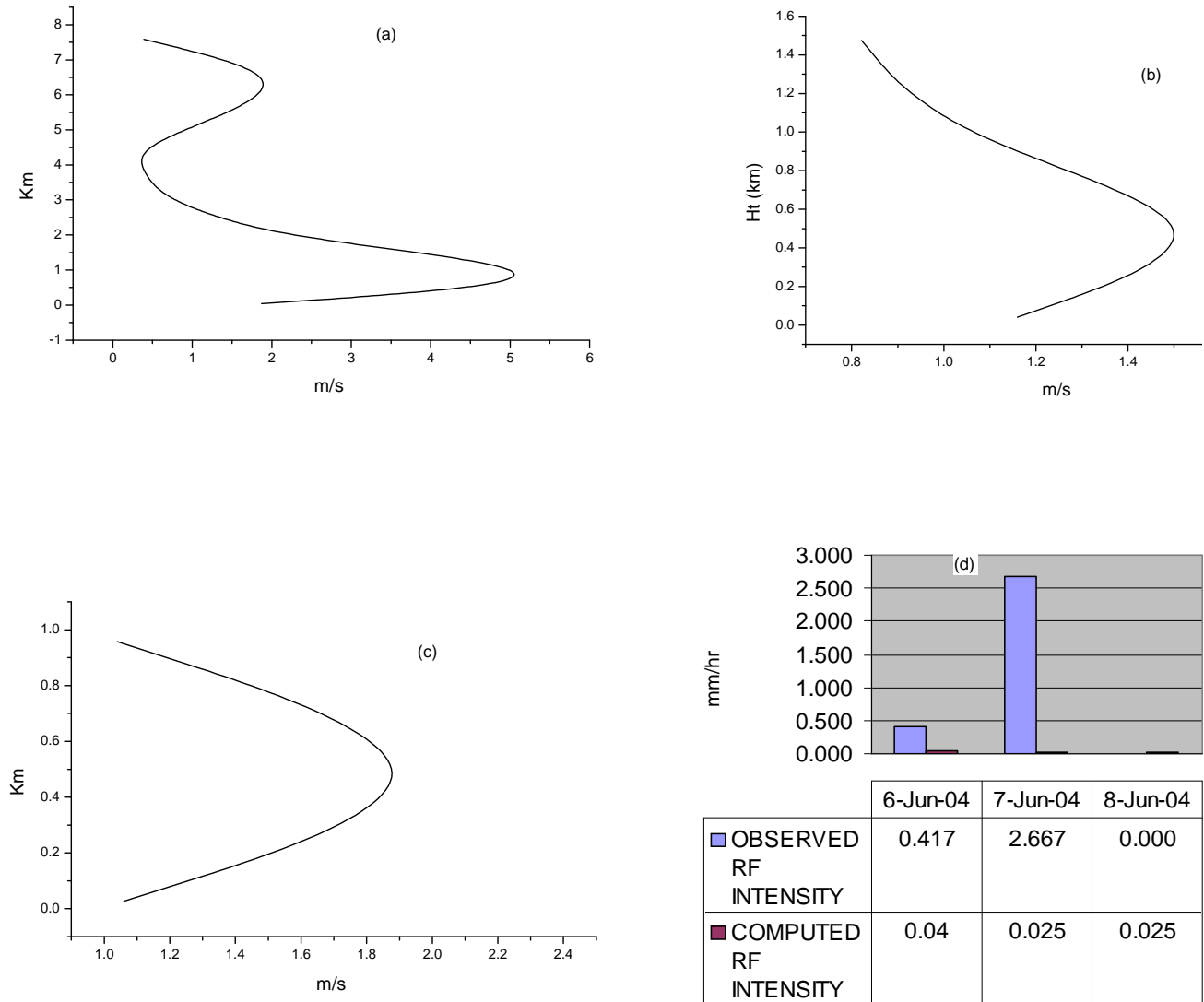
Figs. 1(a-d). (a-c) Vertical profiles of basic westerly wind at Santacruz for the dates from 13th to 15th June 2004 and (d) Observed and computed rainfall intensity at Pune for the dates from 14th to 16th June 2004

where, ‘H’ is the maximum height of the barrier at the center of the model domain (0, 0), ‘a’ is the half width along the basic westerly flow and ‘b’ is that along the cross basic wind direction. For the WG, a = 18 km, b = 45 km and H = 0.77 km (Dutta, 2003, 2005).

(ii) On and above the upper boundary $\hat{w}_1(k, l, z)$ diminishes exponentially with height for any wave number vector *i.e.*, $\hat{w}_1(k, l, z) \propto e^{-\kappa z}$ where

$\kappa = \sqrt{(k^2 + l^2)}$. Then using Eqn. (7), $\hat{w}(k, l, z)$ is computed at each grid level and for each pair (k, l) following Dutta (2003, 2005). Then using numerical 2-D inverse Fourier transformation $w'(x, y, z)$ is computed.

Using this perturbation vertical velocity $w'(x, y, z)$ and the saturated mixing ratio of the basic state (obtained from vertical temperature profile at the far upstream

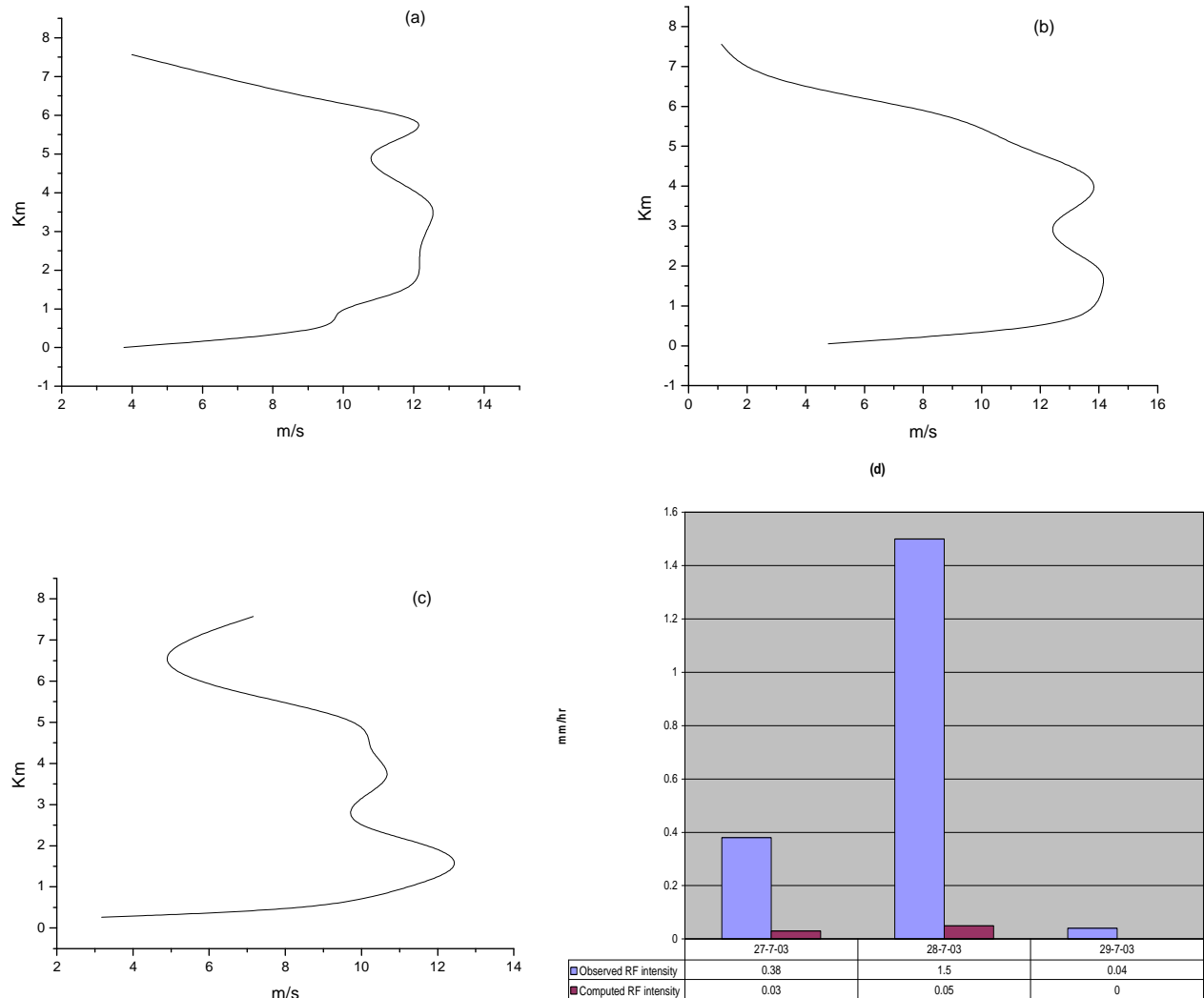


Figs. 2(a-d). (a-c) Vertical profiles of basic westerly wind at Santacruz for the dates from 5th to 7th June 2004 and (d) Observed and computed rainfall intensity at Pune for the dates from 6th to 8th June 2004

station, here Santacruz) the rainfall intensity is computed using the following formula (Sarker 1966, 1967):

According to this method, if q_i, q_{i+1} are humidity mixing ratios of saturated air at the bottom and top of a layer between the two levels $z = z_i$ and $z = z_{i+1}$, and if q' be that at the middle of the layer, then the amount of rain-

fall from the column between $z = z_i$ and $z = z_{i+1}$ is $[\rho_i w'_i (q_i - q') + \rho_{i+1} w'_{i+1} (q' - q_{i+1})]$, where ρ_i, ρ_{i+1} are the densities of basic state air at $z = z_i$ and $z = z_{i+1}$ respectively. Now if density is expressed as kgm^{-3} , humidity mixing ratio as gm kg^{-1} and vertical velocity as cm sec^{-1} , then the rainfall intensity for any column between $z = z_i$ and $z = z_{i+1}$ is given by the expression



Figs. 3(a-d). (a-c) Vertical profiles of basic westerly wind at Santacruz for the dates from 26th to 28th July 2003 and (d) Observed and computed rainfall intensity at Pune for the dates from 27th to 29th July 2003

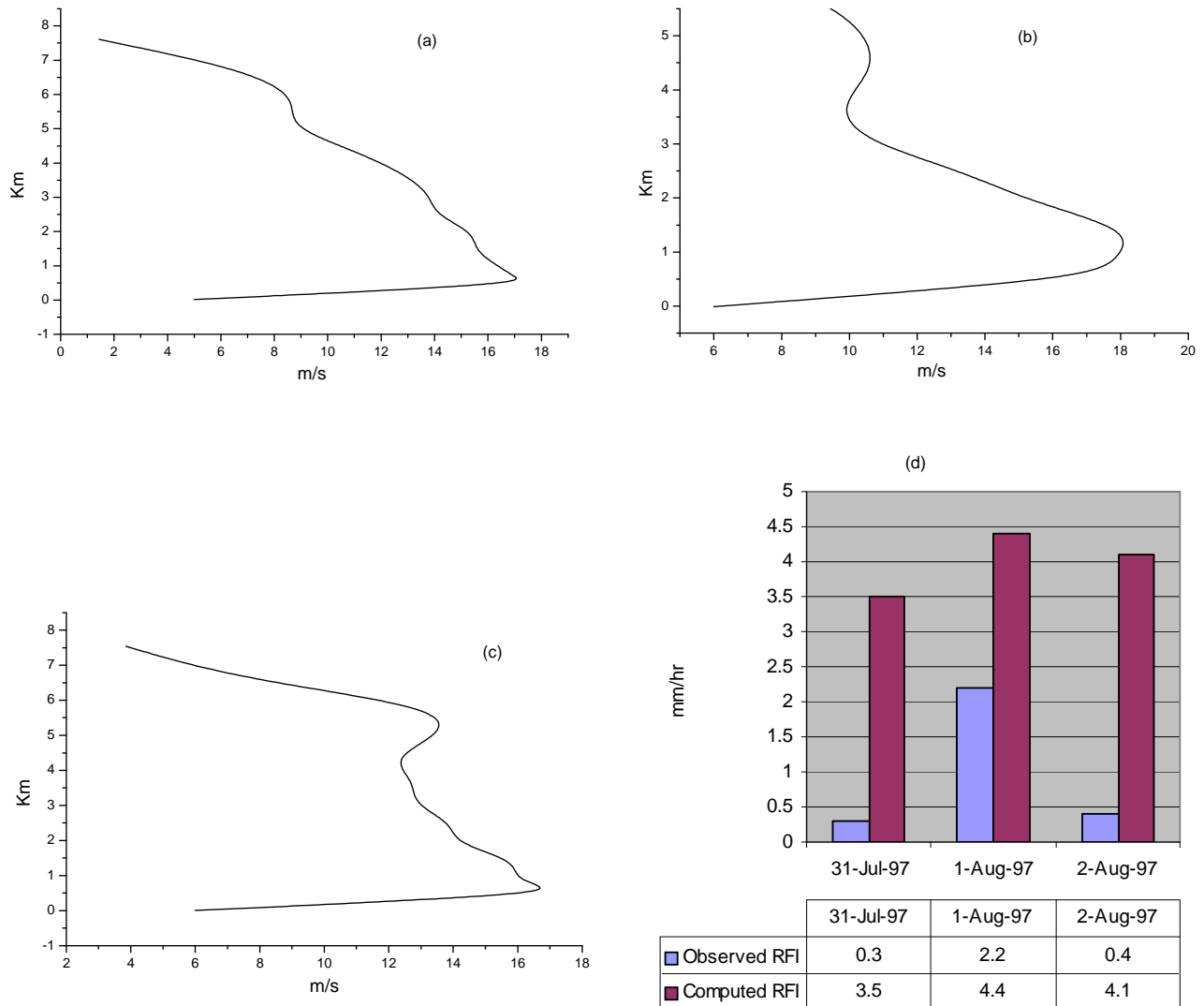
$I = 0.036 [\rho_i w'_i (q_i - q') + \rho_{i+1} w'_{i+1} (q' - q_{i+1})]$ mm hr⁻¹. In this way rainfall intensity in mm/hr may be computed at any horizontal grid point. From the Mumbai-Pune section of the WG, as given in Sarker (1965), it is seen that Pune is approximately at about 50-60 km away from the peak on the lee side. Hence in the present study, we have computed rainfall intensity only at $x = 55$ km along $y = 0$ line.

4. Case study

4.1. Case-1 (14th -16th June 2004)

During this period there was a deep depression (DD) over the west central Bay. It moved in a northwesterly

direction. On 15th the deep depression remained practically stationary and weakened into a depression on the evening. The vertical profile of basic westerly flow at Santacruz on the corresponding dates of Table 1, are given in Figs. 1(a-c) and the observed/computed rainfall intensity (RFI) for those dates are shown in Fig. 1(d). From these figures it is seen that on 13th June westerly at Santacruz had very shallow depth in vertical with mean strength of only 2.08 ms⁻¹. On 14th June westerly at Santacruz had 11 km depth in vertical with a mean strength of 4.04 ms⁻¹ and also in the vertical profile there were two maxima of comparable strength. On 15th June westerly at Santacruz had 12.5 km depth in the vertical and mean strength was only 9.3 ms⁻¹. But in the vertical profile the double maxima was absent. From



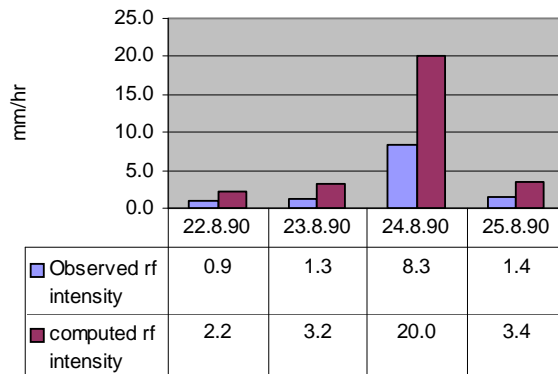
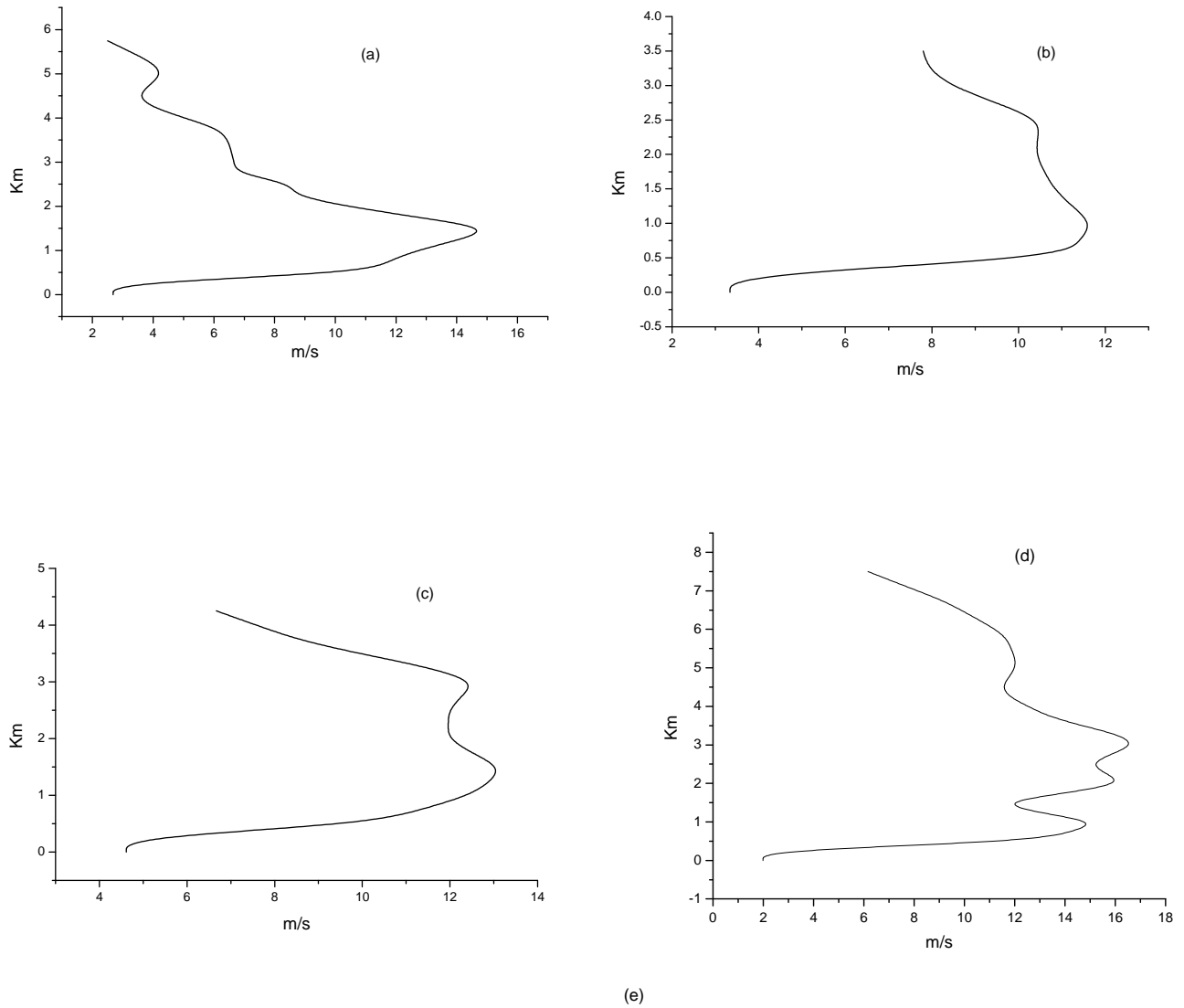
Figs. 4(a-d). (a-c) Vertical profiles of basic westerly wind at Santacruz for the dates from 30th July to 1st August 1997 and (d) Observed and computed rainfall intensity at Pune for the dates from 31st July to 2nd August 1997

Fig.1 (d) it appears that in this case the above model has captured, at least qualitatively, the observed fluctuation of rainfall over Pune.

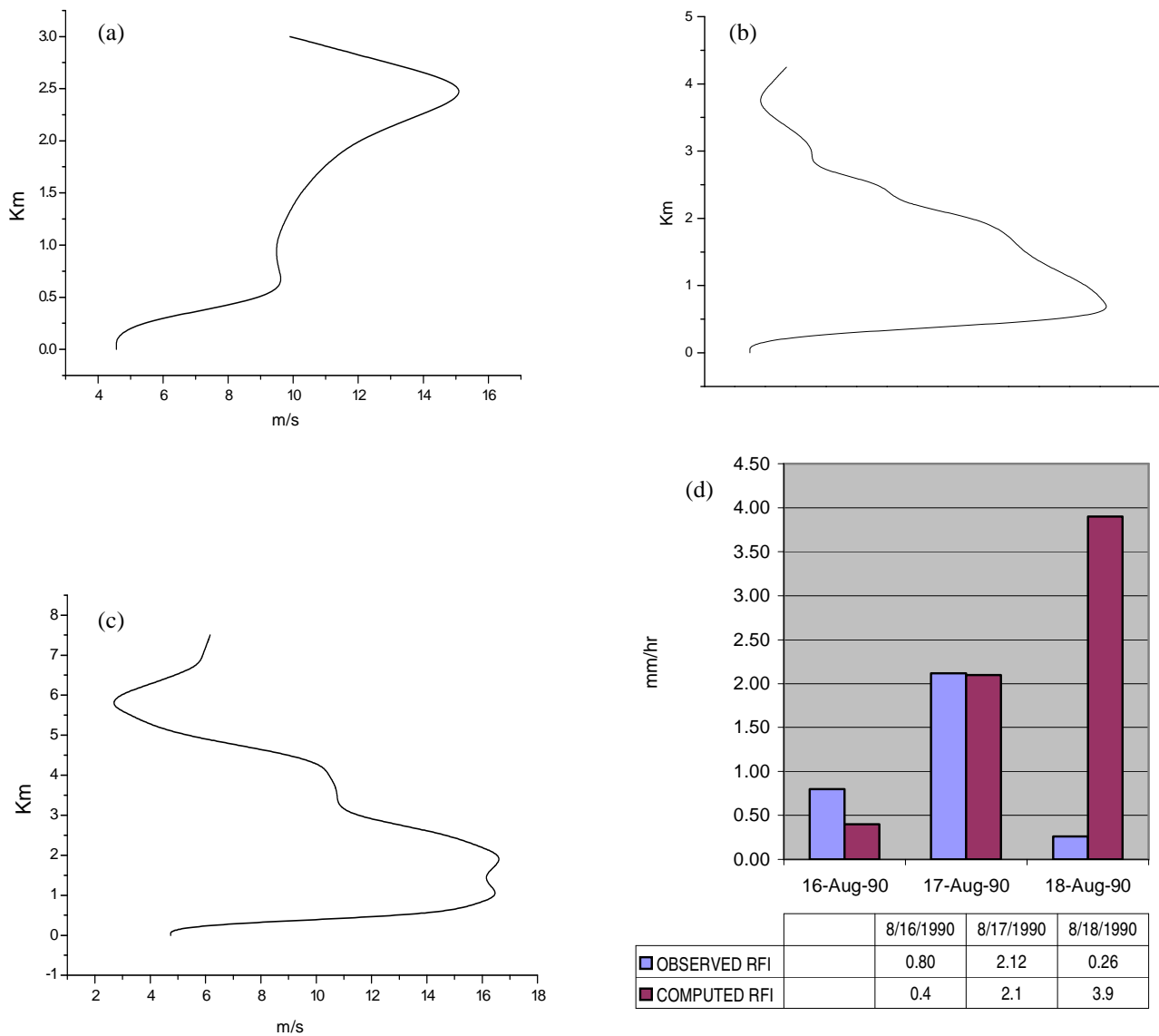
4.2. Case II (6th to 8th June 2004)

During this period there was a feeble low-pressure area, formed over the northwest and adjoining west central Bay off south Orissa and north Andhra coasts. Associated cyclonic circulation extended upto 2.1 kms over Orissa and neighborhood. The vertical profile of basic westerly flow at Santacruz on the corresponding dates of Table 1, are given in Figs. 2(a-c) and the observed/computed

rainfall intensity (RFI) for those dates are shown in Fig. 2(d). From these figures it is seen that on 5th June westerly at Santacruz had 7.5 km depth in vertical and mean strength was only 1.99 ms⁻¹. On 6th June westerly at Santacruz had 1.5 km depth in vertical and mean strength was only 1.2 ms⁻¹. On 7th June westerly at Santacruz had 1.0 km depth in vertical with mean strength of only 1.5 ms⁻¹. The above vertical profiles show that westerly over Santacruz on the last two days were shallow, weak and also did not have double maxima. From Fig. 2(d) it appears that in this case the above model has failed, even qualitatively, to capture the observed fluctuation of rainfall over Pune.



Figs. 5(a-e). (a-d) Vertical profiles of basic westerly wind at Santacruz for the dates from 21st to 24th August 1990 and (e) Observed and computed rainfall intensity at Pune for the dates from 22nd to 25th August 1990



Figs. 6(a-d). (a-c) Vertical profiles of basic westerly wind at Santacruz for the dates from 15th to 17th August 1990 and (d) Observed and computed rainfall intensity at Pune for the dates from 16th to 18th August 1990

4.3. *Case-III (27th to 29th July 2003)*

On 27th July, there was a cyclonic circulation lying over west central Bay between 2.1 and 5.8 kms above sea level. On 28th July the above cyclonic circulation lay over north Orissa and adjoining areas of Jharkhand and

extended upto mid-tropospheric level. The vertical profiles of basic westerly flow at SCZ on the corresponding dates, given in Table 1, are given in Figs. 3(a-c). From these figures it is seen that the westerly over SCZ on 26th, 27th and 28th July was extended up to 7.5 km above sea level. Mean strength of westerly on these dates

were 10.2 ms^{-1} , 10.4 ms^{-1} and 8.9 ms^{-1} respectively. In the vertical profile of westerly on 27th we see double maxima of comparable strength.

The observed and computed rainfall intensities (RFI) are plotted against the dates in Fig. 3(d). From the figure it is seen that observed RFI has increased from 0.38 mm hr^{-1} on 27th July to 1.5 mm hr^{-1} on 28th July and then it has decreased to 0.04 mm hr^{-1} on 29th July. The figure shows similar fluctuation in computed rainfall intensity on these dates, although magnitudes of computed RFI are much less than observed RFI. So in this case also the proposed model has captured, at least qualitatively, the fluctuation in daily observed RFI during the above-mentioned period.

4.4. Case-IV (31st July to 2nd August 1997)

On 29th there was a depression, 220 kms east southwest of Balasore. On 30th it intensified into a deep depression and was at about 50 kms south east of Balasore. It weakened into a depression on 31st evening over Bihar Plateau. On 1st August it was a well-marked low-pressure area over Haryana and neighborhood.

The vertical profile of basic westerly flow at SCZ on the corresponding dates of Table 1, are given in Figs. 4(a-c). From these figures it is seen that the westerly over SCZ on 26th, 27th and 28th July was extended up to 7.6 km, 8.6 km and 7.5 km respectively above sea level. Mean strength of westerly on these dates were 11.7 ms^{-1} , 10.9 ms^{-1} and 12.5 ms^{-1} respectively.

The observed and computed rainfall intensities are plotted against the dates in Fig. 4(d). From Fig. 4(d) it appears that in this case the above model has captured, at least qualitatively, the observed fluctuation of rainfall over Pune.

4.5. Case-V (22nd to 25th August 1990)

During this period a monsoon depression was formed over northwest Bay of Bengal. Initially it was observed as a cyclonic circulation over north Bay on 18th August extending vertically up to mid-tropospheric levels.

The vertical profiles of basic westerly flow at SCZ on the corresponding dates, given in Table 1, have been given

in Figs. 5(a-d). From these figures it is seen that the westerly over SCZ on 21st, 22nd, 23rd and 24th August was extended up to 5.8 km, 3.5 km, 4.5 km and 7.5 km respectively above sea level. Mean strength of westerly on these dates was respectively 7.2 ms^{-1} , 9.2 ms^{-1} and 11.8 ms^{-1} . But the double maxima of equivalent strength in the vertical profile of $U(z)$ was present only on 23rd August.

The observed and computed rainfall intensity has been shown in Fig. 5(e). This figure indicates that in this case the proposed model has been able to capture the fluctuation in daily observed rainfall intensity during 22nd August to 25th August 1990.

4.6. Case VI (16th to 18th August 1990)

During this period there was a monsoon depression over northwest and adjoining west central Bay of Bengal off the south Orissa and north Andhra Pradesh coast. Initially it appeared as a cyclonic circulation extending vertically up to mid-tropospheric levels over the west-central and adjoining north-west Bay of Bengal on 12th August 1990. The vertical profile of basic westerly flow at SCZ on the corresponding dates, given in Table 1, have been given in Figs. 6(a-c). From these figures it is seen that the westerly over SCZ on 15th, 16th and 17th August was extended up to 3.0 km, 4.5 km, and 7.5 km respectively above sea level. Mean strength of westerly on these dates was respectively 10.3 ms^{-1} , 6.2 ms^{-1} and 9.6 ms^{-1} . But the double maxima of equivalent strength in the vertical profile of $U(z)$ was present only on 17th August.

The observed and computed rainfall intensity has been shown in Fig. 6(d). The figure shows similar sharp rise in computed rainfall intensity on 17th August. However there is continuous rise in computed rainfall intensity though there is a fall in observed rainfall intensity on 18th August. Maximum computed rainfall intensity on 18th August may be attributed to the presence of a double-maxima in the vertical profile of $U(z)$ on 17th August.

5. Discussions

In the earlier section we have studied the cases of rainfall enhancement over Pune in association with vortex over the Bay of Bengal. Our objective is to investigate whether the western ghats has any dynamical role to play in enhancing the rainfall over Pune in presence of a vortex over the Bay of Bengal during southwest monsoon season

or not. To achieve this objective the six cases selected, each consists of three consecutive days, with an enhancement of observed rainfall over Pune in the second day, succeeding and preceding days with reduced observed rainfall. Out of the six cases, in four cases the fluctuation (enhancement as well as reduction) in observed rainfall matched qualitatively with that in computed rainfall. In one case enhancement in observed rainfall over Pune has matched qualitatively with that in computed rainfall and in one case the dynamical model has failed to capture, even qualitatively, the fluctuation in observed rainfall.

Dynamical model computes rainfall on lee side due to updraft associated with lee waves. But lee wave generation requires certain conditions in the air stream characteristics. Mainly in a neutrally stratified flow (typically in southwest monsoon), the basic westerly flow at station, far upstream of the western ghats, should have two or more maxima in its vertical profile. These conditions were met for the five earlier cases. (*viz.*, Case I, Case III, Case IV, Case V, Case VI) but did not meet in the Case II. Thus in some cases following dynamical interaction between the vortex over the Bay of Bengal and the Western Ghats may take place to enhance rainfall over lee side.

Vortex over the Bay of Bengal results in the strengthening of westerlies along the west coast. Strong westerly with considerable depth in the vertical, in some cases may produce lee wave across the WG under some favourable condition (presence of two or more maxima in the vertical profile of the westerly). Updraft associated with lee waves along with moisture supply due to the vortex may lead to an enhancement of rainfall at lee side.

6. Conclusions

From the above study following conclusions may be made:

- (i) In many occasions the WG plays some dynamical role in the 'Distance effect' of vortex over the Bay of Bengal on rainfall enhancement over Pune.
- (ii) In four, out of six cases studied, the model has captured, at least qualitatively, the fluctuations in the observed rainfall over Pune, during such period.
- (iii) In these four cases westerly along west coast was strong with considerable depth in vertical and the vertical profile had two maxima.
- (iv) In one case model has failed to capture observed fall in rainfall intensity, although it has captured the observed rise in rainfall intensity. In other case model has failed completely, even qualitatively, to capture the observed fluctuation in rainfall intensity.
- (v) It appears from the study that the strength and depth of westerly at SCZ along with double maxima in the vertical profile of westerly at SCZ are favourable for the dynamical role of the WG in the 'Distance effect' of vortex over the Bay of Bengal on rainfall enhancement over Pune.

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References

- Dutta, Somenath., 2003, "Some studies on the effect of orographic barrier on airflow", Ph.D. thesis submitted to the Vidyasagar University, Midnapur, West Bengal, India, 60-144.
- Dutta, Somenath., 2005, "Effect of static stability on the pattern of three dimensional baroclinic lee wave across a mesoscale elliptical barrier", *Meteorology and Atmospheric Physics*, **90**, 139-152.
- Lal, A. and Sunder, R. S., 1998, "Effect of monsoon depression of east coast at some distant region in west", *Mausam*, **49**, 453-460.
- Mukherjee, A. K. and Sinha Ray, K. C., 1983, "A theoretical study regarding heterogeneity of rainfall over Madhya Maharashtra", *Mausam*, **34**, 167-170.
- Mukherjee, A. K and Shyamla, B., 1985, "Distant effect of monsoon depression on RF activity along the west coast of India", *Mausam*, **36**, 429-434.
- Sarker, R. P., 1965, "A Theoretical study of Mountain waves on Western Ghat", *Indian J. Met. Geophys.*, **16**, 565-584.

Sarker, R. P., 1966, "A dynamical model of orographic rainfall", *Mon. Wea. Rev.*, **94**, 555-572.

Sarker, R. P., 1967, "Some modifications in a dynamical model of orographic rainfall", *Mon. Wea. Rev.*, **95**, 673-684.

Saxena, V. P. and Agarwal, Asha Lata, 1988, "On some aspects of distribution of mesoscale systems in Madhya Maharashtra and Marathwada during monsoon season", *Mausam*, **39**, 3, 283-286

Sen, P. N. and Sundar, R. S., 1994, Pre. Pub. Sc. Report, No./1, India Meteorological Department.
