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Orographic rainfall during southwest monsoon : A dynamic climatological study*

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सार – ऊर्ध्वाधर में आंशिक संतृप्त वायुधारा के मामलों को सम्मिलित करने के लिए पूर्व (सरकार 1966-67) विकसित पार्वतिक वर्षा के द्विविमीय गतिज प्रतिदर्श में संशोधन किया गया है। वर्तमान अन्वेषण में दक्षिण-पश्चिम मानसून ऋतु के दौरान पश्चिमी घाटों और खासी एवं जयंती पहाड़ियों की विषम भूप्रदेश पर की स्थिर पार्वतिक वर्षा को कुलवर्षण में से पृथक करने का और क्षेत्रीय तथा दैनिक वर्षा के विचरण को समझाने का प्रयास किया गया है।

ABSTRACT. A two dimensional dynamical model for orographic rainfall developed earlier (Sarker 1966-67) was modified to include cases of partially saturated airstream in the vertical. In the present investigation an attempt has been made to isolate the steady orographic rainfall from the total precipitation over uneven terrain and to explain the spatial and diurnal variation of rainfall during the southwest monsoon season over the Western Ghats and over Khasi and Jaintia hills.

1. Introduction

Over the Indian sub-continent, the fortuitous orientation of orographic barriers in the shape of the Western Ghats and Assam-Burma hills play a major role in enhancing monsoon rainfall over the country. Seasonal distribution of rainfall over two locations along the Western Ghats and over the Khasi & Jaintia hills (Fig. 1) bring out the strong orographic influence.

Banerji (1929) was the first to mathematically explore the problem by considering the flow of an incompressible fluid over rigid wall like barriers. The enhancement of precipitation occurs due to the lifting of air as a result of the perturbation caused in it by the orography leading to cooling, condensation and precipitation of moisture. However, the nature of the orographic precipitation is closely linked with the dynamics of the airflow and micro-physics of the cloud structure. Nevertheless, over uneven terrain also several factors like horizontal convergence due to synoptic and sub-synoptic systems, convective instability etc add to the motion field in the vertical thereby influencing the total precipitation. In the present investigation an attempt has been made to assess the relative role of terrain-induced vertical motion in the precipitation process over the mountainous regions.

2. Climatology of rainfall

During the southwest monsoon season the windward slopes of the Western Ghats and the Assam hills lie almost in the direct path of the monsoon winds, thus getting copious rainfall and heavy cloudng. The prevailing winds during the southwest monsoon season are from a southerly direction over Assam. The normal rainfall is found to increase from south to north as we proceed along a profile from the plains of Tripura (Agartala) to the Khasi & Jaintia hills. The rainiest place Cherrapunji is located on the southern slope with annual rainfall of 1142 cm of which 837 cm falls from June to September. The hill range is 300 km in length and 70 km in width with highest peaks upto 2 km.

The long range of Western Ghats 1 to 2 km high roughly runs north to south. On the leeward side north of 14 deg. N the land slopes gently after the first drop from the crest eastward. The rainfall variation along stations in these mountain section suggests that rainfall enhancement is a

*The paper was presented in the 'Monsoon Prediction' symposium held at Indian Institute of Technology, New Delhi during 17-18 March 1979 complex process not only dependent upon the height of the peak but also on the slope of the terrain and synoptic systems over these areas (Rao 1976). The leeward decrease of rainfall from the crest on the Western Ghats is quite sharp during the southwest monsoon period as compared to that across the Assam hills. This is mainly due to favourable synoptic flow patterns causing rain in the latter area, *viz.*, during the break monsoon.

In this paper an attempt has been made to study the contribution of orography on the total rainfall in these areas and make an attempt to isolate the relative importance of the orographically induced vertical motion in terms of the flow characteristics like wind speed, direction, shear and stability of air and the role of the synoptic and convective factors also.

3. Data

Sarker *et al.* (1978) computed the rainfall distribution across Bombay-Pune, Mangalore-Agumbe and Agartala-Cherrapunji sections of Western Ghats and Assam hills regions respectively. The computations were made on the basis of a two dimensional steady state linearized model. Briefly, from a given characteristics of the air stream on the windward side, the terrain induced-vertical velocity W was computed from the equation:

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

by a quasi-numerical method, in the above equation $f(Z)$ is a function of wind speed, wind shear and stability of the undisturbed air stream.

Sarker (1966-67) and De (1973) investigated the orographic rainfall in these regions by considering situation during southwest monsoon season. In both these studies the atmosphere was assumed to be saturated. In a later work, Sarker *et al.* (1978) considered situations during the southwest monsoon when the atmosphere was saturated in the lower troposphere while in the middle and upper levels it was unsaturated. With the availability of autographic rainfall records, it has become now possible to isolate situations when the precipitation was of a steady type from those of the convective type. We have worked out the maximum observed intensity of precipitation in the two section over the Western Ghats and one over Khasi & Jaintia hills, for which a two dimensional model of orographic rainfall is available. In addition, the average intensity of observed precipitation has also been computed for the night-morning period (0000-0800 IST) morning-afternoon period (0800-1800 IST) and night (1800-2400 IST). We have examined here such cases with a view to find the orographic component of the rainfall.

4. Discussion

(i) Case studies of diurnal and spatial variation of precipitation

Analyses of the various cases for which the orographic rainfall has been computed using the model developed earlier (Sarker *et al.* 1978) are presented in Tables 1 and 2.

It is seen that the average computed precipitation in Bombay-Pune section was of the order of 10 mm/hr just to the windward side of the peak during an active monsoon spell, while it was of the order of 0.5 mm/hr during a weak monsoon period. The average computed intensity on the leeward side was of the order of 1 mm/hr during active monsoon period and nearly 0.0 mm/hr during weak monsoon spell. The average precipitation near the coast was also of the same order. The observed rainfall intensities show that the coastal precipitation had a very small component of orographic precipitation and the main factors which contributed to the coastal rainfall were synoptic systems and convective instability. Often the coastal precipitation showed peak intensity during the early morning or late evening and night which are typical of a diurnal cycle on a sea-coast. Pune on the leeward side has on the other a fairly steady precipitation which corresponded to the computed intensity from the orographic model.

In the Mangalore-Agumbe section the computed precipitation intensity from the orographic model is very small and much of the observed rainfall near the coastal region occurred during the early morning or late night indicating its association with the instability of the maritime air off the coast, whereas near the peak (Agumbe) a pronounced convective type was super-imposed on the orographic steady component. It is seen from the three cases studied that the computed intensity of precipitation at Agumbe was between 1.5-6 mm/hr. This rate of precipitation which was due to orographic induced vertical velocity field tallied with observed intensity of precipitation during early morning or night (0000-0800 and 1800-2400 IST), while during the morning-afternoon period (0800-1800 IST) the observed intensity of rainfall ranged between 4 and 13.5 mm/hr due to contributions from convective type of precipitation. In the Agartala, Cherrapunji (Mawsynram)-Gauhati section of the Khasi & Jaintia hills, the observed intensity of precipitation on the windward side plains ranged from 0.0-0.9 mm/hr and showed a peak intensity either in the early morning or late evening. At the crest the observed and the computed intensities of precipitation are in close agreement and the precipitation is of an orographic type often the maximum intensity of precipitation is observed in late night or early morning hours, *i.e.*, during

TABLE 1

Date	Air stream characteristic	Vertical velocity characteristic	Intensity of precipitation computed
		Western Ghats – Bombay-Pune section	
4 July 1961	Surface wind 8 mps, max. speed westerly 20.5 mps at 1.5 km becomes easterly at 8.5 km. Relative Humidity between 80-100 % $f(Z)$+ve upto 2.5 km,—ve upto 5.0 km. and then+ve again.	Lee wave length 19.1 km max. vertical velocity 10 cm/sec at $x=-10$ km on the windward side and is +ve upto a height of 5 km in the windward side and is +ve above 4 km near the crest and on the leeward side.	Intensity at coast 0.5 mm/hr max. intensity 12.0 mm/hr. At the crest of the mountain, 4 mm/hr beyond $x=5$ km on the leeward side about 0.2—0.4 mm/hr.
24 June 1961	Surface wind 6.5 m/sec max. wind 25 mps at 2 km. The Relative Humidity varies between 80-90% $f(Z)$ is+ve upto 3.25 km, —ve upto 5.25 km and then+ve again.	Lee wave length 29.2 km max. vertical velocity in this case is 36.0 cm/sec. at $x=-10$ km. On the windward side+ve upto 5 km. In the leeward side vertical velocity is+ve at a height of 3 km and above.	0.4 mm/hr at coast max intensity 8.5 mm/hr. At the crest of the mountain 3 mm/hr. Secondary max 1.7 mm/hr at $x=30$ km
10 -11 July 1958	Surface wind 8 mps max. wind speed 18.5 m/sec. at 2 km. becomes easterly at 8.5 km. Relative Humidity between 85 to 100% $f(Z)$ is +ve upto 2.5 km then—ve upto 4.0 km & then+ ve again.	Lee wave length 31.7 km Max. vertical velocity 48 cm/sec. at $x=-10$ km and positive on the leeward side above 3 km.	At coast .5 mm/hr. Max intensity 8.5 mm/hr. At the crest 1.4 mm/hr.
*1-3 July 1960 (computed analytically)	Surface wind 7 mps increasing sharply to 14 mps at 1 km and then decreases to 5 mps at 8 km becomes easterly at 10.5 km $f(Z)$ is—ve in the layers 2 – 4 km. + ve from surface to 2 km above 4 km almost constant.	Max vertical velocity 31 cm per sec at $x=-10$ km downward vertical velocity prevails on the the leeward side.	At the coast 2.2 mm/hr. Max 9.5 mm/hr.
14 July 1970	Surface wind speed 2.5 km mps increasing slowly to 8 mps at 1.5 km remains almost steady upto 3 km & then decreases and changes over to easterly at 6 km. Relative Humidity nearly saturated upto 2 km above 2 km. Moist adiabatic approximation gives warmer temperature $f(Z)$ values decrease sharply from surface to 2 km increase between 2 to 3 km then increase gradually upto 4 km. The date relates to a weak monsoon condition.	Lee wave length by Model I=14.3 km Model II = 8.3 km. Max. vertical velocity nearly 7 cm/sec. in both the models at $x=-10$ km.	Maximum intensity 0.4 mm/hr at $x=-5$ from Model I and 0.3 mm hr at $x=-5$ km from Model II.
15 July 1970	Surface wind 2.5 mps increasing to 8.5 mps at 2 km then decreasing slowly & changing over to easterly above 7 km. Nearly saturated upto 1.5 km then drier and with the observed lapse rate greater than Pseudo adiabatic lapse rate $f(Z)$ decreases sharply in the first 1 km in Model I but decrease is not so much for Model II. This case refers to weak monsoon condition.	Leewave length by Model I=14.2 km by Model II=8.3 km. Max. vertical velocity 15.5 cm/sec in Model I and 7.1 in Model II at $x=-10$ km.	Max. ainfall intensity 4.2 mm/hr at $x=-5$ km in Model I and 0.8 mm/hr in Model II.
25 July 1974	Surface wind 3 mps increasing slowly to 9 mps at 1 km and then remains almost stationary around 5 mps upto 7 km. Atmosphere drier than the previous two cases of weak monsoon $f(Z)$ values show sharp decrease in the 1st km near the surface with a larger of — ve $f(Z)$ from 1.5 to 3 km. $f(Z)$ values increase from 2.5 km upward in both the cases. This case refers to weak monsoon condition.	Lee wave length 14.5 km and 14.3 km respectively by Model I & II. Maximum vertical velocity 16.4 cm/sec. at $x=-10$ km by Model I and 10.2 cm/sec by $x=-10$ km by Model II.	Max. rainfall intensity 5.1 mm/hr at $x=-5$ km by Model I and 3.2 mm/hr at $x=-10$ km by Model II.

TABLE 1—(*contd.*)

Date	Air stream characteristic	Vertical velocity characteristic	Intensity of precipitation computed
		Western Ghats — Mangalore-Agumbe section	
16 June 1973	Surface wind speed 5 mps increases rapidly upto 1.5 km reaching 15.5 mps & then decreases upto 5 km with a secondary maxima at 6 km and then decreasing again more rapidly and changing over to easterly over 9 km $f(Z)$ increases from surface to 1.5 km and then decreases slowly upto 3 km and then remains constant.	Lee wave length=15.2 km. Max. vertical velocity 8.1 cm/sec at $x=$ —20 km.	Max. rainfall intensity 3.3 mm/hr at $x=$ —15 km.
17 June 1973	Surface wind 5.5 mps increases to 17 mps at 1.5 km further upward decreases gradually upto 5 km and afterwards sharply with easterly winds above 9 km $f(Z)$ decreases from the surface upto 3 km then increases gradually or remains stationary upto 8 km.	Lee wave length 36.9 km Max. vertical velocity 23.2 cm/sec at $x=$ —20 km.	Max. rainfall intensity 6.1 mm/hr at $x=$ —15 km.
18 June 1973	Surface wind 4.8 mps and the vertical distribution similar to earlier two cases except the rate of decrease upto 8 km is slower. $f(Z)$ decreases from surface to 2 km and thereafter shows slight rise or remains constant upto 6 km.	Lee wave length 39.4 km, Max. vertical velocity 15.4 cm/sec at $x=$ —10 km.	Maximum rainfall intensity 3.2 mm/hr at $x=$ —5 km.
		Khasi and Jaintia hills	
4-6 July 1968	Surface wind 5.5 mps increases to 10 m/sec at 2 km. $f(Z)$ is —ve in the layer 1.5 km to 2.5 km above 3 km $f(Z)$ is constant.	Lee wave length 16.5 km, Max. vertical velocity of 30 cm/sec is at a distance of $x=$ —15 km. On the lee side vertical velocities are + ve above 4 km.	Max. intensity 4.05 mm/hr at a distance $x=$ —15 km.
18-19 July 1968	Surface wind 1.5 mps increases to 9.5 m/sec at 2 km then decreases slowly to 8 mps at 4.75 km. The wind speed decreases more rapidly above 5 km $f(Z)$ decreases from surface to 4 km, from 4 km the values of $f(Z)$ increases upto 5 km and then again decreases and becomes —ve above 5.75 km.	Lee wave length 25.3 km, Max. vertical velocity 55 cm/sec at a distance $x=$ —15 km.	Max. intensity 4.0 mm/hr at $x=$ —15 km.
19-20 July 1968	Surface wind 5.5 m/sec increases to 10.5 m/sec at 1 km wind profile has another maxima at 4.5 km and then decreases with height $f(Z)$ decreases sharply from surface, —ve between 1.25 to 4.5 km.	Lee wave length=23.0 km, Max. vertical velocity is 40 cm/sec at $x=$ 15 km.	Max. intensity 6.0 mm/hr at $x=$ —15 km 10 km on the lee side intensity is 0.2 mm/hr.
5 Aug 1967	Surface wind 5.6 m/sec increased to 19 m/sec at 3.0 km $f(Z)$ decreases from surface to 2 km between 3 and 5 km. $f(Z)$ is —ve, above 6 km $f(Z)$ values are very small and are nearly constant.	Lee wave length=17.0 km, Max. vertical velocity 35 cm/sec at a distance $x=$ —15 km. The vertical velocities on the leeward side are —ve upto 5 km.	Max. intensity 3.0 mm/hr at $x=$ —15 km.

TABLE 2

S. No.	Date	Station	Rainfall intensity (mm/hr) Observed	Computed	Max. in a particular hour	Hour in which maximum rainfall occurred	Average rainfall intensity 0000-0800 IST	0800-1800 IST	1800-2400 IST
			Western Ghats—Bombay-Pune section						
1	4 Jul 1961	Santacruz	6.2	0.5	8.0	3- 4	3.56	1.74	2.30
		Khandala	12.0	11.8					
		Poona	1.6	0.8	3.9	14-15	0.01	1.04	1.05
2	24 Jun 1961	Santacruz	2.0	0.4	6.2	4- 5	1.16	0.86	0.70
		Khandala	8.6	8.5					
		Poona	0.7	0.7	3.4	3 -4	0.90	0.04	1.35
3	10-11 Jul 1958	Santacruz	2.2	0.5	25.5	8- 9	5.81	8.37	3.04
		Khandala	7.9	7.7					
		Poona	2.5	1.2	8.1	13-14	3.45	3.84	1.46
4	1-3 Jul 1960	Santacruz	2.7	2.2	8.1	14-15	0.69	2.02	1.35
		Khandala	9.5	9.5					
		Poona	1.5	0.0	4.0	00-01	1.54	0.95	0.90
5	14 Jul 1970	Santacruz	0.2	0.1	1.9	22-23	0.18	0.09	0.38
		Khandala	0.7	0.3					
		Poona	0.2	0.0	0.9	15-16	0.01	0.14	0.04
6	15 Jul 1970	Santacruz	0.1	0.0	0.6	18-19	0.15	0.04	0.10
		Khandala	1.0	0.8					
		Poona	0.9	0.0	1.8	15-16	0.01	0.26	0.00
7	7 Jul 1970	Santacruz	1.3	0.2	12.9	5- 6	4.35	3.36	0.88
		Khandala	5.8	3.8					
		Poona	0.2	0.0	2.7	16-17	0.11	1.21	0.12
			Western Ghats — Mangalore-Agumbe section						
8	16 Jun 1973	Mangalore	3.5	0.1	5.7	16-17	0.01	0.67	2.08
		Agumbe	14.5	3.2	48.4	22-23	2.05	13.64	2.56
9	17 Jun 1973	Mangalore	2.0	0.0	5.2	19-20	1.03	0.38	1.49
		Agumbe	9.2	6.0	24.3	22-23	2.83	9.47	3.23
10	18 Jun 1973	Mangalore	0.2	0.0	3.0	2- 3	1.07	0.09	0.53
		Agumbe	2.5	1.2	25.4	22-23	2.10	3.69	3.23
			Khasi & Jaintia hills						
11	4-6 Jul 1968	Agartala	0.2	0.0	1.1	14-15	0.09	0.14	0.01
		Silchar	0.9	0.1	7.4	4 -5	2.23	0.29	0.63
		Mawsynram	4.8	3.9	—	—	—	—	—
		Shillong	1.5	0.2	1.5	1 -2	0.40	0.02	0.03
		Gauhati	0.6	0.0	10.5	19-20	0.09	0.07	0.00
12	18-19 Jul 1968	Agartala	0.1	0.0	0.3	12-13	0.00	0.05	0.00
		Silchar	0.4	0.1	8.0	2-3	2.13	0.27	1.05
		Mawsynram	4.1	3.8	5.8	23-24	2.13	0.63	2.60
		Shillong	0.4	0.7	0.2	23-24	0.01	0.00	0.03
		Gauhati	0.1	0.0	5.0	2- 3	1.96	0.00	0.00
13	19-20 Jul 1968	Agartala	0.0	0.0	0.1	14-15	0.00	0.01	0.00
		Silchar	0.4	0.1	2.6	17-18	0.20	0.62	1.16
		Mawsynram	6.5	6.0	24.0	5- 6	7.50	1.03	2.38
		Shillong	0.8	0.2	1.7	5 6	0.35	0.13	0.03
		Gauhati	0.5	0.0	1.0	11-12	0.13	0.14	0.00
14	5 Aug 1967	Agartala	0.0	0.0	1.2	11-12	0.00	0.22	0.11
		Silchar	0.5	0.0	2.7	21-22	0.01	0.23	0.45
		Mawsynram	3.2	2.9	18.0	1- 2	5.90	1.85	3.60
		Shillong	0.5	0.2	3.0	23-24	0.06	0.00	0.50
		Gauhati	0.2	0.0	0.4	14-15	0.00	0.77	0.00

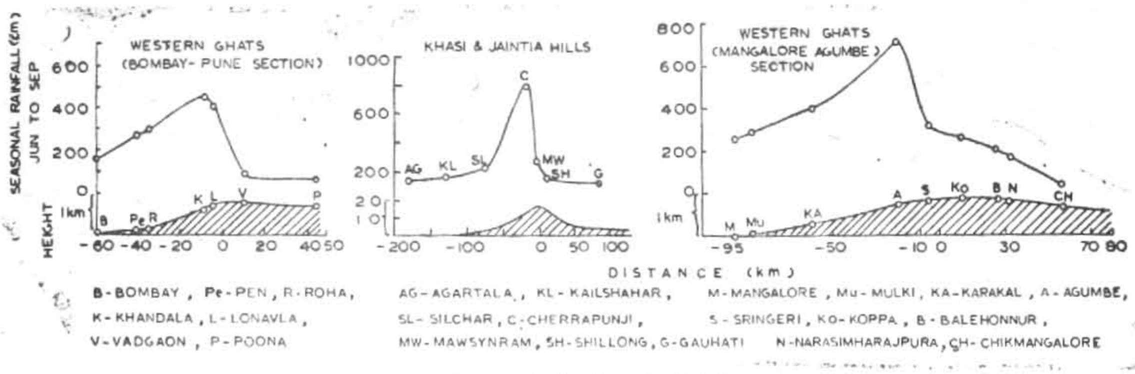

Fig. 1. Distribution of rainfall

TABLE 3

Correlation Coefficient 1966-1975

Correlation between	Jun	Jul	Aug	Sep
(1) Western Ghats—Bombay-Poona section				
Santacruz - Poona	.26	.36	.43	.25
Santacruz-Khandala	.50	.48	.54	.49
Kahandala-Poona	.49	.65	.65	.09
(2) Western Ghats-Agumbe-Chikmagalur section				
Mangalore-Chikmagalur	.06	.19	.20	.02
Mangalore-Agumde	.62	.48	.49	.67
Cgumbe-Chikmagalur	.42	.38	.20	.03
(3)Khasi, Jaintia hills—Agartala-Cherrapunji-Gauhati section)				
Agartala-Gauhati	.09	.29	.04	.03
Agartala-Cherrapunji	—.03	.44	.07	.23
Cherrapunji-Gauhati	.37	.39	.15	.09
Correlation for heavy rainfall at the peak				
Cherrapunji-Agartala	—.12	.42	.44	.02
Mahabaleswar-Santacruz	—.47	.00	.49	—.18
Khandala-Bombay(Colaba)	*	.39	.62	*
Cherrapunji-Gauhati	.13	.53	—.01	.21
Khandala—Poona	*	.55	.21	*

*cc not computed as the sample size is less than 10.

0000-0800 IST. This is a typical feature of the airflow pattern over Assam where due to katabatic winds orographically triggered thunderstorms occur during these hours. On the lee side also Shillong shows similar diurnal variation of rainfall intensities but the computed and observed intensities of precipitation vary between 0.0 & 1 mm/hr. Further, northwards on the lee side Gauhati also shows similar diurnal variation of rainfall intensities with a superposed convective type of precipitation with maxima occurring in the afternoon.

(*ii*) *Nature of heavy rainfall spells*

Table 3 gives the correlation between the rainfall recorded at mountain peak stations like Cherrapunji, Khandala and Agumbe *versus* windward and leeward stations like Agartala, Gauhati, Colaba, Pune, Mangalore and Chickmagalur. It is seen that in general the correlation is fairly high, when all classes of rainfall amounts are included. It is also fairly high during the month of July and August over the northern section of Western Ghats and during the month of July over the Khasi and Jaintia hills. Over the southern section of the Western Ghats it is higher during June and July. In general the correlation coefficient for peak — lee side station is high in the northern section of Western Ghats and is more than the windward-peak station value over the same section whereas it is the other way in the southern section. The correlation coefficients between windward and lee side stations in both the sections of Western Ghats are less than those of windward-peak and leeward-peak stations. The monthwise variation of correlation coefficients is high over the Assam hills regions as compared to the Western Ghats. This is because the Western Ghats are subjected to a more or less steady westerly flow during the southwest monsoon season as a whole whereas over the Khasi and Jaintia hills there is variation in the low level wind directions due to the oscillation of the monsoon trough. The monsoon trough in July and August generally runs from Delhi to Calcutta at 900 mb. The winds to the south of the trough are westsouthwesterly to westnorthwesterly while north of it southeasterly winds prevail. While during the break monsoon, the monsoon trough is close to the foot of the Himalayas and westerly winds prevail over the Khasi & Jaintia hills. Patches of heavy rain over the plains of northeast India occur during this period due to synoptic scale disturbances travelling over the Himalayas typical of the break and as such there is less dependence of rainfall on the leeward side of the Khasi & Jaintia hills on the orographic influence. If only heavy falls (more than 7 cm in 24 hours) are taken into consideration, significant correlation is observed during July & August only and the values for the other months show either small correlation or negative values. Simultaneous occurrence of heavy rainfall over the peak and windward side station over the plains were also examined for the five years period. There were 32 occasions when Colaba reported heavy rainfall and on 66 occasions Khandala reported heavy rainfall during 1966-1970 monsoon season. Out of these 12 occasions were of simultaneous occurrence. During the period 1971-1975 Mangalore recorded 77 days of heavy rainfall while there were 183 days of heavy rainfall over Agumbe of which the simultaneous

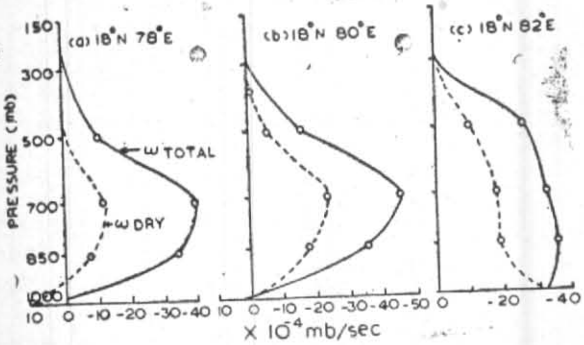

Fig. 2. Vertical profiles of W total & W dry

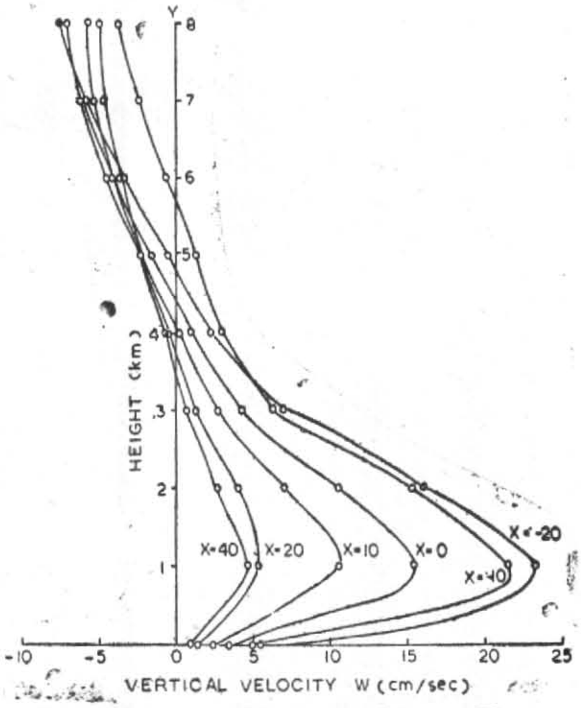

Fig. 3. Mangalore-Agumbe section of Western Ghats (Different distances x along the orography on 17 June 1973 and x=10 is the crest of the mountain)

occurrence of heavy rainfall was on 48 occasions. Similarly Agartala reported heavy falls on 13 occasions while Cherrapunji recorded heavy rainfall on 177 occasions. The simultaneous occurrence of heavy rainfall was on 6 occasions.

It is thus seen that th eheavy rainfall spells on the coast of Western Ghats (Colaba) are less frequently related to heavy falls over the peak of the Ghats (38 per cent) as compared to such occurrences over the Khasi & Jaintia hills (46 per cent) though the number of occurrence of simultaneous heavy falls is less over the Khasi & Jaintia hills. The frequency of simultaneous occurrence of heavy spells over Mangalore-Agumbe section is highest being of the order of 63 per cent. The days of heavy rainfall reported over Agumbe and Cherrapunji are comparable during 5-year spell of southwest monsoon but such occasions over Khandala were less frequent. The heavy rainfall along the west coast specially when Ghat stations get less rainfall than the coastal stations are probably due to vortices embedded in the trough along the west coast, Mukherjee *et al.* (1978). Formation and dissipation of small scale vortices take place incessantly along and off the west coast of India. Some of these vortices develop in significant shape and size causing noteworthy contribution towards rainfall along the west coast (George 1956).

In Khasi & Jaintia hills the causes of windward side stations getting more rainfall in some occasion than Ghat stations is due to synoptic and convective scale systems.

(iii) Comparison of vertical velocities

Das (1962) has shown that the mountain zones over NE India creates a forced ascent of air which is of the order of 5-10 *Cb*/12 hrs which is roughly equal to 11-25 mm/sec. The vertical velocity decreases with height. In order to maintain a steady circulation he postulates a warming rate of 1.6 deg. C/12 hr in the region. Computation on vertical velocities in synoptic scale circulations like monsoon depression has been made by Rao and Rajamani (1975). The order of vertical velocity was between 1 and 40 mm/sec being maximum in the lower levels. Fig.2 shows the distribution of vertical velocity with height along 18 deg. N across the sub-continent from the above study. Their study shows that the vertical motion due to topography in this latitude has a maximum at 74 deg. E which corresponds to the peak in the topographic profile and is or the order of 50 mm/sec. It is, however, seen from our computations that the average order of the vertical velocity due to orographic lifting is of the order of 20-30 cm/sec and reaches its maximum value of about 50-60 cm/sec in some cases, below 850 mb level. This would give maximum precipitation intensity of about 10-15 mm/hr assuming that the vertical velocity decreased rapidly with height and became zero at the height of reversal of the low level monsoon westerlies. The vertical velocity pattern from our model has somewhat similar vertical variation as obtained by Rao and Rajamani (1975). Therefore, the heavy and very heavy rainfall (7 cm/day and 13cm/day) in the orographic sections during the southwest monsoon seasons can also be explained to be an orographic effect. However, the order of vertical velocity is much smaller on the windward and leeward sides, being 5-10 cm/sec and damping out rapidly with height. Often on the leeward side, the vertical velocities are negative at lower levels and positive above 3-4 km and on the windward side maximum vertical velocity is reached at a very low level. This level progressively rises as we approach the crest of the mountain. Thus spells of heavy rain both on the wind-ward and leeward sides are to be accounted for by other causes. The intensity of precipitation from orographically induced vertical velocities (typical case shown in Fig. 3) from a saturated air column works out to be 6.1 mm/hr at the peak, 1.0 mm/hr (about 2.4 cm/day) on the windward side 40 km away from the peak and 0.9 mm/hr (2 cm/day) on the leeward side of the peak at a distance of 20 km.

Even when there is no heavy rainfall either over the peak or on the windward or leeward side stations the orographic influence cannot fully explain the observed precipitation away from the crest of the barrier. Over the crest the airstream characteristic on the windward side, the vertical velocity and microphysical processes within the cloud interact to produce the observed precipitation. The influence of synoptic and convective features appear very minor. Vertical velocities of larger magnitude are therefore required to explain the occurrence of observed rainfall over the coast and the leeward side. Apparently the heavy spells of rain on the windward and the leeward side of a barrier are due to synoptic and convective scale systems. However, over the three different mountainous sections studied the relative importance of synoptic and convective factors on the rainfall of the windward and leeward side is qualitatively different due to climatic factors like continentality and latitude. A quantitative assessment of this complex process needs further investigation.

5. Conclusions

(1). Precipitation along the west coast of India has a very small component of orographic precipitation and the main factors which contribute to the coastal rainfal seem to be synoptic and sub-synoptic scale system and convective instability.

(2 a). Often the precipitation along the west coast shows more intensity during the early morning and late evening and night which are typical of a diurnal cycle of a sea coast.

(2 b). In the Khasi & Jaintia hills rainfalls occurs mostly in late night and early morning hours where due to Katabatic winds orographically triggered thunderstroms occur during these hours.

(3a). The correlation coefficient of rainfall between windward and leeside stations in both the sections of Western Ghats as well as in Khasi & Jaintia hills are less than that between windward and peak stations and leeward and peak stations.

(3b). Correlation is higher during July and August in northern section of Western Ghats. Over the southern section it is higher during June and July.

(3c). The monthwise variation of correlation coefficients is higher over the Assam hills than over the Western Ghats due to variation in low level wind directions over the former caused by oscillations of the monsoon trough.

(4a). In general heavy rainfall amounts are less correlated than all rainfall amounts between windward and peak staions and peak station and leeward side precipitation.

(4b). In July correlation of heavy rainfall between peak stations and leeward stations are fairly high.

(4c). In August correlation of heavy rainfall between peak stations and windward stations are also fairly high.

(5a). Heavy rainfall in the windward side seem to be mainly due to synoptic, sub-synoptic and convective scale systems.

(5b). Heavy rainfall in the leeward side seem to be mainly due to synoptic and convective scale systems.

(5c). Heavy rainfall at the peak stations are almost entirely due to orographic effects.

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References

Banerji, S. K., 1929, *Indian J. Phys.*, pp. 699-745.

Das, P. K., 1962, *Tellus*, **14**, 2, pp. 212-220.

De, U. S., 1973, Some studies on mountain waves Ph.D. Thesis, Banaras Hindu University.

George, P. A., 1956, *Indian J. Met. Geophys.*, **7**, pp. 225-240.

Mukherjee, A. K., Rao, M. K. and Shah, K. C., 1978, *Indian J. Met. Hydrol. Geophys.*, **29**, 1 & 2, pp. 61-65.

Rao, K. V. and Rajamani, S. S., 1975, *Indian J. Met. Geophys.*, **26**, ,3 pp. 369-374.

Rao, Y. P., 1976, *Southwest Monsoon* – Met. Monograph Synop. Met. No. 1/1976, pp. 283-295.

Sarker, R. P., 1966, *Mon. Weath. Rev.*, **94**, 9, pp. 555-572.

Sarker, R. P., 1967, *Mon. Weath. Rev.*, **95**, 10, p. 673-684.

Sarker, R. P., Sinha Ray, K. C. and De, U. S., 1978, Indian *J. Met. Hydrol. Geophys.*, **29**, 1 & 2., pp. 335-348.