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Dynamics of orographic rainfall

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ABSTRACT. A two-dimensional dynamical model for orographic rainfall was developed earlier (Sarker 1966, 1967) with particular reference to the Western Ghats. The model assumes a saturated atmosphere with neutral static stability. In the present paper this model has been applied for some more cases in Western Ghats and also for some cases in Khasi and Jaintia hills. With the model the terrain induced vertical velocities have been computed and the same have been used to compute rainfall. The computed rainfall distribution agrees well with the observed rainfall distribution both for Western Ghats and Khasi and Jaintia hills during the active monsoon situations. The peak in rainfall distribution is seen to be purely an orographic effect.

Some modifications have been made in the model for its application during the weak monsoon situations. The results for the various cases are discussed *vis-a-vis* the different synoptic situations.

1. Introduction

The role of orography in precipitation enhancement has been long known in a qualitative way. The effect of topography at least in broad sense is to enhance the rainfall on the slopes facing the winds and producing a rain shadow zone in the leeward side. The enhancement of precipitation occurs due to the lifting of air as a result of the perturbations caused in it by the orography leading to cooling, condensation and precipitation of the moisture. Nevertheless several other factors like horizontal convergence, convective instability and microphysical process play important parts in the precipitation mechanism even over the mountainous regions. The problem is highly complex.

The monsoon rainfall over the Western Ghats and Khasi and Jaintia hills is believed to be strongly orographic in character. During the southwest monsoon season the windward slopes of the mountains lie almost on the direct path of monsoon winds getting copious rainfall and heavy clouding, the rainfall decreasing on the leeward side. Rao (1976) has pointed out the factors which cause the enhancement of rainfall on account of orography in great details.

In the present investigation an attempt has been made to study the dynamic influence of orography on the rainfall distribution in Khasi and Jaintia hills and the Western Ghats. A simple two-dimensional model based on physical and dynamical considerations of airflow across a barrier was proposed for Western Ghats by Sarker (1966, 67). The model has been used to account for the distribution of rainfall along two sections in the Western Ghats (Bombay-Pune and Mangalore-Agumbe) and over the Khasi and Jaintia hills in Assam. The model appears suitable for explaining the general character of rainfall in these mountainous areas. In addition, some modifications have been introduced to test whether presence of unsaturated initial conditions can be taken into account to explain the differences in observed and computed rainfall during weak monsoon situations.

2. Rainfall distribution in these region

Before proceeding to the actual model of orographic rainfall, it is of interest to examine the observed features of rainfall over the Khasi and Jaintia hills and the Western Ghats in a broad sense. The prevailing winds during the southwest monsoon

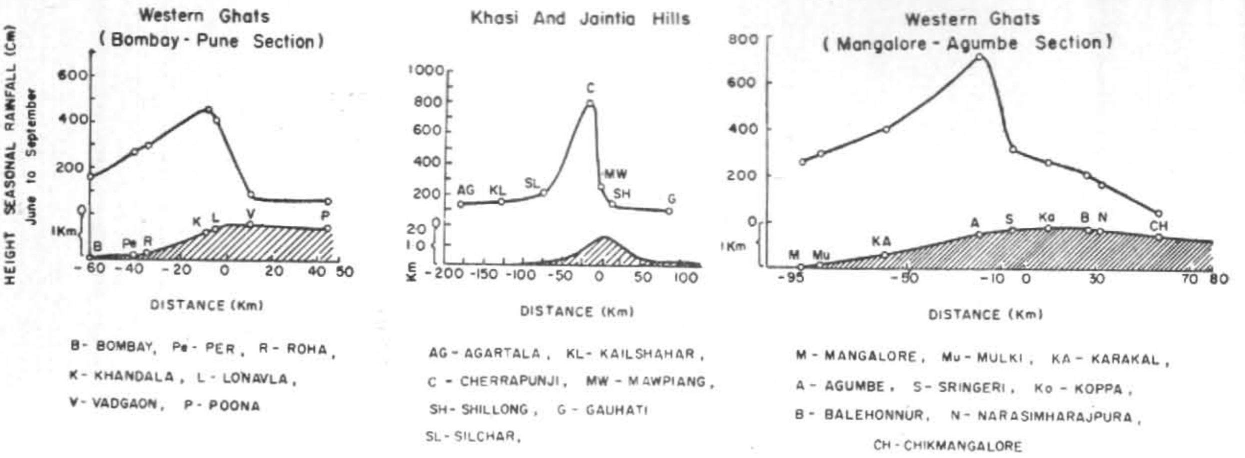

Fig. 1. Distribution of rainfall

season are from a southerly direction (SE to SW) over Assam. The normal rainfall for the period June to September is found to increase from south to north as we proceed along a profile from the plains to the Khasi and Jaintia hills on the windward slopes (Fig. 1). Rainfall is maximum over Cherrapunji (25°15′N and 51°44′E) which is situated on the windward side at about 20 km from the peak. Rainfall decreases between Cherrapunji and Mawphlang sharply and further northwards Shillong has much lesser amount. The Western Ghats in Peninsular India extends in a north-south direction approximately and the southwesterly monsoon current is more or less normal to the longer axis of the barrier. The rainfall distribution along two sections running eastwards from the coast is also shown in Fig. 1. Here the strong orographic effect is seen. The rainfall of Khandala and Agumbe on the windward side are the highest with low lee side values over Pune and Chikmangalur.

3. The model of orographic rainfall

The model of orographic rainfall consists of two parts. First, a model of airflow to compute the vertical velocities due to orographic forcing and a second part, a physical model to compute the rainfall caused due to lifting of saturated or partially saturated airmass at different vertical levels. We consider in this model how far the moist air is lifted by these orographic barriers. The air current during the southwest monsoon season does not have a stable thermal stratification and the lapse rate can be taken as moist adiabatic at least during the strong monsoon situation upto the levels of tropospheric westerlies. During the weak monsoon situations the thermodynamic structure is somewhat different and it has been shown by Srinivasan and Sadasivan (1975) that upto about 850 mb the air is fully saturated. Above 850 mb the air is generally partially saturated during the weak monsoon spells. For weak monsoon cases we have attempted to incorporate this factor in our revised model by taking into consideration lack of saturation beyond 850 mb level.

Over the Western Ghats there is predominently westerly winds in the lower troposphere at least upto 4 to 5 km during the strong monsoon season. The wind speed decreases upwards and changes over to easterly at a height of about 6-7 km. On the other hand the wind has a southerly component over the Khasi and Jaintia hills region. The wind speed has a maximum southerly component between 1-2 km and thereafter decreases and becomes zonal at a height of about 6-7 km. However, with these conditions, it is possible to use the linearised perturbation equations to compute the vertical velocity induced by orography, since the upper level flow pattern does not significantly affect the results at low levels (Corby and Sawyer 1958). In the second part of the model we utilise the computed vertical velocities at different vertical levels and different horizontal distances to determine the amount of rainfall from a saturated atmospheric column. For the weak monsoon case a modification is introduced to consider the unsaturated conditions above 850 mb level.

4(a). Computation of vertical velocity

Following assumptions are made to obtain the linearised two dimensional perturbation equation for vertical velocity.

(*i*) The airflow has a significant component normal to the extension of the orographic barrier.

(*ii*) The motion is pseudo-adiabatic and the actual lapse rate is replaced by pseudo-adiabatic lapse rate.

(*iii*) For weak monsoon situation above the height of 850 mb actual lapse rate is taken into account.

(*iv*) The lower boundary condition is set up to include the variation of wind along the height of the topography.

Considering a rectangular (x, y, z) system of axis with x-axis pointing towards east, y-axis towards north and z-axis vertical reckoned to be positive upwards, the equation for the perturbation of vertical velocity for the Western Ghats for non-rotating frictionless steady motion becomes :

$$\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial z^2} + f(z)\, W = 0 \qquad (1)$$

where
$$f(z) = \frac{g(\gamma^* - \gamma)}{\bar{U}^2\, \bar{T}} - \frac{1}{\bar{U}}\frac{d^2 \bar{U}}{dz^2} + \left\{\frac{\gamma^* - \gamma}{\bar{T}} - \frac{g}{XR\bar{T}}\right\}\frac{1}{\bar{U}}\frac{d\bar{U}}{dz} - \frac{2}{XR\bar{T}}\left(\frac{d\bar{U}}{dz}\right)^2 - \left(\frac{g - R\gamma}{2R\bar{T}}\right)^2 \qquad (2)$$

where $X = \dfrac{g}{g - R\gamma^*}$

and γ^* is pseudo-adiabatic lapse rate. For the Khasi and Jaintia hills, which has an east-west orientation the equation becomes :

$$\frac{\partial^2 W}{\partial y^2} + \frac{\partial^2 W}{\partial z^2} + f(z)\, W = 0 \qquad (3)$$

where
$$f(z) = \frac{g(\gamma^* - \gamma)}{\bar{V}^2\, \bar{T}} - \frac{1}{\bar{V}}\frac{d^2 \bar{V}}{dz^2} + \left\{\frac{\gamma^* - \gamma}{\bar{T}} - \frac{g}{XR\bar{T}}\right\}\frac{1}{\bar{V}}\frac{d\bar{V}}{dz} - \frac{2}{XR\bar{T}}\left(\frac{d\bar{V}}{dz}\right)^2 - \left(\frac{g - R\gamma}{2R\bar{T}}\right)^2 \qquad (4)$$

where, $X = \dfrac{g}{g - R\gamma^*}$

and γ^* is pseudo-adiabatic lapse rate. For weak monsoon case value is taken equal to dry adiabatic lapse rate above 850 mb (1.5 km).

If the vertical velocity $W(x, z)$ is resolved into its harmonic components by Fourier transform we get :

$$W(x,z) = \int_0^\infty W(z,k)\, e^{ikx}\, dk$$

$$\frac{\partial^2 W}{\partial z^2} + [f(z) - k^2]\, W = 0 \qquad (5)$$

$$W(x, z) = \exp\left(\frac{g - R\gamma}{2R\bar{T}} z\right) \int_0^\infty W(z,k)\, e^{ikx}\, dk$$

Solution of (5) can be obtained by a quasi-numerical method developed earlier by Sawyer (1960). In this method there is no need to approximate the value of $f(z)$ by any analytical expression. Similarly for the Khasi and Jaintia hills the parallel expression becomes :

$$W(y, z) = \exp\left(\frac{g - R\gamma}{2R\bar{T}}\, z\right) \int_0^\infty W(z, k)\, e^{iky}\, dk$$

The particular solution for vertical velocity is obtained by assuming a profile representable by the following form :

$$\xi_s(x) = \frac{a^2 b}{a^2 + x^2} + a' \tan^{-1}\frac{x}{a} \quad \text{(For the Western Ghats)}$$

$$= Re \int_0^\infty e^{-ak}\left(ab \cos kx + a' \sin \frac{kx}{k}\right) dk$$

and

$$\xi_s(y) = \frac{a^2 b}{a^2 + y^2} = Re \int_0^\infty (ab e^{-ak} e^{iky})\, dk \qquad (6)$$

(For the Khasi and Jaintia hills)

where $\xi_s(x)$ is the elevation of the ground surface at the level $z = -h$ with numerical values,

$$\left.\begin{aligned} h &= 0.25 \\ a &= 18.00 \text{ km} \\ b &= 0.52 \text{ km} \\ a' &= \frac{2}{\pi} \times 0.35 \end{aligned}\right\} \text{for the E-W Western Ghats section along Bombay-Pune}$$

$$\left.\begin{aligned} \text{and } h &= 0 \\ a &= 70 \text{ km} \\ b &= 0.88 \end{aligned}\right\} \text{for the E-W Western Ghats section along Mangalore-Agumbe}$$

whereas $\xi_s(y)$ is the elevation of the ground surface with numerical values :

$$\left.\begin{aligned} a &= 1.6 \text{ km} \\ b &= 25.0 \text{ km} \end{aligned}\right\} \text{for the N-S Khasi and Jaintia hills section along Silchar-Gauhati}$$

4(b). Boundary conditions

The basic equation for these sections is Eqn. (1) which has to be solved subject to two boundary conditions.

At the lower boundary the flow is considered tangential to the surface, and in view of the assumption that mountain has a shallow slope, a good approximation to the condition is

$$\frac{d\xi_s(x)}{dx} = \frac{W(x,0)}{\overline{U}[\xi_s(x)]} \tag{7}$$

for a mountain profile at $z = 0$.

If again the wind shear near the earth surface is not large the linearised lower boundary condition can be further approximated to :

$$\frac{d\xi_s}{dx} = \frac{W(x,0)}{\overline{U}(0)}$$

However, we take into account the wind shear in lower levels near the ground and thus the lower boundary conditions for the present investigation are the following :

$$\left.\begin{aligned} W(x,-h) &= -\overline{U}(\xi_s)\frac{d\xi_s}{dx} \quad \text{for Bombay-Pune section} \\ W(x,0) &= -\overline{U}(\xi_s)\frac{d\xi_s}{dx} \quad \text{for Mangalore-Agumbe section} \\ W(y,0) &= -\overline{U}(\xi_s)\frac{d\xi_s}{dy} \quad \text{for Khasi-Jaintia hills} \end{aligned}\right\} \tag{8}$$

The upper boundary condition is strictly indeterminate unless the values of $f(z)$ are specified to infinitely great heights. However, it is physically unlikely that the computed flow patterns in the lower troposphere will be greatly affected by the temperature and wind in the upper boundary condition we have assumed that $f(z)=0$ above the level where the wind direction changes to easterly, *i.e.,* about 6-8 km in each case. The choice $f(z)$ has only very small effect at low levels as shown by Palm and Foldvik (1960), Corby and Sawyer (1958) and Swayer (1960).

The appropriate solution of Eqn. (1) in region of constant $f(z)=0$ is of the form :

$$W(z,k) = A \exp(-kz) \tag{9}$$

Since the pressure and vertical velocity are continuous we require that $W(z,k)$ and $\partial W/\partial Z$ are continuous function of z. Eqn. (9) can, therefore, be used to provide boundary condition at the level $z=z_1 \approx 8$ km, which is the upper limit for the numerical solution of Eqn.(1). The condition is :

$$\frac{\partial}{\partial z} W(z,k) = -kW(z,k) \tag{10}$$

5. Numerical solution

To solve Eqn. (1) numerically we specify a function $\psi(z, k)$ satisfying Eqn. (1) and the boundary condition (10) at $z = z_1$ *k*m. Thus,

$$\left.\begin{aligned} \frac{\partial^2\psi}{\partial z^2} + [f(z) - k^2]\,\psi(z,k) &= 0 \\ \frac{\partial\psi}{\partial z} = -k\,\psi(z,k) \quad &\text{at } z = z_1 \end{aligned}\right\} \tag{11}$$

we also assume for convenience

$$\psi(z_1, k) = 1 \tag{12}$$

Then $W(z,k)$ is a simple multiple of $\psi(z,k)$ which satisfies the lower boundary condition (6-8). Thus for the Western Ghats profile

$$W(z,k) = \left(\frac{\overline{\rho_{-h}}}{\rho_0}\right)^{\frac{1}{2}} \overline{U}(\xi_s)\left(ab - i\,\frac{a'}{k}\right) ik \times \frac{\psi(z,k)}{\psi(-h,k)}\, e^{-ak} \tag{13}$$

The vertical velocity, satisfying Eqn. (1) is thus given by :

$$W(x,z) = Re\left(\frac{\rho_{-h}}{\overline{\rho_z}}\right)^{\frac{1}{2}} \overline{U}(\xi_s)\int_0^\infty \left(ab - i\,\frac{a'}{k}\right) ik \times \frac{\psi(z,k)}{\psi'(-h,k)}\, e^{-ak}\, e^{ikx}\, dk \tag{14}$$

The expression for the Khasi and Jaintia hills becomes :

$$W(y,z) = Re\left(\frac{\overline{\rho_0}}{\rho_z}\right)^{\frac{1}{2}} \overline{U}(\xi_s)\int_0^\infty abik\,\frac{\psi(z,k)}{\psi'(0,k)} \times e^{-ak}\, e^{iky}\, dk \tag{15}$$

Having obtained the values of $\psi(z, k)$, according to Eqns. (11) and (12), the integration of Eqn. (15) is performed numerically to get the perturbation vertical velocity due to orographic effect. As shown earlier by Sarker (1967) and others that singularities of the integrand in Eqns. (14) and (15) correspond to the lee waves. The numerical integration is carried out by removing the singularity from the integrand and calculating its effect separately. The technique adopted by Sawyer (1960) and Sarker (1967) was followed to evaluate these parts and the complete solution for $W(x, z)$ is given by :

$$W(x,z) = \left(\frac{\bar{\rho}_{-h}}{\rho_z}\right)^{\frac{1}{2}} \bar{U}(\xi_s) \{ \text{Real part } (X_1 + X_2 + X_3) \}$$

$$\text{where, } X_1 = \int_0^\infty \left(\frac{\psi(z,k)}{\psi(-h,k)}\right) - \sum_r \frac{\psi(z,k_r)}{\psi'(-h,k_r)(k-k_r)} \times$$

$$\times \left(ab - i\frac{a'}{k}\right) ik \,.\, \exp(-ak + ikx)\, dk \qquad (16a)$$

for $X \geqslant 0$

$$X_2 = \sum_r \frac{\psi(z,k_r)}{\psi'(-h,k_r)}\, i(1+i)^2 \times$$

$$\times \int_0^\infty k\left\{ab - \frac{a'i(1-i)}{2k}\right\} \times$$

$$\times \exp\left\{\frac{[-(a+x)+i(x-a)]k}{k(1+i)-k_r}\right\} dk \quad (16b)$$

$$X_3 = 2\pi i \sum \frac{\psi(z,k_r)}{\psi(-h,k_r)}\, ik_r \times$$

$$\times\left(ab - \frac{ia'}{k_r}\right) \exp(-ak_r + ik_r x) \quad (16c)$$

for $X < 0$

$$X_2 = \sum_r \frac{\psi(z,k_r)}{\psi'(-h,k_r)}\, i(1-i)^2 \times$$

$$\times \int_0^\infty k\left\{ab - \frac{a'i(1+i)}{2k}\right\} \times$$

$$\times \frac{\exp[\{-(a-x)+i(x+a)\}]k\,dk}{k(1-i)-k_r} \qquad (16d)$$

$$X_3 = 0 \qquad (16e)$$

Similar expression for $W(x, z)$ along Mangalore-Agumbe section was obtained by replacing the values of a, a' and b and the lower boundary condition at $z = 0$ instead of $z = -h$. For the Assam region (Khasi and Jaintia hills) the expression for vertical velocity takes the form :

$$X_1 = \int_0^\infty \left\{\frac{\psi(z,k)}{\psi(0,k)} - \sum_{r=1}^N \frac{\psi(z,k_r)}{\psi'(0,k_r)(k-k_r)}\right\} \times$$

$$\times\, abik \exp(-ak + ikx)\, dk \text{ for all } X \qquad (17a)$$

We have for region $X \geqslant 0$

$$X_2 = \sum_{r=1}^N \frac{\psi(z,k_r)}{\psi'(0,k_r)} - (i+1)^2 i \int_0^\infty k\, ab \times$$

$$\exp \frac{[\{-(a+x)+i(x-a)\}]\, kdk}{(1+i)k - k_r} \qquad (17b)$$

$$X_3 = 2\pi i \sum_{r=1}^N \frac{\psi(z,k_r)}{\psi'(0,k_r)} - ik_r\, ab \times$$

$$\exp(-ak_r + ik_r x) \qquad (17c)$$

while for $X < 0$

$$X_2 = \sum_{r=1}^N \frac{\psi(z,k_r)}{\psi'(0,k_r)}\, i(1-i)^2 \times$$

$$\times \int_0^\infty \frac{k\, ab \exp[\{-(a-x)+i(x+a)\}k]\, dk}{(1-i)k - k_r} \qquad (17d)$$

$$X_3 = 0 \qquad (17e)$$

The velocity part X_1 and X_2 may be termed as due to mountain forcing and are important near the origin. X_3 can be termed as the wave part. X_3 occurs only on the downstream side of the barrier and vanishes when there is no singularity in the integrand in Eqn. (15) for any value of the wave number. The contour integration is performed along the path shown in Fig. 2 in the complex k-plane. The path was chosen such that the singularity was confined to the upper quadrant only, thereby allowing only waves downstream of the barrier.

For carrying out the numerical integration of Eqn. (5) we solve first Eqns. (11) and (12) for ψ by a finite difference method following Sarker (1967). A similar expression for ψ' was obtained to evaluate the singularities of Eqns. (14) and (15) which depend upon the value of $(0, k)$ and $\psi'(-h, k)$.

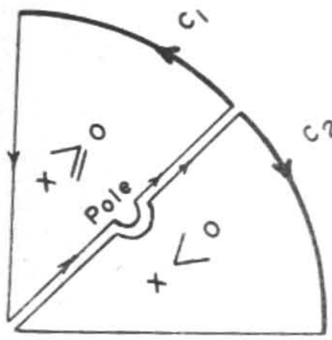

Fig. 2. Path of integration

Evaluation of the integrals in Eqns. 16 (a, b, c, d) and 17 (a, b, c, d) was carried out after determining the values of $\psi(z, k)$ and $\psi'(0, k)$ by considering the integrand to be a slowly varying functions of k as shown by (Sawyer 1960).

6. Computation of rainfall

Making use of the computed vertical velocities, the spatial distribution of rainfall was computed along the three sections of orography, *viz.*, Bombay-Pune section, Mangalore-Agumbe section over the Western Ghats and Silchar-Gauhati section over the Khasi and Jaintia hills. We have used the model earlier developed by Sarker (1967) for a saturated atmosphere throughout the depth of the air column for which the vertical velocities are available. Considering the continuity of mass and moisture in small columns of unit cross-section the intensity of rainfall is given by :

$$I = \rho_1 W_1 (q_1 - \bar{q}) + \rho_2 W_2 (\bar{q} - q_2) \qquad (18)$$

where, ρ_1 and ρ_2 are the densities of dry air at the top and bottom of small layer of thickness $\triangle z$ and W_1 and W_2 the corresponding vertical velocities and q_1, q_2 the corresponding humidity mixing ratios. q the mean humidity mixing ratio of the layer.

If the vertical velocity is expressed as cm sec^{-1}, density in kg/m^3 and humidity mixing ratio as gm/kg, then the rainfall intensity is :

$$I = 0{\cdot}036 \, [\rho_1 W_1 (q_1 - \bar{q}) + \rho_2 W_2 (\bar{q} - q_2)] \text{ mm/hr} \qquad (19)$$

We have used this formula to compute rainfall intensity from surface to a height of 6-7 km upto which the model for vertical velocity is assumed to be valid.

Furthermore, due to presence of horizontal wind the downward falling rain drops are drifted to the lee side and this factor was also accounted for by assuming that (*i*) the rate of descent of the precipitation element is constant and is equal to the terminal velocity and (*ii*) the precipitation element moves horizontally with the speed of the wind at that level.

Modified rainfall model

It has been observed from earlier computations of Sarker (1967) that the model of orographic rainfall does not work satisfactorily during the situations of weak monsoon over the west coast. As a first step we examined the thermodynamic structure of the air streams on those occasions and found that above 1 to 1·5 km the air is not fully saturated. This fact has been also pointed out by Srinivasan and Sadasivan (1975) in an earlier extensive study on the structure of the southwest monsoon. Therefore, we considered a modified model of the atmosphere which is partially saturated. The atmospheric layer above 1·5 km was taken to be unsaturated and the values of $f(z)$ were computed by using actual temperature values instead of the pseudo-adiabatic approximation as hitherto done. However, below 1·5 km the pseudo-adiabatic approximation was maintained. Using the temperature distribution thus obtained and observed winds, the values of $f(z)$ were calculated for the modified model. These values were then utilised to compute the vertical velocities as was done in the earlier model. Needless to say the value of vertical velocities in lower levels were essentially the same. The difference in vertical velocities appeared above 1·5 km only. The modification in the rainfall intensity due to initially unsaturated condition has been discussed by Thompson and Collins (1953). Essentially the method assumes that in a non-saturated environment a part of the total vertical velocity is used in lifting the parcel to saturation level and the remaining part of the vertical velocity is effective in producing actual condensation and precipitation.

Let us consider a layer of thickness $\triangle z$ with a mean vertical velocity of W then the amount of precipitation from the layer M in time $\triangle t$ will be

$$M = IW \triangle z \triangle t'. \qquad (20)$$

where, I is the rate of precipitation from layer of unit

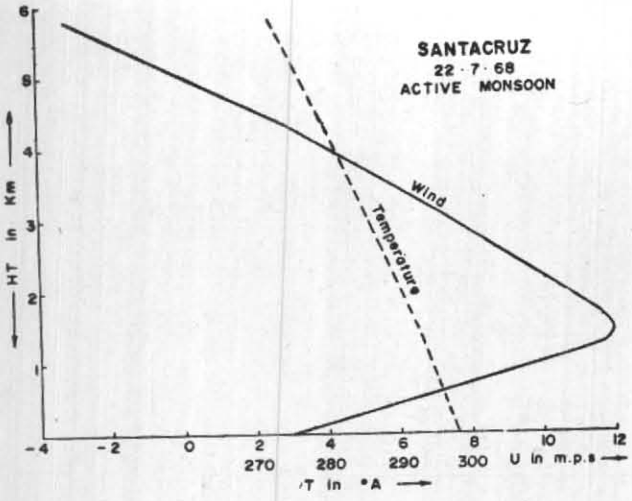

Fig. 3

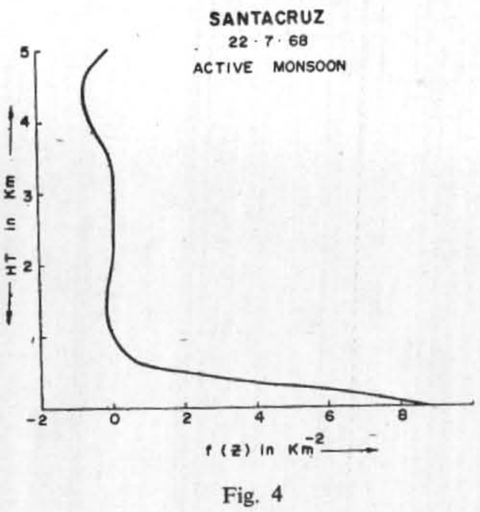

Fig. 4

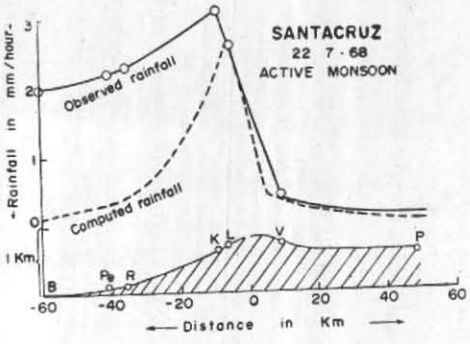

Fig. 5

thickness per unit vertical speed and $\triangle t'$ is the part of $\triangle t$ during which the air is saturated.

$\triangle t'$ can be computed from the vertical velocity and moisture available. It is more convenient for computing purposes to change the equation (20) to form

$$M = I\, W' \triangle z \triangle t$$

where, $\quad W' \triangle t = W \triangle t'$

This new effective speed W' has been calculated by assuming that the computed vertical velocities at any level are steady and can be taken as the mean vertical speed for time interval of several hours. The total ascent of a layer in time is given by :

$$Z = W \triangle t$$

This total ascent is the sum of the lift needed to reach saturation z and the lift which produces precipitation z_2

$$z = z_1 + z_2 \qquad (21)$$

The lift needed to reach saturation is :

$$z_1 = -\frac{T_0 - T_{d_0}}{\dfrac{dT}{dz} - \dfrac{dT_d}{dz}} \qquad (22)$$

where T_d is the dew point temperature of the layer. The lift which produces precipitation (z_2) is equal to :

$$z_2 = W \triangle t' = W' \triangle t \qquad (23)$$

The quantity W can be evaluated by combining equations (21) through (23) giving :

$$W' = W + \frac{T_0 - T_d}{\triangle t\left(\dfrac{dT}{dz} - \dfrac{dT_d}{dz}\right)} \qquad (24)$$

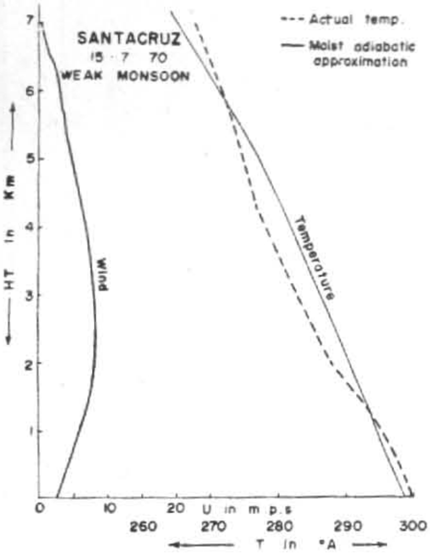

Fig. 6

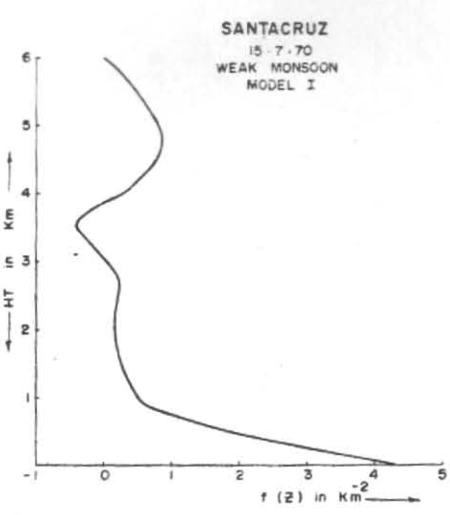

Fig. 7

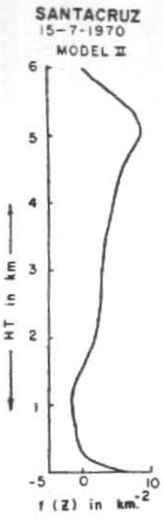

Fig. 8

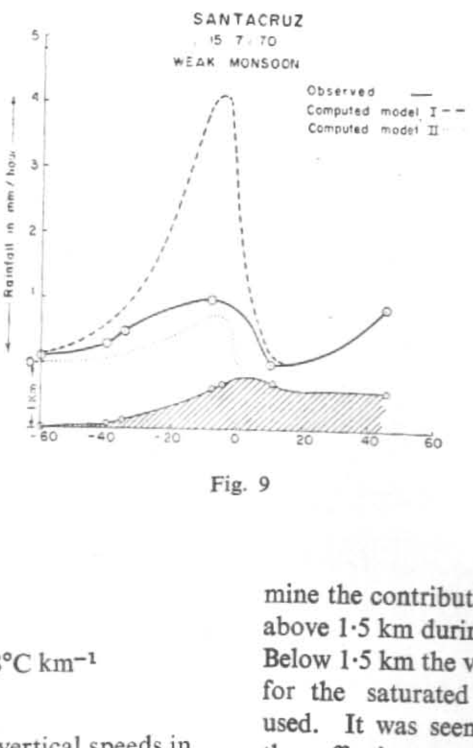

Fig. 9

Substituting in this equation :

$\triangle t = 24$ hrs $\qquad \dfrac{dT}{dz} = -9.8°\text{C km}^{-1}$

$\dfrac{dT_a}{dz} = -1.6°\text{C km}^{-1}$ gives for vertical speeds in cm sec^{-1}.

Effective vertical velocities $W'(x, z)$ at each level were calculated by making use of the vertical velocities $W(x, z)$ computed earlier by using Eqns. 16 (a, b, c, d). These effective vertical velocities were substituted in Eqn. (19) to determine the contribution to rainfall intensity for levels above 1·5 km during the weak monsoon situations. Below 1·5 km the vertical velocities computed earlier for the saturated atmospheric conditions were used. It was seen that in all cases as expected the effective vertical velocities were less than vertical velocities computed for completely saturated atmosphere.

7. Discussions

The model of orographic rainfall was tested for four situations over the Khasi and Jaintia hills,

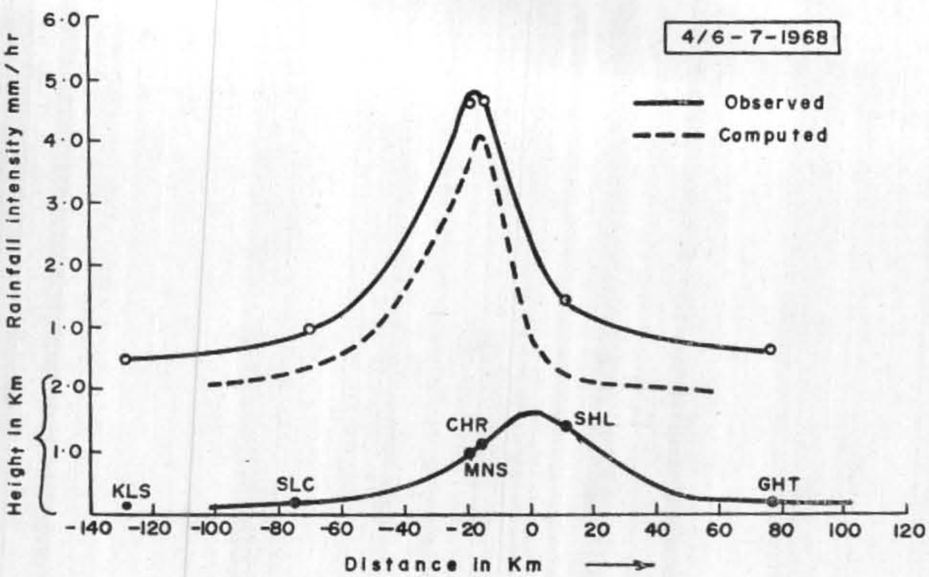

Fig. 10

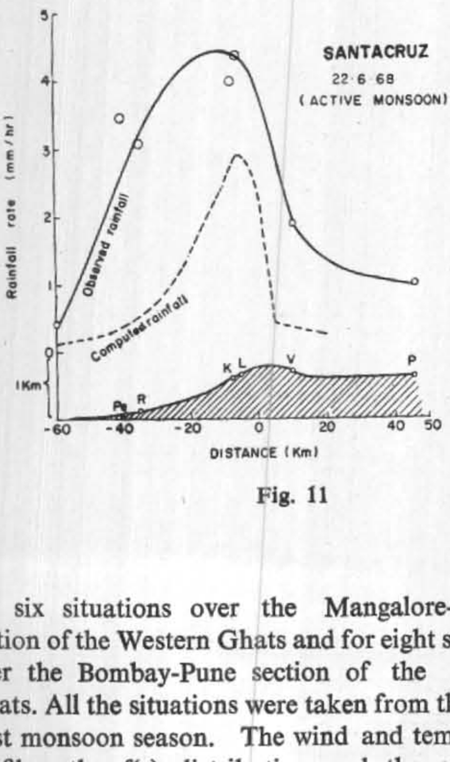

Fig. 11

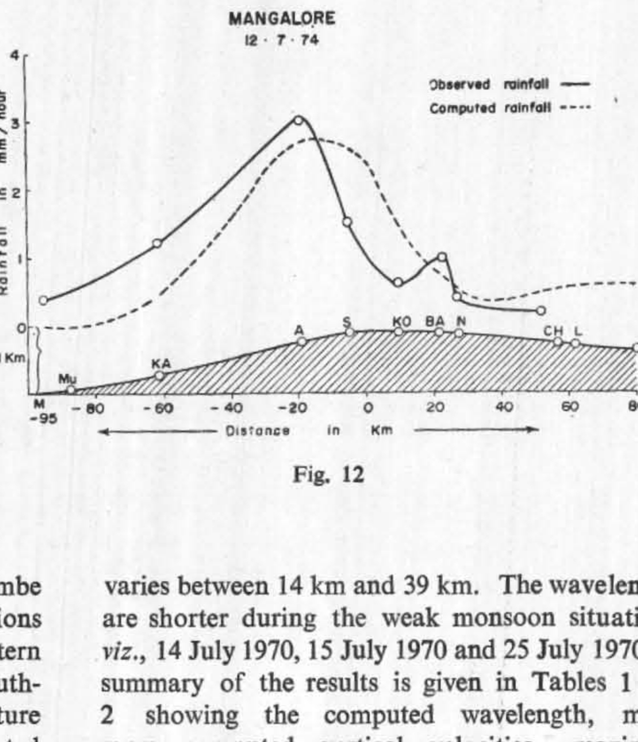

Fig. 12

for six situations over the Mangalore-Agumbe section of the Western Ghats and for eight situations over the Bombay-Pune section of the Western Ghats. All the situations were taken from the south-west monsoon season. The wind and temperature profiles, the $f(z)$ distribution and the computed rainfall intensities for some situations are shown in Figs. 3 to 15 which have been compared with actual rainfall (daily) values recorded in the area. It is felt that paucity of rainfall data at a close network of stations comes in the way of accurate verification of the model. In all these eighteen cases the lee waves are present. The wavelength varies between 14 km and 39 km. The wavelengths are shorter during the weak monsoon situations, *viz.*, 14 July 1970, 15 July 1970 and 25 July 1970. A summary of the results is given in Tables 1 and 2 showing the computed wavelength, maximum computed vertical velocities, maximum computed and observed rainfall intensities. The existence of lee waves in an air stream with neutral static stability is due to variation of wind speed and wind shear with height. Sarker (1967) has reported similar findings earlier over the Western Ghats. The vertical velocities are in general positive on the windward side, at least,

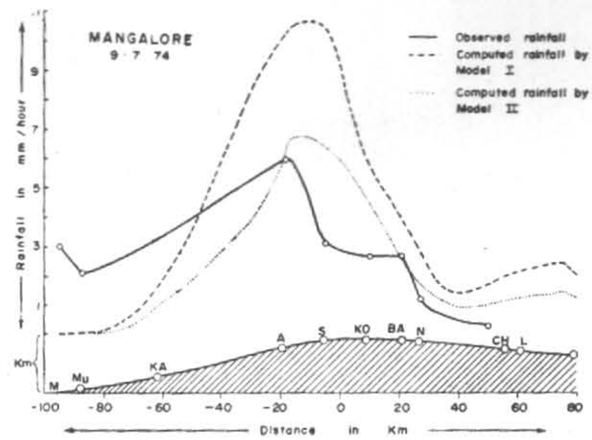

Fig. 13

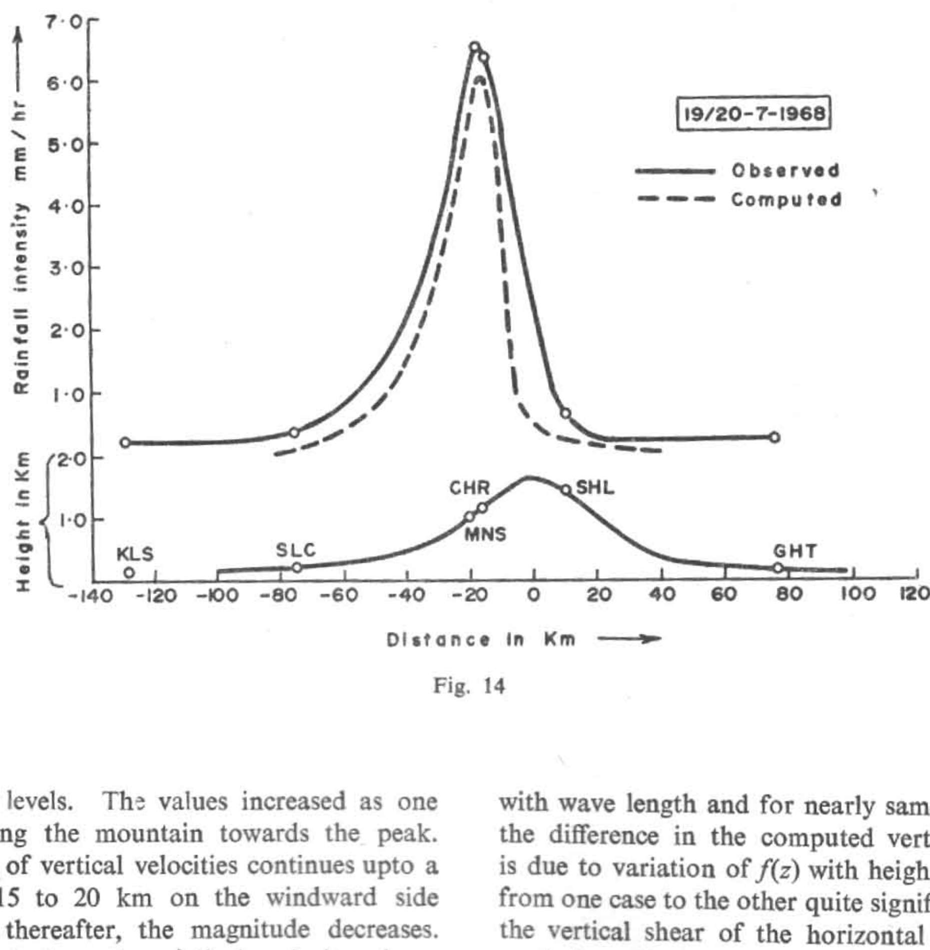

Fig. 14

in the lower levels. The values increased as one proceeds along the mountain towards the peak. The increase of vertical velocities continues upto a distance of 15 to 20 km on the windward side of the peak, thereafter, the magnitude decreases. In the vertical plane the vertical velocity shows cellular pattern, *i.e.*, it shows ascending motion in the lower levels and then decreases and becomes descending at upper levels (above say about 3 to 4 km). In general the vertical velocities increase with wave length and for nearly same wavelengths the difference in the computed vertical velocities is due to variation of $f(z)$ with height which varies from one case to the other quite significantly. Thus the vertical shear of the horizontal wind and its vertical gradient are important factors that determine the purturbation caused in the vertical motion due to orography which in turn controls the rainfall due to orographic effect. During the weak monsoon situation the atmosphere being drier

TABLE 1

Sr. No.	Date	Wavelengths	Maximum vertical velocity W (cm sec^{-1})	Distance of max. W (km)	Height of max. W (km)
		Western Ghats : Mangalore-Agumbe section			
1	16.6.1973	15·2	8·1	—20	2
2	17.6.1973	36·9	23·2	—20	1
3	18.6.1973	39·4	15·4	—10	1
4	9.7.1974	30·9	41	—20	1
5	12.7.1974	26·5	9·2	—20	1
6	26.7.1974	39·8	19·5	—10	1
		Western Ghats : Bombay-Pune section			
7	22.6.1968	34·9	15·2	—10	Surface
8	22.7.1968	19·6	12·0	—10	1
9	7.7.1970	36·9	15·4	—10	1
10	14.7.1970				
	(Model I)	14·3	7·1	—10	Surface
	(Model II)	8·3	7·0	—10	Surface
11	15.7.1970				
	(Model I)	14·2	15·5	—10	1
	(Model II)	8·3	7·1	—10	Surface
12	25.7.1974				
	(Model I)	14·5	16·4	—10	1
	(Model II)	14·3	10·2	—10	1
			Khasi-Jaintia Hills		
13	4·7.1968	16·5	20	—20	2·0
14	18.7.1968	25·3	37	—20	2
15	19.7.1968	23·6	30	—20	2·5
16	5.8.1968	17·9	18	—20	1·5

TABLE 2

Sr. No.	Date	Maximum rainfall intensity mm/hr (Observed)		Maximum rainfall intensity mm/hr (Computed)
		Western Ghats : Mangalore-Agumbe Section		
1	16.6.1973	14·5	at Agumbe	3·3 at x = — 15 km
2	17.6.1973	9·2	,,	6·1 at x = — 15 km
3	18.6.1973	2·5	Agumbe and Sringeri	3·2 at x = — 5 km
4	9.7.1974	6·0	at Agumbe	10·6 at x = — 15 km (Model I)
				6·8 at x = — 15 km (Model II)
5	12.7.1974	3·0	,,	2·7 at x = — 15 km
6	26.7.1974	11·0	,,	8·7 at x = — 5 km
		Western Ghats : Bombay-Pune Section		
7	22.6.1968	4·4	at Lonavala	2·9 at x = — 5 km
8	22.7.1968	3·1	at Khandala	2·7 at x = — 5 km
9	7.7.1970	7·1	,	3·8 at x = — 5 km
10	14.7.1970	0.7	,,	0·4 at x = — 5 km (Model I)
				0·3 at x = — 5 km (Model II)
11	15.7.1970	1·0	,,	4·2 at x = — 5 km (Model I)
				0·8 at x = — 5 km (Model II)
12	25.7.1974	1·3	,,	5·1 at x = — 5 km (Model I)
				3·2 at x = —10 km (Model II)
		Khasi and Jaintia Hills		
13	4·7.1968	4·8	at Cherrapunji	4·05 at x = — 15 km
14	18.7.1968	4·2	,,	4·2 at x = — 15 km
15	19·7.1968	6·5	at Mawnsyuram	6·2 at x = — 15 km
16	5.8.1968	3·0	at Cherrapunji	3·0 at x = — 15 km

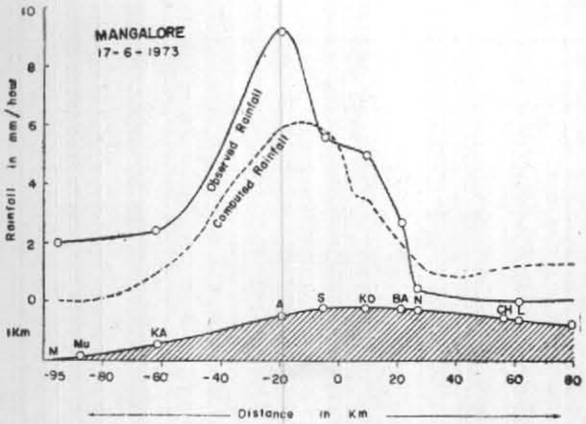

Fig. 15

above about 850 mb level, the thermal stability also hinders vertical motion as seen from the lower wavelengths of the waves which indicate stability. The computed rainfall pattern shows a pronounced orographic effect. However, the computed rainfall intensities are smaller than the observed values. This partly due to the fact that in all the three areas during the SW monsoon season are affected by presence of synoptic systems which are superposed on the orographic effect. The intensity of orographic rainfall during normal and active monsoon situation due to orographic effect varies between 3 mm/hr to 11 mm/hr for the Western Ghats and between 3·0 mm/hr to 8·0 mm/hr for the Khasi and Jaintia hills. However, the cases which were selected for the Assam region were perhaps biased towards fair weather conditions due to lack of upper air sounding on the windward side. It is proposed to test the model with later rawin observations from Agartala at future date.

For the weak monsoon cases as mentioned earlier, computations were made with a modified rainfall model taking into account unsaturated initial conditions. The modification resulted in a better approximation of observed rainfall. This indirectly supports the finding that the air column above 1·5 km level during the weak monsoon situation over the Western Ghats is significantly drier. It is proposed to test the model further over the Assam hill region during spells of weak monsoon.

8. Conclusions

From the present investigation we may draw the following conclusions:

(*i*) The orographic rainfall, computed from this model increases from the plains along the slope and reaches a maximum before the crest of the mountain is reached after which it falls off sharply. The normal rainfall during the southwest monsoon also is seen to have a similar distribution.

(*ii*) The position of the maximum rainfall observed and computed are in good agreement and generally occur at 10-15 km before the crest of the barrier.

(*iii*) The observed rainfall is higher so that only a part of it is explained by orography. The peak rainfall is, however, accounted mainly as an orographic effect where the computed values are nearly 90% or more of the observed values.

(*iv*) By studying the orographic effect in three different sections it may be said that height alone is not the criteria for maximum rainfall, slope and airstream characteristics (lee wavelength) are also important.

(*v*) During spells of weak monsoon by taking into account presence of initial unsaturated conditions a better approximation of rainfall is obtained from the modified model.

(*vi*) The discrepancies between the observed and computed rainfall can be attributed to :

(*a*) The choice of a linear model and taking a smoothed profile for the terrain,

(*b*) Microphysical processes of rainfall being not incorporated in the model and

(*c*) Synoptic scale convergence and instability being not included in the model, which may be significant contributors to vertical velocity in some cases.

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DISCUSSION

(Paper presented by K.C. Sinha Ray)

M. SHANKAR RAO : Did you get lee waves over the Western Ghats ?

AUTHOR : Yes, we got lee waves in all these cases.